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# Modeling and optimization of energy consumption for power line communication systems

Wafae Bakkali

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**THÈSE / Télécom Bretagne**  
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En accréditation conjointe avec l'Ecole Doctorale Sigma  
Mention : Sciences et Technologies de l'Information et de la Communication

présentée par

**Wafae Bakkali**

préparée dans le département Signal et Communications  
Laboratoire Labsticc

# Modélisation et optimisation de la consommation énergétique des systèmes à courants porteurs en ligne

Thèse soutenue le 14 décembre 2015

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N° d'ordre : 2015telb0372

Sous le sceau de l'Université Européenne de Bretagne

**Télécom Bretagne**

En accréditation conjointe avec l'Ecole Doctorale Sicma

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Laboratoire : Lab-STICC

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*To the Memory of My Father  
To my Mother...*



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# Abstract

In the last few years, the research in the area of green and energy-efficient networking has gained a great interest on the part of network providers and equipment manufacturers. Considering Power Line Communication (PLC), more effort has been made on achieving higher data rates, but the topic of energy efficiency has still not been explored very much yet. In this thesis, we focus on the energy efficiency of indoor PLC networks.

On the one hand, we investigate the power consumption of PLC modems by conducting several experiments and measurements of many commercial modems. Based on the results, we provide a detailed analysis of the power consumption behaviour of PLC modems. Then, we propose measurement-based power models for both Single Input Single Output (SISO) and Multiple Input Multiple Output modems (MIMO) PLC modems. The developed models allow us to quantify the power consumption associated with various communication states and different operation modes of PLC modems.

On the other hand, we study the benefits of using relay nodes in PLC networks for energy efficiency purpose. We consider half-duplex Decode and Forward (DF) relay systems and explore their performance for two strategies, i.e., when the time allocation between the source and the relay nodes is set uniform and when it is optimized. We propose an iterative algorithm to derive the optimal time allocation for power minimization. Finally, through extensive numerical results based on both measured PLC channels and PLC noise and simulated ones, we show by considering two representative scenarios, that depending on the idle power consumption of PLC modems, significant power saving can be achieved by implementing relaying in PLC networks.

**Keywords:** Energy efficiency, Power Line Communication, Power consumption measurements, Power consumption models, Decode and Forward, Relay, Optimal time allocation

# Résumé

Au cours des dernières années, la recherche dans le domaine de l'efficacité énergétique des réseaux de télécommunications a suscité un intérêt grandissant pour les fournisseurs de réseaux et les fabricants d'équipements. Dans les systèmes à Courants Porteurs en Ligne (CPL), les efforts se sont principalement concentrés sur l'augmentation du débit. Cependant, très peu d'attention a été accordée au sujet de l'efficacité énergétique. Dans cette thèse, nous nous concentrons sur l'amélioration de l'efficacité énergétique des réseaux CPL indoor.

D'une part, nous investiguons la consommation énergétique des modems CPL en menant plusieurs expérimentations et mesures sur plusieurs modems commerciaux. En se basant sur les résultats obtenus, nous fournissons une analyse détaillée du comportement énergétique des modems CPL. Ensuite, nous proposons des modèles de consommation électrique pour les systèmes CPL SISO (Single Input Single Output) et MIMO (Multiple Input Multiple Output). Les modèles développés permettent de quantifier la consommation d'énergie associée à divers états de communication et modes de fonctionnement des modems CPL.

D'autre part, nous évaluons l'apport énergétique de l'utilisation des relais dans les réseaux CPL. Nous considérons un système de relais Half-Duplex DF (Decode and Forward) et nous étudions ses performances pour deux stratégies, à savoir, pour une allocation de temps uniforme et optimale entre la source et le relais. Nous proposons un algorithme itératif pour calculer l'allocation de temps optimale qui minimise la puissance. Enfin, nous montrons par de nombreux résultats numériques, basés à la fois sur des canaux CPL mesurés et simulés, et en considérant deux scénarios représentatifs, qu'en fonction de la puissance consommée par les modems CPL lorsqu'ils sont en mode de veille, une réduction de consommation d'énergie significative peut être obtenue par la mise en place de relais dans les réseaux CPL.

**Mots clés:** Efficacité Energétique, Courants Porteurs en Ligne, Mesures de consommation de puissance, Modèles de consommation de puissance, Decode and Forward, Relais, Allocation de temps optimale



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# Abbreviations

<b>AC</b>	<b>A</b> lternating <b>C</b> urrent
<b>AF</b>	<b>A</b> mplify and <b>F</b> orward
<b>ARQ</b>	<b>A</b> utomatic <b>R</b> epeat <b>R</b> equest
<b>ATS</b>	<b>A</b> rrival <b>T</b> ime <b>S</b> tamp
<b>AWGN</b>	<b>A</b> dditive <b>W</b> hite <b>G</b> aussian <b>N</b> oise
<b>BPSK</b>	<b>B</b> inary <b>P</b> hase <b>S</b> hift <b>K</b> eying
<b>BS</b>	<b>B</b> ase <b>S</b> tation
<b>CB</b>	<b>C</b> ircuit <b>B</b> reaker
<b>CCo</b>	<b>C</b> entral <b>C</b> oordinator
<b>CF</b>	<b>C</b> ompress and <b>F</b> orward
<b>CM</b>	<b>C</b> ommon <b>M</b> ode
<b>CP</b>	<b>C</b> yclic <b>P</b> refix
<b>CSMA/CA</b>	<b>C</b> arrier <b>S</b> ense <b>M</b> ultiple <b>A</b> ccess with <b>C</b> ollision <b>A</b> voidance
<b>D</b>	<b>D</b> estination
<b>DC</b>	<b>D</b> irect <b>C</b> urrent
<b>DemF</b>	<b>D</b> emodulate and <b>F</b> orward
<b>DF</b>	<b>D</b> ecode and <b>F</b> orward
<b>DSP</b>	<b>D</b> igital <b>S</b> ignal <b>P</b> rocessecor
<b>DT</b>	<b>D</b> irect <b>T</b> ransmission
<b>EMC</b>	<b>E</b> lectromagnetic <b>C</b> ompatibiliy
<b>EC</b>	<b>E</b> uropean <b>C</b> ommission
<b>EU</b>	<b>E</b> uropean
<b>FDMA</b>	<b>F</b> requency <b>D</b> ivision <b>M</b> ultiple <b>A</b> ccess
<b>FFT</b>	<b>F</b> ast <b>F</b> ourier <b>T</b> ransform

<b>HD</b>	<b>Half Duplex</b>
<b>GP</b>	<b>Green PHY</b>
<b>ICT</b>	<b>Information and Communication Technologies</b>
<b>ICV</b>	<b>Integrity Check Value</b>
<b>ISI</b>	<b>Inter Symbol Interference</b>
<b>LAN</b>	<b>Local Area Network</b>
<b>LDPC</b>	<b>Low Density Parity Check Code</b>
<b>LS</b>	<b>Least Square</b>
<b>MAC</b>	<b>Mac Access Control</b>
<b>MPDU</b>	<b>Mac Protocol Data Unit</b>
<b>MIMO</b>	<b>Multiple Inputs Multiple Outputs</b>
<b>MP</b>	<b>Main Panel</b>
<b>MTL</b>	<b>Multi Conductor Transmission Lines</b>
<b>MISO</b>	<b>Multiple Inputs Single Output</b>
<b>N</b>	<b>Neutral</b>
<b>OFDM</b>	<b>Orthogonal Frequency Division Multiplexing</b>
<b>QAM</b>	<b>Quadrature Amplitude Modulation</b>
<b>QoS</b>	<b>Quality of Service</b>
<b>QPSK</b>	<b>Quadrature Phase Shift Keying</b>
<b>P</b>	<b>Phase</b>
<b>PB</b>	<b>Physical Block</b>
<b>PE</b>	<b>Protective Earth</b>
<b>PLC</b>	<b>Power Line Communication</b>
<b>PSD</b>	<b>Power Spectral Density</b>
<b>R</b>	<b>Relay</b>
<b>RF</b>	<b>Radio Frequency</b>
<b>S</b>	<b>Source</b>
<b>SIMO</b>	<b>Single Input Multiple Putputs</b>
<b>SISO</b>	<b>Single Input Single Output</b>
<b>SNR</b>	<b>Signal to Noise Ratio</b>
<b>TCC</b>	<b>Convolutional Code</b>
<b>TCP</b>	<b>Transmission Control Protocol</b>

<b>TDMA</b>	<b>T</b> ime <b>D</b> ivision <b>M</b> ultiple <b>A</b> ccess
<b>UDP</b>	<b>U</b> ser <b>D</b> atagram <b>P</b> rotocol
<b>UMTS</b>	<b>U</b> niversal <b>M</b> obile <b>T</b> elecommunications <b>S</b> ystem
<b>WLAN</b>	<b>W</b> ireless <b>L</b> ocal <b>A</b> rea <b>N</b> etwork
<b>2TL</b>	<b>T</b> wo <b>C</b> onductor <b>T</b> ransmission <b>L</b> ines



# Introduction générale

L'amélioration de l'efficacité énergétique des systèmes de communication fait partie des principaux défis auxquels la science doit faire face dans le futur. En effet, l'énergie joue un rôle important dans notre vie quotidienne, en permettant des applications variées, dont le chauffage, l'éclairage, la mobilité et la communication. Cependant, en dépit de son rôle primordial dans l'amélioration de nos conditions de vie, l'utilisation excessive et inefficace de l'énergie a plusieurs impacts négatifs environnementaux, économiques et sociaux comme les émissions de gaz à effet de serre, la pollution de l'air ou bien les coûts élevés liés à l'exploitation de l'énergie. Pour relever ces défis, des efforts considérables ont été consacrés ces dernières années pour améliorer l'efficacité énergétique, à savoir, réduire la quantité d'énergie requise pour fournir des produits et services, afin d'économiser de l'argent et de protéger l'environnement.

Les technologies de l'information et de la communication (TIC) représentent un pourcentage allant d'environ 2% à 10% de la consommation énergétique mondiale, augmentant de 16% à 20% par an, et d'un pourcentage de 2% environ des émissions totales de carbone. En outre, il est estimé que les réseaux de télécommunication sont responsables d'une grande quantité de ces pourcentages. (Pour plus de détails, voir Chapitre 2).

Vu l'impact important du secteur des TIC sur la consommation d'énergie et les émissions de gaz à effet de serre, plusieurs collaborations académiques, industrielles et gouvernementales ont pris des mesures pour améliorer l'efficacité énergétique des

réseaux TIC. Ces initiatives couvrent plusieurs technologies sans fil et filaires, incluant les systèmes à courant porteurs en ligne (CPL).

La technologie CPL, qui utilise le réseau électrique comme un support de transmission de données, est une technologie de télécommunication qui possède un long historique de développement et qui a un large champ d'applications et d'implémentations. Jusqu'à présent, les efforts se sont principalement concentrés sur l'augmentation du débit dans les réseaux CPL, tandis que très peu d'attention a été accordée au sujet de l'efficacité énergétique.

Avec l'évolution rapide de la technologie CPL, l'efficacité énergétique est sans aucun doute une priorité pour la conception des futurs systèmes CPL.

## 0.1 Contexte de la thèse et objectifs de recherche

Le travail présenté dans cette thèse a été réalisé au sein d'Orange Labs (Lannion) et de Telecom Bretagne (Brest), et a été mené dans le cadre du projet de recherche FUI14 GREENCoMM [[GREENCoMM](#)], qui implique huit partenaires industriels et académiques, incluant Orange Labs et Télécom Bretagne, et vise à améliorer l'efficacité énergétique des technologies de connectivités domestiques, à savoir, WiFi, CPL et fibres optiques.

Le principal objectif de la thèse est de mesurer, modéliser et optimiser la consommation électrique des systèmes CPL. En particulier, ce travail de recherche tente principalement de répondre aux questions suivantes:

- Quelles sont les méthodes à utiliser pour mesurer et analyser la consommation énergétique des modems CPL?
- Quelles sont les parties qui consomment le plus d'énergie dans les systèmes CPL?
- Comment modéliser la consommation d'énergie des systèmes CPL?
- Comment réduire la consommation d'énergie des modems et réseaux CPL?

- Quelle est la quantité d'énergie qu'on peut économiser?

## 0.2 Contributions de la thèse

Dans cette thèse, nous avons menés des travaux de recherche afin de répondre aux questions cités précédemment. Nos principales contributions peuvent être résumés comme suit:

Tout d'abord, nous avons monté des bancs de mesures pour caractériser la consommation électrique des modems CPL. Ensuite, nous avons mené une étude analytique détaillée afin de quantifier l'énergie consommée par les modems CPL en fonction du débit binaire, du nombre de trames Ethernet, et de la taille des trames Ethernet. En premier lieu, nos expérimentations ont été réalisées en utilisant 6 paires de modems CPL commerciaux SISO "Single Input Single Output". Ensuite, elles ont été étendues pour inclure la nouvelle génération de modems CPL avec la fonctionnalité MIMO "Multiple Input Multiple Output". De plus, afin de généraliser notre analyse, nos mesures ont été basées sur des modems possédant des caractéristiques différentes, par exemple, les modems ont des chipsets, ports Ethernet, débits binaires utiles, débits maximaux et bandes de fréquences différents. Les modems CPL utilisés sont également compatibles avec des standards différentes. A notre connaissance, cette analyse est la première étude présentée dans la littérature CPL à accès ouvert sur le comportement énergétique des modems CPL.

En se basant sur ces mesures de consommation d'énergie, nous avons par la suite développé des modèles de consommation électrique réalistes qui permettent de quantifier l'énergie consommée pour divers états de communication, différents modes de fonctionnement, différents débits de communication et différents tailles de trames Ethernet, pour les modems CPL SISO et MIMO. En particulier, nous avons montré que la puissance totale consommée par les modems CPL est la somme des éléments suivants: la consommation à vide, la consommation relative aux ports Ethernet, la consommation d'énergie liée à la transmission, la consommation d'énergie liée à

la réception, la consommation d'énergie associée au traitement des trames Ethernet et la consommation d'énergie associée au traitement des blocs physiques CPL. Les paramètres des modèles développés ont été ensuite estimés en utilisant une régression linéaire multiple. A notre connaissance, nos modèles sont les premiers modèles de consommation d'énergie des modems CPL existants dans la littérature CPL à accès ouvert.

Suite aux modèles de consommation développés, nous nous sommes concentrés sur la mise en place des relais dans les réseaux CPL afin d'améliorer leur efficacité énergétique. Dans ce cadre, nous avons développé un modèle général de consommation d'énergie pour les systèmes de relais CPL SISO DF "Decode and Forward", dans lequel la consommation de puissance statique des modems CPL est prise en considération. Cette partie statique que les modems consomment lorsqu'ils sont en mode de veille n'est généralement pas tenue en compte dans les travaux précédents.

Ensuite, nous avons optimisé le temps de transmission entre les liens du réseaux à relais afin d'obtenir la meilleure performance de la stratégie DF. Nous avons proposé un algorithme itératif pour trouver le temps optimal qui minimise la puissance de transmission, et nous avons comparé sa performance avec la stratégie d'allocation de temps uniforme, qui est simple à implémenter, mais ne tient pas en compte des atténuations variables des canaux CPL sur le réseau à relais.

Finalement, en utilisant à la fois des canaux CPL (fonctions de transfert et bruits stationnaires) simulés et mesurés, et en tenant compte des valeurs mesurées de la consommation de puissance statique des modems CPL, nous avons montré en considérant deux scénarios représentatifs, qu'en fonction de la puissance consommée par les modems CPL lorsqu'ils sont en mode de veille, un gain énergétique important peut être obtenu par la mise en place de relais dans les réseaux CPL.

### 0.3 Structure de la thèse

Ce document est constitué de six chapitres. Le premier chapitre fournit une introduction qui présente les concepts de base des systèmes CPL et les éléments les

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plus importants pour la compréhension du travail mené dans le cadre de la thèse. Le deuxième chapitre donne un aperçu sur l'état de l'art actuel des techniques de communications à faible consommation d'énergie, et cite les principales approches permettant d'améliorer l'efficacité énergétique dans les réseaux sans fil et filaires. Une classification de ces approches en fonction de leur principe et niveau de fonctionnement est également donnée au chapitre 2. Le chapitre 3 est consacré aux mesures et analyses de consommation d'énergie des modems CPL SISO et MIMO. Le chapitre 4 présente les modèles de consommation d'énergie proposés pour les modems CPL SISO et MIMO. Les chapitres 4 et 5 analysent la performance de l'efficacité énergétique des réseaux CPL avec relais, et comparent le gain obtenu en utilisant les stratégies d'allocation de temps uniforme et optimale.

# General Introduction

Energy efficiency is recognized today as one of the most critical issues which science must face in the near future. Indeed, energy plays an important part in our daily lives, by enabling heating, lighting, mobility and communication. However, despite its potential uses in improving our living conditions in many ways, there are a variety of environmental, economic and social negative impacts associated with the extensive and inefficient use of energy such as greenhouse gas emissions, air pollution or high energy operating costs. To address these challenges, valuable efforts have been dedicated in recent years to improving energy efficiency, i.e., reducing the amount of energy required to provide products and services, with the primary goal of saving money and protecting the environment.

The Information and Communication Technologies (ICT) sector accounts for a percentage ranging from around 2% to 10% of the world's annual electrical energy consumption, rising from 16% to 20% per year, and for around 2% of total carbon emission. In addition, it is estimated that the telecommunication networks are responsible for a large amount of these percentages. (See details in Chapter 2).

Conscious of the important impact of the ICT sector on energy consumption and greenhouse gas emissions, various industry-academia-governments collaborations and initiatives have taken steps for improving the energy efficiency of ICT networks. These initiatives cover several wireless and wired technologies, among which Power Line Communications (PLC).

PLC, which uses the electrical grid as a transmission medium, is a telecommunications technology with a long history, a wide scope of applications and implementations. Up to now, more attention has been given to increasing data rates in PLC, while the energy efficiency has still not been explored very much.

With the rapid evolution of the PLC technology, energy efficiency is undoubtedly a priority for the design of future PLC systems.

## 0.4 Thesis overview and research objectives

The work presented in this thesis was carried out at Orange Labs (Lannion) and Telecom Bretagne (Brest), and is part of the french research project FUI14 GREEN-CoMM [GREENCoMM], which involves eight industrial and academic partners, including Orange Labs and Telecom Bretagne, and aims at improving the energy efficiency of home network technologies, i.e., Wi-Fi, PLC and optical fibers.

The main objective of the thesis is power consumption measuring, modeling and optimizing for PLC systems. In particular, this research primarily attempts to answer the following questions:

- What are the methods to measure and analyze the power consumption of PLC modems?
- What are the most consuming parts in PLC modems?
- How can we model the power consumption of PLC modems?
- How could power consumption be reduced in PLC modems and networks?
- How much power could be saved by the power management solutions?

## 0.5 Thesis Contributions

Throughout this thesis, we carried out researches to answer the research questions outlined previously. Our main contributions can be summarized as follows:

We first designed experiments to measure the electrical power consumption of PLC modems and conducted a detailed measurement study to quantify the power consumed by PLC modems as a function of bit rate, Ethernet frames rate and Ethernet frames size. Our experiments were first performed using 6 pairs of traditional Single Input Single Output (SISO)-based commercial PLC modems. Further, they were extended to include the new family of PLC modems with Multiple Inputs Multiple Output (MIMO) functionalities. To show the general applicability of our analysis, our measurements were based on modems with different features, e.g., different chipsets, Ethernet ports speed, useful bit-rates, maximum bit-rates, frequency bands. Modems are also compliant with different standards. We believe that this is the first work presented in the open PLC literature that analyzes the power consumption behaviour of PLC modems.

Based on these power consumption measurements, we developed realistic models that can be used to predict the power consumed for various communication states, different operation modes, variable data rates and variable Ethernet frame sizes, of both SISO and MIMO PLC modems. In particular, we showed that the power consumed by PLC modems consists of the following components: idle power consumption, standby power consumption, transmission power consumption, reception power consumption, power consumption associated to the processing of Ethernet frames and power consumption associated to the processing of PLC Physical Blocks (PBs). These power components were then estimated by applying a multiple regression analysis to the measured data. To the best of our knowledge, our models are the first power consumption models of PLC presented in the open literature.

Following these models, we turned our interest towards the energy efficiency performance associated with the use of relay nodes in PLC networks. We derived a general power consumption model for Decode and Forward (DF) SISO PLC relay systems, in which the static power consumption of PLC modems, which is usually neglected in previous works, is taken into account.

We found the best performance for DF strategy by optimizing the transmission time between the links of the relay network. We proposed an iterative algorithm to find

the optimal time share for power minimization and compared its performance with that of the uniform time allocation strategy, which is simple to be implemented, but doesn't take advantage of the PLC channel variability.

Then, using both simulated and measured PLC channels and PLC noise and considering the measured static power consumption values of PLC modems, we showed by considering two representative scenarios, that depending on the idle power consumption value of PLC modems, i.e., the static power value consumed by the modem when it is in idle mode, significant power efficiency gain can be obtained by using the DF relay protocol in PLC networks.

## 0.6 Structure of the thesis

This thesis is divided into six chapters. The first chapter provides an introduction that highlights the basic concepts of PLC systems and the most important elements for the understanding of the work presented in the thesis. The second chapter gives an overview of the current state of the art of green communications, and briefly surveys the main approaches to improve energy efficiency in both wireless and wired networks. A classification of these approaches based on their principle and level of operation is also given in chapter 2. Chapter 3 is dedicated to the power consumption measurements and analysis of SISO and MIMO PLC modems. Chapter 4 presents the proposed power consumption models for both SISO and MIMO PLC modems. Chapters 5 and 6 analyze the energy efficiency performance of relay-assisted PLC networks, and compare the gain obtained while using uniform and optimal time allocation strategies.

# Publications

## Peer-reviewed journal paper

1. **W. Bakkali**, P. Pagani and T. Chonavel, “Throughput Analysis and Energy Efficiency Optimization of Relay-Assisted PLC Networks,” IET Communications (Under submission).

## International conferences

2. **W. Bakkali**, M. Tlich, P. Pagani and T. Chonavel, “A Measurement-Based Model of Energy Consumption for PLC Modems,” IEEE International Symposium on Power Line Communications and its Applications (ISPLC), Glasgow, UK, 2014.  
**(Best student paper award)**
3. **W. Bakkali**, P. Pagani and T. Chonavel, “Energy Efficiency Performance of Relay-Assisted Power-Line Communication Networks,” IEEE Consumer Communications and Networking Conference (CCNC), Las Vegas, USA, 2015.
4. **W. Bakkali**, P. Pagani and T. Chonavel, “Experimental Analysis and Modeling of Energy Consumption Behaviour for MIMO PLC Modems,” IEEE Global Communications Conference (GLOBECOM), San Diego, USA, 2015.
5. **W. Bakkali**, P. Pagani, T. Chonavel and A. M. Tonello, “Energy Efficiency Performance of Decode and Forward MIMO Relay PLC Systems,” IEEE ISPLC, Bottrop, Germany, 2016. **(Best student paper award)**

# Chapter 1

## Broadband Power Line Communications

### 1.1 Introduction

Power Line Communications is a technology that exploits the existing electric power infrastructures to provide multimedia services for various applications, e.g., home or office networks, vehicles, by coupling radio frequency (RF) signals onto the power line. Depending on their operating frequencies, PLC can be categorized into: Ultra Narrowband (30 Hz-3 KHz), Narrowband (3-500 kHz), and Broadband (1.8-250 MHz) [Berger2014, p. 253–266]. PLC systems have many advantages over other wired and wireless communication technologies. The first advantage is that PLC systems provide available access to the Internet anywhere there is an alternating current (AC) outlet, without any need for additional installations. In most cases, building a communication network using the existing AC electrical wiring is easy to install and very cost effective. Another potential benefit of PLC is the possibility of its use for smart grid applications since it could offer the opportunity to remotely control the appliances without supplementary installations [Galli2010].

This chapter provides an introduction to the PLC technology. Indeed, basic understanding of the main features of PLC systems is necessary for the investigation and development of new energy efficient PLC techniques. The chapter will only focus

on broadband PLC. The historical development and current advances in the PLC technology are first outlined. Then, after a brief description of the typical indoor PLC network structure, information related to PLC standardization is given. The main transmission techniques exploited by PLC systems and the related Electromagnetic Compatibility (EMC) issues are highlighted, and a brief overview of PLC channel and noise modeling is also provided. Finally, a conclusion is given in the last section.

## 1.2 Brief history of the PLC technology

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

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

### 1.3 Indoor power line network structure

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

### 1.4 The status of broadband PLC standardization

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

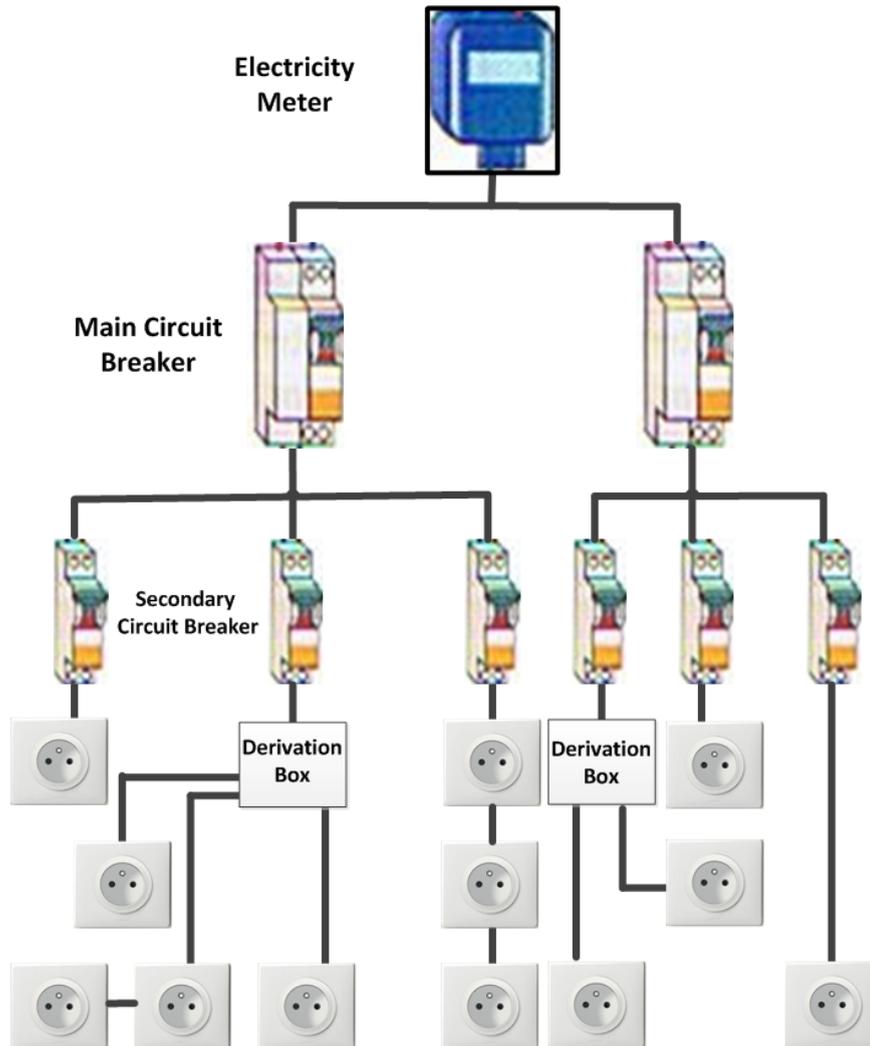


FIGURE 1.1: A simplified diagram of the typical structure of an indoor power line network

### 1.4.1 IEEE 1901

The IEEE 1901 standards are developed by the IEEE P1901 workgroup and define the technology for high-speed power line communications. The standards defines methods for both in-home networking and access networking (Internet access). The IEEE 1901.2010 standard uses transmission frequencies below 100 MHz and achieves high data rates up to 500 Mbps at the physical layer. It includes two different physical layers, one based on Fast Fourier Transform (FFT) Orthogonal Frequency Division Multiplexing (OFDM) modulation (mainly in use in the USA and Europe) and another based on Wavelet OFDM modulation (restricted to Japan). The

standard is also compliant with EMC limits set by national and international regulatory authorities, so as to ensure successful coexistence with wireless and other telecommunications systems.

#### **1.4.1.1 HomePlugAV**

HomePlug AV is a standard defined by the HomePlug Alliance and currently one of the most implemented specifications in PLC modems. It is an evolution of its predecessor, HomePlug 1.0, which was released by the alliance in 2003. HomePlug AV operates in the frequency range from 2 to 30 MHz and can achieve data rates up to 200 Mbps at the physical layer and 150 Mbps at the MAC layer. It uses windowed OFDM modulation together with Turbo Convolutional Code (TCC). Regarding OFDM symbols, 1155 carriers from 1.8 MHz to 30 MHz are used in HomePlug AV, so that the separation between carriers is approximately 24.4 KHz. However, some of these carriers coincide with radio amateur emission bands and cannot be used, which brings the total of usable carriers down to 917. The carriers used for data transmission may be coherently modulated with a Binary phase-shift keying (BPSK), Quadrature phase-shift keying (QPSK), 16 Quadrature amplitude modulation (QAM), 64 QAM, 256 QAM or 1024 QAM. On the Media Access Control (MAC) Layer, HomePlug AV provides two different kinds of communication services:

- Quality of Service (QoS) connection-oriented, contention-free service, based on periodic time division multiple access (TDMA) allocations of adequate duration, to support the QoS requirements of demanding applications
- Connectionless, prioritized contention service, based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), to support both best-effort applications and applications that rely on prioritized QoS.

### 1.4.1.2 HomePlug AV2

HomePlug AV2 was introduced in January 2012 and is dedicated to next-generation powerline networking. Compared to Homeplug AV, HomePlug AV2 provides additional key features

- Extended frequency bandwidth (30 to 86 MHz) and data rates up to 2 Gbps.
- MIMO with beamforming for higher data rates. (Further details on MIMO techniques may be found in Section 1.5.2 of this chapter)
- Power save modes to improve energy efficiency. Specifically, HomePlug AV2 introduces two techniques for transmit power optimization. The transmit power back-off technique which reduces the transmitted power spectral density for a selected set of carriers when this can be done without adversely affecting performance, and the EMC Friendly Power Boost technique that allows the transmitter to increase the power on some carriers without exceeding regulatory limits.
- Higher order modulation (4096 QAM) and higher code rates (16/18 code rate).
- Routing and repeating, that is, communication between devices that cannot communicate directly with other devices in the PLC network is provided using one or more intermediate nodes acting as repeaters.

### 1.4.1.3 HomePlug GP

HomePlug Green PHY is a special simplified version of the standard, derived entirely from HomePlug AV and designed for Smart Grid applications like smart electric meters and appliance monitoring. HomePlug GP uses the same frequency band, modulation technique (OFDM) and code rate as HomePlug AV. However, since a high data rate is not required for Smart Grid applications, HomePlug GP has a peak rate of only 10 Mbps, due to the restriction of OFDM carrier modulation exclusively to QPSK.

HomePlug GP and HomePlug AV2 are completely interoperable with HomePlug

TABLE 1.1: HomePlug, HomePlug AV2 and HomePlug GP comparison

	HomePlug AV	HomePlug AV2	HomePlug GP
Main applications	Multimedia net- working	Next generation powerline multi- media networking	Smart grid home
Frequency band- width (MHz)	2-30	1.8-86	2-30
Number of sub- carriers	1155	4096	1155
Supported sub- carrier modula- tion formats	BPSK, QPSK, 16 QAM, 64 QAM, 256 QAM, 1024 QAM	BPSK, QPSK, 16 QAM, 64 QAM, 256 QAM, 1024 QAM, 4096 QAM	QPSK only
Forward error correction (FEC) (turbo code) rate	1/2 or 16/21	1/2, 16/21 or 16/18	1/2
Maximum PHY data rate	200 Mbps	2 Gbps	10 Mbps

AV and with IEEE P1901, while each provides a distinct set of capabilities focusing on different aspects and issues related to different applications and operating environments. A comparative overview on the main differences between HomePlug AV, HomePlug AV2 and HomePlug GP is given in Table 3.1.

#### 1.4.2 ITU-T G.hn

The ITU-T G.hn standard is a home network standard, and unlike IEEE 1901 which is just a PLC standard, it defines networking over power lines and also over phone lines and coaxial cables, with data rates up to 1 Gbps. ITU-T G.hn is promoted by the HomeGrid Forum; an industrial consortium developing products based on the ITU-T G.hn standard.

In the same way as HomePlug GP that was developed by the HomePlug Powerline Alliance, ITU-T G.hn includes a low complexity profile specifically to support

Smart Grid home applications. Although ITU-T G.hn and IEEE 1901 have many similar features, one major difference is the use of different FECs, that is, low-density parity-check code (LDPC) is used by ITU-T G.hn instead of TCC.

## 1.5 Transmission techniques exploited by the PLC technology

### 1.5.1 Modulation

The power line transmission environment is particularly hostile to digital communications, due to its strong frequency selective behavior, the presence of impulsive noise, etc. Therefore, the choice of a modulation technique that can stand up against the PLC channel peculiarities is very crucial. Among a variety of techniques, including single-carrier, multi-carrier and spread spectrum [Agarwal2009], OFDM is considered as an excellent candidate for high data rate transmission over powerline. OFDM is currently the most commonly used modulation scheme in PLC. Moreover, all PLC standards and specifications discussed previously, e.g., IEEE 1901, ITU-T G.hn, and HomePlug AV define physical layers based on OFDM.

The general idea of OFDM is to split high-speed data symbols into slow narrowband data streams. Specifically, a high rate serial data stream is divided into a number of sub-streams, and the data within each sub-stream are modulated, and transmitted simultaneously over parallel and separate subcarriers occupying a sub-band which is so narrow that the associated sub-channel has a flat frequency response. Then, a frequency-selective channel becomes equivalent to a set of multiple flat-fading sub-channels, which allows the use of simple equalization.

In OFDM, the sub-carrier frequencies are chosen so that the sub-carriers are orthogonal to each other. This requires that the sub-carrier frequencies must fulfill the orthogonality condition, i.e., the sub-carrier spacing is  $\Delta f = \frac{1}{T_s}$ , where  $T_s$  is the useful OFDM symbol duration. Fig. 1.2 illustrates an OFDM signal in both frequency and time domains.

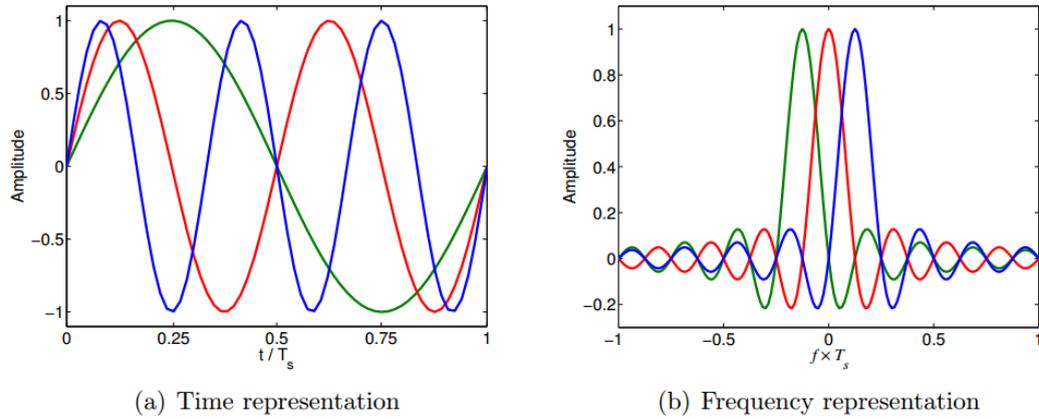


FIGURE 1.2: Time and frequency domain representation of an OFDM signal

In practice, the orthogonality allows for a simplified design of both the transmitter and receiver. That is, the modulator and the demodulator are implemented using the FFT algorithm on the receiver side, and inverse FFT on the transmitter side.

Also, by dividing the data stream into  $N$  subcarriers, the symbol duration in a subcarrier will be  $N$  times longer than at the transmitter input, which means that each symbol occupies a narrower band but a longer time period. To avoid Inter Symbol Interference (ISI), a guard interval is introduced for each OFDM symbol. During this interval, which has to be filled with a cyclical extension of the same OFDM symbol, no useful data is transmitted. This extension is called the cyclic prefix (CP).

Finally, note that, a very important property of OFDM is its adaptability. Specifically, according to the PLC signal-to-noise ratio (SNR), it is possible to assign different data rates, constellation sizes and transmit power to distinct subcarriers in order to optimize the system performance in terms of bit rate or power consumption. This important property will be exploited as a resource allocation technique in this thesis in order to minimize the power consumption or to maximize the data rate of the system by appropriately allocating bits and transmit power to different sub-carriers. (For further details about resource allocation techniques, see Section 2.4.4 in Chapter 2).

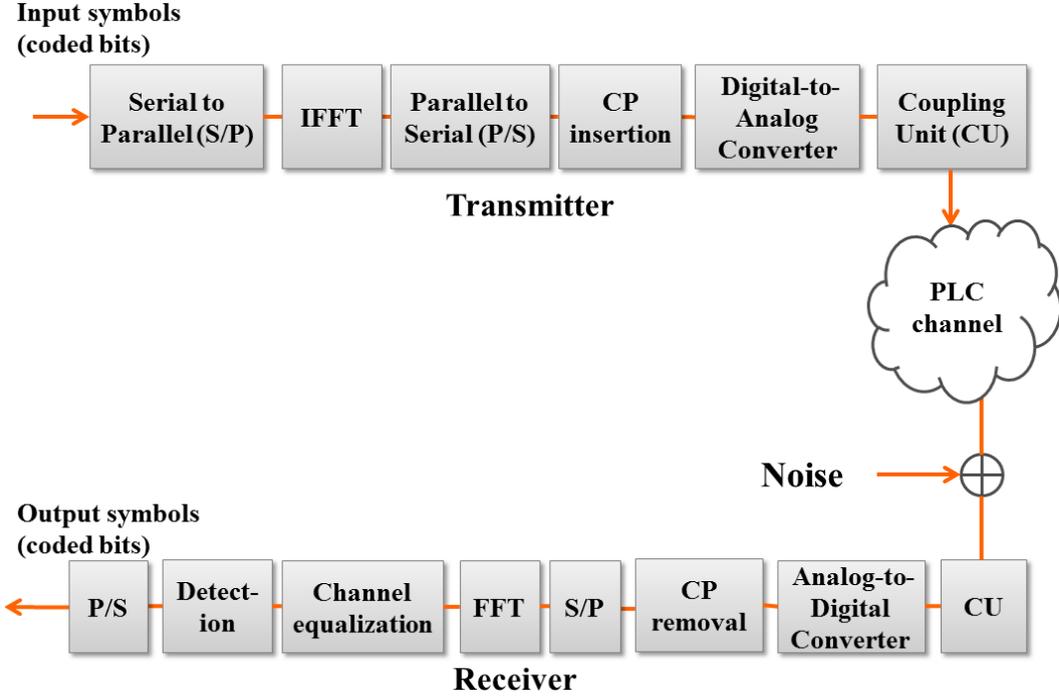


FIGURE 1.3: Block diagram of an OFDM system including a transmitter, a PLC channel and a receiver.

### 1.5.1.1 OFDM Transmission chain

Fig. 1.3 depicts the functionality of an OFDM communication chain consisting of a transmitter, a receiver and a PLC channel. At the transmitter side, as discussed earlier, the data stream is split into  $N$  parallel streams that modulate  $N$  subcarriers using Inverse FFT. Each base-band sub-carrier is of the form:

$$\phi_k(t) = e^{j2\pi k \frac{t}{T_s}} \quad (1.1)$$

One baseband OFDM symbol (without a cyclic prefix) is expressed as

$$s(t) = \sum_{k=0}^{N-1} x_k \phi_k(t), \quad 0 < t < T_s \quad (1.2)$$

where  $x_k$  are the data symbols (typically taken from a PSK or QAM symbol constellation). The CP is added in all OFDM symbols before preparing the signal for

transmission. The OFDM signal with CP is thus:

$$s(t) = \sum_{k=0}^{N-1} x_k \phi_k(t), \quad -T_g < t < T_s \quad (1.3)$$

where  $T_g$  is the duration of the guard interval.

At the receiver side, more or less the opposite happens in addition to the required channel equalization and symbol detection steps.

### 1.5.2 MIMO PLC

PLC networks promise to get faster with the release of a new family of devices using MIMO techniques [Berger2014]. The concept of MIMO has been developed over many years, mainly for wireless communications, and considered the use of multiple antennas at both the transmitter and the receiver.

MIMO technology can be similarly applied to PLC by using all three wires: phase (P), neutral (N) and ground or protective earth (PE) in a typical electrical outlet (as opposed to just phase and neutral for SISO systems). Therefore, two streams of data can be sent simultaneously on the different paths. MIMO PLC presents the potential to increase the transmission rate by up to 90 % compared to SISO [Hashmat2010], [Schneider2008]. Thanks to its advantage in improving the communication system capacity, the MIMO technology has been adopted by PLC network standards such as HomePlug AV2 and ITU-T G.hn.

Fig. 1.4 shows the PLC MIMO channel for 3-wire installations. Signals are fed and received differentially between pairs of wires. Therefore, three realizations of feed ports are possible, e.g., N to PE, P to N and P to PE. However, according to Kirchhoff's law, the sum of the 3 input signals has to be 0, it means that only 2 out of the 3 independent input ports can be used. At the receiving side, all 3 differential reception ports are available. Additionally, there is a 4th reception path, the so called common mode path (CM). Several possible realizations exist depending on the number of transmit and receive ports. (See Table 1.2)

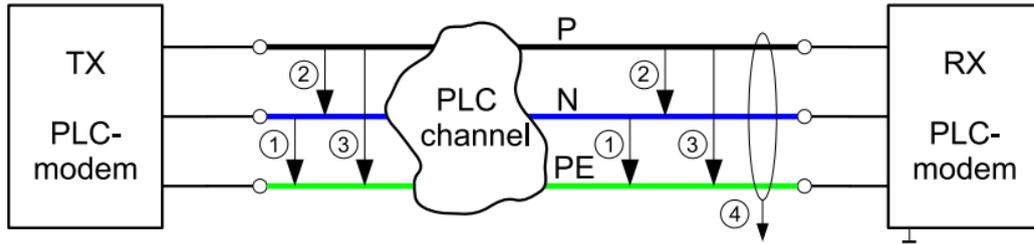


FIGURE 1.4: Possible PLC MIMO channel realizations [Schneider2008]

TABLE 1.2: PLC MIMO arrangements [Stadelmeier2008]

MIMO mode	Tx ports	Rx ports
$1 \times 2$	P-N	P-N, CM
$1 \times 3$	P-N	P-N, P-PE, N-PE
$1 \times 4$	P-N	P-N, P-PE, N-PE, CM
$2 \times 3$	2 best of: P-N, P-PE, N-PE	P-N, P-PE, N-PE
$2 \times 4$	2 best of: P-N, P-PE, N-PE	P-N, P-PE, N-PE, CM

### 1.5.2.1 MIMO PLC channel capacity

The channel matrix of a MIMO channel between  $n_T = 1, 2$  feeding ports and  $n_R = 1, \dots, 4$  receiving ports can be written as:

$$H = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h_{31} & h_{32} \\ h_{41} & h_{42} \end{pmatrix}.$$

where  $h_{n_R, n_T}$  represents the channel transfer function from the  $n_T$ th emitter to the  $n_R$ th receiver. Theoretically, the channel matrix  $H$  can be decomposed into 2

parallel and independent SISO branches by a singular value decomposition (SVD):

$$H = UDV^\dagger \quad (1.4)$$

where

$$D = \begin{pmatrix} \sqrt{\lambda_1} & 0 \\ 0 & \sqrt{\lambda_2} \\ 0 & 0 \\ 0 & 0 \end{pmatrix}.$$

$\lambda_1, \lambda_2$  are the eigenvalues of the channel matrix  $H \cdot H^\dagger$ ,  $U$  and  $V$  are unitary matrices, i.e.  $U^{-1} = U^\dagger$  and  $V^{-1} = V^\dagger$  and the superscript  $\dagger$  indicates the Hermitian operator which is the transposed and complex conjugate of a matrix. Therefore, the total MIMO OFDM channel capacity can be expressed in bits/s as:

$$C_{MIMO} = \frac{B}{N} \sum_{i=1}^N \sum_{j=1}^2 \log_2 \left( 1 + \frac{\lambda_{i,j} P_S}{n_T N_o} \right) \quad (1.5)$$

where  $B$  is the channel bandwidth,  $N$  is the number of frequency subbands,  $P_S$  is the transmitted power in dBm/Hz, which is assumed to be constant over the frequency,  $n_T$  represents the number of transmit ports and  $N_o$  is the noise level at the receiver in dBm/Hz. Note that, in Equation 1.5, the noise at the receive ports is assumed to be Gaussian and uncorrelated. Additionally, the noise power is assumed to be the same for all receive ports. It should be also noted that practical PLC systems are subject to restrictions concerning the transmitted power level and therefore a power or PSD constraint can be considered (Further details on PSD constraints may be found in the next section).

## 1.6 Electromagnetic compatibility issues

The electromagnetic compatibility is the ability of devices or systems to operate sufficiently well in their electromagnetic environment without introducing electromagnetic disturbances which may influence other products and systems. Regarding PLC systems, these issues are very important since they operate in an environment

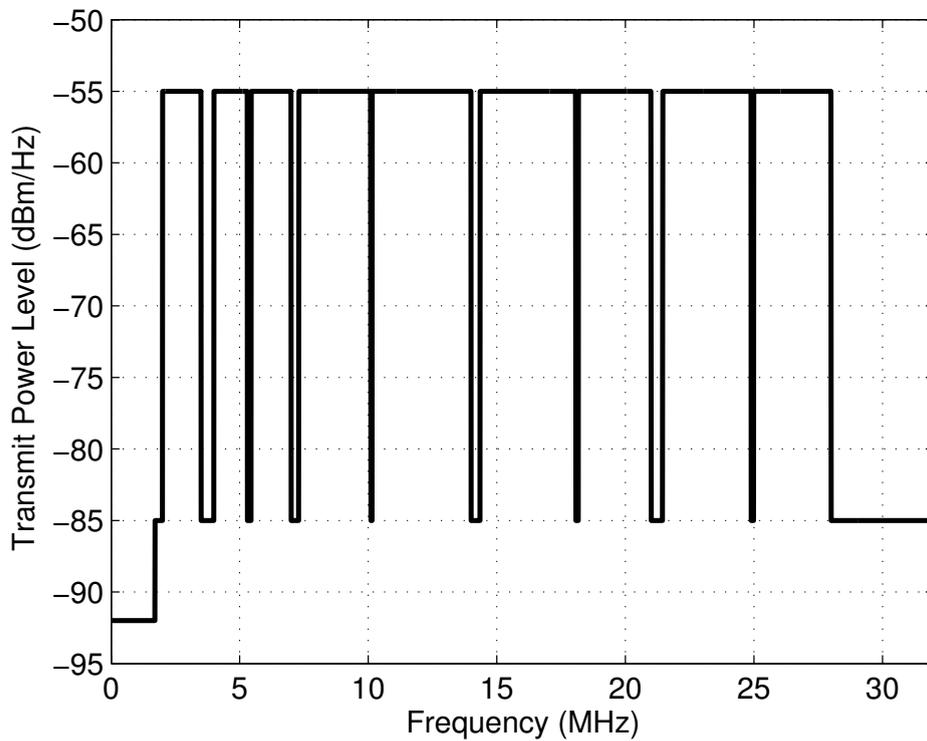


FIGURE 1.5: Transmit mask versus frequency

already populated by other services operating at the same frequencies, so that fair co-existence is needed. Therefore, PLC systems are subject to severe restrictions concerning the transmitted power level. The levels of immunity and emission are regulated by EMC standards such as CENELEC FprEN 50561-1 [CENELEC2011] (in Europe). Depending on this, ITU-T G.hn and IEEE 1901 PLC standards currently specify a PSD mask and impose several notches in which the PSD mask has an upper bound at  $-55$  dBm/Hz below 30 MHz and  $-85$  dBm/Hz above 30 MHz, to avoid interfering with other applications (such as amateur radio for instance). An illustration of the PSD mask vs frequency for the frequency band 0-30 MHz is given in Fig. 1.5.

## 1.7 PLC channel and noise

### 1.7.1 PLC channel modeling

The electrical network topology, composed of several nodes and branches, leads to a complex communication channel with multiple propagation paths and frequency selective fading, in a similar way to classical wireless channels [Tlich2008], [Tlich2008a]. Therefore, indoor PLC channel modeling is one of the critical challenges in PLC systems.

Two different approaches exist for PLC channel modeling, namely, the bottom-up and the top-down approaches.

#### 1.7.1.1 Bottom-up approach

The bottom-up approach [Tonello2010], [Tonello2011], generally referred to as deterministic approach, is generally based on transmission line theory applied to a statistical description of the PLC network topology, e.g., powerline cable characteristics, connections, path lengths and load impedance. This approach considers the power cables as Two conductor Transmission Lines (2TL) or Multi conductor Transmission Lines (MTL). The advantage of the bottom-up approach is that it doesn't require any field measurements. However, a common problem of this approach is the necessity of a precise knowledge of the power network topology features. In addition, it requires an accurate characterization of several properties of the network, such as the cable characteristics or the value of every terminating impedance at each network node. These elements cannot be determined with good precision since they are generally time-variant.

#### 1.7.1.2 Top-down approach

The top-down or empirically-based approach [Tonello2012] is based on fitting a parametric model of the channel frequency response with data obtained from measurements. The major advantage of this approach is that knowledge of network

characteristics is not necessary. In addition, the statistical results obtained from measurements allow fast channel generation. A basic top-down channel model was developed in [Zimmermann2002]. This model takes into account the multipath nature of PLC channel and is defined as:

$$H(f) = \sum_{i=0}^L g_i e^{-(a_0 + a_1 f^k) d_i} e^{-j2\pi f \frac{d_i}{v_p}} \quad (1.6)$$

where  $L$  is the number of dominant signal paths,  $g_i$  is the weight of the  $i$ th path determined by reflections and transmissions,  $a_0$  and  $a_1$  are the attenuation parameters of cable,  $k$  represents the dependency of attenuation on frequency  $f$ ,  $d_i$  is the length of the  $i$ th path, and  $v_p$  is the phase velocity of the signal along the electrical cable.

Many other top-down channel models can be found in literature. In [Tonello2007], a random channel generator based on the multipath model in [Zimmermann2002] is proposed. An extension of the model for frequencies up to 100 MHz is found in [Tonello2012]. Reference [Galli2011] includes a time domain statistical analysis based model for the frequency band 1.8-30 MHz.

In chapters 5 and 6 of this thesis, we use a random channel generator (WITS software) [Tlich2010] based on a top-down model developed by Orange Labs [Tlich2008]. This model considers statistical properties of the magnitude and phase of the measured channel transfer function. Based on measurements in the 30 kHz to 100 MHz band on realistic living environments (144 transfer functions from seven houses), a PLC channel classification, according to the capacity is realized. Then, an average magnitude and phase channel model for nine defined classes, with multipath, is proposed. Hence, according to the desired channel class and bandwidth, the corresponding channel realization is generated in frequency, by means of WITS software as can be seen in Fig. 1.6. An overview of the channel classification results and the average attenuation models of the channels are respectively shown in Table 1.3 and Table 1.4.

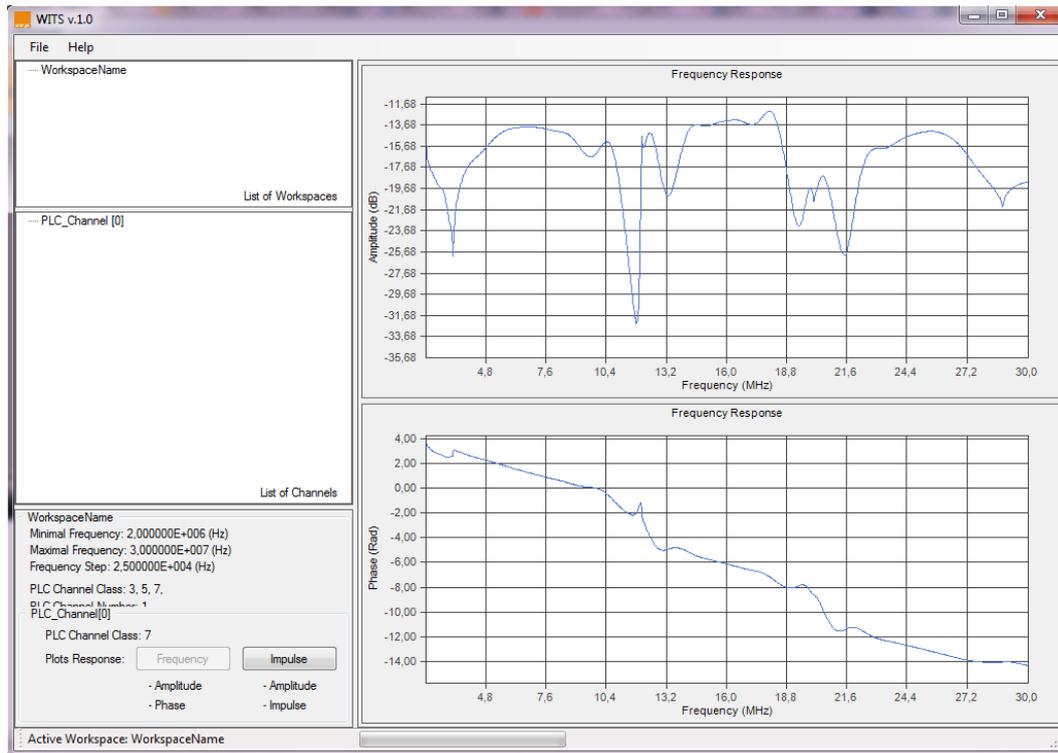


FIGURE 1.6: Example of one generated PLC channel by WITS software

## 1.7.2 PLC noise

In contrast to many other communication channels the noise in a powerline channel can not be described by an Additive White Gaussian Noise (AWGN) model. A precise description of the noise characteristics in PLC networks is given in [Berger2014, p. 22–25], which classifies the indoor PLC noise, depending on its origin, level and time domain signature, into three major components, as shown in Fig. 1.7.

### 1.7.2.1 Impulsive noise

This noise is of short duration and is caused by electronic devices connected to the mains grid, e.g., switched mode power supplies, light dimmers or compact fluorescent lamp. Due to its relatively higher level, impulsive noise is considered as the main cause of burst error occurrence in data transmitted over the high frequencies of the PLC medium.

According to [Berger2014, p. 3–38], one can distinguish three categories of impulsive noise:

TABLE 1.3: Channel occurrence percentage and average capacity for classes 1 to 9 (based on [Tlich2008])

Class	Percentage of channel occurrence (%)	Capacity interval (Mbps)	Average capacity distributions (Mbps)
1	3.49	1000-1200	1120
2	16.78	1200-1400	1307
3	18.18	1400-1600	1486
4	11.88	1600-1800	1687
5	11.88	1800-2000	1899
6	12.58	2000-2200	2098
7	9.79	2200-2400	2298
8	7.69	2400-2600	2499
9	7.69	2600-2800	2699

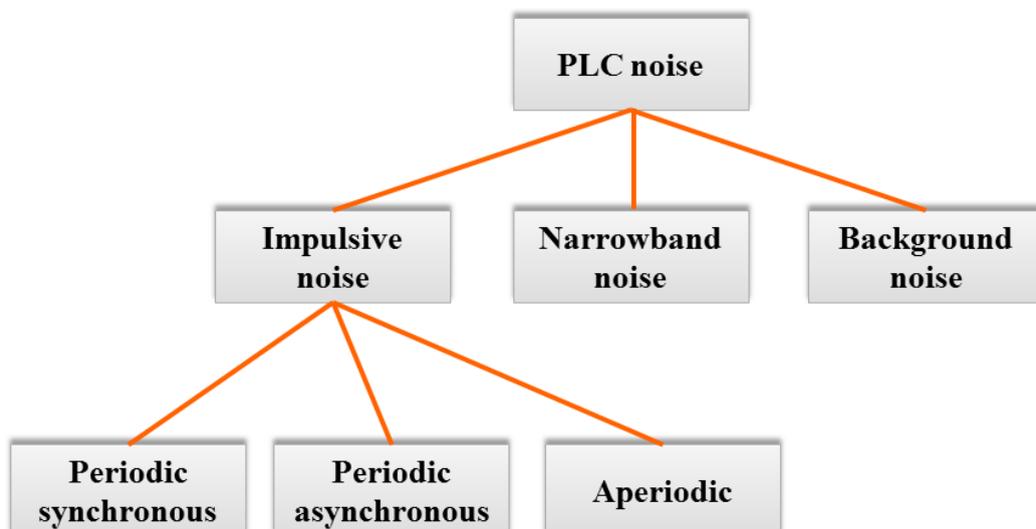


FIGURE 1.7: Classification of PLC noise (based on [Berger2014, p. 22-25])

- Periodic and synchronous to the mains frequency: with a repetition rate at multiplies of 50 or 60 Hz, is mainly caused by power supplies operating synchronously with the mains cycle

TABLE 1.4: Average attenuation model for classes 1 to 9 (based on [Tlich2008])

Class	Average Attenuation Model
1	$-80 + 30\cos(\frac{f}{5.5 \times 10^7} - 0.5)$
2	$-43 + 25\exp(\frac{f}{3 \times 10^6} - 0.5) - \frac{15}{10^8} f$
3	$-38 + 25\exp(\frac{f}{3 \times 10^6} - 0.5) - \frac{14}{10^8} f$
4	$-32 + 20\exp(\frac{f}{3 \times 10^6} - 0.5) - \frac{15}{10^8} f$
5	$-27 + 17\exp(\frac{f}{3 \times 10^6} - 0.5) - \frac{15}{10^8} f$
6	$-38 + 17\cos(\frac{f}{7 \times 10^7})$
7	$-32 + 17\cos(\frac{f}{7 \times 10^7})$
8	$-20 + 9\cos(\frac{f}{7 \times 10^7})$
9	$-13 + 7\cos(\frac{f}{4.5 \times 10^7} - 0.5)$

- Periodic and asynchronous to the mains frequency: with a repetition rate between 50 and 200 kHz, is most of the time, caused by switching power supplies
- Aperiodic: with durations of microseconds up to milliseconds, these strong impulses are generated by the switching transients events in the network. It is considered as the worst noise in the powerline environment, because of its magnitude which can easily reach several dBs above the other types of PLC noise.

### 1.7.2.2 Narrowband noise

This noise is confined to a narrow portion of the frequency band. It is principally caused by the ingress of broadcast stations in the medium and short wave broadcast bands. The level is generally varying with daytime, high in the evening because of the atmosphere reflection and much lower by the daylight.

### 1.7.2.3 Background noise

This noise is generally colored, in the sense that its power spectral density (PSD) decreases for increasing frequencies, with an average 35 dB/decade in the low frequency range up to 10 kHz and a low rate in the high frequency range. It is generally caused by the summation of numerous noise sources with low power, whose variation is slow over long time periods.

## 1.8 Conclusion

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

The second chapter of this document will give an insight into the current state of the art for green communication.

## Chapter 2

# Introduction to Green Communications

### 2.1 Introduction

Energy consumption of Information and Communication Technologies is currently a very important research topic, and several research communities worldwide are collaborating to propose solutions for the so-called green communications, i.e. energy-efficient communications. Green communications can be defined as the practice of adopting and developing energy-efficient networking technologies, methods and products, in order to reduce the energy consumption of communication systems as much as possible, while still maintaining satisfactory Quality of Service (QoS) in terms of coverage, capacity and user needs. The main goal is to decrease negative influence on the environment, e.g. reduce the amount of waste, reduce the amount of consumed resources, and reduce the carbon footprint. Moreover, decreasing energy consumption is translated to lower operating costs in the ICT industry.

This chapter aims to provide an overview about green communications. We first discuss and provide some statistics for the power consumption and the impact on environment of different ICT sectors. Next, we present several European collaborative projects that aim on proposing energy efficient solutions. We continue by reviewing

existing metrics for power and energy efficiency. Later, we provide a brief survey of various techniques that have been considered in the literature to improve energy efficiency in both wireless and wired networks. Then, we classify these approaches based on their principle and level of operation; this section will be restricted to the most important studies on these subject, and will put forward the main techniques used in this thesis. We finally present our conclusions in the last section.

## 2.2 Energy Consumption of ICT Networks

Over the years, the use of ICT has exploded and it has actively contributed to environmental issues. According to [Smart], the impact of the ICT sector on the worldwide energy consumption could range from 2% to 10 %. Moreover, ICT accounts for around 2% of total carbon emissions. Within ICT, more than 50% of the power consumption is due to telecommunication networks including LANs, Wireless Local Area Network (WLANs), fixed-line telecommunication networks, mobile networks, etc. The repartition of energy consumption, and the percentage of carbon footprint of different ICT sectors are provided in Fig. 2.1 and Fig. 2.2 respectively. With the enormous increase of the ICTs, these numbers will likely increase over time. Reference [Haardt2008] indicates that growth in energy consumption is 16% to 20% per year in the field of ICT. As an example, Fig. 2.3 reports a prediction of the energy consumption growth of telecommunication networks in the coming years [Lange2011]. It shows that home networks consume a high amount of the overall energy associated with the operation of ICT networks. Therefore, new challenges arise due to the rapid increase of the traffic volume of broadband telecommunications, which require a massive research effort into the energy efficiency of ICT systems. The challenge of the European Commission (EC) is to reduce at least 20% of Europe's energy consumption by 2020. In order to achieve this challenge, the EC has financed more than 30European (EU) research projects working on energy efficiency in ICT. In the next section we present major academic and industrial EU research projects dedicated to green communications.

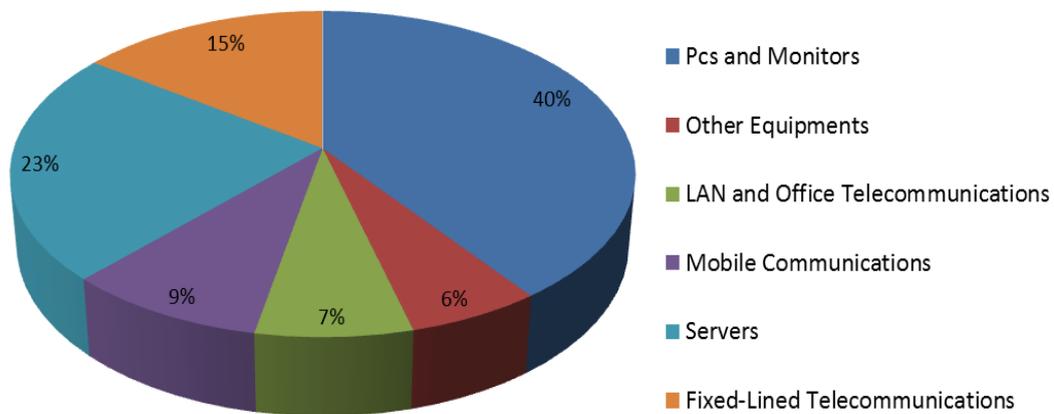


FIGURE 2.1: Energy consumption of ICT sectors

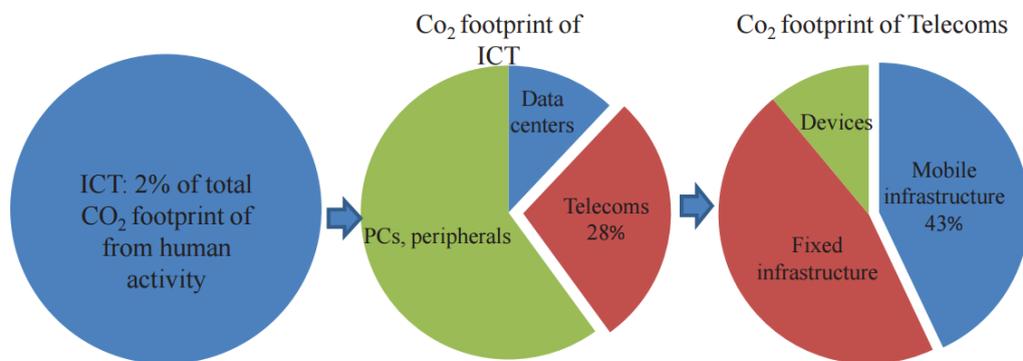


FIGURE 2.2: Carbon footprint of ICT setors

## 2.3 Projects

### 2.3.1 EARTH

The EARTH (Energy Aware Radio and neTwork tecHnologies) project [EARTH] is an Integrated Project of the EU 7th Framework Programme (FP7 IP) which started in January 2010, finished in June 2012 and aimed to address the global environmental challenge by investigating and proposing effective solutions to reduce the power consumption and improve the energy efficiency of mobile broadband communication systems. The overall target of the EARTH project was to reduce the energy consumption of mobile broadband networks by 50% with preserved quality

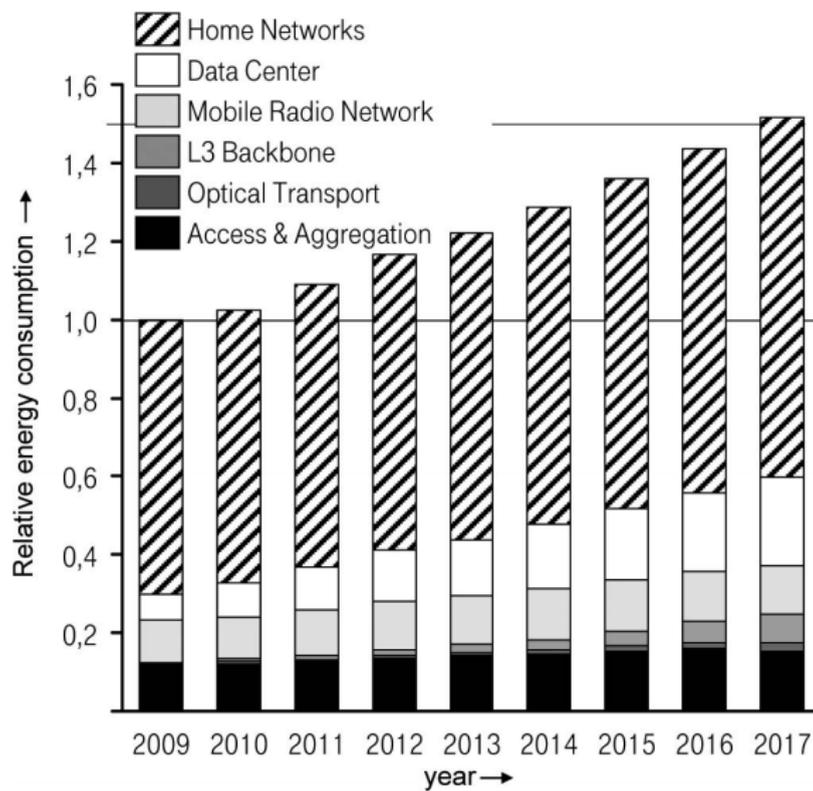


FIGURE 2.3: Energy-consumption forecast for the telecommunication network

of service. By using a holistic approach affecting all layers, from hardware components up to system level, EARTH overachieved its ambitious target by providing integrated solutions allowing for savings in the range of 70%. The main results of the EARTH project are:

- Energy efficient deployment strategies
- Energy efficient network architectures
- New network management mechanisms, adaptive to load variations with time
- Innovative component designs with energy efficient adaptive operating points
- New radio and network resource management protocols for multi-cell cooperative networking

### 2.3.1.1 OPERA-Net

The OPERA-Net (Optimising Power Efficiency in Mobile Radio Networks) Celtic-Plus project [[OPERA-Net](#)] started on June 2008 for a duration of 3 years. It was then extended by the Celtic-Plus project OPERA-Net 2 [[OPERA.Net2](#)], which ended on November 2014. This project investigated the opportunities to reduce the overall environmental impact of mobile radio networks by considering optimized cooling and energy recovery from the base stations and the optimization of the components used in communication systems. The energy efficiency approaches and the the main results of the OPERA-Net project include models to reduce energy consumption, new hardware architectures and designs, energy efficiency measurements methods, energy-aware scheduling algorithms for joint energy consumption and interference optimization, radio resource management in a live 3G cellular network, key performance indicators for 4G equipment energy efficiency and network-level power saving protocols.

### 2.3.2 Green Radio

The Mobile Virtual Centre (VCE) Green Radio project [[GreenRadio](#)] was established in 2009. This project is still ongoing and sets the goal of achieving a 100-fold reduction in power consumption over current wireless communication networks. This must be achieved without compromising the QoS for the user and without negative impacts to the deployment costs for network operators, equipment manufacturers, content providers, etc. The main achievements of the project are the definition of energy metrics to accurately quantify power consumption, the design of advanced power amplifiers (PA) with higher efficiency, the identification of energy-efficient cooperative physical (PHY) layer architecture using emerging information theory ideas to mitigate interference and the development of energy efficient DSP techniques.

### 2.3.3 ECONET

ECONET (low Energy CONsumption NETworks) [[ECONET](#)] project is a three year FP7 IP project (from October 2010 to September 2013) which aimed at studying and exploiting dynamic adaptive technologies (based on standby and performance scaling capabilities) for wired network devices that allow saving energy when a device (or part of it) is not used. The objective of ECONET project is to introduce novel green network-specific paradigms and concepts enabling the reduction of energy requirements of wired network equipment by 50% in the short to mid-term and by 80% in the long term. To this end, the main challenges have been to design, to develop and to test novel technologies, integrated control criteria and mechanisms for network equipment enabling energy saving by dynamically adapting network capacities and resources to current traffic loads and user requirements, while ensuring end-to-end Quality of Service. Among the main achievements of ECONET project, the following results deserve a special mention:

- The characterization of energy consumption sources and traffic profiles in today's telecommunication network infrastructures.
- The methodologies to be used for evaluating the effectiveness and the impact of the green technologies developed in the project.
- The design, definition, development and experimentation of energy saving solutions for network devices.

#### 2.3.3.1 GreenTouch

The GreenTouch initiative [[GreenTouch](#)] was formed in 2010. GreenTouch is a global research consortium of equipment providers, operators, research institutes and academic organizations with the mission to deliver architectures, specifications and solutions, and to demonstrate key technologies, that, if combined in an end-to-end network architecture, improve the network energy efficiency by a factor of 1000 compared to 2010 levels by 2015. This private sector and academic global research consortium offers the most focused attempt for technology breakthroughs in network

energy efficiency. Some interesting power consumption reduction techniques that were considered by GreenTouch can be summarized as follows

- Sleep Mode: power consumption is reduced by switching components from the full power active state to a low power sleep state depending on the traffic load and redundancy requirement
- Improved network components with lower power consumption. Routers and transponders were identified as the main power consuming components. Power consumption reduction was achieved in routers through the introduction of optical interconnects and packet processing adapted to packet sizes. In transponders power savings were achieved through optical interconnects and improved Digital Signal Processors (DSP) with voltage and frequency scaling for lower power consumption
- Intelligent management resources by adapting the power consumption to different traffic load conditions and service demands.
- Optimum end-to-end resource allocation based on dynamic optimization of joint transmit and processing power.

#### 2.3.4 GREENCoMM

GREENCoMM [[GREENCoMM](#)] is a three year French Fonds Unique Interministériel (FUI) project built by a consortium of eight industrial and academic actors, among which Orange Labs and Telecom Bretagne. The ambition of GREENCoMM project, which started in 2013 is to improve energy efficiency of home network technologies: Wi-Fi (at 2.4, 5 and 60 GHz), Power Line Communications and optical fibers. The project also aims at a better integration of these technologies in the domestic environment through measure and evaluation of exposure of the users to electromagnetic waves, and development of solutions to minimize radiation. The project should bring solutions to the following issues:

- Evaluate the energy consumption of a digital communication system, on both hardware basis and protocol layer basis

- Define the tools and mathematical models to develop signal processing techniques minimizing energy consumption both at the transmission side and reception side
- Optimize technologies enabling connectivity in home networks in order to reduce energy consumption induced by their utilization
- Model consumption and radiation inside the home, in order to better inform the user on electromagnetic radiation inside his home

The originality in GREENCoMM project lies in the research of techniques, as generic as possible, helping solve these issues, while also proposing solution directly adjustable to current standards. The project combines a long term approach, with the detection and design of signal processing, analogical transmission and implementation techniques, with a short term approach, focused on compatibility with existing technologies. Note that, the work presented in this thesis was conducted as part of the project GREENCoMM.

## 2.4 Current strategies for green communications

In this section we briefly review the relevant literature in wireless and wired communications to provide the most promising tracks and research areas of green communications. We classify these strategies according to their principle and level of operation. Our classification includes energy efficiency metrics, hardware energy saving techniques, network management energy saving techniques and resource allocation techniques.

### 2.4.1 Energy efficiency metrics

Energy efficiency (EE) is a concept related to comparison. To this end, a basic task for green communications consists in developing energy efficiency metrics. These metrics provide information that can be used to evaluate and compare the energy consumption of various components of a communication network or device and of

the networks and devices as a whole. These metrics also help for setting long-term research goals for reducing energy consumption. An energy-efficiency metric can be defined as the ratio of attained utility (e.g. reached transmission distance, covered area, output power, bits transmitted, etc.) to the consumed power/energy used. In other words, an or power energy consumption metric corresponds to the energy or power consumed per unit of attainable utility. There are lots of metrics for energy consumption of network elements used in telecommunication networks [Hasan2011],[ATIS]. The most simple EE metrics are the power consumption in [Watts] and the energy consumption in [Joules].

According to [Hasan2011], energy efficiency metrics of telecommunication systems can be classified into three main categories: facility-level metrics, which refers to high level systems where a device is deployed, e.g., Internet service provider (ISP) networks; equipment-level metrics, related to the power consumption of an individual equipment; and network-level which are defined to evaluate the performance of equipments while also considering features and properties related to capacity and coverage of the network. Another classification of energy efficiency metrics in [Chen2010] defines two classes: absolute EE metrics which simply express the performance of a device or a network in terms of the actual energy consumed (the bits/Joule ratio, which is the number of bits transmitted per Joule of energy, is the most popular absolute metric); and relative EE metrics which show how EE is improved, e.g., the ratio of output to input power in power amplifiers.

Another well known and basic energy efficiency comparative metric, that will be used in chapter 3 of this thesis, is the energy consumption rating (ECR) [ECR], which is an equipment-level metric that can be defined as the ratio of the energy consumption to the effective system capacity, measured in Watt per Gbps or Watt per Mbps.

### 2.4.2 Hardware techniques

Hardware techniques refer to strategies that enable power reduction at the equipment level. Energy efficient hardware is a big challenge in both wireless and wired

networks since it can represent a large part of the overall power consumption, e.g., up to 60% of total energy consumption of a wireless access network [Hasan2011], [Wang2012]. In this regard, we find two common energy saving trends in the literature: energy efficiency improvement at component level or the use of different operating modes, i.e., power saving modes.

#### **2.4.2.1 Improvement on Component Level**

The first trend is minimizing the consumption of specific components. For example, this approach was considered in EARTH project where energy efficiency improvements were focused on four major components of a base station (BS): antennas, RF transceivers, baseband processor and power amplifier. The project discussed the main approaches for power consumption reduction of BS hardware components, i.e., the use of innovative materials such as advanced nano technologies, improved processes and smart design methodologies [EARTH.D2.3].

Following the component level approach, more efforts have been made to improve the energy efficiency of power amplifiers, since they are the most energy consuming components. Several techniques have been proposed in the literature such as the use of Doherty designs [Luo2012], a special design technique, which uses a second transistor, and helps to improve Power Amplifiers (PA) energy efficiency. The use of amplifiers with gallium nitride (GaN) [Preis2013], a special material used in the manufacture of PA transistors, has also been investigated.

#### **2.4.2.2 Power saving modes**

The main idea behind power saving modes is that a node can be typically in one or several operating states, e.g., sleep, awake..., which have their own energy consumption. One can distinguish two different strategies: putting devices to sleep during phases of idleness [Vereecken2012] or reducing devices performance in phases of low utilization [Correia2010]. Energy-saving solutions through sleep modes, based on network traffic load, have been proposed by the OPERA-Net project. Some sleep mechanisms have also been introduced in the HomePlug AV2 and HomePlug GP

specifications, which allows PLC stations to reduce their average power consumption by periodically transitioning between Awake and Sleep states. Stations in the awake state can transmit and receive packets over the power line, while stations in sleep state temporarily suspend transmission and reception of packets over the power line.

Despite many efforts, hardware-based power reduction techniques have not been able to achieve significant energy savings. Moreover, applying most of these techniques is a difficult task in practice because they require characterization and building power consumption models of each individual component. If the model is not accurate, the policies using this model may not provide an efficient low power system. These factors have led to solutions such as resource allocation and network management approaches.

### 2.4.3 Network management techniques

From a network point of view, power management can be done by taking advantage of the network topological information. The most common technique used to reduce power consumption at the network level is cooperative communications or relay networks [Ray2009]. In cooperative communication, a relay node (R) is assigned to help a source (S) in forwarding its information to a destination (D) as illustrated in Fig. 2.4. A key feature of the relay networks process is the processing of the signal received from the source node done by the relay. There are different processing schemes that result in different relay protocols [Zimmermann2005]. Depending on the principle of operation of the relay in use, four classic cooperative relay protocols are proposed: Decode-and-Forward (DF) relay [Huang2011], Amplify-and-Forward (AF) relay [Jose2009], Compress-and-Forward (CF) relay [Wu2013] and Demodulate-and-Forward (DemF) [Annavajjala2010]. The main relay protocols strategies are described in the rest of the section.

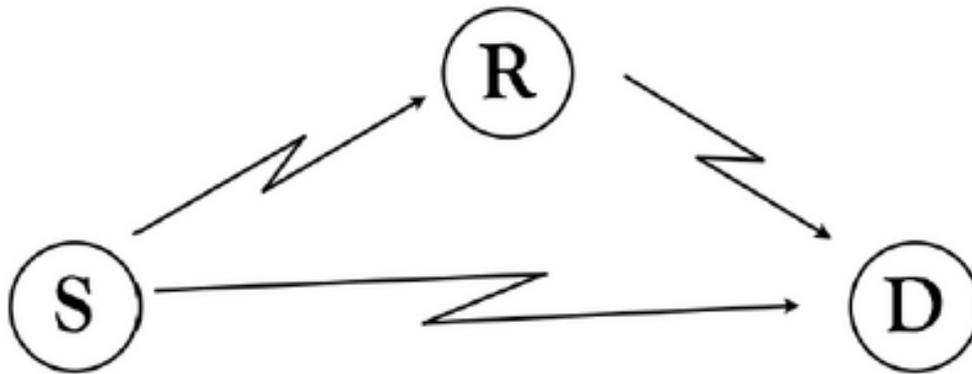


FIGURE 2.4: The cooperative relay network, also known as the relay channel

#### 2.4.3.1 Decode and forward

In the DF strategy, the relay demodulates and decodes the received signal, and then re-modulates and forwards the decoded signal to the destination. (Fig. 2.5). DF is mainly a digital signal processing scheme and is also called regenerative relaying scheme, since it regenerates the signal, and therefore corrects errors at the relay. A very important advantage of DF, which may be employed in PLC, is that the time allocation between the source and the relay is not required to be identical. For example, if the source-relay link is weakly attenuated and the relay-destination link is highly attenuated, the duration of the source transmission time can be increased. Moreover, the modulation constellations at the source and relay nodes can be different in order to adapt them to the channels qualities. However, the challenge in DF is that as the relay decodes the signal, the relay can detect errors present in the signal, which comes at the cost of added complexity.

#### 2.4.3.2 Amplify and Forward

AF relay simply amplifies analogically the received signals from the source, and forwards them to the destination (Fig. 2.6). Since the relay does not perform any kind of decoding, this transmission protocol has reduced hardware complexity. The main drawback of this method is that the noise present in the received signal at

the relay also gets amplified. In addition, AF is difficult to implement in TDMA systems because it requires the storage of a large amount of analog data.

### **2.4.3.3 Compress and Forward**

In CF, the relay quantizes, without decoding, the source data through its Analog to Digital Converter (ADC) before transmitting to the destination through its Digital to Analog Converter (DAC). The compression is generally done by Wyner-Ziv compression [Hu2006]. The use of Wyner-Ziv compression in the CF cooperative transmission protocol may cause the relay encoder and the destination decoder to be complicated.

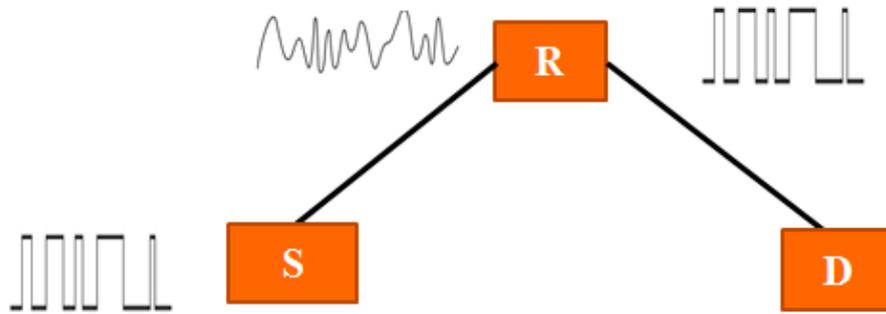
### **2.4.3.4 Demodulate-and-Forward**

DemF is a variant of DF where relays only demodulate and remodulate the received signals, but does not decode, the data from the source and forwards to the destination.

Among the proposed relaying strategies, DF and AF protocols have received considerable attention. In [Llado2014], [Q.Chen2010], the use of AF relays is considered as an energy efficient solution in wireless sensor networks. Previous studies also investigated the use of DF for energy saving purpose in wireless networks [Mohana2014] and in PLC [D'Alessandro2011], [D'Alessandro2012]. In the latter two references, the focus was only on transmit power when considering energy consumption and the circuit power consumption wasn't considered in the performance evaluation.

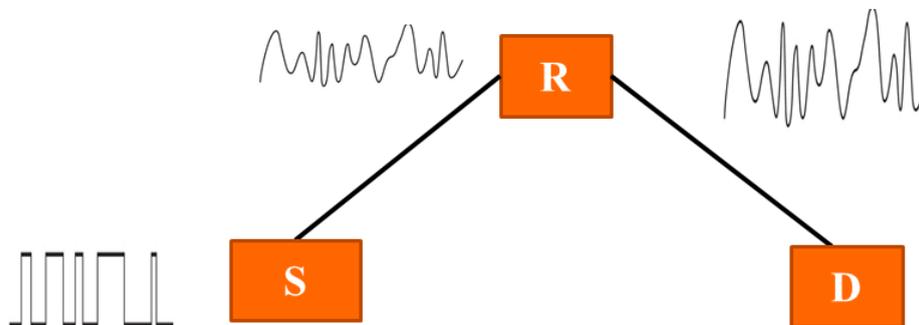
## **2.4.4 Resource allocation techniques**

Resource allocation is the process of deciding how a set of network resources are used. The available networks resources are the transmission time, the power budget and the frequency spectrum. The efficient assignment of these resource can be energy consumption or cost optimizing. Generally speaking, two classes of resource allocation schemes exist, namely: fixed resource allocation [Lawrey1999] and



DF protocol : R acts as a digital repeater

FIGURE 2.5: Decode and Forward



AF protocol : R amplifies analogically  
the received signal from S

FIGURE 2.6: Amplify and Forward

dynamic resource allocation [Wong1999]. Fixed resource allocation schemes, such as TDMA and frequency division multiple access (FDMA), assign an independent dimension, e.g., time slot or subchannel, to each user. A fixed resource allocation scheme is not optimal, since the scheme is fixed regardless of the current channel condition. On the other hand, dynamic resource allocation allocates a dimension adaptively to the users based on their channel gains. Dynamic resource allocation can be studied from two perspectives:

- Subscriber: in OFDM based systems, resource allocation refers to the rate and power allocation over subcarriers. The resource allocation can be seen

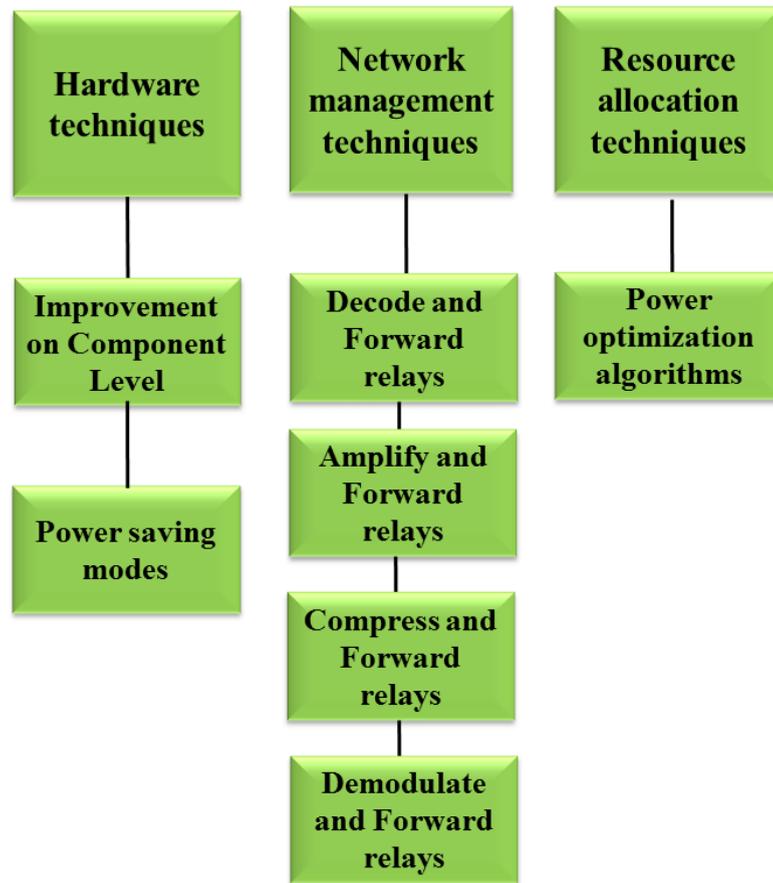


FIGURE 2.7: Classification of green communications research approaches

as a constraint optimization problem and literature about resource allocation problem include two major categories [Papandreou2008]:

- Minimizing the total transmit power subject to fixed data rate
- Maximizing the data rate subject to fixed power constraint

An overview of resource allocation algorithms proposed for OFDM based PLC systems can be found in [Zou2008].

- Network: from the network point of view, in order to maximize the total throughput, each resource should be allocated to each device with the strongest channel gain.

For completeness of information, Fig. 2.7 illustrates the proposed classification of green communications techniques and Table. 2.1 presents a summary of the main

TABLE 2.1: Comparative summary of different energy efficiency approaches

Approaches	Related works
Metrics	<p><b>EARTH</b>: Metrics on network-level</p> <p><b>Green Radio</b>: Absolute and relative metrics</p> <p><b>ECONET</b>: Metrics on equipment and network levels</p> <p><b>GreenTouch</b>: Metrics on facility-level</p> <p><b>Other related works</b>: [Hasan2011] [ATIS], [Chen2010]</p>
Hardware	<p><b>EARTH</b>: Component level</p> <p><b>OPERA-Net</b>: Component level</p> <p><b>Green Radio</b>: Component level</p> <p><b>GreenTouch</b>: Component level and power saving modes</p> <p><b>GREENCoMM</b>: Component level and power saving modes</p> <p><b>Other related works</b>: [EARTH.D2.3] [Luo2012], [Preis2013] [Vereecken2012], [Correia2010]</p>
Network management	<p><b>EARTH</b>: Combination of AF, DF and CF relays</p> <p><b>Green Radio</b>: Multi-hop routing</p> <p><b>GreenTouch</b>: Multi-hop transmission, Optimum end-to-end resource allocation</p> <p><b>Other related works</b>: [Preis2013] [Zimmermann2005], [Huang2011] [Jose2009], [Wu2013] [Annavajjala2010], [Hu2006] [Llado2014], [Q.Chen2010] [Mohana2014], [D'Alessandro2011] [D'Alessandro2012]</p>
Resource allocation	<p><b>EARTH</b>: Joint power and resource allocation</p> <p><b>Green Radio</b>: Power minimization under rate constraints</p> <p><b>GreenTouch</b>: Joint power and resource allocation</p> <p><b>Other related works</b>: [Lawrey1999] [Wong1999] [Papandreou2008], [Zou2008]</p>

techniques discussed in this chapter. Table. 2.1 also highlights the most important previous works related to these techniques.

## 2.5 Conclusion and future directions

The challenges posed due to the tremendous growth in ICT systems include the development of methods for the efficient use of energy. In this chapter we provided the current state-of-the-art in energy efficiency for communications systems. We discussed the environmental and energy context of ICT. We presented some EU green projects and related works. Then, we described the main global approaches used in both wireless and wired systems for green communications, and presented some references for each of them. Finally, we proposed a classification of the major research areas.

In the overview of general energy efficiency solutions we notice that most of current research efforts are spent in wireless networks. Relatively very little attention has been given to wired networks, mainly to PLC. Additionally, in the area of PLC, we find that nothing has been revealed about the power consumption behaviour of PLC modems. In order to face the energy efficiency issue in PLC networks, we have to firstly understand and accurately characterize the actual sources of energy consumption in a PLC modem. Such a power analysis is very important for the design and development of future green PLC modems and networks.

In the next chapter, we will present the experimental analysis and electrical power consumption measurements of commercial PLC modems that were performed during the thesis. Then, in Chapter 4, we will propose power consumption models for both SISO and MIMO PLC modems. Following these models, in Chapter 5, we will investigate the use of DF relay nodes as a power consumption reduction technique in PLC networks.

## Chapter 3

# Power Consumption Behaviour of PLC Modems: Measurements and Experimental Analysis

### 3.1 Introduction

In the last few years, extensive research on improving data rates in PLC systems and networks has been performed. Today's PLC networks can achieve PHY data rates of up to 500 Mbps with SISO PLC modems, and up to 2 Gbps with MIMO PLC modems. However, energy efficiency is still a critical issue for PLC network providers and equipment manufacturers, because high transmission rates are usually achieved at the expense of higher power consumption. Therefore, the development of energy efficient PLC technologies requires a good understanding of where and how the power is consumed in PLC modems.

The purpose of this chapter is to experimentally analyze and to provide measurements for understanding the electrical power consumption behaviour of PLC modems.

Power consumption measurement is a key issue in the community of green communications and systems. Accurate measurements of power consumption provide

valuable data for benchmarking the power consumption of systems, networks and devices and gives insights on which energy improvements can be evaluated.

Power measurement has been widely used as a method for analyzing the power consumption in several previous works. For example, in [Riggiol2012], a measurement-based study of power consumption of commercial third generation (3G) femtocell base station (BS) for both voice and data application is presented. In this work, traffic was generated by Iperf [iPerf], a software traffic generator tool, while the electrical power consumption was measured by Energino instrument [Gomez2012], a plugload meter designed to monitor the power consumption of direct current (DC) devices. The authors found that BS power consumption relies on traffic load, packet size, and has an idle part. Additionally, a significant amount of the power consumed by these devices is not traffic dependent. Specifically, increasing data rates in the network until the saturation point results in only a 20% increase in power consumption compared to the power consumed when there is no traffic in the network.

In [Sivaraman2011] and [Vishwanath2010], several experiments have been done to measure per-packet and per-byte energy consumption of NetFPGA Gigabit routers, by using a hardware-based traffic generator and analyzer, and a high-fidelity digital oscilloscope. Based on this experiments, the authors proposed a fine-grained profile of power consumption as a function of the network traffic and different applications of the NetFPGA card.

In [Vishwanath2013], the authors empirically quantify the power consumption associated with packet processing, storage and switching in Optical-IP routers. Both IXIA and Spirent hardware-based traffic generators were used to generate data rate. The power consumption was measured by a digital power meter and logged to a computer for post processing. The authors show in this work that power consumption values of today's Optical-IP routers when idle and under full traffic load are very similar.

In [Warty2012], measurements of IEEE 802.11n [IEEE2009] power consumption in smartphones are presented. Using a popular 802.11n-enabled smartphone and an 802.11n wireless testbed, power and energy consumption on the phone for a variety

of configurations including different MAC bitrates, frame sizes, and channel conditions were evaluated. The authors show that the reception power consumption of the phone's WiFi chipset increases significantly with the bitrate.

In all these previous works, the authors illustrate the importance of measurement and utilize the measured power consumption data in order to develop realistic models for the power consumption, and then to identify opportunities and most promising tracks for power consumption reduction.

In this chapter, we designed experiments to measure the electrical power consumption of PLC modems as a function of bit rate, frame rate and frame size. Namely, using a high-precision hardware-based traffic generator and accurate power measurement instruments, we carried out detailed measurements of power consumption of several pairs of commercial PLC modems. Our measurements were first conducted with 6 pairs of traditional SISO-based PLC modems. Later, they were extended to include the new family of modems with MIMO capabilities. To the best of our knowledge, these are the first such power consumption measurements of PLC modems presented in the open literature. On the basis of these measurements, power consumption models of both SISO and MIMO PLC modems will be presented in chapter 4.

The chapter is organized as follows. In the next section we introduce the measurement campaign and the experimental setup related to SISO PLC modems. Then, we present an extension of these measurements to MIMO-based modems. Finally, the conclusions are presented in the last section.

## **3.2 Power consumption behaviour of SISO PLC modems**

This section is dedicated to the power consumption analysis of SISO PLC modems. In order to investigate the influence of data rate on power consumption, we first give theoretical information about the framing process in PLC modems. Thereafter, we present our SISO measurement set up.

### 3.2.1 Processing of Ethernet frames through the PLC modem

Even though PLC specifications have different characteristics, they still share the main PHY and MAC layer functionalities. Fig. 3.1 shows the protocol layer architecture of an HomePlug AV system, which can be sufficiently representative of all standards of the PLC technology.

A HomePlug AV system consists of three functional blocks 1) the Convergence Layer (CL) which performs bridging, classification of traffic into connections, and data delivery smoothing functions, 2) the MAC layer, which determines the correct position of transmission, formats data frames into fixed-length entities for transmission on the channel and ensures timely and error-free delivery through Automatic Repeat reQuest (ARQ) and 3) the PHY layer, which performs error-control correction, mapping into OFDM symbols, and generation of time-domain waveforms.

Furthermore, the architecture defines two planes: the control plane and the data plane. Protocol entities that are involved in creating, managing and terminating the flow of data make up the control plane. The HomePlug AV control plane is defined as a monolithic entity, called Connection Manager (CM) entity. Although in the figure appears a Central Coordinator (CCo) module, this entity will be active in only one station in a single HomePlug AV network.

On the other hand, protocol entities that are directly involved in the transfer of user payload make up the data plane. The data plane defines the packets process chain. Therefore, it includes the HomePlug AV MAC frame generation that will be part of a MAC frame stream, as well as the segmentation and encapsulation processes of this stream.

Fig. 3.2 shows a high-level view of the processing of an Ethernet frame through a PLC modem. In the Data Plane, the MAC accepts MAC service data units (MSDUs) arriving from the CL (e.g., Ethernet frames from the Ethernet Service Access Point (SAP)), encapsulates them with the following parts as shown in Fig. 3.3:

- An optional Arrival Time Stamp (ATS), which indicates the time when the MSDU arrived at the CL. It is used as a part of a jitter control mechanism

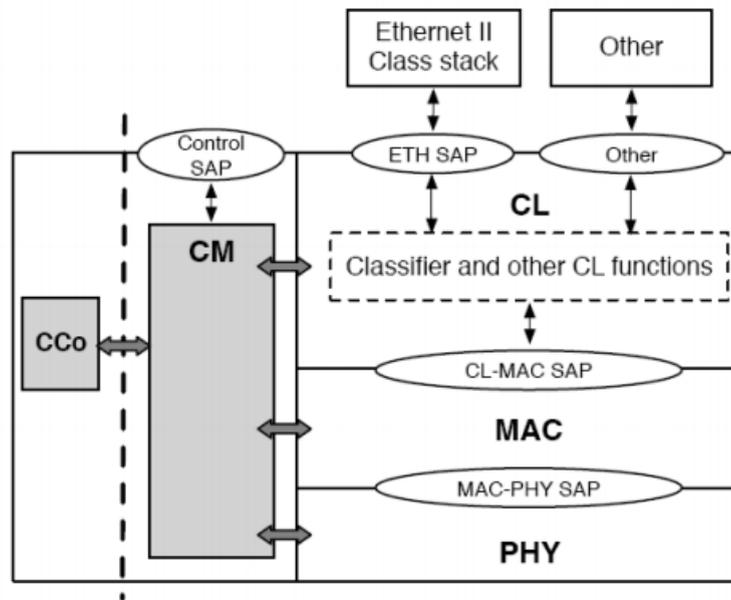


FIGURE 3.1: HomePlug AV protocol layer architecture [Meftah2011]

deployed to ensure QoS.

- A MAC data frame header which carries information about the presence of ATS and the length of the MAC frame.
- An Integrity Check Value (ICV).

Next, MAC data frames are concatenated to form an Ethernet frames stream. Each MAC frame stream is divided into 512 or 136 bytes segments, each of which is encrypted and encapsulated into a serialized PB. Fig. 3.4 illustrates the 512-byte and 136-byte PB (136-byte PBs can only be used for management purposes). The PB header contains the segment number, which is used for reassembly purposes, and the size of payload data it contains, while a PB Check Sequence (PBCS) is added to check data integrity at the receiver side. The PBs are then packed into a Mac Protocol Data Unit (MPDU), as shown in Fig. 3.5, which is delivered to the PHY [HomePlugAV2007].

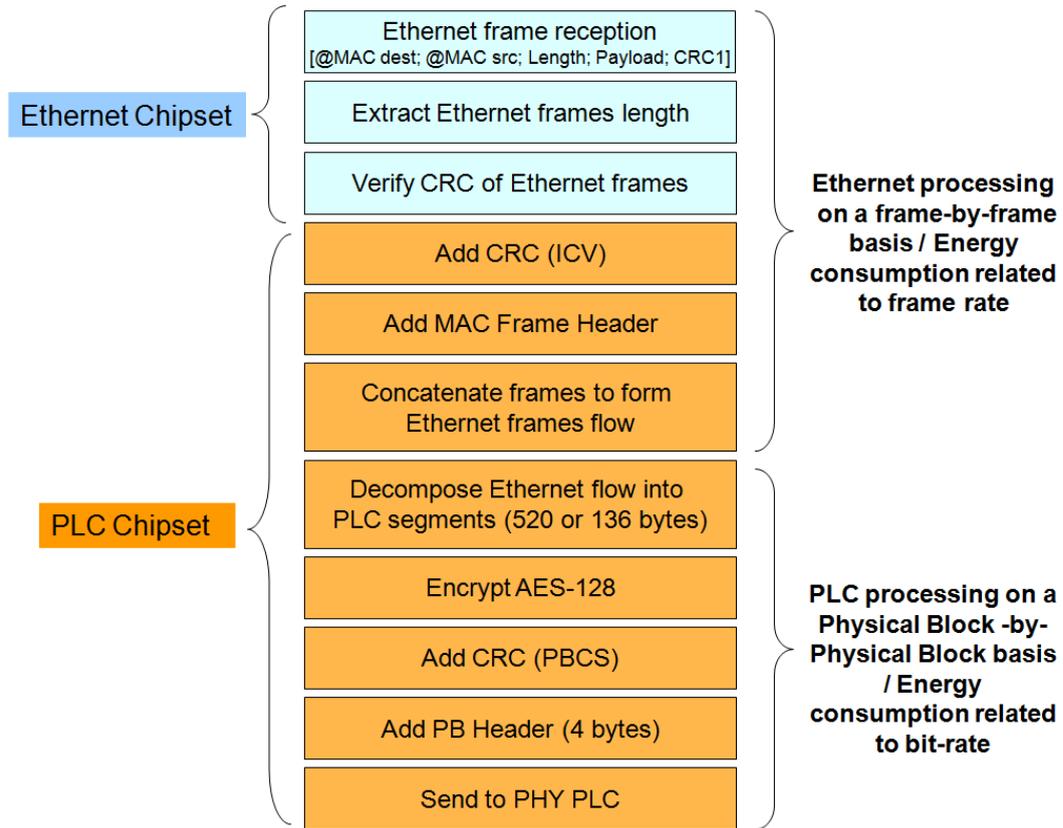


FIGURE 3.2: Processing of an Ethernet frame through the PLC modem

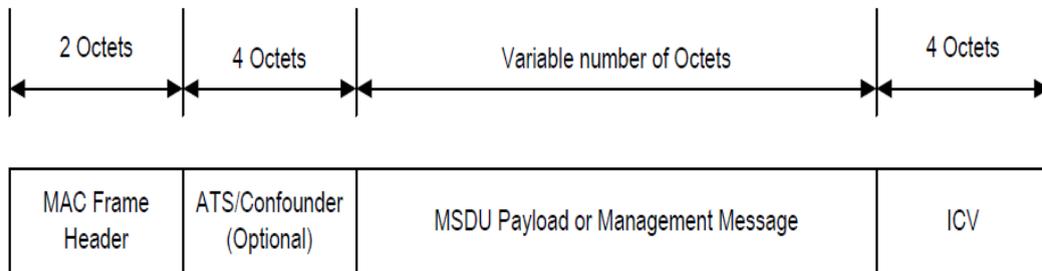


FIGURE 3.3: HomePlug AV MAC frame format [Meftah2011]

### 3.2.2 SISO Experimental setup

The SISO test environment reported in Fig. 3.6 is composed of a high-precision traffic generator, 6 pairs of SISO PLC modems, and a power quality analyzer for power measurement. Each of these devices is described below.

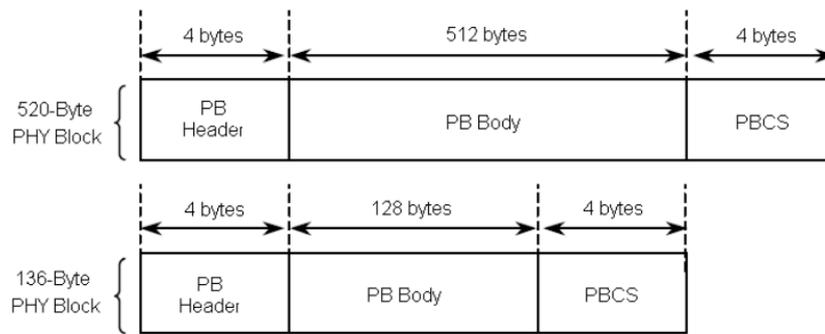


FIGURE 3.4: 520-byte and 136-byte PBs according to HomePlug AV standard

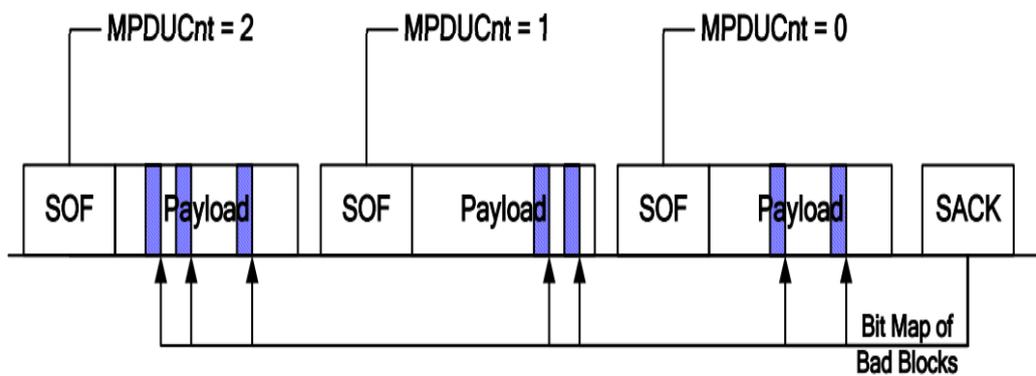


FIGURE 3.5: HomePlug AV MAC Segmentation and MPDU Generation [HomePlugAV]

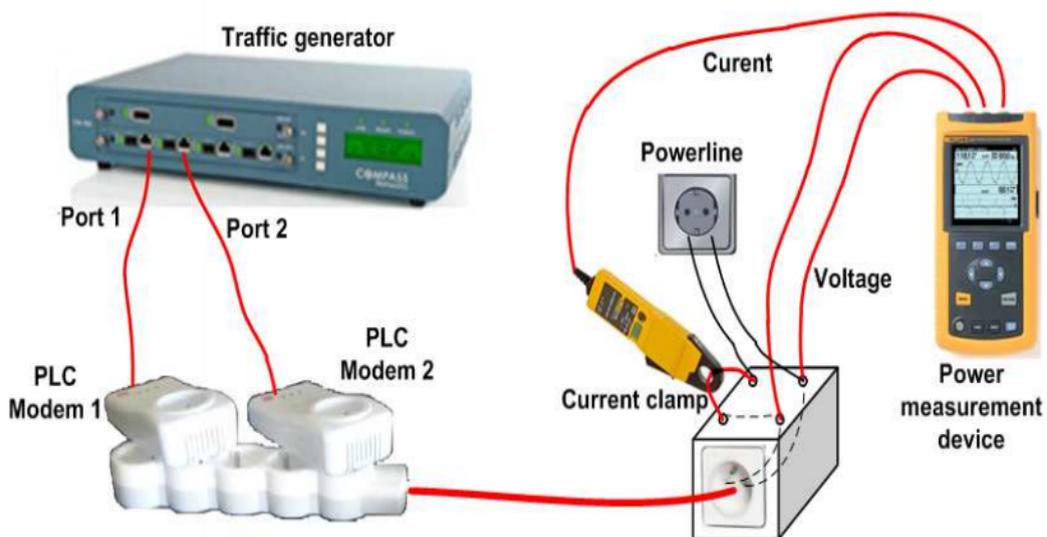


FIGURE 3.6: SISO experimental setup

### 3.2.2.1 Traffic generation

We used a COMPASS CN-100 network analyzer [COMPASS], which is a high-precision hardware traffic analyzer which offers the latest capabilities for generating Ethernet frames with various configurable parameters, e.g., bandwidth utilization, frame rate, frame payload, and frame length. Thanks to its traffic generation abilities, this networks analyzer offers the possibility to simulate different network traffic conditions.

Control of the CN-100 hardware is accomplished by a graphical user software interface (CN-100 Manager). As can be seen in Fig. 3.7, CN-100 manager is a windows-based graphical interface that has the look and feel of the CN-100 hardware. The CN-100 Manager connects to the CN-100 via the RS-232 port or 10/100 Ethernet connections. The Manager program allows complete control of the installed interface modules to run a variety of predefined or user defined tests that can be easily saved and recalled later, e.g., up to 255 individual streams may be created in which predefined packets and protocols such as IPv4, IPv6 can be selected, (See Fig. 3.8). Moreover, the length and type of packet such as IPv4, IPv6, UDPv4, TCPv4, IPX, UDP-IPv6, TCP-IPv6 can be specified.

In our experiments, Ethernet port 1 of the CN-100 analyzer is connected to the transmitter modem (PLC modem 1) and Ethernet port 2 of the CN-100 analyzer is connected to the receiver modem (PLC modem 2).

### 3.2.2.2 SISO PLC modems

We measured power consumption for 6 pairs of SISO PLC commercial modems S1, S2, S3, S4, S5 and S6. The tested modems have different chipsets and are using either HomePlug AV or HD-PLC standards. Table. 3.1 shows details about the modems used. For example, the maximum PHY bitrate, which is the maximum number of physically transferred bits per second allowed by the standard, including both useful data as well as protocol overhead; and the useful bitrate, which defines the physical layer net bitrate exuding the PHY layer protocol overhead (e.g., framing

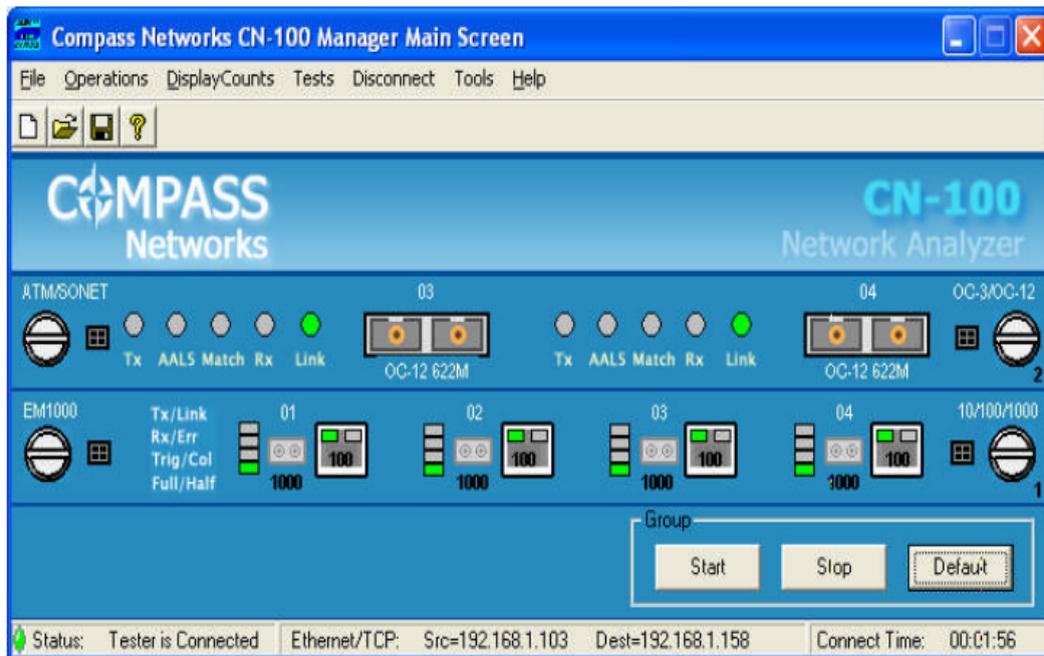


FIGURE 3.7: CN-100 Manager main screen

bits, FEC codes). Moreover, all tested modems have one Ethernet port with a maximum speed of 100 Mbps, or 1 Gbps (case of modems S4 and S6).

### 3.2.2.3 Measuring electrical power consumption

We used a Fluke 43B Power Quality Analyzer [Fluke] to measure the electrical power consumption of SISO PLC modems. This instrument has two input channels and can simultaneously measure both voltage, current measured values and automatically takes the phase angle into account to display the power consumption value.

In our experiments, the pair of PLC modems is plugged to a single power strip and connection is made as shown in Fig. 3.6. The Fluke i30s AC/DC current clamp is used with the Fluke 43B Power Analyzer for current measurements.

## 3.3 Power consumption behaviour of MIMO PLC modems

Transmission over two channels enables a significantly higher data rate. However, a drawback of MIMO techniques is that they could require large amount of signal

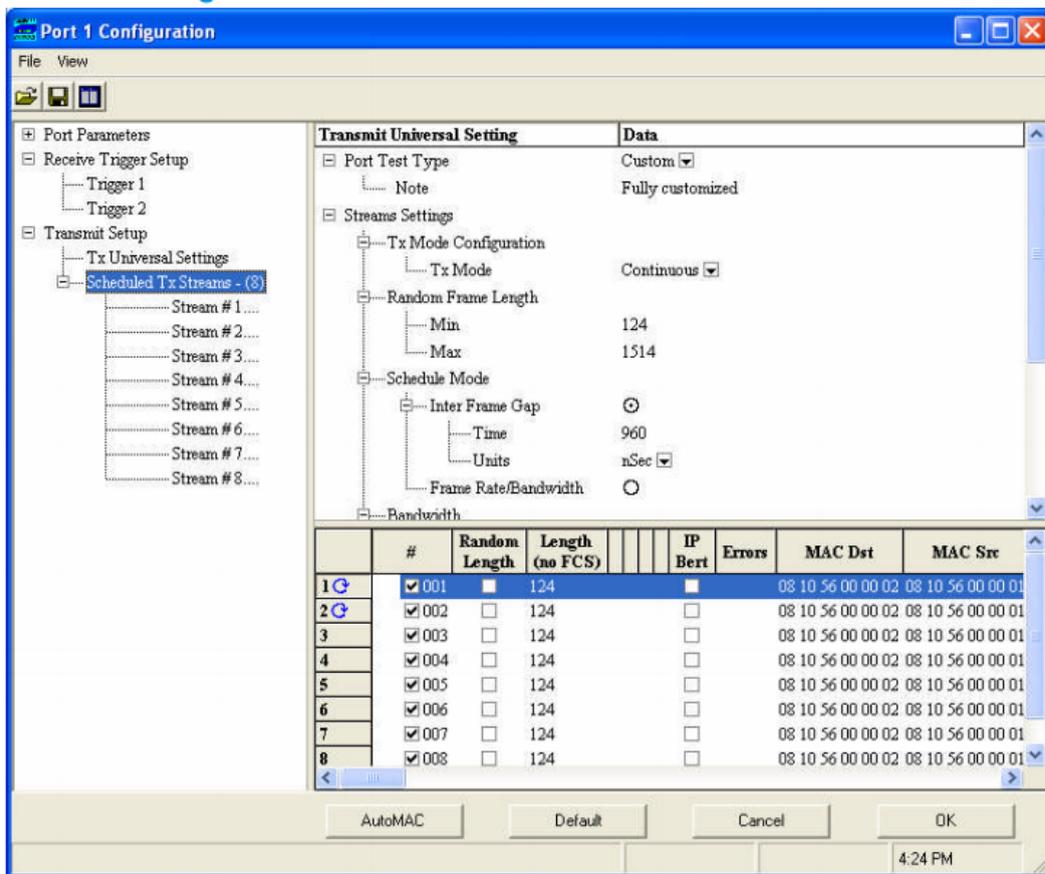


FIGURE 3.8: Illustrating example of the CN-100 port configuration

processing power due to multiple active RF chains, that may lead to higher transmit power consumption. Thus, in evaluating the power consumption of MIMO PLC modems, we need to take into account the differentiation between the transmit side power associated with the transmission of Ethernet frames and the receive-side power associated with the reception of Ethernet frames. Therefore, differently from the SISO measurements that were done on the basis of pairs of modems, in the MIMO case, we will focus on the analysis of the power consumption behaviour of the transmitter modem (PLC modem Tx) and the receiver modem (PLC modems Rx) separately. To this end, a different measurement setup was used for MIMO measurements. The MIMO experimental setup is described in the next section.

TABLE 3.1: List of tested SISO PLC modems

SISO PLC Modems	Standard	Chipset	Ethernet port speed (Mbps)	Maximum PHY bit-rate (Mbps)	Useful bit-rate (Mbps)	Frequency band (MHz)
S1	HD-PLC	KHN13100	100	240	60	2-28
S2	HomePlug AV	Atheros INT6400	100	200	90	2-30
S3	HomePlug AV	Atheros AR6405	100	200	80	2-28
S4	HomePlug AV	Atheros AR7400	1000	500	230	2-68
S5	HomePlug AV	Atheros INT6400	100	200	80	2-30
S6	HomePlug AV	Atheros AR7400	1000	500	90	2-68

### 3.3.1 MIMO Experimental setup

The experimental setup for MIMO modems, represented in Fig. 3.9, consists of a COMPASS CN-100 network analyzer, 3 pairs of MIMO PLC modems, and a digital power meter for power measurement. A brief description of the tested modems and the power measurement device used in this experiment is given below.

#### 3.3.1.1 MIMO PLC modems

We measured power consumption for 3 pairs of MIMO PLC commercial modems M1, M2 and M3. In each pair, the first modem is considered as a transmitter and the second as a receiver. The tested pair of modems have different chipsets and are compliant with HomePlug AV2 or ITU G.9963 standards. Table. 3.2 shows details about the modems used.

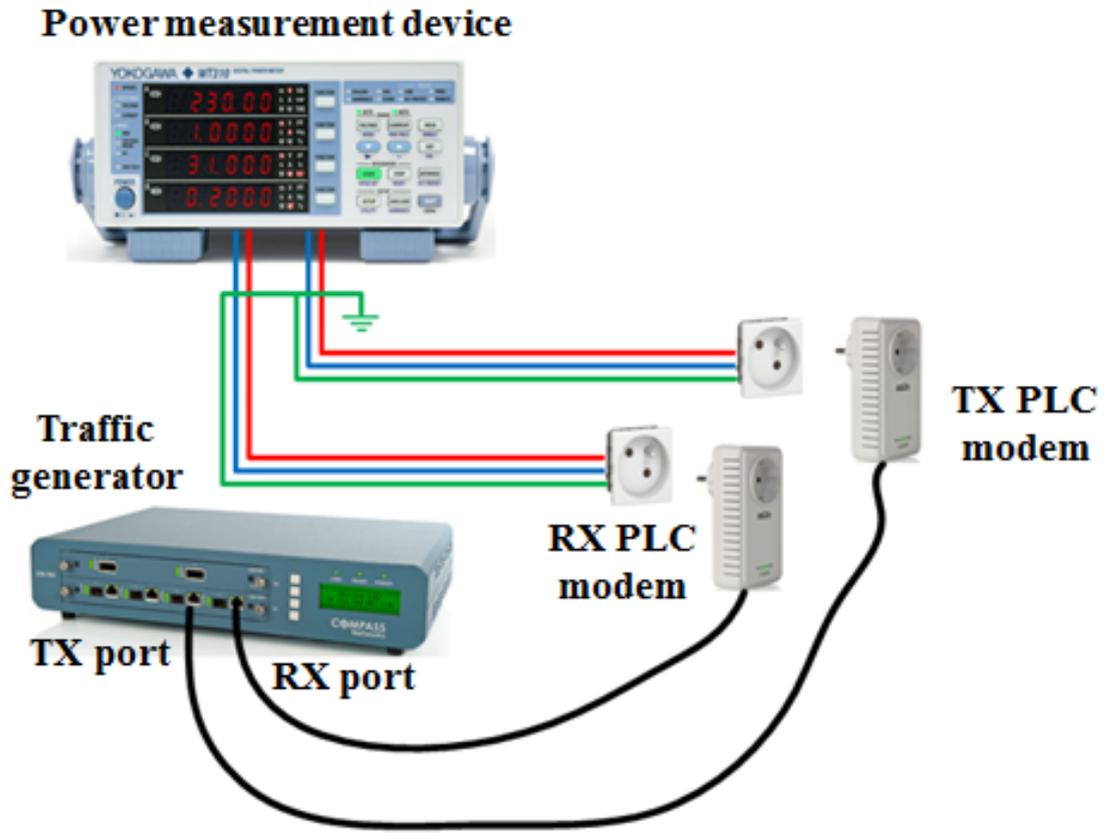


FIGURE 3.9: MIMO experimental setup

TABLE 3.2: List of tested MIMO PLC modems

MIMO PLC Modems	Standard	Chipset	Ethernet port speed (Gbps)	Maximum PHY bit-rate (Gbps)	Useful bit-rate (Mbps)	Frequency band (MHz)
M1	ITU G.9963	Marvell 88LX3142	1	1	280	2-50
M2	HomePlug AV2	Broadcom BCM60500	1	1.8	440	2-86
M3	HomePlug AV2	Qualcomm QCA7500	1	1.2	300	2-67.5

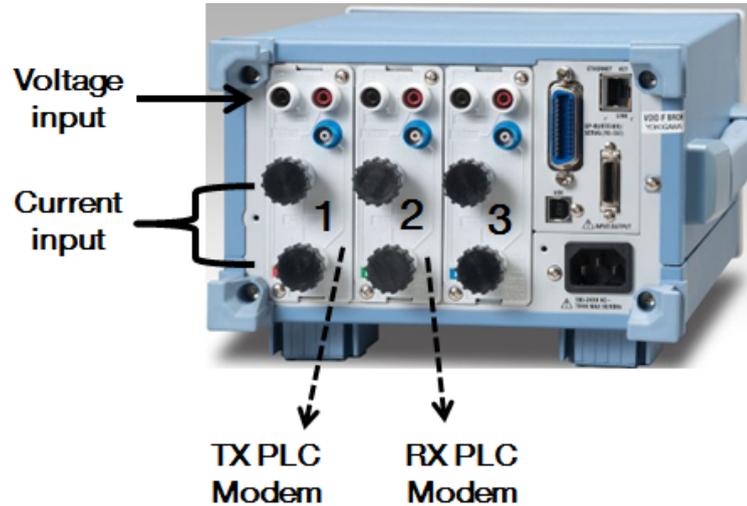


FIGURE 3.10: Power measurement device input terminals

### 3.3.1.2 Measuring electrical power consumption

We used a Yokogawa WT330 Digital Power Meter [Yokogawa] to measure the electrical power consumption of MIMO PLC modems. This power measurement instrument is equipped with three input terminals where a single phase of voltage and current can be applied to each terminal. These input element numbers range from 1 to 3 as can be seen in Fig. 3.10. In our experiment, measurement of the power consumption of the transmitter modem and the receiver modem were performed simultaneously by connecting the TX PLC modem to input terminal 1 and the RX PLC modem to input terminal 2.

## 3.4 Measurements

In the following sections we present measurements of power consumption for different states of both SISO and MIMO PLC modems:

- Idle mode: without any Ethernet ports connected, and hence no traffic.
- Standby mode: as the Ethernet cables are plugged into the modems.
- Variable datarate: when the data rate is varied.
- Variable Ethernet frame size: as the Ethernet frames size is varied.

TABLE 3.3: Measured baseline power consumption of SISO PLC modems

SISO PLC modems	Baseline power consumption $C(W)$
S1	2.2
S2	1.5
S3	0.6
S4	2.5
S5	2
S6	3.1

### 3.4.1 Baseline power consumption

We first measured the baseline power consumed by each PLC modem when it is idle and Ethernet ports are not connected. We repeated our measurements several times (each 10 seconds during 2 minutes) and computed their average value. Table. 3.3 and Table. 3.4 show the average baseline power consumption for the 6 tested SISO PLC modems and for the 3 MIMO PLC modems respectively. In addition, Fig. 3.11 and Fig. 3.12 show the measured electrical power consumption versus time of SISO modems and MIMO modems respectively (The results reported in Table. 3.3, Table. 3.4, Fig. 3.11 and Fig. 3.12 correspond to the power consumption values of one PLC modem). At this point we note that depending on the chipset and standard used, baseline powers of various modems can be significantly different. We also mention that some manufacturers propose advanced Power-Saving modes that reduce power consumption when there is no data transmission or reception (Case of S3).

### 3.4.2 Per-Ethernet port power $P_E$

After measuring the baseline power, we plugged the Ethernet cables into each PLC modem port to activate it. We did this by adding one cable at a time and no traffic was involved. Results show that for a pair of PLC modems, the increase in power

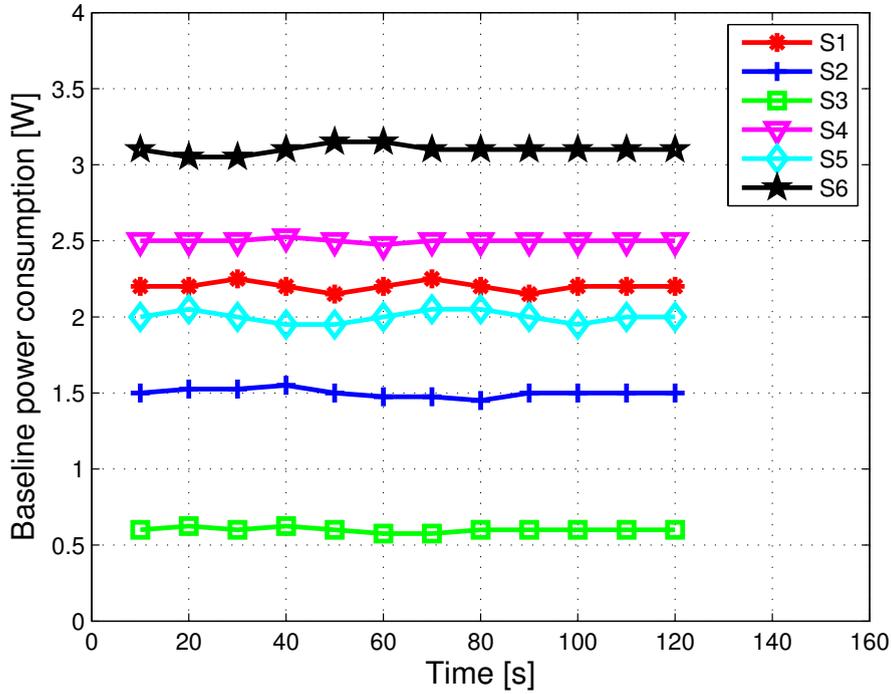


FIGURE 3.11: Measured power consumption of SISO PLC modems when they are idle and Ethernet ports are not connected

TABLE 3.4: Measured baseline power consumption of MIMO PLC modems

MIMO PLC modems	Baseline power $C(W)$
M1	2.85
M2	3.9
M3	2.3

was almost perfectly linear: each plugged Ethernet port brings a constant power value  $P_E$  (see Table. 3.5 and see Table. 3.6). This increase in power consumption can mainly be attributed to the fact that most of the modules of the Ethernet and PLC chips are continuously active as soon as a cable is plugged in, leading to a power consumption that is large and independent of the traffic load [Spurgeon2000]. It can be observed (from Table. 3.5 and Table. 3.6) that per-port power consumption is higher when using 1000 BASE-T port (case of modems S4 and S6). 1000 BASE-T Ethernet chips are in fact consuming more power than 100 BASE-T (100 Mb/s) chips.

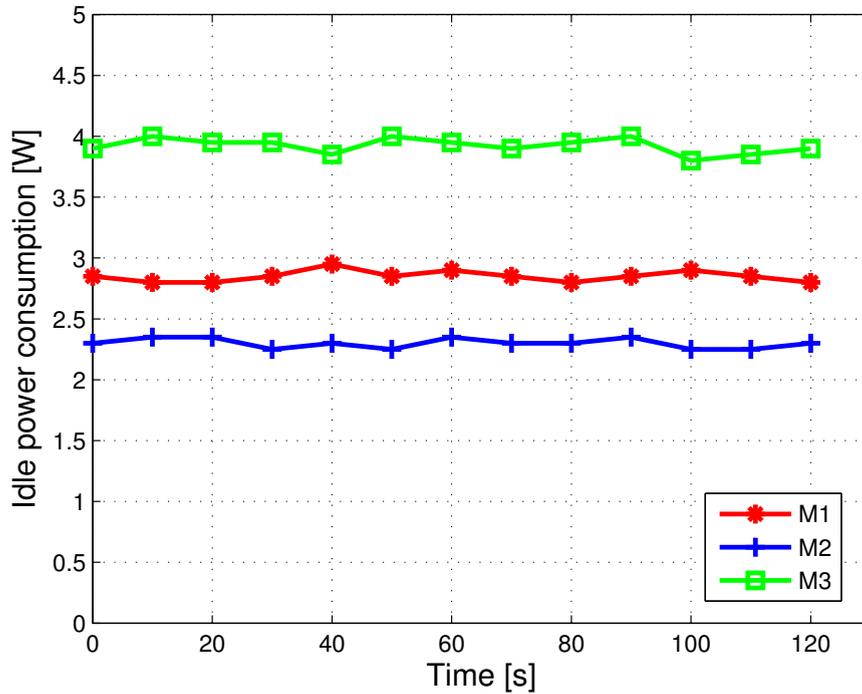


FIGURE 3.12: Measured power consumption of MIMO PLC modems when they are idle and Ethernet ports are not connected

TABLE 3.5: Per-Ethernet port power

SISO PLC modems	$P_E$ (W)
S1	0.2
S2	0.5
S3	0.3
S4	0.6
S5	0.3
S6	1.05

### 3.4.3 Power consumption vs data rate

This experiment aims to evaluate the power consumption related to the traffic load. Our approach is as follows: we fix the frame size (L Bytes), and send an IPv4 stream of frames from the transmitter port (which is connected to the transmitter

TABLE 3.6: Ethernet per-port power  $P_E$ 

MIMO PLC modems	$P_E(W)$
M1	0.5
M2	0.5
M3	0.4

modem, denoted modem 1 in the SISO case and TX modem in the MIMO case) of the CN-100 Compass network analyzer to the receiver port (SISO modem 2 or RX MIMO modem). The experiment is repeated for different values of bit-rates (10 Mbps, 20 Mbps, 40 Mbps, etc.). The whole process is repeated for several frame sizes. Bit-rates are increased up to 80 Mbps for the SISO case and up to 300 Mbps for the MIMO case without resulting in any Ethernet frame loss. This high bit-rate is obtained thanks to the small distance between transmitter and receiver modems (signal attenuation is negligible).

Figures 3.13, 3.14 and 3.15 report the measurements of the power consumption of the 6 pairs of SISO PLC modems (the total power consumption of both transmitter and receiver modems) when transmitting frames of constant size from modem 1 to modem 2. In this work, we only report measurements when transmission rate is equal to reception rate (no frame loss). Fig. 3.13 shows how power consumption of SISO PLC modems changes as a function of bit-rate for a fixed frame size of 1500 Bytes. Measured values for other frames sizes are shown in Fig. 3.14 (1000 Bytes) and Fig. 3.15 (500 Bytes).

Similarly, Fig. 3.16 shows how power consumption of TX MIMO PLC modem M1 and RX MIMO PLC modem M1 changes versus bit-rate when considering fixed frame sizes of 1500 Bytes, 1000 Bytes and 500 Bytes. Measured values for other pairs of modems are shown in Fig. 3.17 (M2) and Fig. 3.18 (M3).

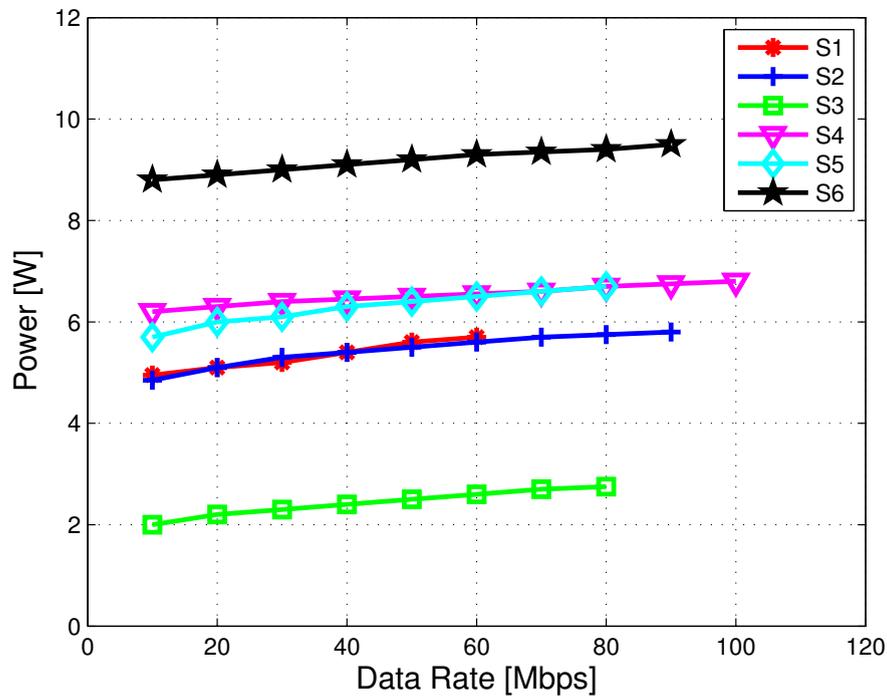


FIGURE 3.13: Power consumption of SISO modems versus bit-rate for fixed frame size  $L=1500$  Bytes

### 3.5 Analysis and main findings

The following are the main findings of the measurements-based evaluation of the power consumption behaviour of PLC modems:

- In both SISO and MIMO cases, the power consumption increases almost linearly with bit-rate.
- The increase of power consumption with bit-rate is higher for the small frames than for the large frames. For example, for SISO PLC modem S4, power increases by 7 mW/Mbps with 500 Bytes frames and 6.2 mW/Mbps with 1500 Bytes frames. In the same way, for MIMO PLC modem M1, power increases by 6.3 mW/Mbps with 500 Bytes frames and 5 mW/Mbps with 1500 Bytes frames. Indeed, when the frame size increases, the number of frames sent per second decreases as the data load in Mbps is held fixed. Per frame overheads (framing, ARQ, etc) are therefore reduced.

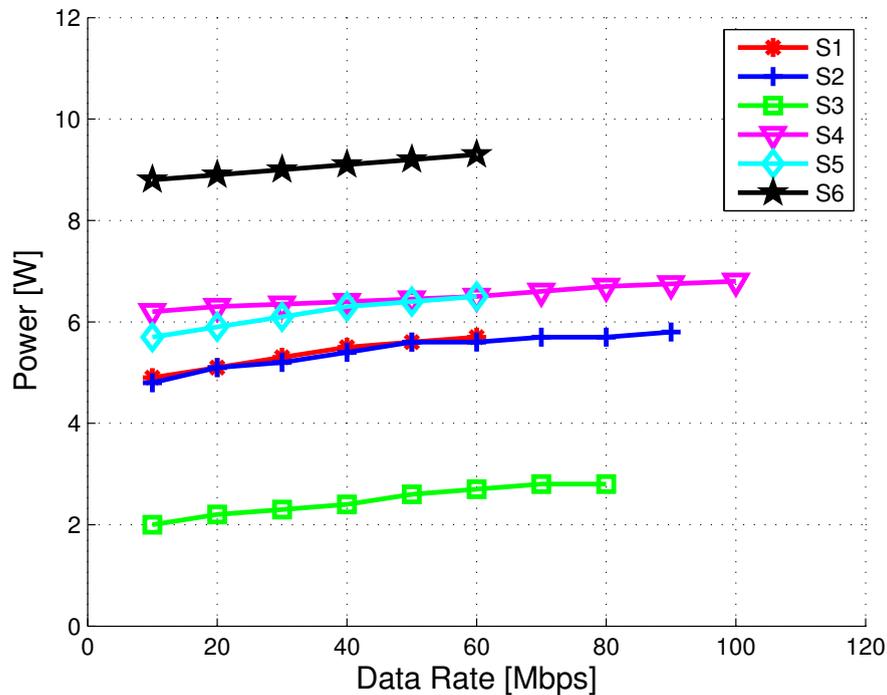


FIGURE 3.14: Power consumption of SISO modems versus bit-rate for fixed frame size  $L=1000$  Bytes

- The power consumption reaches a plateau as the offered load attains the network capacity. For example, with 500 Bytes frames, the maximum network throughput is observed to be 50 Mbps for SISO modem S1 and 220 Mbps for MIMO modem M1. At offered loads above this level, significant packet loss is observed. Note that this effect is channel dependent and will not be taken into account in our analysis.
- Regarding the MIMO case, for all tested modems, the power consumption is significantly larger at the transmission compared to the reception. This is mainly because the power consumed during transmission is largely contributed by the RF power amplifiers.

### 3.6 Conclusion

While the current focus in the development of PLC systems and devices is on increasing systems data rate, energy efficiency remains an important concern for the

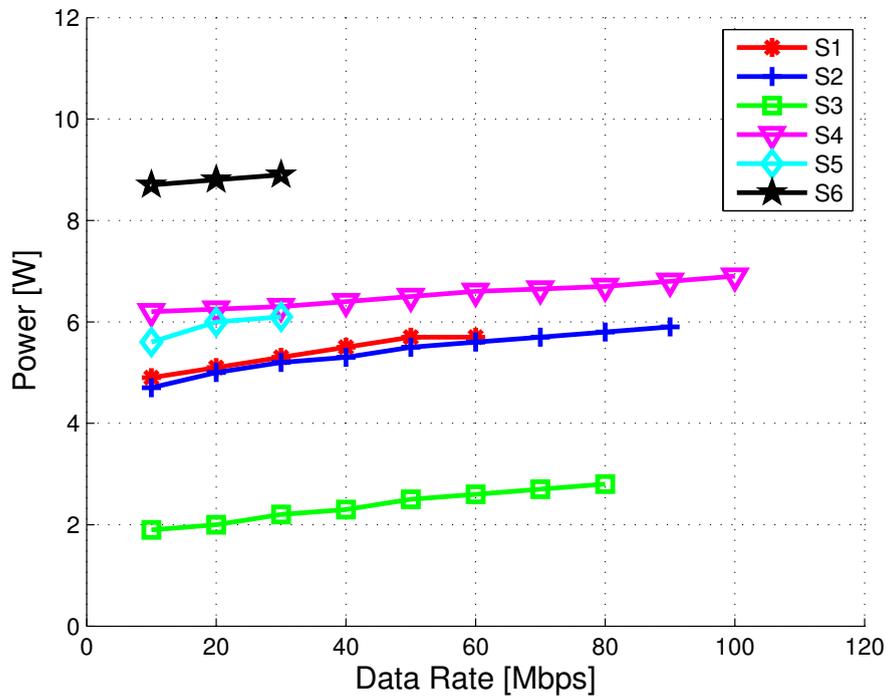


FIGURE 3.15: Power consumption of SISO modems versus bit-rate for fixed frame size  $L=500$  Bytes

PLC community. Investigating and measuring power consumption of PLC devices is an essential step in the process of PLC systems modeling.

In this chapter, we designed and conducted a measurement campaign to investigate the power consumption of several commercial PLC modems, including the latest generation of PLC devices with MIMO functionality. After a description of the experimental setup used in our study, measurements of the power consumption when no traffic load is flowing through the PLC modems are presented. Then, the effect of the variation of traffic load on power consumption is illustrated for different bit rates, frame rates and Ethernet frames with variable sizes.

The measurements provided in this chapter will be used in chapter 4 for power consumption modeling of PLC modems.

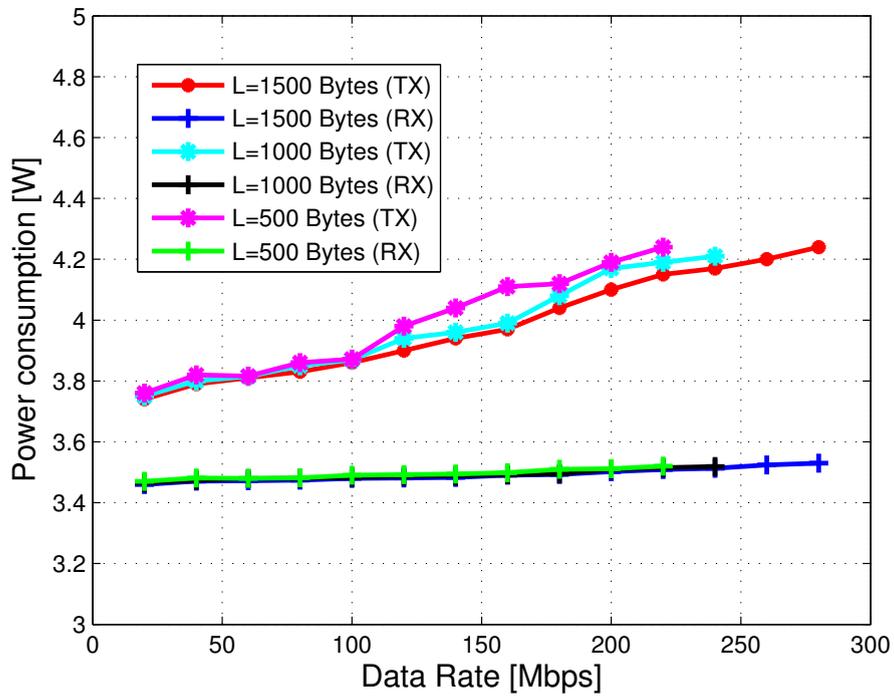


FIGURE 3.16: Power consumption versus bit-rate for different frame sizes of MIMO TX PLC modem M1 and MIMO RX PLC modem M1

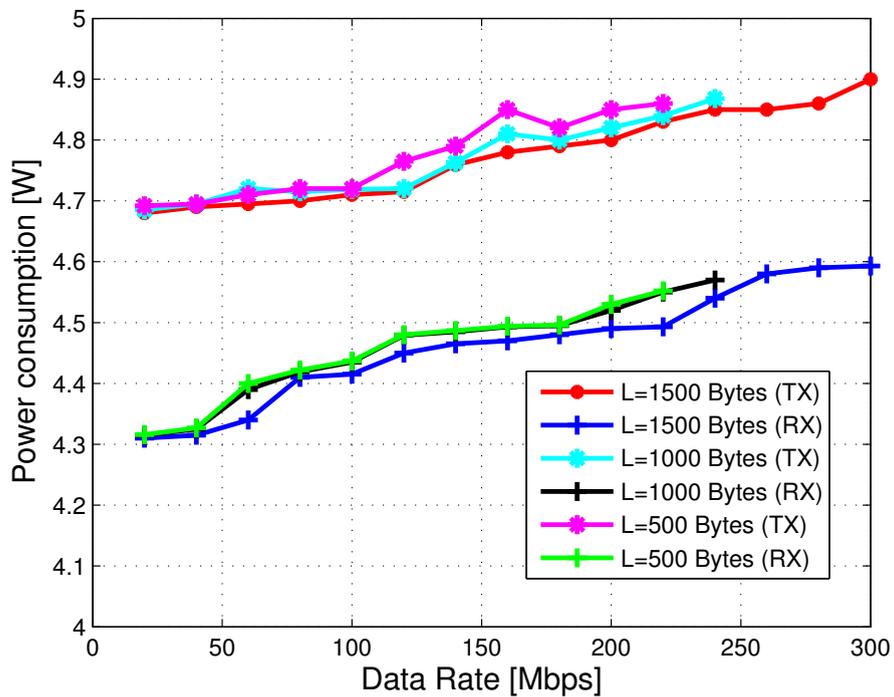


FIGURE 3.17: Power consumption versus bit-rate for different frame sizes of MIMO TX PLC modem M2 and MIMO RX PLC modem M2

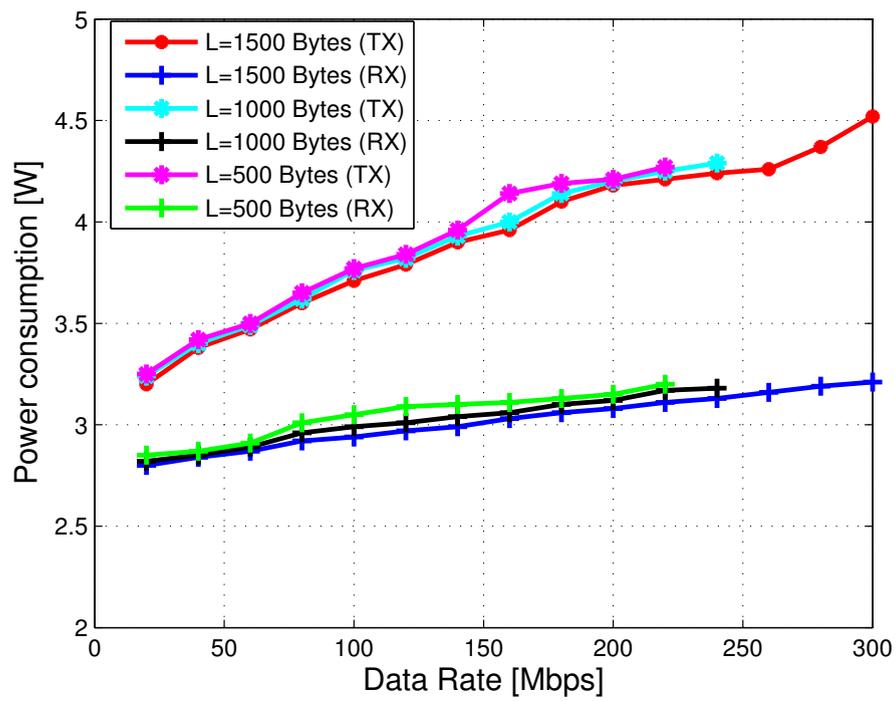


FIGURE 3.18: Power consumption versus bit-rate for different frame sizes of MIMO TX PLC modem M3 and MIMO RX PLC modem M3

## Chapter 4

# Power Consumption Modeling for PLC Modems

### 4.1 Introduction

An accurate power consumption model represents a basis for developing energy efficient techniques and protocols in PLC networks. In most literature works about power consumption of communication networks, devices, and systems [Riggiol2012], [Gomez2012], [Sivaraman2011], [Vishwanath2010], [Vishwanath2013], [Warty2012], which were previously discussed in chapter 3, various formal models for the power consumption were presented, with the device load being the main optimization criteria. A device load is usually defined as a measure of the aggregate traffic transmitted by this device by time unit. Depending on the nature of the transmitted data, the load can be expressed in Frames/s or Bits/s. The generic model of power consumption may be defined as follows :

$$P(l) = P_0 + f(l) \tag{4.1}$$

where  $l$  is the traffic,  $P_0$  is the power consumption in the idle state (in Watts) (this parameter is constant for a given network or device) and  $f(l)$  is an increasing load function.

In this chapter, based on the power consumption measurements presented in Chapter 3, we propose a new power modeling approach for PLC modems. Specifically, we present fine-grained, general and simple analytic linear models that can be used to predict the power consumed for various communication states and different operation modes of both SISO and MIMO PLC modems, namely, idle power consumption, standby power consumption, transmission power consumption, reception power consumption, power consumption as a function of variable data rates and variable Ethernet frame sizes, and the power consumption associated to the processing of Ethernet frames and PLC Physical Blocks (PBs). Then, we use a multiple regression analysis to estimate models parameters.

The rest of this chapter is structured as follows. We first give an overview about power consumption modeling metrics and main strategies. We then present our proposed power consumption models for both SISO and MIMO PLC modems. Next, after a brief introduction to regression analysis, we estimate models parameters by using a least-squares method. Finally, the chapter is concluded after an extensive discussion of the obtained results.

## 4.2 power consumption modeling

A very common classification of power consumption modeling approaches is the distinction between deterministic and statistical approaches, depending on how the model is derived. In this section, a brief overview and examples of both deterministic and statistical modeling strategies are given. Also, most important metrics that are generally used to compare and evaluate the effectiveness of these power modeling approaches are listed.

## **4.2.1 Metrics of power modeling**

### **4.2.1.1 Accuracy**

The accuracy of the power model defines how accurate the estimated power is relative to the measured power. Power modeling accuracy is important since an inaccurate model is useless. Furthermore, depending on the modeled system, not all components require the same accuracy. The components that are the most power consuming and the most contributing to the total system power generally require higher accuracy since the penalty of mispredicting the power consumption is higher. In contrast, higher modeling errors can be tolerated for less power consuming components.

### **4.2.1.2 Complexity**

Complexity in power modeling comes from the need to capture all the relevant features expressed by software and hardware components to serve as inputs to build the model. However, if the power model is too complicated, the overhead of the power estimation will be too high to be able for practical use. Complexity of power models generally increases with accuracy, i.e., a more accurate power model is usually relying on a more complicated power model.

### **4.2.1.3 Generality**

A power modeling approach is more or less general depending on how many cases it covers. Specifically, a power model should be suitable for as many systems as possible, different families of devices and technologies. Moreover, the model derivation technique should be independent of any specific implementation.

### **4.2.1.4 Granularity**

One of the most important properties of power modeling is granularity, i.e., to which level the power model can estimate the power consumption. Power can be

modeled at the level of an entire system or at an individual subsystem. Usually, high granularity means high accuracy and high complexity.

### 4.2.2 Deterministic power modeling

The deterministic power modeling divides a system or a device in several power components and predicts the corresponding power consumption of each component to later derive the overall power consumption. Deterministic power modeling has been widely used for studying power consumption of many communication technologies.

In [Xiao2014], the authors present a deterministic model that describes the power consumption of Wi-Fi data transmission with traffic burstiness, network performance metrics like throughput and retransmission rate, and parameters of the power saving mechanisms in use. In this model, the power consumption of hardware components were estimated with the help of predefined state machines.

In [Bertran2010], a deterministic model of power consumption for current multi-core architectures, e.g., IntelR CoreTM 2 Duo is presented. The model derived in this work were validated using empirical measurements and specifically designed microbenchmarks that isolate and decouple each component activity to derive per component power consumption.

Another deterministic power model to evaluate the power consumption in smart phones is also derived in [Bruno2015] by analyzing the network flow characteristics and traffic bursts. This model quantifies the impact of traffic patterns and network performance on the transmission cost and power consumption mainly caused by the operations of the wireless network interface. The proposed model can be used for estimating the power consumption of various network applications that are implemented with multiple Transmission Control Protocol (TCP)/User Datagram Protocol (UDP) flows.

In [Deruyck2010], the authors compare the power consumption of various access network technologies including Worldwide Interoperability for Microwave Access

(WIMAX), Long-Term Evolution (LTE), High Speed Packet Access (HSPA) under different scenarios, i.e., SISO, and MIMO. This work provided a deterministic model that calculates the amount of power consumed by each part of the system separately rather than the power consumption of the system as a whole.

In all of these works, a major drawback of the deterministic approach is the requirement for an expert knowledge of the underlying system architecture to produce more reliable and accurate power models. Even though deterministic modeling is able to individually breakdown the power components of systems and devices, it is more complex to deploy than the statistical power modeling.

### 4.2.3 Statistical power modeling

The statistical power modeling is based on statistical models like linear regression and aims at finding out the relationship between power consumption and some measured variables. e.g., transmission rate or processor clock speed. The statistical approach defines simple, fast and easy models since it doesn't require a specific knowledge of the modeled architecture.

Examples of previous studies based on these methodology are given below.

A statistical approach is reported in [Nagasaka2010], where the power consumption of graphics processing units (GPU) kernels is estimated by using a linear regression model. In this model, performance counters are used as independent variables and power consumption is the dependent variable. On the basis of experimental evaluation, the authors show that this approach is able to provide a high estimation accuracy for many of the tested kernels, i.e., the average error ratio was 4.7%.

Similar work in term of methodology is presented in [Lorincz2012], where a statistical approach for base stations (BS) of both Global System for Mobile Communications (GSM) and Universal Mobile Telecommunications System (UMTS) is followed. In this approach, a conventional linear regression power consumption model is also used to express the interdependence between instantaneous BS power consumption and traffic load.

In [Shang2001], a high-level power modeling technique to estimate the power consumption of reconfigurable devices such as complex programmable logic devices (CPLDs) and field-programmable gate arrays (FPGAs) is provided. The authors in this work propose the use of an adaptive regression method to model FPGA power consumption and experimentally show that the average relative error is only 3.1% compared to low-level FPGA power simulation methods.

The previous works show that linear regression is the most commonly used statistical method for power consumption modeling. In the following section, we describe the linear regression modeling approach that we use to fit the measured power data in this chapter.

#### 4.2.4 Linear regression modeling

Linear regression is used to express the relationship between a dependent variable  $Y$  and one independent variable denoted  $X$  for the simple linear regression case, or more than one independent variable for the multiple linear regression case. This linear relationship summarizes the amount of change in one variable that is associated with change in another variable or several other variables. For example, the following model is a multiple linear regression model with  $n$  independent variables

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n + \epsilon \quad (4.2)$$

where

- $Y$  is the dependent variable
- $x_1, x_2, \dots$  and  $x_n$  are the independent variables
- $\beta_1, \beta_2, \dots$  and  $\beta_n$  are the partial regression coefficients
- $\beta_0$  is the intercept
- $\epsilon$  is the error

The Least Square (LS) method is usually used to find  $n$  coefficients in  $\beta_i$  based on the observations. Specifically, if the estimated LS equation is

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \dots + \hat{\beta}_n x_n \quad (4.3)$$

where  $\hat{Y}$  is the fitted value of  $Y$  and  $\hat{\beta}_0, \hat{\beta}_1, \hat{\beta}_2, \dots, \hat{\beta}_n$  are the estimates of  $\beta_0, \beta_1, \beta_2, \dots, \beta_n$ .

The estimates  $\hat{\beta}_0, \hat{\beta}_1, \hat{\beta}_2, \dots, \hat{\beta}_n$  are chosen such that the sum of squared residuals, namely,  $\sum (Y - \hat{Y})^2$ , is minimized.

## 4.3 power consumption model for PLC modems

### 4.3.1 SISO PLC modems

Here, we present our proposed power consumption model for SISO PLC modems. As previously mentioned, we choose to model power consumption for pairs of PLC modems. In each pair, the first modem is considered as a transmitter and the second as a receiver. The power consumption  $P$  of a pair of PLC modems can be expressed as a sum of four terms, as shown below

$$P = 2 \times C + 2 \times P_E + E^F N + E^{PB} R \quad (4.4)$$

where

- $C$  is the constant baseline power of SISO PLC modems (in Watts) (i.e. without any Ethernet ports connected, and hence no traffic).
- $P_E$  is the power consumed by each Ethernet port when it is only connected and without any traffic flowing (in Watts).
- $E^F N$  is the power consumed for processing Ethernet frames, which is the product of per-frame processing energy  $E^F$  and the input frame rate  $N$  (in frames/second).  $E^F$  depends on frame rate because each frame that enters a PLC modem requires the same processing (i.e. Adding headers, CRC,...).

- $E^{PB}R$  is the power consumed for processing PLC Physical Blocks, which is the product of per-byte energy  $E^{PB}$  and the input data byte-rate  $R$  (in bytes/sec).

### 4.3.2 MIMO PLC modems

As previously discussed, to properly analyze the power consumption behaviour of MIMO PLC devices, the separation between the power required for transmission and the power required for reception is included. Since we consider in our analysis that the transmission rate is equal to the reception rate (no frame loss), we note the term  $R = R_t = R_r$  to define the data rate in Bytes/second and  $N = N_t = N_r$  to define the data frame rate in frame/second. Thus, the total power consumption at the MIMO transmitter modem and the MIMO receiver modem are respectively given by:

$$P_{TX} = C + P_E + E_t^F N_t + E_t^{PB} R_t \quad (4.5)$$

and

$$P_{RX} = C + P_E + E_r^F N_r + E_r^{PB} R_r \quad (4.6)$$

where

- $C$  is the MIMO modems baseline power consumption as defined in Eq. 4.4.
- $P_E$  is the per-ethernet port power as defined in Eq. 4.4.
- $E_t^F N_t$  is the power consumed for transmitting Ethernet frames, which is the product of per-frame transmitting energy  $E_t^F$  and transmission frame rate  $N_t$  (in frames/second).
- $E_r^F N_r$  is the power consumed for receiving Ethernet frames, which is the product of per-frame receiving energy  $E_r^F$  and reception frame rate  $N_r$ .

- $E_t^{PB} R_t$  is the power consumed for transmitting PLC Physical Blocks, which is the product of per-byte transmitting energy  $E_t^{PB}$  and transmission data byte-rate  $R_t$  (in bytes/sec).
- $E_r^{PB} R_r$  is the power consumed for receiving PLC Physical Blocks, which is the product of per-byte receiving energy  $E_r^{PB}$  and reception data byte-rate  $R_r$ .

### 4.3.3 Estimation of the power consumption model parameters

The energy components

$$E^F = \begin{cases} E^F, & \text{for pair of SISO modems} \\ E_t^F, & \text{for MIMO transmitter modem} \\ E_r^F, & \text{for MIMO receiver modem} \end{cases} \quad (4.7)$$

and

$$E^{PB} = \begin{cases} E^{PB}, & \text{for pair of SISO modems} \\ E_t^{PB}, & \text{for MIMO transmitter modem} \\ E_r^{PB}, & \text{for MIMO receiver modem} \end{cases} \quad (4.8)$$

are estimated using a multiple regression analysis. Specifically, we rewrite equations 4.4, 4.5 and 4.6 in the form:

$$P_{ij} = \begin{cases} a + bN_j + cR_i, & \text{for pair of SISO modems} \\ a + b_t N_j + c_t R_i, & \text{for MIMO transmitter modem} \\ a + b_r N_j + c_r R_i, & \text{for MIMO receiver modem} \end{cases} \quad (4.9)$$

where

- $i \in 1, 2, \dots, 15$  represents the data rate index within data-byte rates  $R_i = (\frac{20}{8}$  Mbps,  $\frac{40}{8}$  Mbps, ...,  $\frac{300}{8}$  Mbps).
- $j \in 1, 2, 3$  represents the packet size index within the packet sizes  $L_j = (500, 1000, 1500)$ .
- $a = C + P_E$ .
- $b = E^F$ ,  $c = E^{PB}$ ,  $b_t = E_t^F$ ,  $b_r = E_r^F$ ,  $c_t = E_t^{PB}$  and  $c_r = E_r^{PB}$ .

Since the frame rate is  $N = R/L$ , the previous system of equations can be rewritten as:

$$P_{ij} = \begin{cases} a + bRi/Lj + cR_i, & \text{for pair of SISO modems} \\ a + b_t Ri/Lj + c_t R_i, & \text{for MIMO transmitter modem} \\ a + b_r Ri/Lj + c_r R_i, & \text{for MIMO transmitter modem} \end{cases} \quad (4.10)$$

The system of equations in 4.10 can be represented in the matrix notation as follows:

$$P = a\mathbf{1}_n\mathbf{1}_m^\top + bRM^\top - cR\mathbf{1}_m^\top \quad (4.11)$$

where the superscript  $\top$  denotes the matrix transpose operation,

$$\begin{cases} i = 1, \dots, n \\ j = 1, \dots, m \end{cases}, \quad n > m$$

$$M = \begin{pmatrix} 1/L_1 \\ 1/L_2 \\ \vdots \\ 1/L_m \end{pmatrix},$$

$$R = \begin{pmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{pmatrix},$$

$$P = \begin{pmatrix} P_{11} & \dots & P_{1m} \\ \vdots & & \\ P_{n1} & \dots & P_{nm} \end{pmatrix},$$

$$1_k = \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \begin{matrix} \uparrow \\ k \text{ terms,} \\ \downarrow \end{matrix}$$

$$b = \begin{cases} b, & \text{for pair of SISO modems} \\ b_t, & \text{for MIMO transmitter modem} \\ b_r, & \text{for MIMO receiver modem} \end{cases} \quad (4.12)$$

and

$$c = \begin{cases} c, & \text{for pair of SISO modems} \\ c_t, & \text{for MIMO transmitter modem} \\ c_r, & \text{for MIMO receiver modem} \end{cases} \quad (4.13)$$

In order to estimate  $b$  and  $c$ , we use a least squares approach. That is, we seek for

$$\min_{b,c} \left\| P - a1_n 1_m^\top - bRM^\top - cR1_m^\top \right\|^2 \quad (4.14)$$

The criterion in Eq. 4.14 can be rewritten as follows:

$$g(b, c) = \text{Tr}((P - a1_n 1_m^\top - bRM^\top - cR1_m^\top)^\top (P - a1_n 1_m^\top - bRM^\top - cR1_m^\top)) \quad (4.15)$$

where  $\text{Tr}(\cdot)$  is the trace.

The minimum is obtained by calculating its partial derivative with respect to  $b$  and

$c$

$$\partial g / \partial b = -2Tr(MR^\top(P - a1_n1_m^\top - bRM^\top - cR1_m^\top)) = 0 \quad (4.16)$$

$$\partial g / \partial c = -2Tr(1_mR^\top(P - a1_n1_m^\top - bRM^\top - cR1_m^\top)) = 0 \quad (4.17)$$

From 4.16 and Eq. 4.17, we get

$$Tr(MR^\top P) - aTr(MR^\top 1_n1_m^\top) = b \|RM^\top\|^2 + cTr(MR^\top R1_m^\top) \quad (4.18)$$

$$Tr(1_mR^\top P) - aTr(1_mR^\top 1_n1_m^\top) = bTr(1_mR^\top RM^\top) + c \|R1_m^\top\|^2 \quad (4.19)$$

Equations 4.18 and 4.19 can be rewritten as

$$\begin{pmatrix} \|RM^\top\|^2 & Tr(MR^\top R1_m^\top) \\ Tr(1_mR^\top RM^\top) & \|R1_m^\top\|^2 \end{pmatrix} \begin{pmatrix} b \\ c \end{pmatrix} = \begin{pmatrix} R^\top PM - aTr(MR^\top 1_n1_m^\top) \\ R^\top P1_m - aTr(1_mR^\top 1_n1_m^\top) \end{pmatrix} \quad (4.20)$$

Then, we get

$$b = \frac{\begin{vmatrix} Tr(MR^\top P) - aTr(MR^\top 1_n1_m^\top) & Tr(MR^\top R1_m^\top) \\ Tr(1_mR^\top P) - aTr(1_mR^\top 1_n1_m^\top) & \|R1_m^\top\|^2 \end{vmatrix}}{\begin{vmatrix} \|RM^\top\|^2 & Tr(MR^\top R1_m^\top) \\ Tr(1_mR^\top RM^\top) & \|R1_m^\top\|^2 \end{vmatrix}} \quad (4.21)$$

$$c = \frac{\begin{vmatrix} \|RM^\top\|^2 & Tr(MR^\top P) - aTr(MR^\top 1_n1_m^\top) \\ Tr(1_mR^\top RM^\top) & Tr(1_mR^\top P) - aTr(1_mR^\top 1_n1_m^\top) \end{vmatrix}}{\begin{vmatrix} \|RM^\top\|^2 & Tr(MR^\top R1_m^\top) \\ Tr(1_mR^\top RM^\top) & \|R1_m^\top\|^2 \end{vmatrix}} \quad (4.22)$$

where  $|\cdot|$  denotes the determinant.

In the next section, we will present and discuss the results that we obtain by applying the above approach to fit the measured power consumption values of both SISO and MIMO modems.

## 4.4 Summary and Discussion

### 4.4.1 SISO case

Table 4.1 provides the estimated parameters of our proposed power consumption model for the 6 tested SISO PLC modems. Fig. 4.1 presents static and dynamic consumed power consumptions for each pair of SISO PLC modems when considering a frame size  $L = 1500$  Bytes and a bit-rate  $r = 60$  Mbps. The static power consumption is the sum of baseline power  $C$  and per-port Ethernet power  $P_E$  (without traffic flowing through PLC modems) and the dynamic power consumption is the power consumed for processing Ethernet frames and PLC Physical Blocks (power associated to the term:  $E^F N + E_{PB} R$ ). It can be observed that static power consumption of SISO PLC modems is the largest component of the total power consumption. That means that commercial SISO modems consume most of their power just to be on, while the impact of traffic load on power consumption is relatively small.

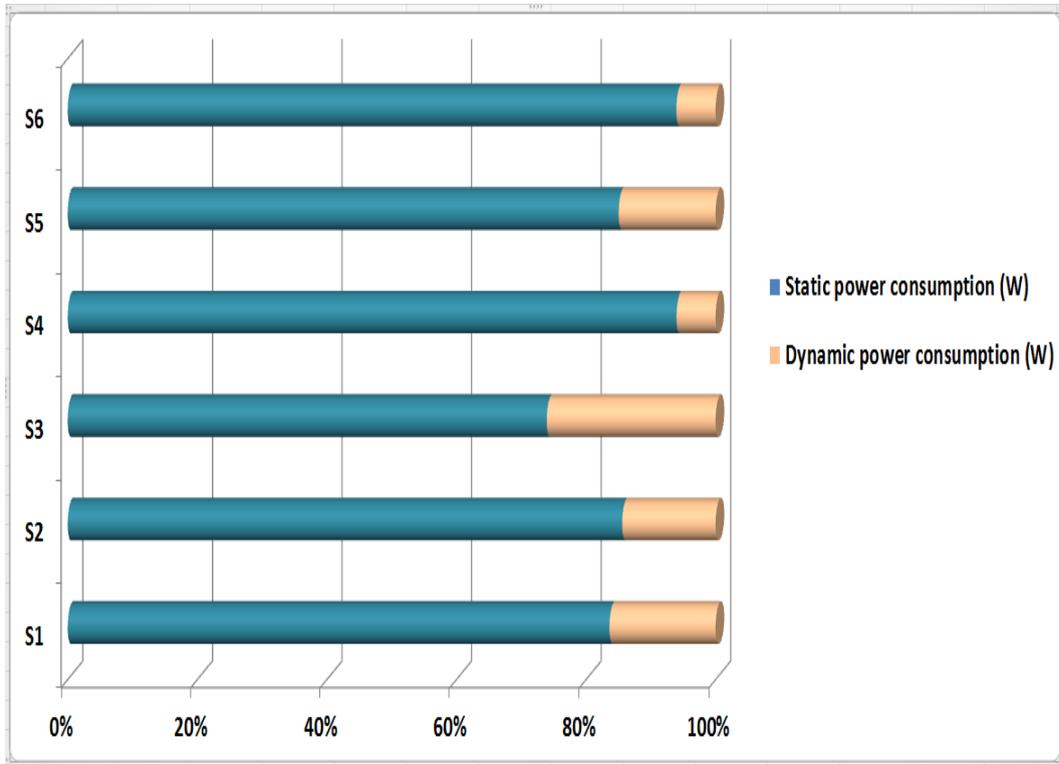
Then, Fig. 4.2 illustrates Ethernet frame processing Energy and Physical Blocks processing Energy of SISO devices. In all cases, PLC Physical Blocks processing power consumption is higher than Ethernet frame processing power consumption.

### 4.4.2 MIMO case

Table. 4.2 depicts the values of the estimated parameters for our proposed model of power consumption with the 3 tested MIMO PLC modems respectively. Fig. 4.3 compares transmission and reception power values consumed by each tested MIMO PLC modem when considering a frame size  $L = 1500$  Bytes and a bit-rate  $r = 300$  Mbps. The transmission power is the power consumed for transmitting Ethernet

TABLE 4.1: Summary of the power profile for the 6 pairs of SISO PLC modems

PLC modems	Baseline power $2 \times C(W)$	Ethernet per-port power $2 \times P_E(W)$	Ethernet frames processing energy $E^F(nJ)$	PLC frames processing energy $E_{PB}(nJ)$
S1	4.4	$2 \times 0.2$	$11.3 \times 10^3$	99.2
S2	3.0	$2 \times 0.5$	$10.2 \times 10^3$	72.0
S3	1.2	$2 \times 0.3$	$23.4 \times 10^3$	63.5
S4	5.0	$2 \times 0.6$	$8.7 \times 10^3$	40.5
S5	4.0	$2 \times 0.3$	$71.3 \times 10^3$	52.7
S6	6.2	$2 \times 1.1$	$9.2 \times 10^3$	60.0

FIGURE 4.1: Repartition of the power consumption of SISO PLC modems calculated for a frame size  $L = 1500$  Bytes and a bit-rate  $r = 60$  Mbps

frames and PLC Physical Blocks ( $P_t = E_t^F N + E_t^{PB} R$ ), and the reception power is the power consumed for receiving Ethernet frames and PLC Physical Blocks

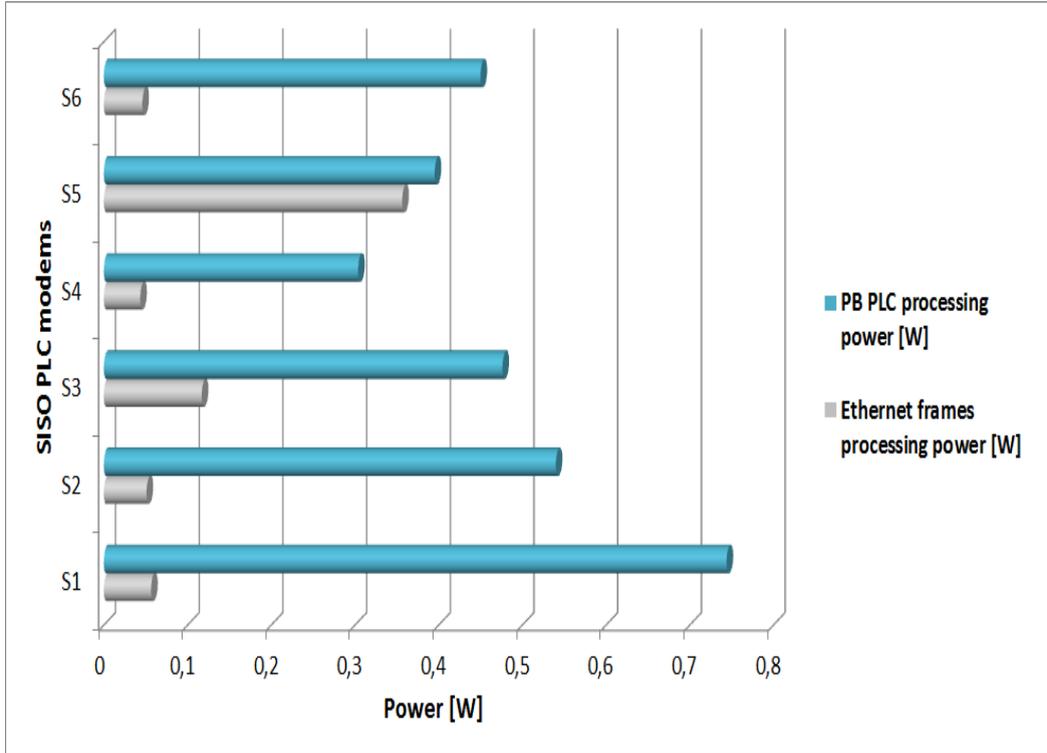


FIGURE 4.2: Power consumption model parameters calculated for a frame size  $L = 1500$  Bytes and a bit-rate  $r = 60$  Mbps

TABLE 4.2: Summary of the power profile for the 3 tested MIMO PLC modems

PLC Modems	M1	M2	M3
$C(W)$	2.8	3.8	2.3
$P_E(W)$	0.5	0.5	0.4
$E_t^F(nJ)$	$1.71 \times 10^3$	$1.42 \times 10^3$	$2.38 \times 10^3$
$E_t^{PB}(nJ)$	17.62	8.55	37.87
$E_r^F(nJ)$	$0.07 \times 10^3$	$0.26 \times 10^3$	$0.71 \times 10^3$
$E_r^{PB}(nJ)$	3.35	7.97	11.91

( $P_r = E_r^F N + E_r^{PB} R$ ). Fig. 4.3 indicates that the power required for transmitting and receiving PLC PB is higher than the power consumed for transmitting and receiving Ethernet frames. Next, Fig. 4.4 provides the distribution of the power consumption of the 3 modems when considering a frame size  $L = 1500$  Bytes and

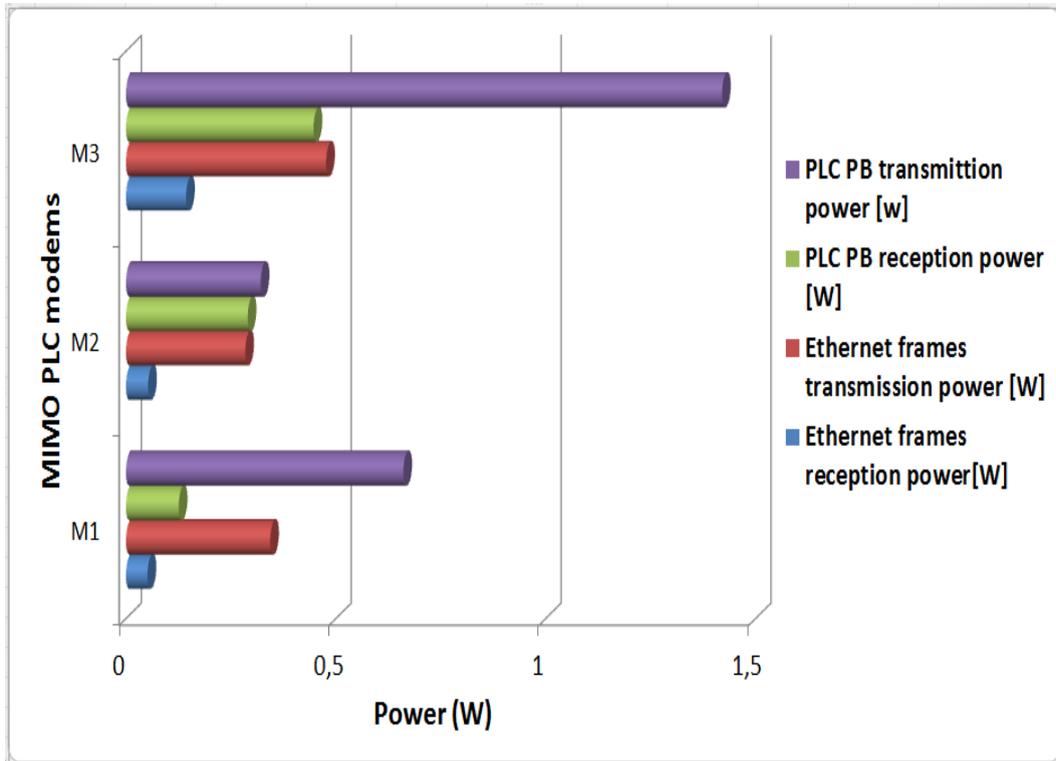


FIGURE 4.3: Power consumption model parameters calculated for a frame size  $L = 1500$  Bytes and a bit-rate  $r = 300$  Mbps

a bit-rate  $r = 300$  Mbps. It can be seen from Fig. 4.4 that in general, the baseline power consumption represents the main contribution to power loss and may increase the total power consumption by up to 65%. However, the part of power associated to the traffic load can also be an important contributor to total power consumption (e.g., about 50% of total power consumption in the case of Modems M3). Fig. 4.4 also shows that transmission consumes significantly more power than reception that consumes around 22% to 25% less power. Finally, the impact of per-Ethernet port power is relatively small but still non negligible especially when compared to the reception power.

## 4.5 Conclusion

In this chapter, we proposed a linear power consumption model based on measurements carried out on many commercial SISO and MIMO PLC modems. In this model, the power consumption for different states and operations of the modems

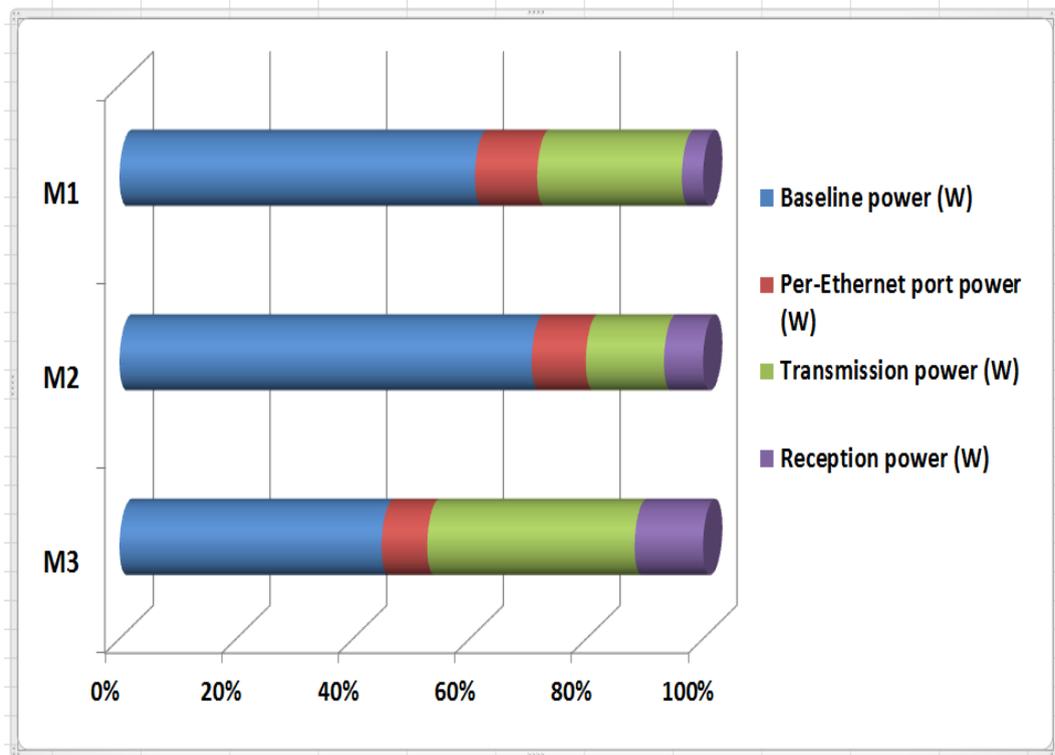


FIGURE 4.4: Repartition of the power consumption of MIMO PLC modems calculated for a frame size  $L = 1500$  Bytes and a bit-rate  $r = 300$  Mbps

(Ethernet frame processing, Physical Blocks processing, etc.) are quantified separately. Such an experimental campaign shows which are the most consuming components of MIMO PLC modems and permitted us to ascertain the impact of traffic on the energy efficiency of PLC modems. In general, the total power consumption is dominated by the idle component (when no traffic is flowing through the pair of PLC modems). For the part of power associated to the traffic load, Physical Blocks processing power appears to be the most critical element.

Regarding MIMO modems, transmission power can represent up to 40% of the overall consumption budget. Additionally, the impact of reception power and Per-Ethernet port power is relatively small. The obtained results can be used to guide the future green PLC modems design and development.

As a next step, we intend to study how the power consumption can be reduced by using relay nodes in PLC networks. To this end, a simulation and measurement-based evaluation of the energy efficiency performance of relay PLC networks will be presented in chapters 5 and 6. In this evaluation, we will consider the measured

baseline power consumption values of PLC modems to develop a realistic power consumption model for PLC relay systems.

## Chapter 5

# Relay-Assisted PLC Networks with uniform time allocation

### 5.1 Introduction

The concept of cooperative transmission or relaying, which is well known in wireless communications, has been regarded as a powerful method to improve communication systems performance. It has attracted the interest of research and standards communities thanks to its advantages, such as throughput increase, power efficiency improvement, and coverage extension [Sendonaris2003], [Sendonaris2003a]. An overview of different proposed protocols for the implementation of relays in wireless networks has already been given in chapter 2 (See Section 2.4.3). In addition, there are two basic working modes for a relay system: full-duplex and half-duplex mode. A half-duplex relay receives in a given time slot and transmits in the next one. In the full-duplex mode, the relay is assumed to be able to transmit and receive simultaneously; full-duplex relays are generally difficult to implement in practice.

Regarding the broadcasting nature of PLC channels, research on the application of modern relaying techniques largely carried out for wireless communications have found their way into PLC. In particular, the Decode and Forward (DF) protocol has been shown to have significant advantages in the PLC context [Zou2009],

[Valenciaz2014], [Tan2011]. In previous researches, the focus is mainly on maximizing the achievable transmission rate under a power constraint, but power efficiency performance of DF PLC relaying and the problem of power minimization under given rate requirements have not been extensively explored. With the rapid growth of data traffic in PLC networks, the power consumption increases and it is insufficient to only consider the system achievable rate while ignoring the power efficiency. In [D'Alessandro2011], [D'Alessandro2012], the authors considered the use of opportunistic DF protocol in In-Home PLC networks, and showed that it allows for saving several dBs of transmitted power. To the best of our knowledge, those are the only works that are directly related to the study that we present in the current chapter, and in chapter 6 of this thesis. However, the results derived in [D'Alessandro2011], [D'Alessandro2012] focus only on transmit power (dynamic power) when considering the power consumption of PLC modems, and the static power of modems is not considered. Indeed, as shown in chapters 3 and 4, a PLC modem will incur additional static power during transmission which is fixed and independent of the transmission rate [Bakkali2014].

In this chapter, we evaluate the benefits of half-duplex DF PLC relays in terms of throughput and power efficiency. We first derive a general power consumption model for DF SISO PLC relay systems, in which the dynamic power and the static power are taken into account. Then, through extensive numerical results based on both simulated and measured PLC channels and PLC noise (obtained from measurements performed in five French houses and from WITS software), measured static power consumption values of PLC modems (obtained from the power consumption measurements presented in chapter 3) and two representative scenarios, we show that depending on the idle power consumption value of PLC modems, i.e., the static power value consumed by the modem when it is in idle mode, significant power efficiency gain can be obtained by using the DF relay protocol in PLC networks.

The chapter is organized as follows. A description of the relay system that we consider is presented in the next section, followed by a presentation of the proposed power consumption model. Then, details about the measured and simulated PLC

channels and PLC noise are given. Finally, numerical results are presented and concluding remarks are given in the last section.

## 5.2 System model

Let's consider a system with three SISO PLC modems: a single source (S), single destination (D) pair and an available relay (R) located between S and D as shown in Fig. 5.1. Multiplexing is accomplished via TDMA, where time is divided in frames of duration  $T$ . We assume that each frame is divided into two time slots, whose durations are  $t_1$  and  $T - t_1$ . Modem S sends data to modem D, and modem R is a half-duplex relay that helps to transfer data between S and D in a DF relaying scheme. Two phases are required during transmission time  $T$ . In this chapter, we allocate equal transmission time on the first and the second phase of transmission between the source and relay nodes; the optimal time division strategy will be studied in chapter 6. Therefore, modem S first sends its data to relay R (duration time for the first phase is  $t_1 = \frac{T}{2}$  seconds). In the second phase relay R sends these bits with a different coding to modem D, (duration time for the second hop is  $T - t_1$ ).

Furthermore, we assume that each PLC modem has three modes: transmission mode, reception mode and idle mode. Therefore, when modem S is in the first hop of its transmission, relay R is in receiving mode and modem D is in idle mode. Then in the second hop of transmission, modem S is in idle mode, relay R is in transmission mode and modem D is in receiving mode. Throughout this chapter, we focus on the scenario where S and D cannot communicate directly with each other due, for example, to a strong attenuation in the S-D link or to the hidden node effect [Mushkin2001]. Therefore, when the relay is used, the direct path from S to D is not taken into account.

In the rest of the chapter, the direct transmission scheme is used as a reference when comparing the performance of the relaying strategies under investigation.

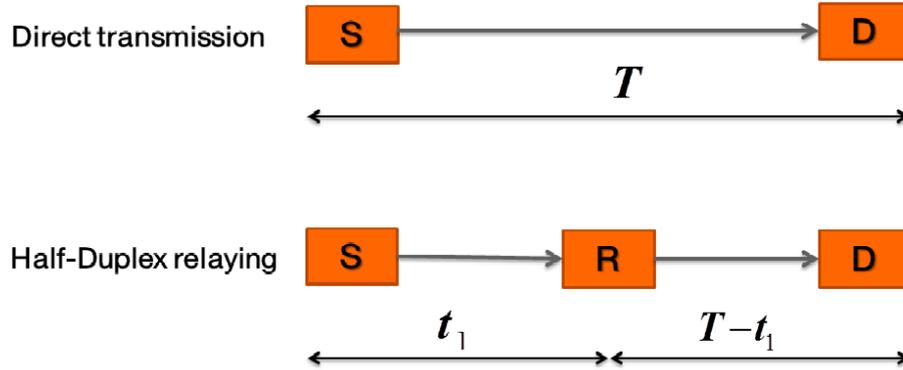


FIGURE 5.1: Illustration of the system model

### 5.3 power consumption model

In this section, the following power consumption model is applied both for direct transmission (DT) and Half-Duplex Decode and Forward relaying (HD). As mentioned above, in order to take realistic constraints into account, we consider the static power of PLC modems in the power consumption model. According to the results obtained in chapters 3 and 4, the total power consumption of SISO PLC modems is dominated by the static component (when no traffic is flowing through the PLC modems). Hence, there are two kinds of power: the dynamic power (part of power associated to flowing traffic), which mainly depends on the transmission power  $P_{tr}$  and the static power  $P_{st}$  ( $P_{tr}$  can be obtained for a target capacity using the Shannon formula, as will be developed later, while  $P_{st}$  is constant and independent of the bit-rate). At this point, we note that a great deal of effort is spent in research to propose some low-power idle modes that reduce static power consumption when there is no data transmission or reception.

So, in our analysis we assume that:

- Each PLC modem has a dynamic power consumption  $P_{dyn} = \frac{P_{tr}}{\eta}$  where  $\eta \in ]0, 1]$  represents the radio-frequency front-end architecture efficiency including the power amplifier efficiency.

- Each PLC modem has a static power  $P_{st}$ .
- Static power values for transmitter, relay and receiver modems are identical.
- Modems support a low-power idle mode, where the power consumption is denoted  $P_{idle}$ .
- Idle power values for transmitter, relay and receiver modems are identical.

### 5.3.1 Direct Transmission (DT)

In DT, there is no relay. PLC modem S transmits to modem D. The transmitter consumes  $P_{tr}^{SD}$  Watts for transmission and  $P_{st}^S$  Watts for static power, while the receiver just requires  $P_{st}^D$  Watts for its static power. So the power consumption model for direct transmission is obtained as

$$P_{DT} = \frac{P_{tr}^{SD}}{\eta} + P_{st}^S + P_{st}^D \quad (5.1)$$

### 5.3.2 Half-Duplex DF Relaying

In HD DF relaying, modems D and S are in idle mode in the first and the second phase respectively. We introduce the idle power for this strategy. Idle power refers to the static power consumed by the modem when it is in idle mode. The power consumption model for HD relaying can be obtained as

$$P_{HD} = \frac{1}{2} \left( \frac{P_{tr}^{SR}}{\eta} + P_{st}^S + P_{st}^R + P_{idle}^D \right) + \frac{1}{2} \left( \frac{P_{tr}^{RD}}{\eta} + P_{st}^R + P_{st}^D + P_{idle}^S \right) \quad (5.2)$$

Where

- $P_{tr}^{SR}$  is the transmission power of modem S.
- $P_{tr}^{RD}$  is the transmission power of relay modem R.
- $P_{st}^S$ ,  $P_{st}^R$  and  $P_{st}^D$  denote the corresponding static power values of transmitter, relay and receiver modems respectively.
- $P_{idle}^D$  corresponds to the power consumed by modem D when it is idle.

- $P_{idle}^S$  corresponds to the power consumed by modem S when it is idle.

## 5.4 Performance analysis

In the following, we investigate the rate and power efficiency improvement of Half-Duplex DF relaying to see the advantage of relay-aided transmission over direct transmission. Our performance metrics are the maximum achievable bit rate and the minimum consumed power. For this purpose, we use the instantaneous capacity of direct transmission  $C_{DT}$  and the minimum required power to achieve a target rate for the direct transmission case  $P_{DT}$  as the baselines of performance comparison in our work.

### 5.4.1 Rate improvement for given power

In this section, we are interested in quantifying the advantage of relaying in terms of achievable rate. Assuming a fixed amount of the overall available power, we first derive the maximum achievable rate  $C_{DT}$  for the direct transmission case, and then we derive the maximum achievable rate  $R_{H DU}$  of Half-Duplex DF relaying with uniform time division. HDU relaying performs better than direct transmission if  $R_{H DU} - C_{DT} > 0$ .

#### 5.4.1.1 Direct transmission

According to the Shannon capacity formula [Shannon1949], the maximum rate of a given communication system channel, is given in bits/s by

$$C_{DT} = \frac{B}{N} \sum_{k=0}^{N-1} \log_2 \left( 1 + \frac{P_{tr}^{SD}(k) |H_{SD}(k)|^2}{P_W(k)} \right) \quad (5.3)$$

where  $N$  is the number of available considered sub-carriers,  $B$  the frequency bandwidth,  $P_{tr}^{SD}(k)$  the allocated power to the  $k$ -th sub-carrier,  $H_{SD}(k)$  the channel transfer function of the  $k$ -th sub-carrier for the direct link and  $P_W(k)$  the noise power at the  $k$ -th sub-carrier.

The optimal power allocation over sub-carriers for rate maximization under a total power constraint in the direct transmission case is found by the classical Water-filling Method. ([Tse2005], pp. 182 – 184).

#### 5.4.1.2 HD DF relaying

The maximum achievable rate of Half-Duplex DF relaying with an uniform time sharing (HDU) between the first and the second time slot can be obtained as [Zou2009]:

$$R_{HDU} = \frac{1}{2} \min \{C_{SR}, C_{RD}\} \quad (5.4)$$

where  $C_{SR}$  and  $C_{RD}$  denote the instantaneous capacities of the (S-R) and (R-D) channels, respectively:

$$C_{SR} = \frac{B}{N} \sum_{k=0}^{N-1} \log_2 \left( 1 + \frac{P_{tr}^{SR}(k) |H_{SR}(k)|^2}{P_W(k)} \right) \quad (5.5)$$

$$C_{RD} = \frac{B}{N} \sum_{k=0}^{N-1} \log_2 \left( 1 + \frac{P_{tr}^{RD}(k) |H_{RD}(k)|^2}{P_W(k)} \right) \quad (5.6)$$

where  $H_{SR}$ ,  $H_{RD}$  are the channel transfer functions of (S-R) and (R-D) links respectively and  $P_W$  is the noise power.

#### 5.4.2 power saving for a given target rate

In this section, we study the power efficiency performance of HDU relaying. Here, in contrast to the previous section where the rate is maximized provided a fixed amount of the available power, we suppose that a relay is used and we want to achieve a given target rate  $R_{ta}$ .

HDU relaying is more power efficient if  $P_{HD} < P_{DT}$ .

According to the definitions of  $P_{HD}$  and  $P_{DT}$  above, this conditions leads to

$$\begin{aligned} \frac{1}{2} \left( \frac{P_{tr}^{SR}}{\eta} + P_{st}^S + P_{st}^R + P_{idle}^D \right) \\ + \frac{1}{2} \left( \frac{P_{tr}^{RD}}{\eta} + P_{st}^R + P_{st}^D + P_{idle}^S \right) < \frac{P_{tr}^{SD}}{\eta} + P_{st}^S + P_{st}^D \end{aligned} \quad (5.7)$$

Let  $P_{st}^{DT}$ ,  $P_{st}^{HD}$  be the static power values consumed by the direct transmission and HD relaying respectively, and  $P_{dyn}^{DT}$ ,  $P_{dyn}^{HD}$  the dynamic power values consumed by the direct transmission and HD relaying respectively:

$$P_{st}^{DT} = P_{st}^S + P_{st}^D = 2P_{st} \quad (5.8)$$

$$P_{st}^{HD} = \frac{1}{2}(P_{st}^S + P_{st}^R) + \frac{1}{2}(P_{st}^R + P_{st}^D) = 2P_{st} \quad (5.9)$$

$$P_{dyn}^{DT} = \frac{P_{tr}^{SD}}{\eta} \quad (5.10)$$

$$P_{dyn}^{HD} = \frac{\frac{1}{2}P_{tr}^{SR} + \frac{1}{2}P_{tr}^{RD}}{\eta} \quad (5.11)$$

Since we assume  $P_{st} = P_{st}^S = P_{st}^R = P_{st}^D$  and  $P_{idle} = P_{idle}^D = P_{idle}^R$ , Eq. 5.7 can then be simplified to

$$P_{st}^{HD} + P_{dyn}^{HD} + P_{idle} < P_{st}^{DT} + P_{dyn}^{DT} \quad (5.12)$$

In the rest of the section we derive the transmit power consumed by DT to achieve  $R_{ta}$ , and then the minimum transmit power required by HDU relaying to reach the same target rate.

#### 5.4.2.1 Direct transmission

Now, the optimum power allocation must be found so that the sum of  $P_{tr}^{SD}(k)$  over all subcarriers, is minimized for a given transmission rate  $R_{ta}$ . Note that, to

be compliant with the CENELEC FprEN 50561-1 EMC standard, we consider the PSD limit  $P_{tr}^{max} = -55$  dBm/Hz that defines the sub-channels power limit in the transmission band.

Mathematically, we can formulate this optimization problem as

$$(DT) \left\{ \begin{array}{l} \min_{\{P_{tr}^{SD}(k)\}_{k=0,\dots,N-1}} \sum_{k=0}^{N-1} P_{tr}^{SD}(k) \\ \text{subject to} \\ \frac{B}{N} \sum_{k=0}^{N-1} \log_2 \left( 1 + \frac{P_{tr}^{SD}(k) |H_{SD}(k)|^2}{P_W(k)} \right) = R_{ta}, \\ P_{tr}^{max} \geq P_{tr}^{SD}(k) \geq 0, \quad \forall k : 0 \leq k \leq N-1 \end{array} \right.$$

By using the Lagrange multipliers method and applying the Karush-Kuhn-Tucker (KKT) optimality conditions, it can be shown that the optimum power allocation that minimizes the sum of  $P_{tr}^{SD}(k)$  over all sub-carriers for a given transmission rate  $R_{ta}$ , can be obtained as follows [D'Alessandro2012]

$$P_{tr}^{SD*}(k) = \min \left( \max \left( \mu - \frac{1}{\alpha(k)}, 0 \right), P_{tr}^{max} \right) \quad (5.13)$$

where

$$\alpha(k) = \frac{|H_{SD}(k)|^2}{P_W(k)} \quad (5.14)$$

and  $\mu$  is obtained by solving the following target rate equation

$$\frac{B}{N} \sum_{k=0}^{N-1} \log_2 \left( 1 + \frac{P_{tr}^{SD*}(k) |H_{SD}(k)|^2}{P_W(k)} \right) = R_{ta} \quad (5.15)$$

Note that, equation (5.13) represents a modified version of the water filling scheme, referred to as “cap limited water filling”, where the sub-channels power constraints are taken into account. Therefore, equations (5.13) and (5.15) can be solved by using the cap limited water filling algorithm that can be found in [Papandreou2008].

### 5.4.2.2 HD relaying

The optimization problem of HDU relaying refers to the minimization of the total transmitted power required by HDU under a constraint on the achievable rate  $R_{HDU}$ .

It can be formulated as follows

$$(HDU) \left\{ \begin{array}{l} \min_{\{P_{tr}^{SR}(k), P_{tr}^{RD}(k)\}_{k=0, \dots, N-1}} f(P_{tr}^{SR}(k), P_{tr}^{RD}(k)) \\ \text{subject to} \\ R_{HDU} = R_{ta}, \\ P_{tr}^{max} \geq P_{tr}^{SR}(k) \geq 0, \quad \forall k : 0 \leq k \leq N-1, \\ P_{tr}^{max} \geq P_{tr}^{RD}(k) \geq 0, \quad \forall k : 0 \leq k \leq N-1 \end{array} \right.$$

where

$$f(P_{tr}^{SR}(k), P_{tr}^{RD}(k)) = \frac{1}{2} \sum_{k=0}^{N-1} P_{tr}^{SR}(k) + \frac{1}{2} \sum_{k=0}^{N-1} P_{tr}^{RD}(k) \quad (5.16)$$

Clearly, capacity is an increasing function of the transmit power. As such, for a given target rate  $R_{Ta}$ , we observe from Eq. 5.4 that the problem (HDU) becomes

simply

$$(HDU)' \left\{ \begin{array}{l} \min_{\{P_{tr}^{SR}(k), P_{tr}^{RD}(k)\}_{k=0, \dots, N-1}} f(P_{tr}^{SR}(k), P_{tr}^{RD}(k)) \\ \text{subject to} \\ C_{SR} = 2 \times R_{Ta}, \\ C_{RD} = 2 \times R_{Ta}, \\ P_{tr}^{max} \geq P_{tr}^{SR}(k) \geq 0, \quad \forall k : 0 \leq k \leq N - 1, \\ P_{tr}^{max} \geq P_{tr}^{RD}(k) \geq 0, \quad \forall k : 0 \leq k \leq N - 1 \end{array} \right.$$

The required transmission powers  $P_T^{SR}$  and  $P_T^{RD}$  can then be computed as in the direct transmission case using equations 5.13 and 5.15.

## 5.5 Numerical results and analysis

### 5.5.1 Experimental channels

To experimentally analyze the benefits of using DF relays in PLC networks, we first use measured PLC channels and PLC noise. To do so, we exploit a database that has been collected by Orange Labs during an experimental measurement campaign across five French houses. Measurements were performed in the frequency band ranging up to 100 MHz. A total amount of 300 indoor PLC SISO transfer functions were measured using a Vector Network Analyzer. Similarly, 300 PLC noise measurements were acquired using a Digital Sampling Oscilloscope.

### 5.5.2 Wideband Indoor Transmission Channel Simulator (WITS)

Here, PLC channel transfer functions are generated by WITS software. This generator is based on a statistical analysis of PLC channels measured in several indoor

environments, more or less favorable to the PLC technology. (See details in section 1.7.1.2).

This analysis led to the classification of PLC channels into 9 classes, class 1 corresponding to the worst channels while class 9 includes the less attenuated ones. According to [Tlich2010], for all channels falling between classes 1 to 6, modems S and D for (S-D) links are always connected to two power outlets belonging to two different electrical circuits. These channels experience higher attenuation than channels from other classes. As for classes 8 and 9, S and D are connected to two power outlets belonging to the same electrical circuit.

For the performance study, by exploiting both measured and WITS generated channels, we consider two scenarios of links configuration:

### 5.5.3 Scenario 1

First, we consider a scenario where S-D links are highly attenuated and therefore could strongly benefit more from the help of relay, while corresponding channels for S-R and R-D links are less attenuated. Fig. 5.2 presents an example of the corresponding channel transfer functions of one set of (S-R), (R-D) and (S-D) links. Then, on one hand, for the experimental channels case, using the measurements in the [1,8 - 30] MHz frequency range, we choose corresponding channels for (S-D) links to be the ones that suffer from higher attenuation. While for the relay channels, we consider all possible configurations that we can obtain considering that (S-R) and (R-D) links belong to the same house.

On the other hand, using WITS, we choose 40 (S-D) channels from classes 1 to 6 and 40 (S-R) and (R-D) channels from classes 8 and 9.

### 5.5.4 Scenario 2

In the second scenario, the relay is assumed to be located along the line between the source and the destination modems as it can be seen in Fig. 5.3. Therefore, any outlet located on the main path from the source S to the destination D can be chosen for the relay node deployment. In such case, the equivalent channel

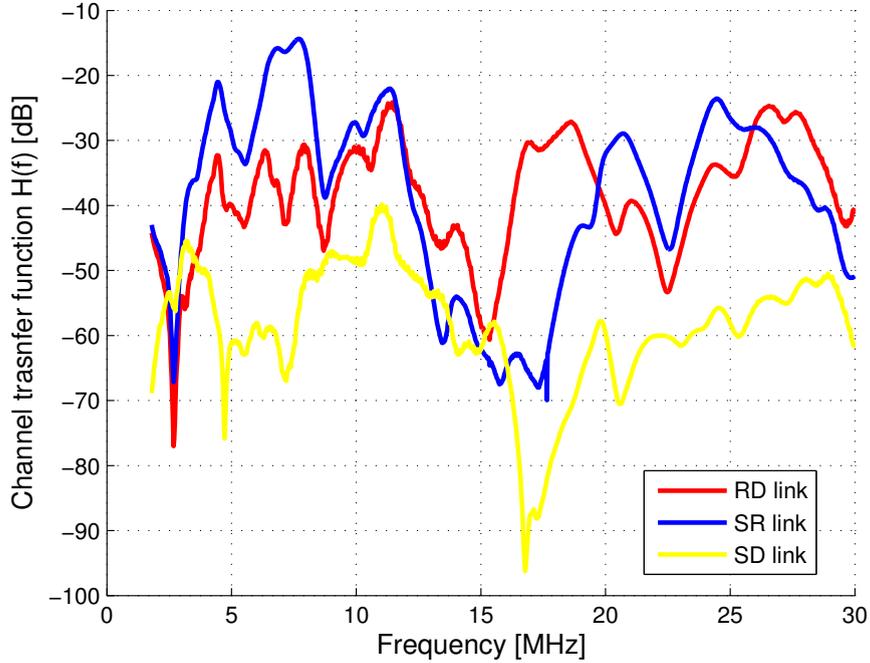


FIGURE 5.2: Illustration example of Scenario 1: measured channel transfer functions of (S-D), (S-R) and (R-D) links

source-relay-destination can be obtained as [Lampe2012]:

$$H_{SD} = H_{SR} \times H_{RD} \quad (5.17)$$

For this configuration, we randomly choose (S-R) and (R-D) channels from the measurements database, or from classes 1 to 9 (WITS). The equivalent channel source-relay destination is then calculated from Eq. 5.17.

We note that, for the WITS case, we assume an Additive White Gaussian Noise (AWGN) with a Power Spectral Density (PSD) of -100 dBm/Hz.

Furthermore, we fulfill the specifications of the HomePlug AV standard. To do so, we account for the notches defined by the spectral mask: among 1155 carriers that are defined in the frequency range of [1,8 - 30] MHz, only 917 carriers can be used for transmitting the symbols and the other ones are switched off. Also, we respect the bit-cap condition which is used to limit the maximum allocated number of bits per sub-carrier (bit-cap = 10 according to HomePlug AV specification). This constraint is mainly related to the ADC performance.

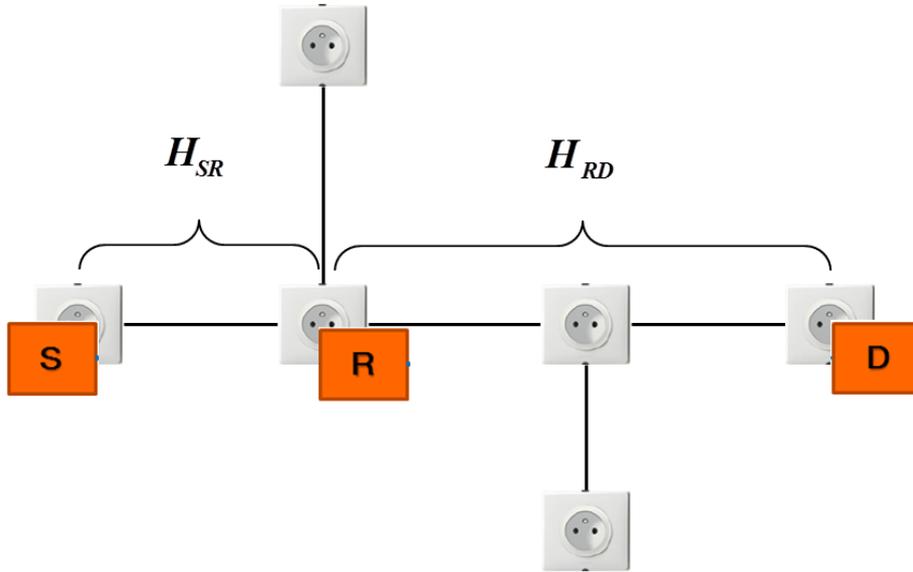


FIGURE 5.3: Illustration example of Scenario 2

TABLE 5.1: Simulations parameters

Standard	HPAV
Frequency band	[1.8 MHz, 30 MHz]
Carrier width	25 KHz
PSD mask limit	-55 dBm/Hz
Transmission time $T$	1s
RF front-end efficiency $\eta$	0.1

Values of the parameters used in the simulations are presented in Table. 5.1.

### 5.5.5 Achievable rate benefits

Figures 5.4 and 5.5 show the comparison between the achievable transmission rates (averaged over all channel realizations) obtained for DF relay scheme when using uniform time sharing and for DT strategy as a function of PSD masks (-63 dBm/Hz, -61 dBm/Hz, -59 dBm/Hz, -57 dBm/Hz and -55 dBm/Hz). Figure 5.4 represents

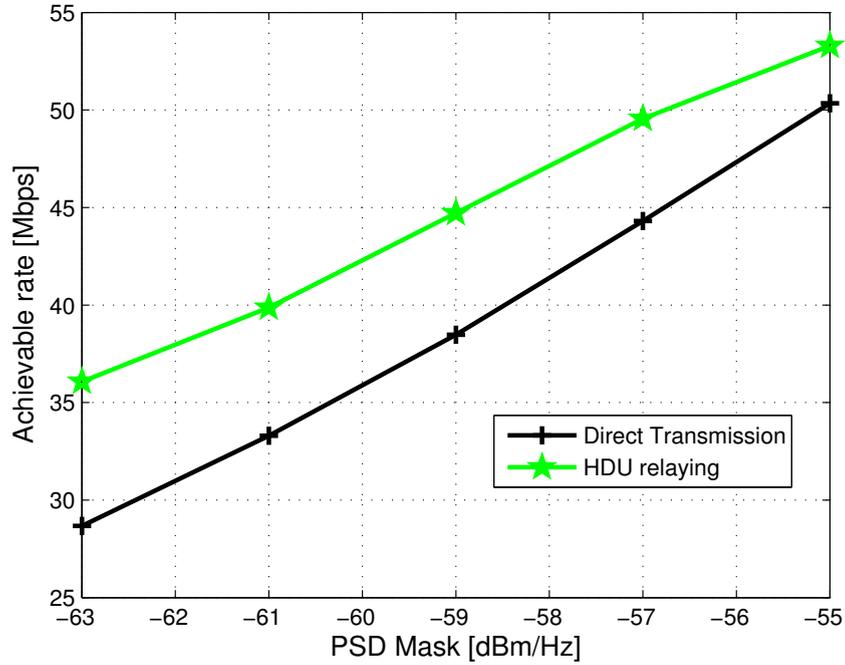


FIGURE 5.4: Average achievable rate of direct transmission and HDU relaying versus PSD Mask: Scenario 1, Experimental channels

the experimental channel results for scenario 1, and figure 5.5 represents the WITS ones. Then, figures 5.6 and 5.7 represent the same results for scenario 2.

It can be seen that, for every fixed transmitted power, the rate performance of relay-aided transmission is better than DT. For example, with the maximum PSD mask  $P_{max}^{tr} = -55$  dBm/Hz, the maximum achievable rate for scenario 1 (WITS case) with HDU relaying is around 82 Mbps, while the DT achieves only 48 Mbps (Fig. 5.5). Moreover, it is also seen that when the transmitted power is relatively low, the achievable rate gain which corresponds to the gap between the achievable rates of DT and HDU is relatively high, and with the increase of the transmitted power, the gap decreases. This is explainable by the fact that for high PSD masks, high transmission rates are also achievable by the DT.

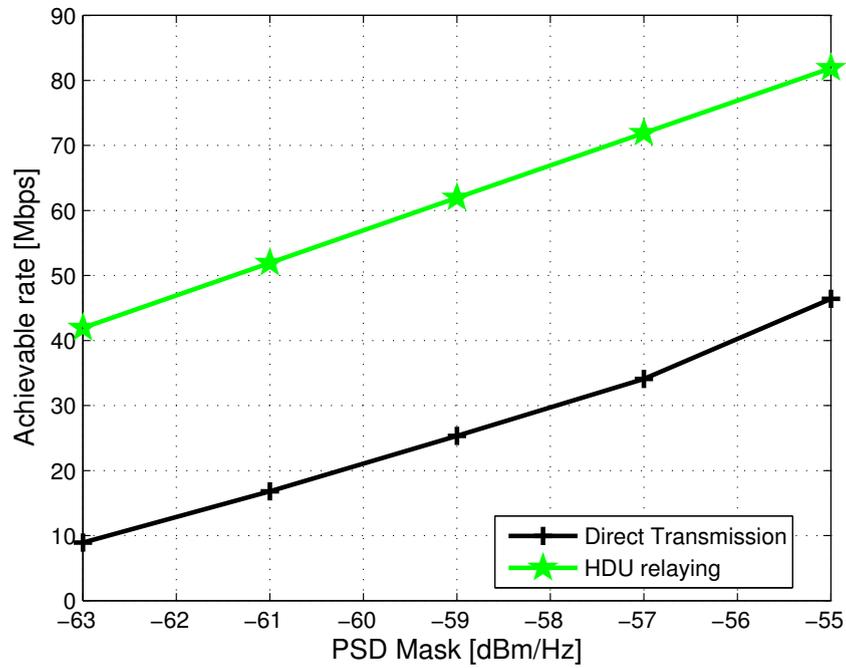


FIGURE 5.5: Average achievable rate of direct transmission and HDU relaying versus PSD Mask: Scenario 1, WITS

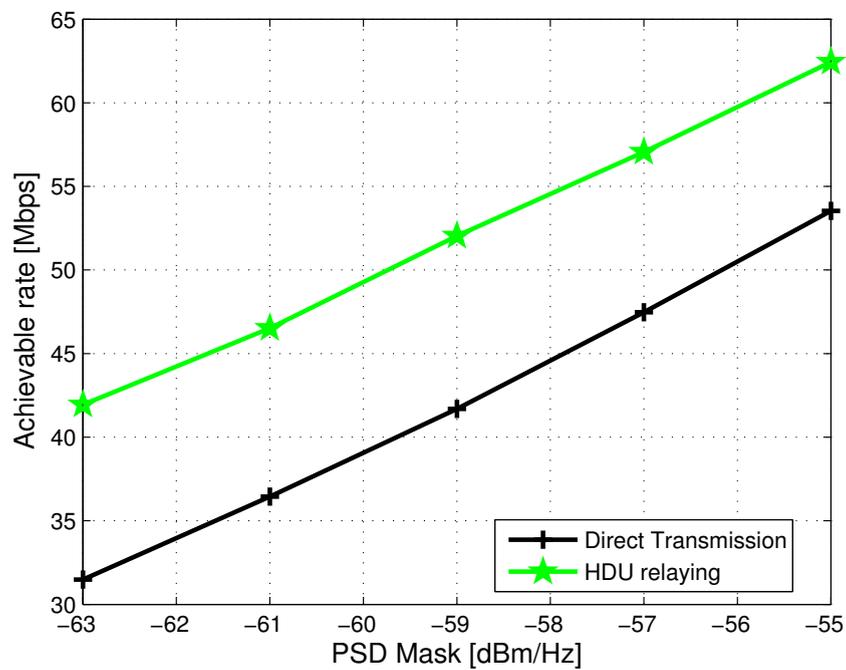


FIGURE 5.6: Average achievable rate of direct transmission and HDU relaying versus PSD Mask: Scenario 2, Experimental channels

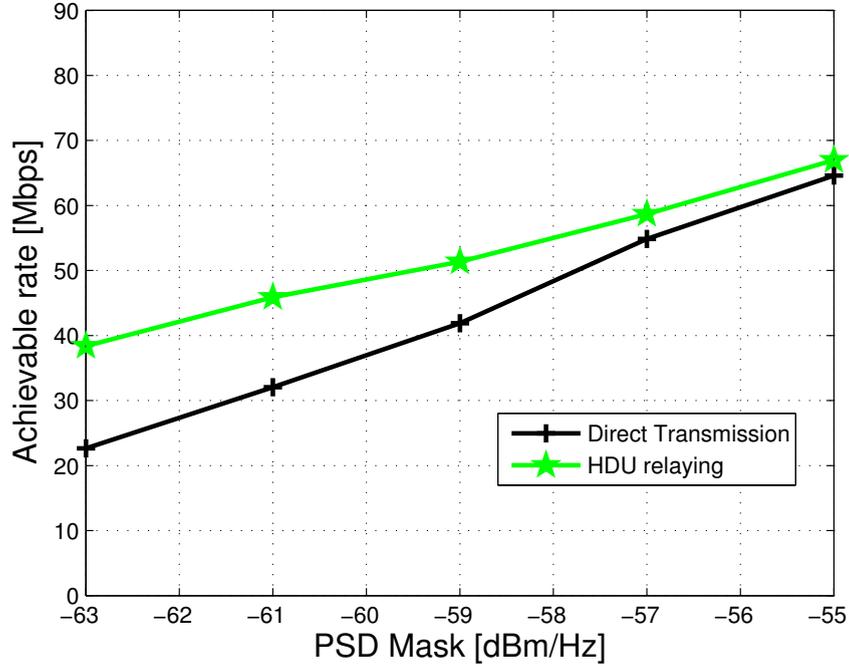


FIGURE 5.7: Average achievable rate of direct transmission and HDU relaying versus PSD Mask: Scenario 2, WITS

## 5.5.6 power efficiency benefits

### 5.5.6.1 Zero static power

For scenario 1, figures 5.8 and 5.9 show the comparison between the average total transmitted power required by the DF relay scheme when the time allocation is uniform, and the average transmitted power of the DT strategy as a function of target rates (10 Mbps, 15 Mbps, 20 Mbps, 25 Mbps and 30 Mbps) related to both experimental channel and WITS cases.

Further, corresponding results for Scenario 2 are reported in figures 5.10 and 5.11

If we consider transmitted powers only, i.e.,  $P_{st} = P_{st}^S = P_{st}^R = P_{st}^D = 0$  and  $P_{idle} = P_{idle}^D = P_{idle}^R = 0$ , we can see that in general, for both scenarios, relay-aided transmission achieve better power efficiency performance than DT and allows for saving up to 7.5 dB (Fig. 5.10) of the transmitted power for the experimental channel case and up to 12 dB (Fig. 5.9) of the transmitted power for the WITS case.

Next, in order to get a more practical view on the power savings obtained through

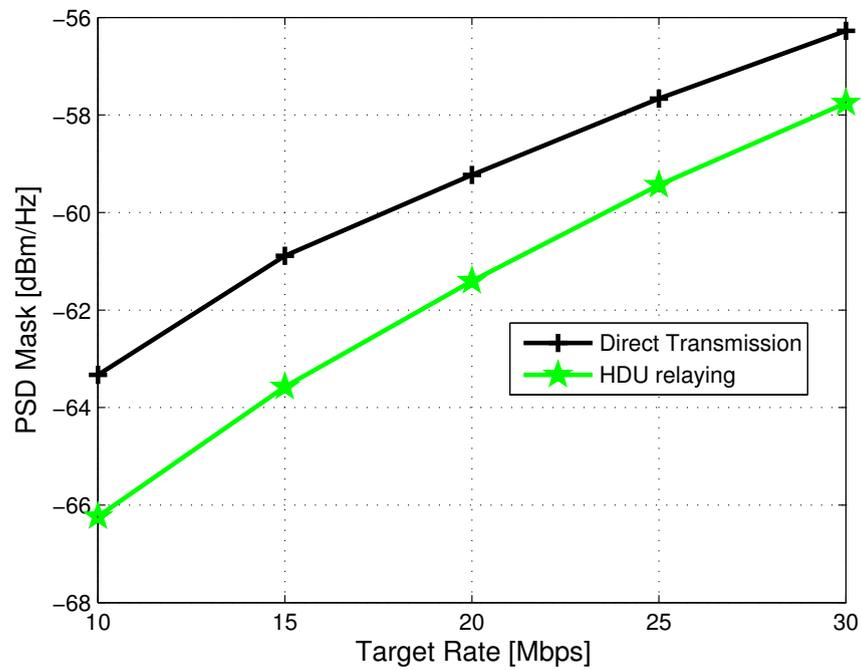


FIGURE 5.8: Average transmit power of direct transmission and HDU relaying versus target rate: Scenario 1, Experimental channels

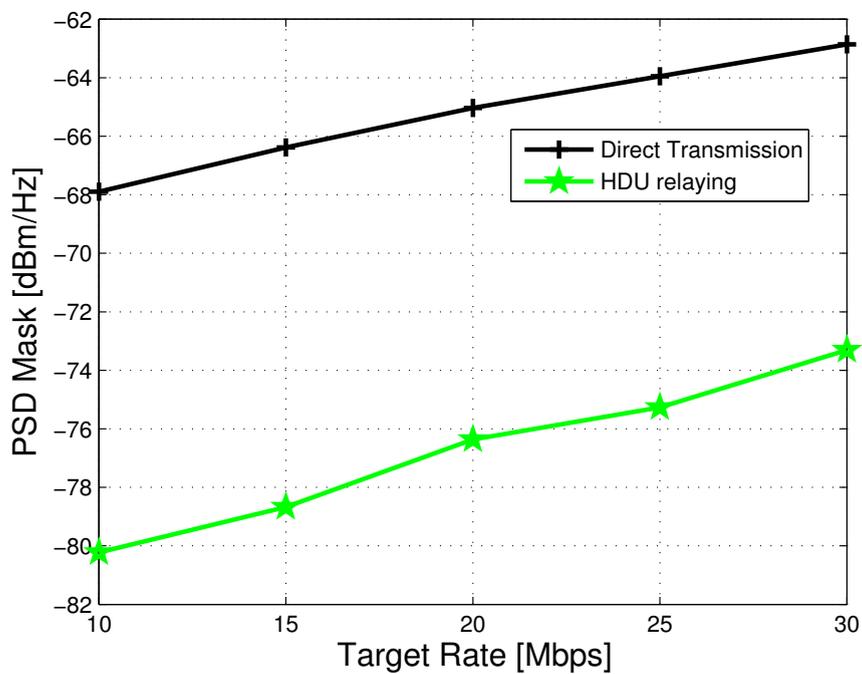


FIGURE 5.9: Average transmit power of direct transmission and HDU relaying versus target rate: Scenario 1, WITS

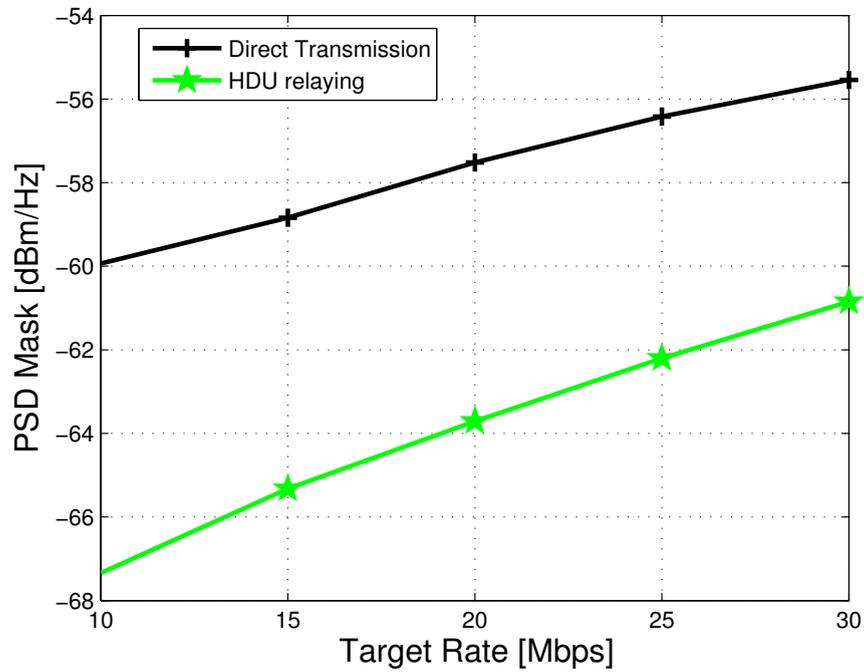


FIGURE 5.10: Average transmit power of direct transmission and HDU relaying versus target rate: Scenario 2, Experimental channels

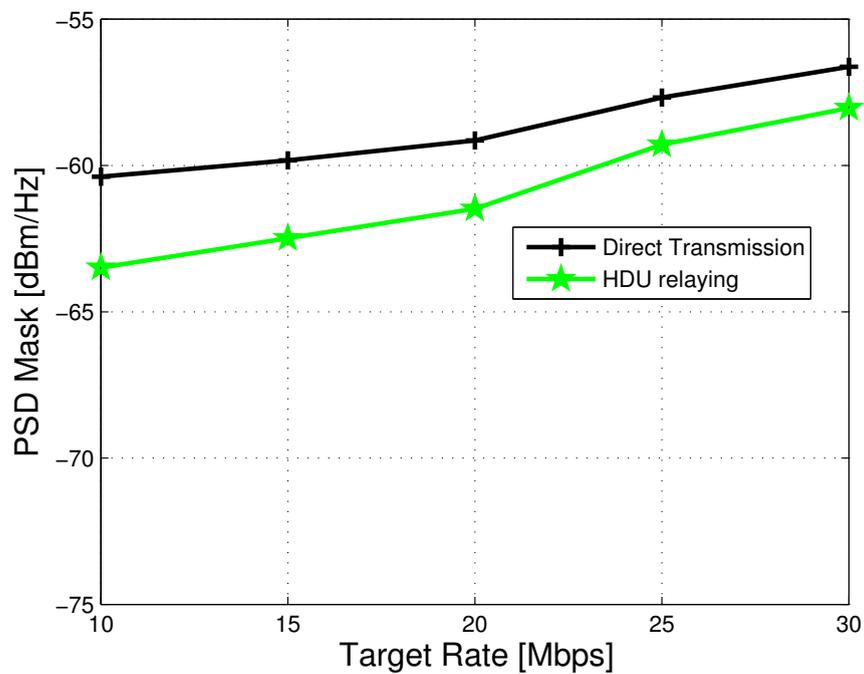


FIGURE 5.11: Average transmit power of direct transmission and HDU relaying versus target rate: Scenario 2, WITS

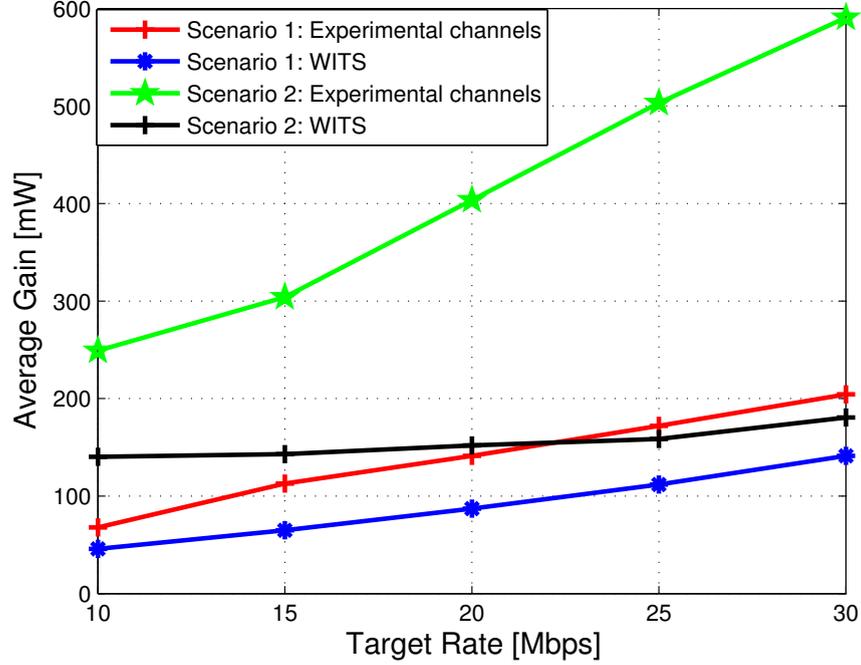


FIGURE 5.12: Average dynamic power saving gain of HDU relaying

relaying, Fig. 5.12 reports the average dynamic power saving gain, i.e.,  $Gain = P_{dyn}^{DT} - P_{dyn}^{HD}$  in mWatts for HDU. We observe that higher power savings are obtained for high throughputs. Indeed, the power consumption of DT is larger in high throughput regimes, and therefore any gain in the transmission power becomes more significant and have a larger impact on the total power saving gain.

### 5.5.6.2 Non-zero static power

The results of the zero static power case can be generalized to the non-zero static power case ( $P_{st} = P_{st}^S = P_{st}^R = P_{st}^D \neq 0$  and  $P_{idle} = P_{idle}^D = P_{idle}^R \neq 0$ ) if  $P_{st}^{HD} + P_{dyn}^{HD} + P_{idle} < P_{st}^{DT} + P_{dyn}^{DT}$  (According to Eq. 5.12).

Since the static power consumption values remain the same for both direct transmission and HD relaying (Equations 5.8 and 5.9), whether HDU relaying is more power efficient than direct transmission thus depends on  $P_{idle}$  only. If  $P_{idle} < P_{dyn}^{DT} - P_{dyn}^{HD}$ , then HD relaying saves power.

When considering a target rate  $R_{ta} = 30$  Mbps, a static power  $P_{st} = P_{st}^S = P_{st}^R =$

TABLE 5.2: Power consumption model parameters calculated for a target rate  $R_{ta} = 30$  Mbps and different values of  $P_{idle}$ 

$P_{idle}(W)$	0.2	0.3	0.4	0.5	0.6
<b>Experimental channels: Scenario 1</b>					
$P_{DT}(W)$	2.5	2.5	2.5	2.5	2.5
$P_{HDU}(W)$	2.5	2.6	2.7	2.8	2.9
<b>WITS: Scenario 1</b>					
$P_{DT}(W)$	1.96	1.96	1.96	1.96	1.96
$P_{HDU}(W)$	2.01	2.11	2.21	2.31	2.41
<b>Experimental channels: Scenario 2</b>					
$P_{DT}(W)$	2.6	2.6	2.6	2.6	2.6
$P_{HDU}(W)$	2.2	2.3	2.4	2.5	2.6
<b>WITS: Scenario 2</b>					
$P_{DT}(W)$	2.45	2.45	2.45	2.45	2.45
$P_{HDU}(W)$	2.47	2.57	2.67	2.77	2.87

$P_{st}^D = 0.9$  W (See chapter 3) and for different values of  $P_{idle}$ , Table. 5.2 presents the total power consumption for the direct transmission  $P_{DT}$  to achieve  $R_{ta}$  and the total power required by HDU relaying  $P_{HDU}$  to achieve the same target rate. We can clearly see from Table. 5.2 and Fig. 5.12 that for the non-zero static case, if the idle power of modems is larger than 204.4 mW for Scenario 1, and 590,6 for Scenario 2, direct transmission consumes less power than HDU relaying. If the idle power drops below this value, HDU relaying saves power compared with the direct transmission case.

## 5.6 Conclusion

In this chapter, we analyzed the use of Half-duplex Decode and Forward relaying protocol with uniform time sharing in PLC networks, mainly for power saving purpose, and compared its performance with that of the direct transmission. We first presented a power consumption model of PLC relay systems that takes into account the influence of the static power consumption of PLC modems on the total consumed power. Then, by using realistic indoor PLC channels and by considering two scenarios, we showed that the power efficiency performance of DF protocol with uniform time sharing is dependent on the static power consumption values of PLC modems. That is, DF relaying with uniform time sharing is more power efficient than DT only if the static power of PLC modems is lower than 204.4 mW for the first considered scenario, and less than 590,6 mW for the second scenario.

Note that, the above idle values are difficult to obtain in practice since current modems have idle powers of at least 600 mW. Therefore, in order to achieve higher power gains, a better way to take advantage of the PLC channel variability is to adapt the time allocation according to the quality of the links. To this end, in the next chapter, we will study the effect of time sharing in DF relay systems. Specifically, we will provide an iterative algorithm to minimize the power in DF with the optimal time division strategy.

## Chapter 6

# Relay-Assisted PLC Networks with optimal time allocation

### 6.1 Introduction

Optimal resource allocation is a challenging work to effectively improve the performance of Decode and Forward (DF) relay-assisted systems. In the performance analysis of DF protocol in PLC that we presented in chapter 5 of this thesis, we considered equal transmission time sharing between the source and the relay nodes. However, even though half-duplex relaying with uniform time allocation strategy (HDU) is simple to be implemented, and still widely utilized in the current literature [Sung2010], [Fu2014], [Ezzine2015], it does not consider the channel variability among links of PLC systems.

In this chapter, we will complete our performance evaluation of DF relay-assisted PLC networks by investigating the achievable rate and power efficiency benefits of the optimal time allocation between the source and the relay nodes, i.e., the optimal time slot allocation between the source and the relay nodes that maximizes the achievable rate under power constraints [Madsen2005], [Gunduz2007], or minimizes the power consumption under rate constraints. The chapter is organized as follows. We start by discussing the rate improvement obtained with the optimal time

allocation (HDO) strategy. Then, we formulate the power minimization problem under rate constraints and provide an iterative algorithm to solve this optimization problem. Finally, using the same channel configurations and numerical parameters as in chapter 5, we compare performance of HDO with the uniform time allocation strategy, and with the direct transmission.

## 6.2 Optimal time share to improve the data rate for a given power

As mentioned in Chapter 5, we focus in our study on the scenario where the capacity of the SD link is zero, i.e.,  $C_{SD} = 0$ . Therefore, the expression of the achievable rate for Half-Duplex relaying with an optimal time sharing (HDO) is obtained as [Raeis2013]

$$R_{HDO} = \min \{ \rho \times C_{SR}, (1 - \rho)C_{RD} \} \quad (6.1)$$

Since  $\rho \times C_{SR}$  increases with  $\rho$  and  $(1 - \rho)C_{RD}$  decreases with  $\rho$ , it is clear that the optimal time share for rate maximization is achieved when

$$\rho \times C_{SR} = (1 - \rho)C_{RD} \quad (6.2)$$

Then, we get [Raeis2013]

$$\rho = \frac{C_{RD}}{C_{SR} + C_{RD}} \quad (6.3)$$

and

$$(1 - \rho) = \frac{C_{SR}}{C_{SR} + C_{RD}} \quad (6.4)$$

Eq. (6.1) can then be rewritten in this case as

$$R_{HDO} = \frac{C_{SR} \times C_{RD}}{C_{SR} + C_{RD}} \quad (6.5)$$

### 6.3 Optimal time share to save power for a given target rate

The power efficiency optimization problem of DF relaying in the case of optimal time division can be formulated as follows:

$$\left. \begin{array}{l}
 \min_{\rho, \{P_{tr}^{SR}(k), P_{tr}^{RD}(k)\}_{k=0, \dots, N-1}} f(\rho, P_{tr}^{SR}(k), P_{tr}^{RD}(k)) \\
 \text{subject to} \\
 (HDO) \left\{ \begin{array}{l}
 R_{HDO} = R_{ta}, \\
 P_{tr}^{max} \geq P_{tr}^{SR}(k) \geq 0, \quad \forall k : 0 \leq k \leq N-1, \\
 P_{tr}^{max} \geq P_{tr}^{RD}(k) \geq 0, \quad \forall k : 0 \leq k \leq N-1
 \end{array} \right.
 \end{array} \right.$$

Due to the combinatorial complexity involved by the inequality constraints, the global optimal solution to the problem (HDO) is hard to obtain. In our work, we address this problem by providing an iterative algorithm, that will be explained in the following section.

#### 6.3.1 Calculating the optimal time allocation $\rho$

Since the capacity is an increasing function of the transmit power, we observe from Eq. (6.2) that for a given target rate  $R_{ta}$  and fixed  $\rho$ , the minimum transmission powers required by HDO relaying  $P_{tr}^{SR}$  and  $P_{tr}^{RD}$  can be obtained as

$$C_{SR} = \Delta f \sum_{k=0}^{N-1} \log_2 \left( 1 + \frac{P_{tr}^{SR}(k) |H_{SR}(k)|^2}{P_W(k)} \right) = \frac{R_{ta}}{\rho} \quad (6.6)$$

and

$$C_{RD} = \Delta f \sum_{k=0}^{N-1} \log_2 \left( 1 + \frac{P_{tr}^{RD}(k) |H_{RD}(k)|^2}{P_W(k)} \right) = \frac{R_{ta}}{1-\rho} \quad (6.7)$$

In this case, the problem (HDO) can be decomposed into two independent sub-problems that can be solved similarly to the direct transmission case (by using equations (5.13) and (5.15)).

In this case, we rewrite our optimization problem as

$$(HDO') \left\{ \begin{array}{l} \min_{\rho, \{P_{tr}^{SR}(k), P_{tr}^{RD}(k)\}_{k=0, \dots, N-1}} f(\rho, P_{tr}^{SR}(k), P_{tr}^{RD}(k)) \\ \text{subject to} \\ \rho \times \Delta f \sum_{k=0}^{N-1} \log_2(1 + P_{tr}^{SR}(k)\alpha_1(k)) = R_{ta}, \\ (1 - \rho)\Delta f \sum_{k=0}^{N-1} \log_2(1 + P_{tr}^{RD}(k)\alpha_2(k)) = R_{ta}, \\ P_{tr}^{max} \geq P_{tr}^{SR}(k) \geq 0, \quad \forall k : 0 \leq k \leq N - 1, \\ P_{tr}^{max} \geq P_{tr}^{RD}(k) \geq 0, \quad \forall k : 0 \leq k \leq N - 1 \end{array} \right.$$

where

$$\alpha_1(k) = \frac{|H_{SR}(k)|^2}{P_W(k)} \quad (6.8)$$

and

$$\alpha_2(k) = \frac{|H_{RD}(k)|^2}{P_W(k)} \quad (6.9)$$

Now, to solve the optimization problem of HDO relaying, we propose an iterative algorithm that updates the time slot  $\rho$  in every iteration  $i$ , in order to converge towards the optimal time share for minimum powers. In particular, at the first iteration, the transmitted powers at S and R are set equal to the ones defined in the EN 50561 electromagnetic compatibility EMC directive, i.e,  $P_{tr}^{SR} = P_{tr}^{RD} = -55$  dBm/Hz. Then, we compute the corresponding time slot  $\rho$  by using equation (6.3). Note that, the maximum achievable rate of HDO relay system in this case is

equal to  $\rho C_{SR}$ . If  $\rho C_{SR} < R_{ta}$ , it is clear that the target rate can not be achieved. Once  $\rho$  has been computed, it can be used in the next iteration to compute the minimum powers needed by HDO relay at S and R to reach the rate  $R_{ta}$  by using equations (6.6), (6.7), (5.13) and (5.15). With these powers,  $\rho$  can be updated again. The iteration will terminate when there is no significant change in  $\rho$  such that  $|\rho(i+1) - \rho(i)| \leq \epsilon$ , where  $\rho(i+1)$  and  $\rho(i)$  denote the values of the time allocation coefficient at next and current iteration respectively, and  $\epsilon > 0$  is an arbitrarily small error. From numerical results, it is noticeable that the proposed algorithm converges in less than 10 iterations for  $\epsilon = 0.005$ .

## 6.4 Numerical results and analysis

In this section, we present numerical results to test the power efficiency performance of the optimal time sharing in DF PLC relay systems. As previously said, for numerical results, we use the same channel configurations and numerical parameters as in chapter 5.

Figures 6.1 and 6.2 present the rate performance comparison of HDO relaying, HDU relaying and the direct transmission for the experimental channels case and the WITS case, with respect to scenario 1. The results obtained for scenario 2 are illustrated in figures 6.3 and 6.4.

It can be observed that HDO outperforms HDU and provides additional rate gain up to 12 Mbps (Fig. 6.1).

Then, considering scenario 1, figures 6.5 and 6.6 report the average total transmitted power consumed by HDO, HDU and DT as a function of the target rate, when using the experimental channels and the WITS simulated channels respectively.

In the same way, results for scenario 2 are depicted in figures 6.7 and 6.8.

It can be seen that adapting the time allocation depending on the quality of S-R and R-D links provides important power gain compared to the uniform time sharing, e.g., up to 7.8 dB when using experimental channels for the case of Scenario 1 (Fig. 6.5). In contrast, we remark that for scenario 1, with the simulated

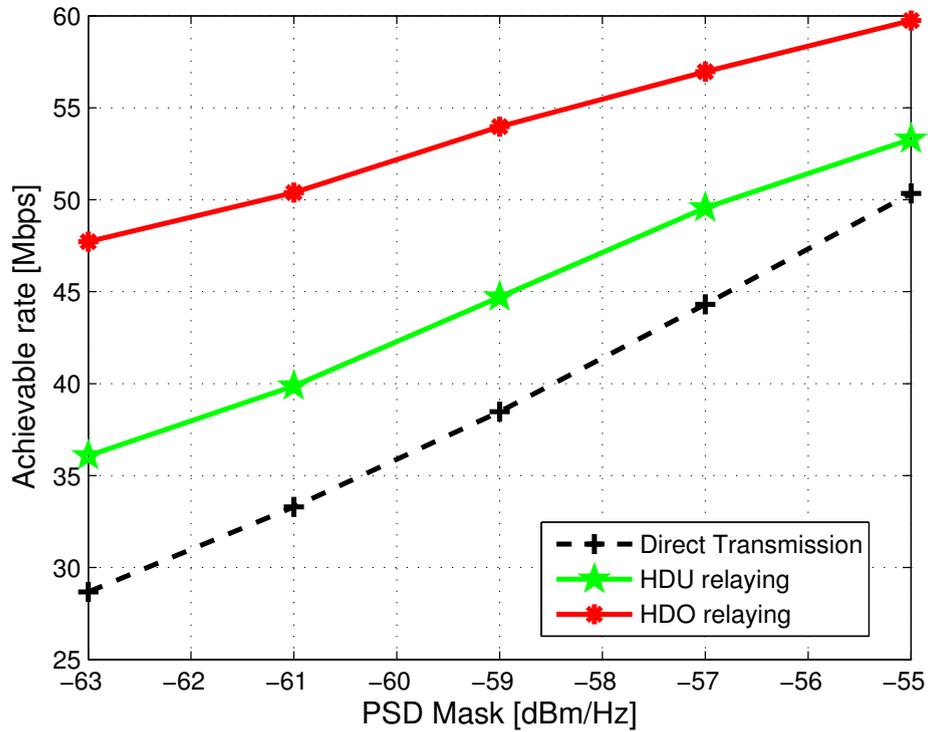


FIGURE 6.1: Average achievable rate of direct transmission, HDU relaying and HDO relaying versus PSD Mask: Scenario 1, Experimental channels

WITS channels ((Fig. 6.6), uniform time allocation has very close performance to optimal time allocation. The reason is that (S-R) and (R-D) links under this case belong to the same classes, and hence have almost the same quality.

Figures 6.9 and 6.10 depict in more details, for both scenarios, the power saving gain of HDU and HDO relaying in mW when considering the experimental channels and the WITS simulated ones respectively. With the use of HDO, Figures 6.9 and 6.10 show that if we consider the static power consumption of PLC modems, HDO remains more power efficient than DT at idle power values of up to 645.8 mW.

Note that, most next generation PLC modems could profit from such advanced low-power idle modes in the near future since low power consumption will become more and more important. In fact, some manufacturers already propose commercial PLC modems with reduced power consumption when there is no data transmission or reception. Our previous measurements showed that current products already

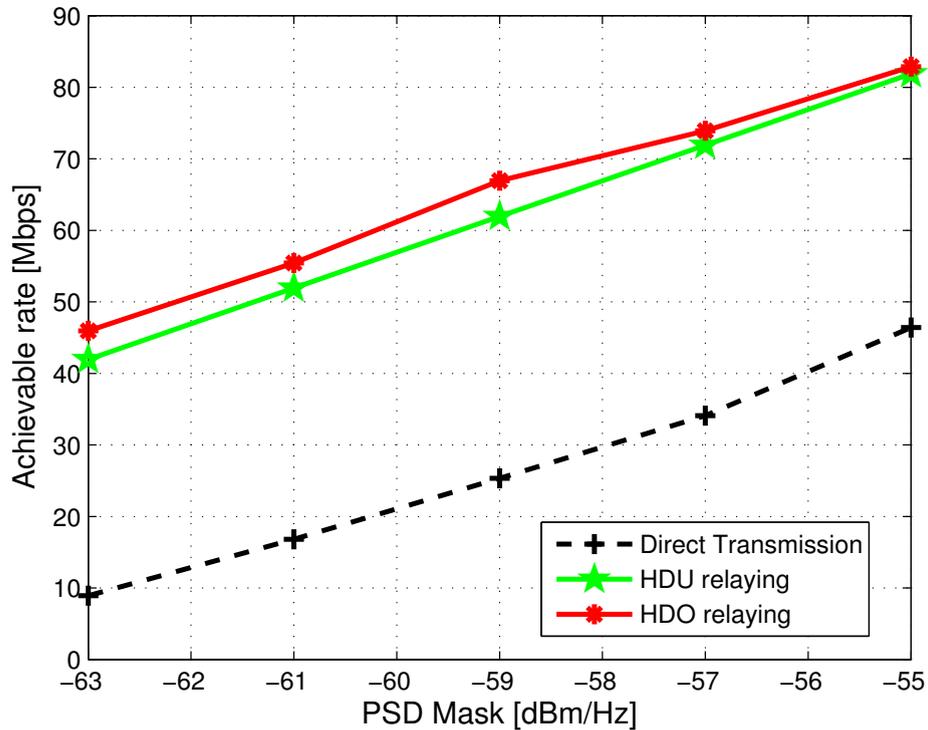


FIGURE 6.2: Average achievable rate of direct transmission, HDU relaying and HDO relaying versus: Scenario 1, WITS

feature idle modes with reduced static power values as low as 0.6 Watts.

In addition, we notice that the use of DF HDO relaying for the relay in the middle scenario (scenario 2) gives the best results in term of dynamic power saving gain.

## 6.5 Conclusion

In this chapter, we considered DF protocol with optimal time allocation strategy to provide additional rate and power efficiency improvement in PLC networks. We proposed an iterative algorithm to derive the optimal time share that minimizes the power consumption under rate constraints. Through simulations, we defined the amount of performance gain that optimal time allocation strategy can introduce in comparison with the uniform time allocation scheme.

We note that, the results obtained in the current chapter, and in chapter 5, agree

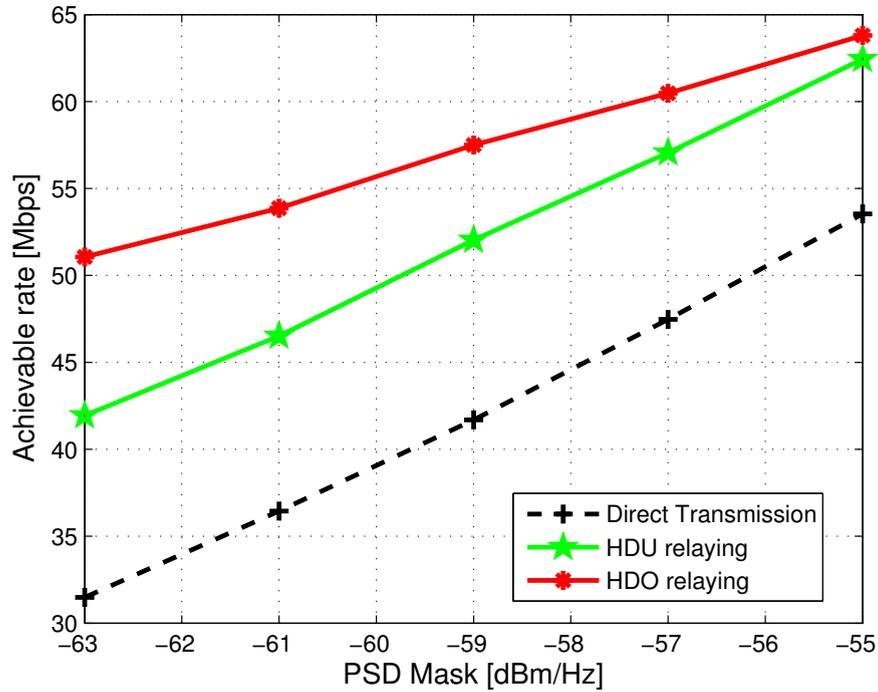


FIGURE 6.3: Average achievable rate of direct transmission, HDU relaying and HDO relaying versus: Scenario 2, Experimental channels

with what is reported in [D'Alessandro2012], where it is shown that if we only consider the transmit power of PLC modems, the use of DF relaying in indoor PLC networks can indeed improve the system rate and the power efficiency. Furthermore, our analysis reveals that DF protocol with optimal time allocation has a notable impact on power efficiency and can result in improved performance even when considering the static power consumption of PLC modems.

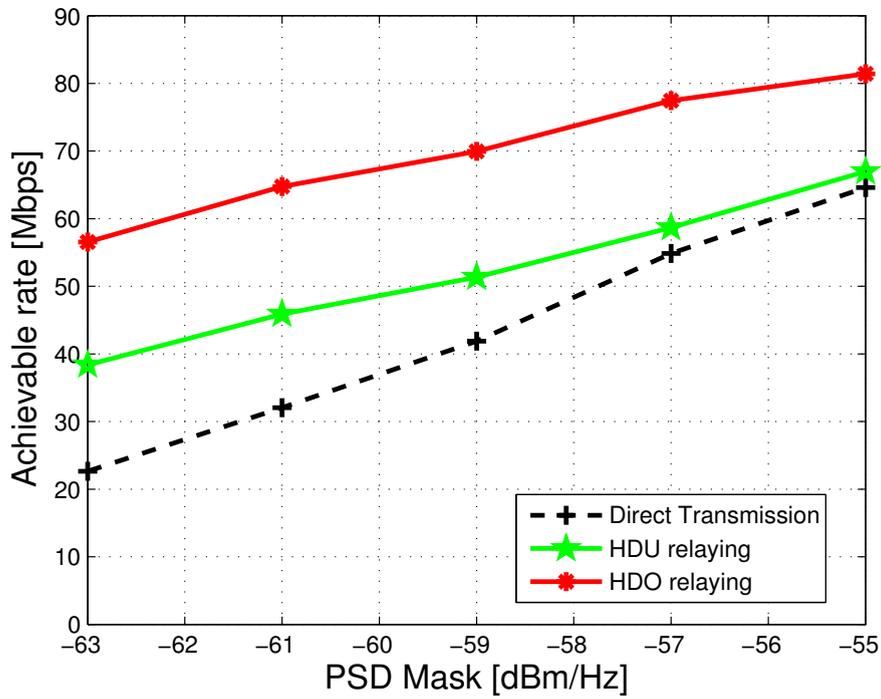


FIGURE 6.4: Average achievable rate of direct transmission, HDU relaying and HDO relaying versus PSD Mask: Scenario 2, WITS

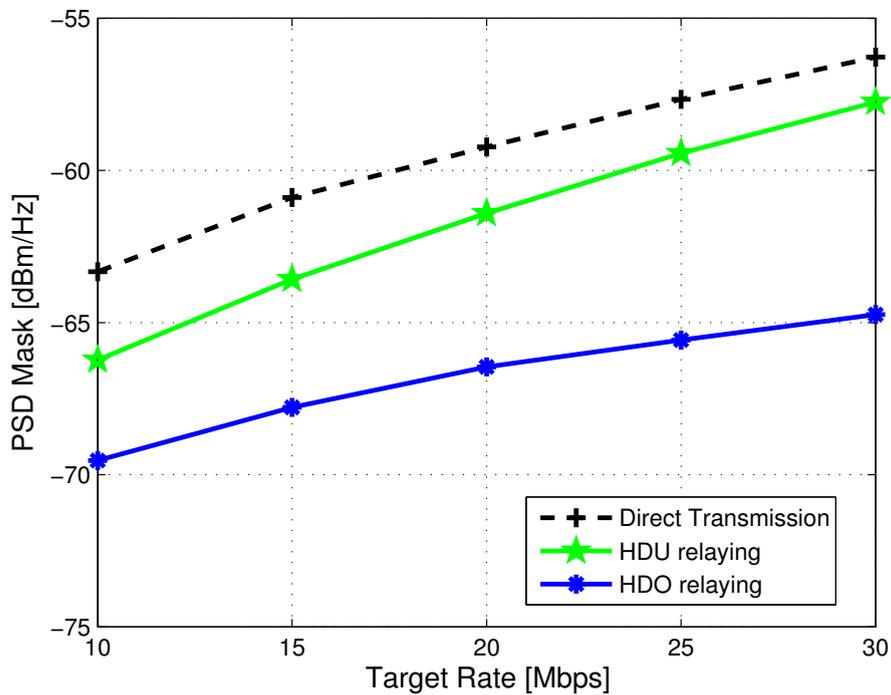


FIGURE 6.5: Average transmit power of direct transmission, HDU relaying and HDO relaying versus target rate: Scenario 1, Experimental channels

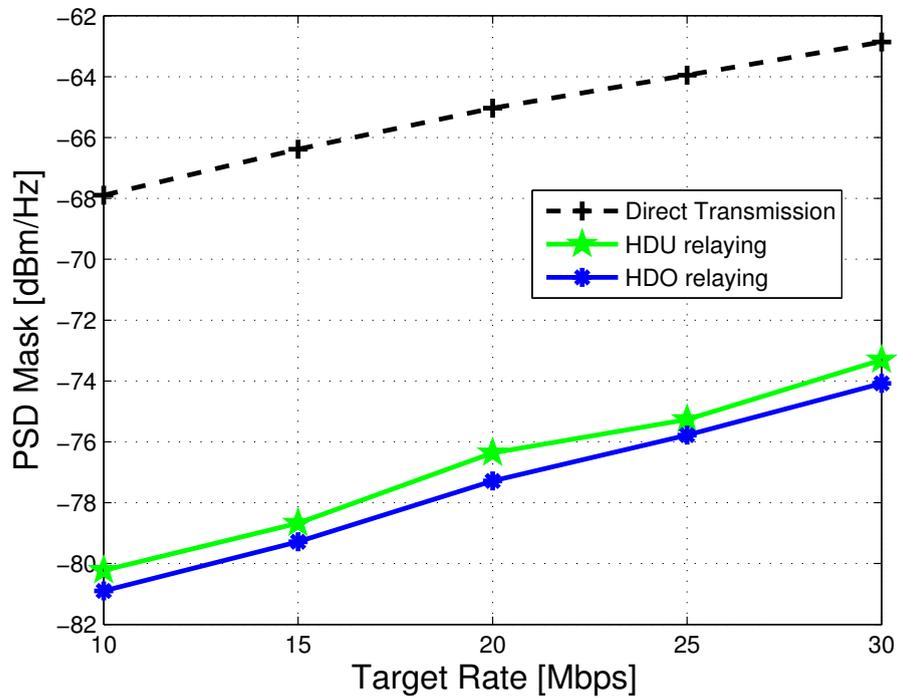


FIGURE 6.6: Average transmit power of direct transmission, HDU relaying and HDO relaying versus target rate: Scenario 1, WITS

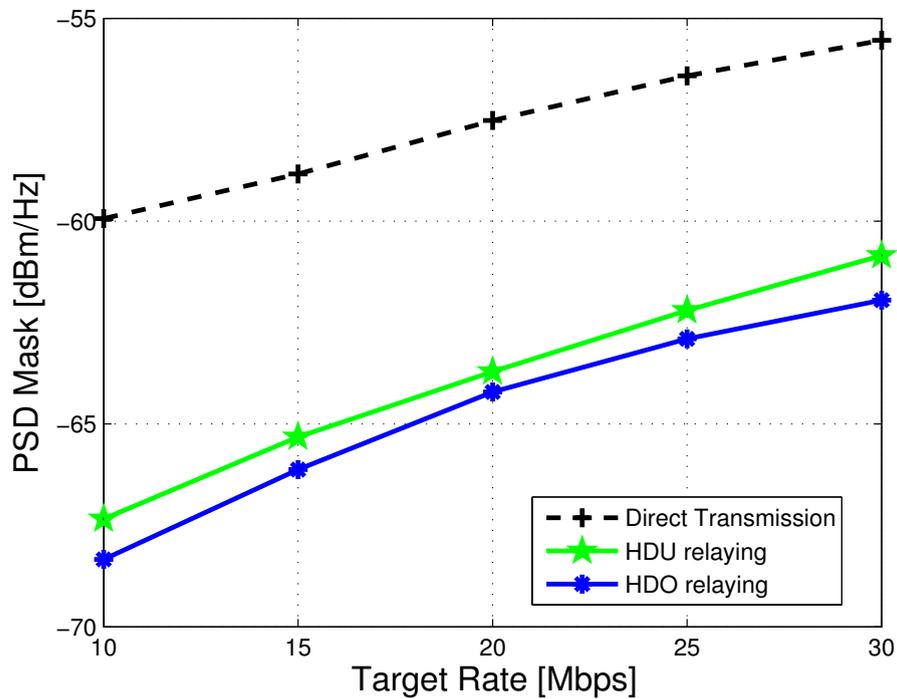


FIGURE 6.7: Average transmit power of direct transmission, HDU relaying and HDO relaying versus target rate: Scenario 2, Experimental channels

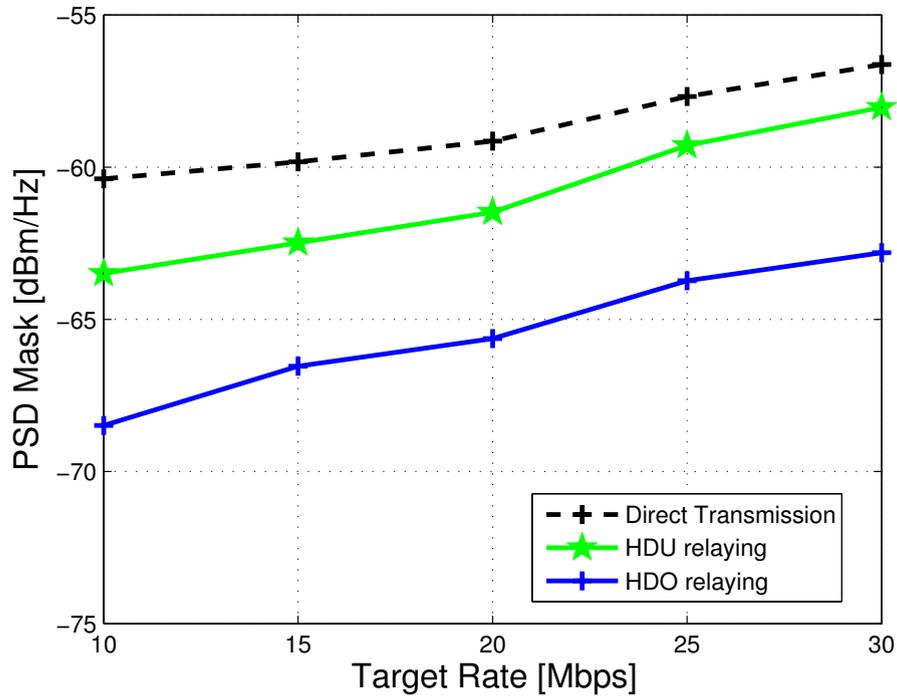


FIGURE 6.8: Average transmit power of direct transmission, HDU relaying and HDO relaying versus target rate: Scenario 2, WITS

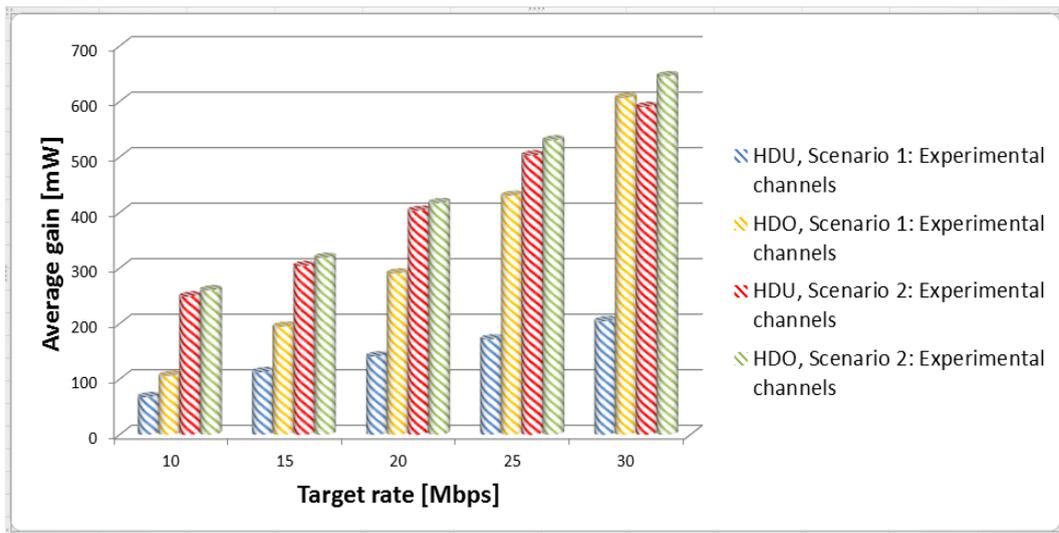


FIGURE 6.9: Average dynamic power saving gain of HDU and HDO relaying for the experimental channels case: Scenario 1 and Scenario 2

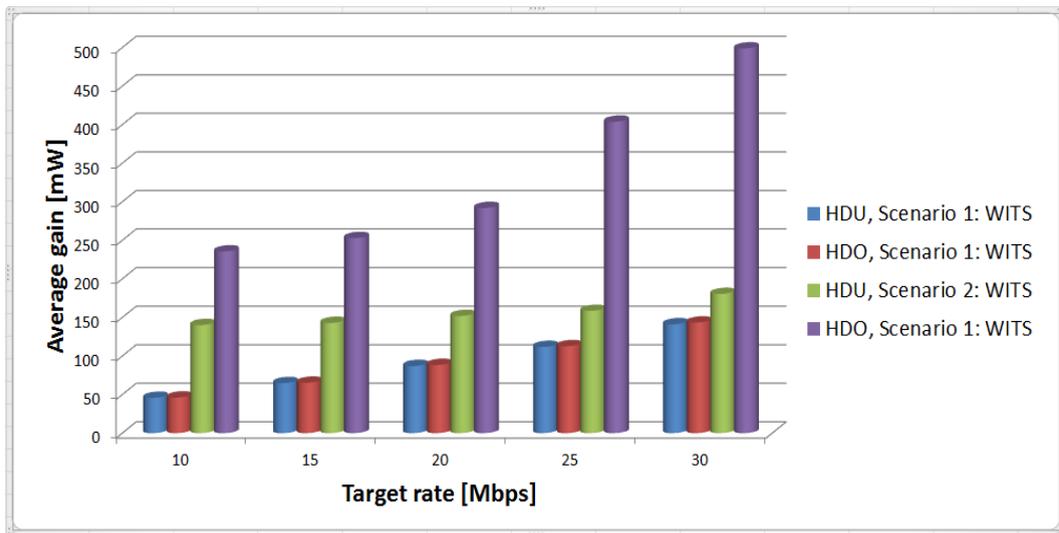


FIGURE 6.10: Average dynamic power saving gain of HDU and HDO relaying for the WITS case: Scenario 1 and Scenario 2

# General Conclusion and Perspectives

In this thesis, towards the evolution of green Power Line Communications (PLC), we focused on measuring, analyzing, modeling and optimizing the power consumption of power line communication systems. After presenting the fundamental aspects of the PLC technology as a background for our work, and giving an overview about the current state of the art for green communications, we addressed the following issues.

We started by developing methodologies for power consumption measurements of Single Input Single Output (SISO) PLC modems, and later extended them to include the last generation of PLC modems which implements the Multiple Input Multiple Output (MIMO) technology. We measured the power consumption of many commercial PLC modems, having different implementation features and using different standards, and provided a detailed analysis of their power consumption.

Informed by this analysis, we proposed novel power consumption models for both SISO and MIMO PLC modems which separately quantify the idle power of PLC modems, the power consumed by Ethernet ports, the power required for transmitting Ethernet frames, transmitting PLC Physical Blocks (PB), receiving Ethernet frames and receiving PLC PB. A multiple regression analysis was used to estimate the model parameters.

The major findings that we derived from the measurements and modeling part of our work are summarized in what follows

- In general, idle power of modems, which is independent of traffic load (the power consumed by modems just to be on) is the dominant part of the total power consumption of PLC modems.
- In both SISO and MIMO cases, the power consumption increases almost linearly with the bit-rate.
- For the part of power associated to the traffic load, transmission power appears to be the most critical element and can represent up to 40% of the overall consumption budget.
- The power required for processing PLC PB is higher than the power consumed for processing Ethernet frames.
- For MIMO-based modems, transmission power is significantly larger than reception power.
- The impact of per-Ethernet port power is relatively small but still non negligible especially when compared to the reception power.

Our measurement-based modeling study provides a power consumption benchmark for the PLC research community. Specifically, other researchers can use our measurements and power models as a basis of reference when designing new modems or for evaluating the performance of their power reduction techniques for PLC modems. In addition, our approach is generic and can also be used for characterizing or modeling the power consumption of other systems or modems.

Our next step was about investigating how the power can be reduced by using relay nodes in PLC networks. To this end, we conducted a simulation-based study to evaluate the performance of PLC relay systems with time division Decode-and-Forward (DF) scheme in terms of power and throughput. In addition to the transmission power, we considered the static power of PLC modems in our power consumption model. Further, we studied the effect of time sharing in the DF relay system and found the best power efficiency performance for DF strategy by optimizing the transmission time allocation between both S-R and R-D links. We proposed an iterative algorithm to find the optimal time sharing for power minimization, and

compared its performance with that of the uniform time sharing strategy.

Then, through extensive numerical results based on both measured PLC channels, PLC noise and simulated ones; and by considering two representative scenarios, we showed that depending on the static power consumption of PLC modems, DF protocol with optimal time allocation allows for better performance than direct transmission, yet achieving the same rate of the direct transmission.

The results presented in this thesis can be used as a basis for extending the investigated topics. Regarding the modeling part, since our analysis showed that an important part of the total power consumption of PLC modems is traffic-dependent, an interesting perspective of this work would be to consider different traffic models for the analysis.

Also, in the analysis of the power efficiency performance of PLC relays, we considered SISO modems. However, since MIMO PLC modems will play an important role in next-generation PLC networks, it is interesting to explore their power efficiency performance when used as relays. We are currently working for an extension of this work by considering MIMO-based modems in the relay system model. Specifically, MIMO relays introduce additional configurations compared to SISO relay systems such as Single Input Multiple Output (SIMO) or Multiple Input Single Output (MISO). This can have an impact on the power efficiency of the whole PLC network. Our aim is therefore to compare the power efficiency advantages offered by these different PLC relay configurations.

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## Résumé

Au cours des dernières années, la recherche dans le domaine de l'efficacité énergétique des réseaux de télécommunications a suscité un intérêt grandissant pour les fournisseurs de réseaux et les fabricants d'équipements. Dans les systèmes à Courants Porteurs en Ligne (CPL), les efforts se sont principalement concentrés sur l'augmentation du débit. Cependant, très peu d'attention a été accordée au sujet de l'efficacité énergétique. Dans cette thèse, nous nous concentrons sur l'amélioration de l'efficacité énergétique des réseaux CPL indoor.

D'une part, nous investiguons la consommation énergétique des modems CPL en menant plusieurs expérimentations et mesures sur plusieurs modems commerciaux. En se basant sur les résultats obtenus, nous fournissons une analyse détaillée du comportement énergétique des modems CPL. Ensuite, nous proposons des modèles de consommation électrique pour les systèmes CPL SISO (Single Input Single Output) et MIMO (Multiple Input Multiple Output). Les modèles développés permettent de quantifier la consommation énergie associée à divers états de communication et modes de fonctionnement des modems CPL.

D'autre part, nous évaluons l'apport énergétique de l'utilisation des relais dans les réseaux CPL. Nous considérons un système de relais Half-Duplex DF (Decode and Forward) et nous étudions ses performances pour deux stratégies, à savoir, pour une allocation de temps uniforme et optimale entre la source et le relais. Nous proposons un algorithme itératif pour calculer l'allocation de temps optimale qui minimise la puissance. Enfin, nous montrons par de nombreux résultats numériques, basés à la fois sur des canaux CPL mesurés et simulés, et en considérant deux scénarios représentatifs, qu'en fonction de la puissance consommée par les modems CPL lorsqu'ils sont en mode de veille, une réduction de consommation d'énergie significative peut être obtenue par la mise en place de relais dans les réseaux CPL.

**Mots-clés :** Efficacité Énergétique, Courants Porteurs en Ligne, Mesures de consommation de puissance, Modèles de consommation de puissance, Decode and Forward, Relais, Allocation de temps optimale

## Abstract

In the last few years, the research in the area of green and energy-efficient networking has gained a great interest on the part of network providers and equipment manufacturers. Considering Power Line Communication (PLC), more effort has been made on achieving higher data rates, but the topic of energy efficiency has still not been explored very much yet. In this thesis, we focus on the energy efficiency of indoor PLC networks.

On the one hand, we investigate the power consumption of PLC modems by conducting several experiments and measurements of many commercial modems. Based on the results, we provide a detailed analysis of the power consumption behaviour of PLC modems. Then, we propose measurement-based power models for both Single Input Single Output (SISO) and Multiple Input Multiple Output modems (MIMO) PLC modems. The developed models allow us to quantify the power consumption associated with various communication states and different operation modes of PLC modems.

On the other hand, we study the benefits of using relay nodes in PLC networks for energy efficiency purpose. We consider half-duplex Decode and Forward (DF) relay systems and explore their performance for two strategies, i.e., when the time allocation between the source and the relay nodes is set uniform and when it is optimized. We propose an iterative algorithm to derive the optimal time allocation for power minimization. Finally, through extensive numerical results based on both measured PLC channels and PLC noise and simulated ones, we show by considering two representative scenarios, that depending on the idle power consumption of PLC modems, significant power saving can be achieved by implementing relaying in PLC networks.

**Keywords :** Energy efficiency, Power Line Communication, Power consumption measurements, Power consumption models, Decode and Forward, Relay, Optimal time allocation