Faculdade de Engenharia da Universidade do Porto

System for Acquisition, Processing and Presentation of Energy Consumption

António João Resende Fernandes

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Supervisor: Prof. Dr. José Ruela

Co-supervisor: Eng. Carlos Pinho

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Presidente Professor Doutor José Alberto Peixoto Machado da Silva
Professor Associado do Departamento de Engenharia Electrotécnica e de Computadores da Faculdade de Engenharia da Universidade do Porto

Professor Doutor Artur Miguel do Amaral Arsénio
Professor Auxiliar do Departamento de Engenharia Informática do Instituto Superior técnico da Universidade Técnica de Lisboa

Professor Doutor José António Ruela Simões Fernandes
Professor Associado do Departamento de Engenharia Electrotécnica e de Computadores da Faculdade de Engenharia da Universidade do Porto

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Autor - **ANTÓNIO JOÃO RESENDE FERNANDES**

Faculdade de Engenharia da Universidade do Porto

Abstract

Energy peak demand growth, new markets and volatile energy prices, long-term supply of energy uncertainty accompanied with new regulations, laws and environmental concerns among other problems represent a serious threat to energetic sustainability of power grids. The power grids have served for more than a hundred years and have done it well but the traditional approach is not enough to overcome the rising and challenging problems it faces. Smart grids and smart metering are the most promising new, fresh concepts to help power grids to keep up the energetic sustainability.

There are already several similar proposals of smart metering being tested around the world; they all have common goals and answer similar challenges. This project proposes an alternative solution to these platforms based on a different approach that consists in offering a platform to support smart metering: the system developed provides smart metering functions with reduced communication costs to current and future meters while being easily expanded to support new added value services.

The results of the followed approach show that the system is capable of meeting the essential smart metering functional specifications, proving that the alternative solution developed can support smart metering concepts with current meters and bring benefits to smart metering adoption.

Resumo

Aumentos de picos de consumo energético, novos mercados, preços de energia voláteis, incertezas relacionadas com fornecimento de energia a longo prazo acompanhados com novos regulamentos e leis, preocupações ambientais e outros problemas representam uma séria ameaça à sustentabilidade das actuais redes energéticas. As redes de energia eléctrica convencionais foram usadas durante mais de uma centena de anos e serviram bem o seu propósito, mas começam a mostrar-se insuficientes para encarar os problemas acima mencionados. Redes inteligentes e *smart metering* são os conceitos recentes que se mostram mais promissores para conseguir acompanhar os requisitos energéticos.

Existem já várias propostas para aplicação de *smart metering* um pouco por todo o mundo, ainda que todas tenham objectivos comuns e encaram desafios idênticos.

Este projecto propõe uma solução alternativa às plataformas de *smart metering* convencionais, baseada numa aproximação diferente que oferece funcionalidades equivalentes: o sistema desenvolvido providencia funções de *smart metering* com custos de comunicação reduzidos para contadores eléctricos actuais e futuros, ao mesmo tempo que expande o suporte a novos serviços de valor acrescentado.

Os resultados obtidos de acordo com esta estratégia mostram que o sistema desenvolvido é capaz de cumprir as especificações funcionais de *smart metering*, provando que pode ser aplicada a contadores eléctricos actuais e promove a adopção de *smart metering*.

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Abbreviations and Symbols

AES	Advanced Encryption Standard
AMI	Advanced Metering Infrastructure
BW	Bandwidth
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSV	Comma Separated Value
DG	Distributed Generation
DNO	Distribution Network Operator
DSM	Distributed Systems Management
ESD	Electrostatic Discharge
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FIS	Flash Image System
GPIO	General Purpose Input/Output
GPL	General Public License
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HAN	Home Area Network
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IP	Internet Protocol
Ipkg	Itsy Package Management System
ISAM	Indexed Sequential Access Method
ISM	Industrial, Scientific and Medical
ISP	Internet Service Provider
JFFS2	Journaling Flash File System version 2
JTAG	Joint Test Action Group
LAN	Local Area Network
MB	Mega Bytes
MHz	Mega Hertz
MIPS	Microprocessor without Interlocked Pipeline Stages
MMC	MultiMedia Card
OCR	Optical Character Recognition
OEM	Original Equipment Manufacturer
PAMR	Public Access Mobile Radio

PC	Personal Computer
PDA	Personal Digital Assistant
PLC	Power Line Communication
PMR	Professional Mobile Radio
PNG	Portable Network Graphics
RAM	Random Access Memory
RF	Radio Frequency
RP-SMA	Reverse Polarity SubMiniature version A
RRD	Round Robin Database
RS-232	Recommended Standard 232
SD	Secure Digital card
SPI	Serial peripheral Interface
SOC	System-on-chip
SSH	Secure Shell Host
SSID	Service Set Identifier
TFTP	Trivial File Transfer Protocol
TTL	Transistor-transistor logic
UMTS	Universal Mobile Telecommunications System
WAN	Wide Area Network
WEP	Wired Equivalent Privacy
WPA	Wi-Fi Protected Access
XML	Extensible Markup Language

Chapter 1

Introduction

Energetic sustainability of power grids is currently facing several serious threats and the traditional approach is revealing not to be enough to overcome the new problems faced by the power grids. As a response to these threats the smart grid vision was born.

Section 1.1 introduces the smart grid vision, even though the whole smart grid vision is out of the scope of this project; it is a fundamental concept to contextualize the problem statement presented in section 1.2. The goals to achieve and strategy used during development are described is section 1.3 to provide insight into the decision making process used throughout development. Section 1.4 provides the structure of the thesis.

1.1. Motivation

Power grids of today face several problems, i.e. lack of long term supply options or unstable prices; problems that need to be addressed in order to achieve energetic sustainability [1].

The power grids of today look pretty much like they did when they were deployed. Most part of power grids still continues to use the same technologies for generation, transmission, distribution and metering, only the kind of materials and construction style of poles, lines, insulators, and transformers have changed significantly. Reliability and quality of service continues to be achieved by constructing and planning with enough redundancy and extra capacity to adapt to the predicted customer disturbances. This traditional approach is not keeping up the pace with the changes of the environment in which the electricity industry operates [2].

The new market circumstances like “rising costs” of fuel and materials, “financial constraints” due to competition, as well as “environmental impact / climate changes” enforced new regulatory laws that try to reduce the environmental impacts by the power facilities, “no more cost-plus monopoly expansion” due to the former circumstances. Also the “new operating conditions” and the “customer requirements” [2] enforce a change in the actual power grids state. For example in the U.S., growth in electricity peak demand has surpassed transmission growth by almost 25% every year since 1982, however the investment in research and development of current power grids infrastructures is one of the lowest when compared to other industries [3], as shown in Figure 1.1.

However the figure also shows that the maximum R&I investment is oriented towards energy and management services, which is a measure against the actual limitations of current electric power infrastructures. The up growing demand, chronic underinvestment, market circumstances in the electricity industry and environmental concerns acted towards the smart grid as a necessary change in the electricity industry.

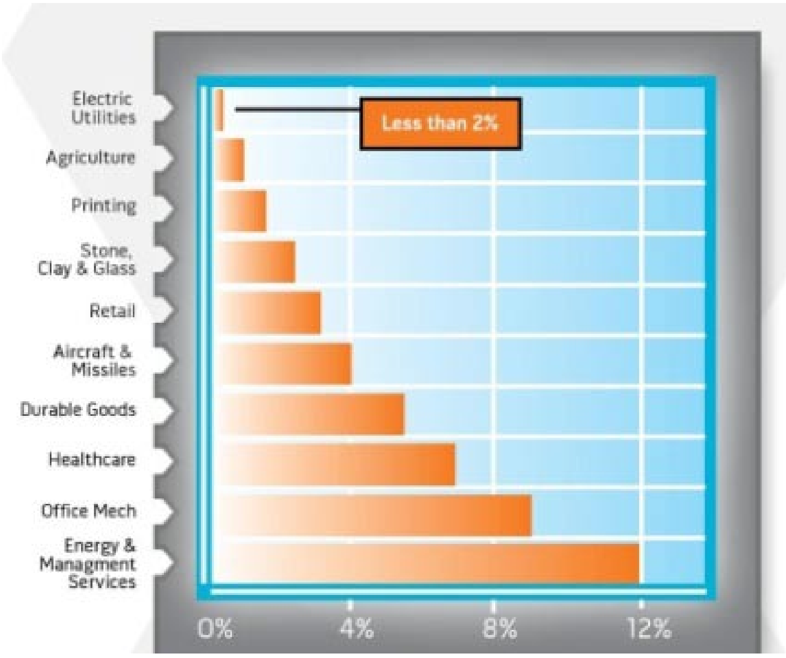

Figure 1.1 - Industry investment in the U.S. in percentage to their revenue [3].

There is not one single and unified vision about smart grid but there are several proposals and they are all centred on the same goals. The smart grid is an operational framework to transform the electricity industry from a centralized, producer-controlled network to one that is less centralized and more consumer-interactive, and this paradigm is revolutionizing the electricity market and industry. Figure 1.2 gives an overview of the smart grid, encompassing all parts in an Internet-like distribution grid.

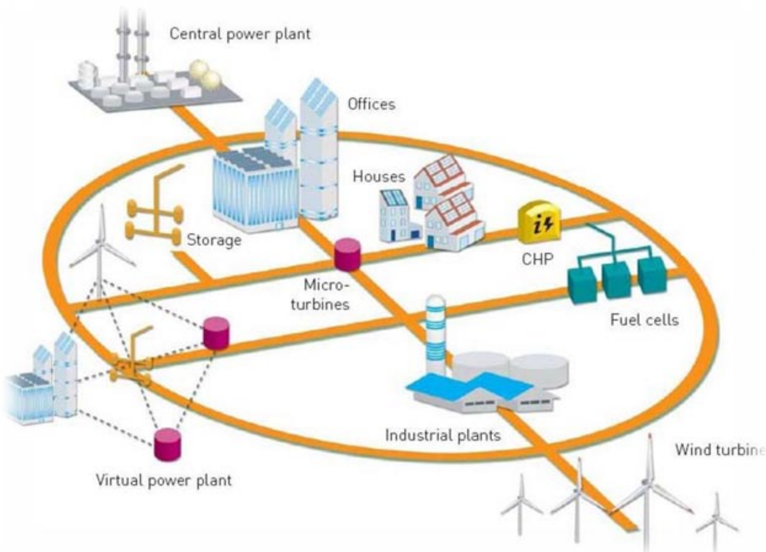

Figure 1.2 – Internet-like distribution grid [4].

In overall terms the smart grid can be summarized as [2]-[5]:

- Motivating – make the consumer informed, involved and active;
- Intelligent – capable of sensing the system overloads or faults and prevent them by autonomously rerouting power;
- Efficient – meet increased consumer demand without additional resources;
- Accommodating – capable of integrating all generation and storage options;
- Opportunistic – enables new markets and opportunities;
- Quality-focused – capable of meeting industry standards and consumer needs;
- Resilient – capable of resisting attacks and natural disasters;

The need to change and the goals to be met are stated above but they will not work without new technologies. Active distribution networks, improved power flow, power electronic technologies, stationary energy storage and smart metering are some examples of technologies that will enable the smart grids.

Table 1.1 - Comparison between the actual grid and the smart grids of the future [5].

20th century Grid	**21st Century Smart Grid**
Electromechanical	Digital
Very limited or one-way communications	Two-way communications every where
Few, if any, sensors – “Blind” Operation	Monitors and sensors throughout – usage, system status, equipment condition
Limited control over power flows	Pervasive control systems – substation, distribution and feeder automation
Reliability concerns – Manual restoration	Adaptive protection, Semi-automated restoration and, eventually, self-healing
Sub-optimal asset utilization	Asset life and system capacity extensions through condition monitoring and dynamic limits
Stand-alone information systems and applications	Enterprise Level Information Integration, inter-operability and coordinate automation
Very limited, if any, distributed resources	Large penetrations of distributed, Intermittent and demand-side resources
Carbon based generation	Carbon Limits and Green Power Credits
Emergency decisions by committee and phone	Decision support systems, predictive reliability
Limited price information, static tariff	Full price information, dynamic tariff, demand response
Few customer choices	Many customer choices, value added services, integrated demand-side automation

One of the main characteristics of the smart grids is making the customer part of the “network-loop” [5]; as a result they are developed with a domestic focus [3]. Empowering the consumers and “prosumers” with new methods and by giving them information and price signals enables them to react in real-time and contribute to the optimization of grid operation [5]. The real-time communication between the consumers and utility should motivate the consumers to tailor their energy consumption based on individual preferences, like price and/or environmental concerns [2]. Focusing on the homeowners, namely in providing the tools and means for them to actively participate in a more efficiently power grid with reduced investment. This is, without requiring the smart grids infrastructures ready and using current technologies, giving the homeowner the possibility to better manage power consumption, thus saving money, help the power grid to be more efficient and as an added bonus, be environmental friendly. In fact, giving the customers one of the key emerging industry trends, enabling technologies and increased participation, are the driving factors for the transition towards future smart grids [4].

The electricity industry is moving towards inclusion of technologies such as two-way communications, sensing and measurement, advanced components, advanced control methods and improved interfaces [3]. Two-way communications will allow every component to talk and listen in real-time that along with sensing and measurement will support remote monitoring, time-of-use pricing and demand-side management for improvement of the efficiency, reliability and safety of power delivery and use. Smart metering will make use of these technologies to empower the consumers, making smart metering a fundamental component of the smart grid.

As several projects in smart grids and smart metering are still under development, this project provides some tools and means for homeowners concerning the law presented by the European Parliament in December 2005, "Energy End-Use Efficiency and Energy Services Directive", mandating better standards of metering throughout the European Union [1]. At the moment smart grids and smart metering become commercially available, the system and applications proposed in this project can still find applicability as a mean to complement those systems regarding communications technologies and services that can be supported.

1.2. Problem statement

Electricity grids exist for more than a hundred years without major changes to their original model; however, things are changing. Current power grids are at their limit due to the up growing demand - European electricity consumption is expected to grow 1.4% every year up to 2030 according to International Energy Agency (IEA) [4]. Consumption is surpassing the growth in capacity and traditional construction methods may suffer an impact due to environmental concerns in order to reach Kyoto Protocol targets. Power losses have to be reduced. Even business has changed due to market liberalization. New challenges and needs arise, calling for new solutions. And smart grids are a logical step forward.

Smart grids have to respond to the following needs [4]:

- User-centric approach;
- Electricity network renewal and innovation;
- Security of supply;
- Interoperability of European electricity networks;
- Distributed generation and renewable energy sources;
- Central generation;
- Environmental issues;
- Demand response and demand side management;
- Politics and regulatory aspects;
- Social and demographic aspects.

Smart grids will use new technologies, products and services to create a strongly user-centric approach [4]. Smart metering provided by smart meters is one of the technologies that will aid the smart grid fruition. It should allow real-time measurement of consumption, based on computerized circuit modelling, and be able to determine voltages and power flows in the grid leading to an active grid management. Moreover, it will permit the implementation of the user-centric approach by allowing customers to access value added services, supporting flexible energy demand and creating micro generation opportunities. It is also expected that the dynamic consumption reading along with the choice of type of supply (green, cheapest, etc.), new tariffs and value services made available by smart meters will help the costumer to take more informed decisions, as they are one key element for achieving energy sustainability and meet environmental issues. However, social responsibility is not easy to achieve. Even with more information available it is not sure if this will have the desired effect.

Energy prices have some degree of predictability associated with the time of day and season. Billing according to time as well as quantity of energy spent is expected to force an increased awareness by consumers to adjust their consumption based on market prices and thus reducing the need to build new power plants or at least reduce the amount of electricity bought from expensive sources.

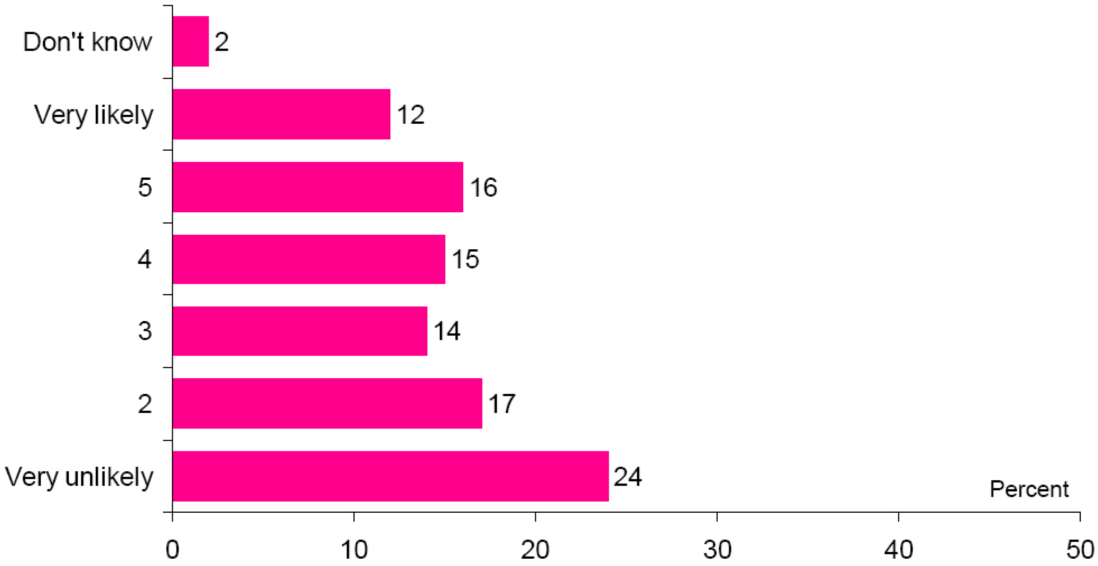

Figure 1.3 – Norwegian customer survey about changing energy consumption habits [6].

Migration to smart meter is not without challenges and uncertainties: cost is the most relevant, namely who will support the burden of cost - consumers or utilities? A Norwegian consumer study [6] shows that in 2006, 88% responded that they were not willing to pay to have this technology installed, even if the total cost is spread through a 10 year period. However willingness to pay is higher amongst consumers that already have smart metering (39%). This study also shows little interest in changing consumption behaviour – figure 1.3 shows the answers of a customer survey in Norway when consumers were ask: “In the event you had the opportunity to pay less for electricity you use during the night or at weekends, how likely is it that you would change your habits so that your electricity consumption would take place when prices were lower? (n=1000) percent”. Users do not want to be bothered to track electricity price information; they are accustomed to use electricity without considering price. Moreover, it shows moderate interest in new products and services as shown in figure 1.4. The study justifies these numbers by lack of clearness and usefulness by the costumers about the new products. Many consumers also have the opinion that smart metering will benefit most electricity providers, so they should be exempted from paying for it. In conclusion, the same study states that consumers have little or no knowledge of the benefits and opportunities in automatic smart metering. This lack of knowledge makes it hard for suppliers to request payment for the new services offered.

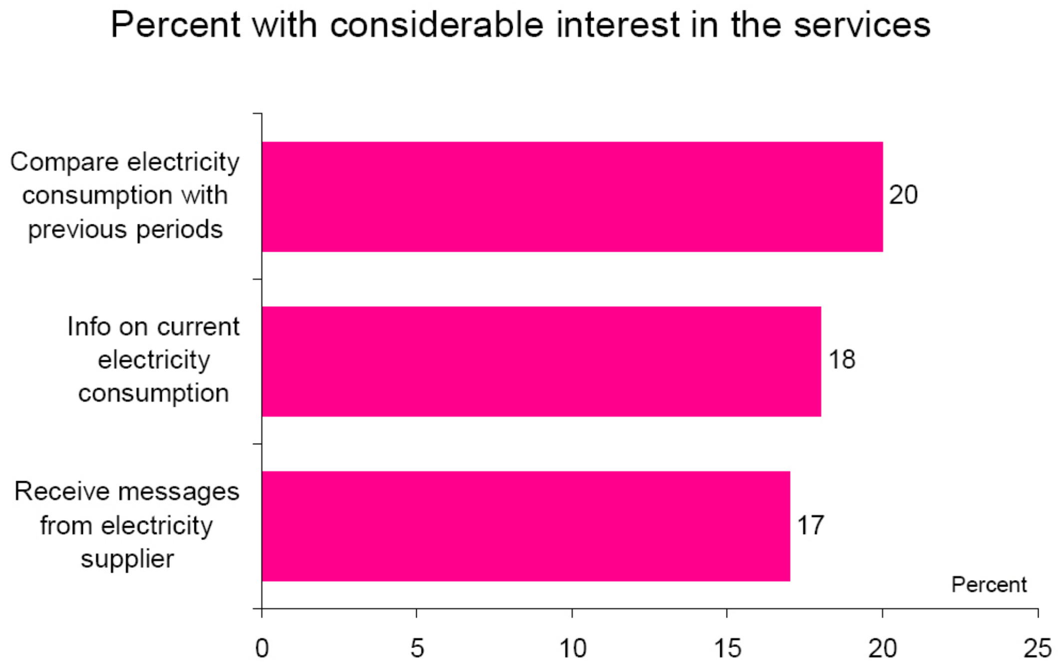

Figure 1.4 – Interest in new products and services from the electricity market in Norway [6].

Currently smart grids and smart metering projects are under development or testing but the problems remain present, i.e. inconstant energy costs and users could benefit today from functionalities that shall be provided by smart metering. Still, some regulatory issues regarding who will burden the costs of the smart meter, stranded devices, communications and new services offered continue without a definition – problem yet to be solved. The main focus of this thesis is to create a system and corresponding applications that can provide the user with functionalities of smart metering, such as updated energy consumption through current technologies and devices broadly used today while being able to easily communicate with the utility in a low cost fashion, and provide/support emerging services like energy consumption benchmarking, lifestyle tariffs: home worker, young family, professional, differential time of day tariffs, different payment options [8].

1.3. Objectives and strategy

The objective of this thesis is to develop a system capable of providing some of the functionalities of smart metering that can benefit today the consumers while the smart metering and smart grid infrastructures are under development. It is intended that the system and respective applications being developed serve as an incentive to the costumers' smart use of energy and allow a faster adoption of the future smart metering and smart grid infrastructures. In order to allow this faster adoption of smart metering, the system objectives have to take into account the particular context and restrictions posed to smart meters. Also, as stated in section 1.2, smart meters or similar systems developed for consumers will have a cost associated to it and, without a decision of who will support the costs, reducing those costs is an objective. In fact, this will have a major influence in the strategy and technologies adopted during development.

For allowing a future integration in the smart metering platform the system development has to follow the operational framework of smart metering in order to achieve interoperability [9]:

- Developed with a Domestic Focus;
- Developed for true smart metering;
- Deliver a framework that could be used for non-domestic applications;
- Key to interoperability:
    - Network protocols;
    - Data Exchange Format;
    - Access and system security;
    - The smart metering has to be upgradable, this allows new developments in smart grids without making the old smart meters outdated;
    - Whenever possible it is recommended the use of open protocols to avoid problems with proprietary protocols and allow more market competition.

The objectives and associated strategy to contribute to cost reduction are:

- Stranded energy meters – the system requires two-way communications and current meters do not have this feature. This would make them obsolete in a smart meter infrastructure and the substitution of all of them would be costly.
- Communications means – In [7] it is concluded that when cost is an important case, the adoption of PLC/RF and/or an existing broadband connection are preferable for use as communication mean. These also meet the real time constrains with the support of a form of broadcasting or parallelism.
- System developed cost - The system will be designed to interface with energy meters already deployed and future ones. Interoperability is one of the key objectives to achieve low cost of deployment and long life span. These objectives are only valid if the final cost of the system is lower than changing to a new meter.
- Data visualization and system configuration - The SMA should give the homeowner the ability to check for the consumption and see an historic of the consumption for a pre-defined time. This historic of data is information not available in current meters, so it is up to the system to develop and to save and deliver this new data. For lowering system cost this data visualization should make use of already existing devices in households. Browser enabled devices, such as PCs, are just an example. Data access may be done through a web page that besides that should let the user manage and configure the system.

The strategy was centred on re-engineering network equipment, which enabled us to:

- Use a low cost and widely available equipment;
- Benefit from high user adoption;
- Benefit from natural network interconnection;
- Provide a simple and widely used user interface that is independent of devices (as long as they have a browser);
- Support smart metering using current meters.

Further development can incorporate the creation of a comparison algorithm. The comparison is based on the information from several smart metering users or pre-created energy usage consumption of the typical household. For the first method it would be necessary the construction of an additional data base infrastructure, while the second could be downloaded from the energy supplier or system seller, being then uploaded to the system afterwards for comparison. The idea behind this comparison algorithm is to support education for conscious and intelligent use of energy by consumers.

1.4. Structure of dissertation

This thesis/project report is composed of 6 chapters and 2 annexes.

This first chapter is an introduction to the project. It is a short, contextualizing chapter dedicated to the logic analysis, problem statement, goals to achieve and strategy guidelines to be used during development and decision making. It also introduces the work structure.

The following chapter describes the actual state of development achieved in smart metering. It describes the smart metering vision, the challenges, benefits and the different perspectives of all the elements involved in the process. Descriptions of possible architectures, protocols and home area technologies that can serve as a base of development are also presented.

The third chapter presents the functional specification of the developed system and the strategy adopted. The latter describes the relation between the objectives to achieve and the approach taken during development, mentioning the benefits and drawbacks that result from those decisions. The technologies to be used in the project and why were they chosen, as well as the system architecture, including the components and constituents modules, are also described.

The fourth chapter describes the development of this project, from the device preparation to operation as desired, passing through communication ports and memory expansion, software development and corresponding decisions made during development to data visualization and system configuration.

The fifth chapter presents the functionalities implemented as well as assessment. An overview of the overall system cost is also presented as a result of the strategy adopted.

The last chapter presents the project conclusions and discusses the system developed, the benefits and some possible improvements, pointing out possible solutions. It also presents some possible directions for future work.

Chapter 2

State-of-the-art

Smart metering vision is a framework to allow measuring, collecting and analysing energy usage from remote locations through some communication mean. This vision allows the distribution of information between authorized parties and the consumers and is one fundamental component that will drive to the smart grids deployment around the world.

This chapter will present the smart metering vision followed by the challenges it faces today and which will be the benefits of the adoption of this vision. The different perspectives of the involved parties, utilities, regulators and consumers shared by the smart metering vision will be described in section 2.3. The remaining sections will describe possible architectures of this vision along with the presentation of protocols and home area technologies that can act as a base for development.

2.1. Smart metering vision

The smart metering vision supports the creation of an advanced metering operational framework, having as its key objective the creation of an interoperable platform. The development of the framework was made as an approach to integrate consumers and true smart metering. Although the main focus goes to the domestic costumer, the framework should allow the usage from other participating parts of the grid giving them specialized meter variants. The operational framework is not an inspection and control framework to be used by governments [9]. Sometimes there is some misunderstanding between the terms smart grid and smart metering. Are they not the same? The smart grid is the operational framework in which smart meters will operate. So the smart grid creates and defines an interoperability platform for smart meters, but smart metering does not apply only to power metering, it can also address other kinds of metering, like water or gas [3], [9].

Achieving interoperability under the operational framework means demands for compliance between metering system, industry participants and devices within premises. Figure 2.1 exemplifies the infrastructure elements, showing all the parts that need to be covered by the framework for interoperability between the various elements. In order to achieve interoperability, the interfaces have to be interoperable, requiring the definition of the local and WAN interface, their protocols and data exchange format, and access control.

Some principles apply when trying to define interoperability; the smart metering platform should be able to support innovation within smart metering and other related technologies and try to use open standards to avoid issues associated with proprietary protocols and communication, facilitating a competitive market.

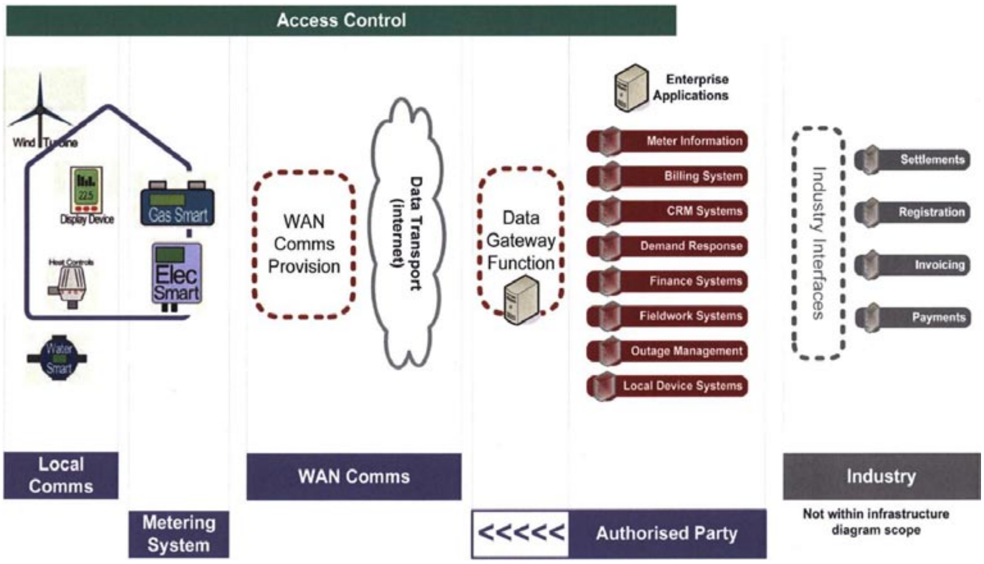

Figure 2.1 – Scope of all infrastructure elements [9].

The metering system is essential to the infrastructure shown in Figure 2.1, since it operates as a gateway between the “Local Comms” and the “WAN Comms”. Thus, the metering system requires two defined interfaces for communication; one towards the Local/Home network of devices within the premises that can include other utility meters, and the other to outside devices. The technology making this possible is smart meters.

2.2. Challenges and benefits

Smart metering is already being tested and deployed around the world, as seen in figure 2.2, but some challenges remain. Electric utilities, due to limited competition or monopoly of the market, are cautious in the use of new technology and market liberalization has made the electric industry even more reluctant towards innovation [5]. For the full scale deployment of smart metering there is a need to change the actual metering infrastructure, which requires substantial and long-term investment to support its sustainability. There is also the need for industry agreements and standards to ensure smart metering assets and services [10]. This is the most important challenge, the creation of a unified project that allows interoperability between different suppliers. Once a smart meter has been deployed in some premises, the supplier will retain ownership even if the customer changes supplier. So there has to be an operational framework or regulation to address the issue of stranded smart metering assets. There are also some technical issues that worry utilities. The requirement for more active network monitoring and control is driven by real-time performance requirements, which makes harder the upgradeability of components. Adequate security of the system is also a major concern from the suppliers. For instance, if the smart meter permits the remote connection/disconnection and management, and some hacker cracks the security and gains access to the network, this may allow sending commands through all system, unplugging every one. As some constraints apply to the development of the advanced metering infrastructure

(AMI), some may affect the security policies to be implemented. "Smart meters need to be very cost effective because millions will be purchased" [11] and most requirements are related to the smart grid features, so adding computing power for security can increase the costs. Also the location of the smart meters is very insecure, as they will be connected inside the premises of the costumer [11].

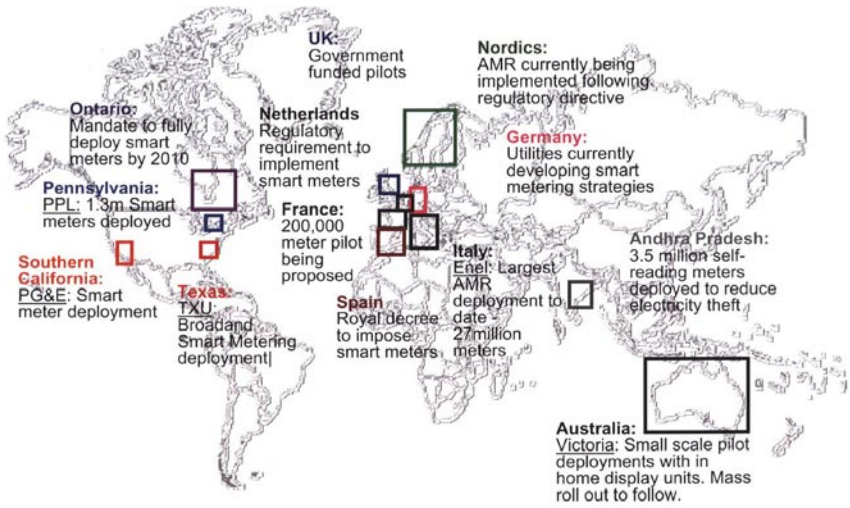

Figure 2.2 – Smart metering around the world [12].

The challenges are plenty and the difficulty in changing an almost static and monopolized industry is hard, but the benefits are many. The industry will benefit from the implementation of smart metering; in this advanced metering infrastructure the supplier will have remote meter reading, remote connections/disconnections, enhanced customer service and theft avoidance. This can reduce some operational cost for the supplier, although today in the U.K., "the costs of meter reading are highly dependent on the legal requirements for frequency, and it remains the case that manual readings can still be economic where cheap labour is available to carry out this task" [1]. The implementation of smart metering will also give the possibility to implement a smart grid improving demand side management, system reliability and reduction in peak demand. For instance, in Ireland "an 8% reduction can reduce capacity requirement by up to 400 MW" [12]. This will lead to an improved revenue management, limit non-technical losses and operational and capital cost savings [12]. Figure 2.3 represents the costs and benefits in case of AMI deployment in Netherlands.

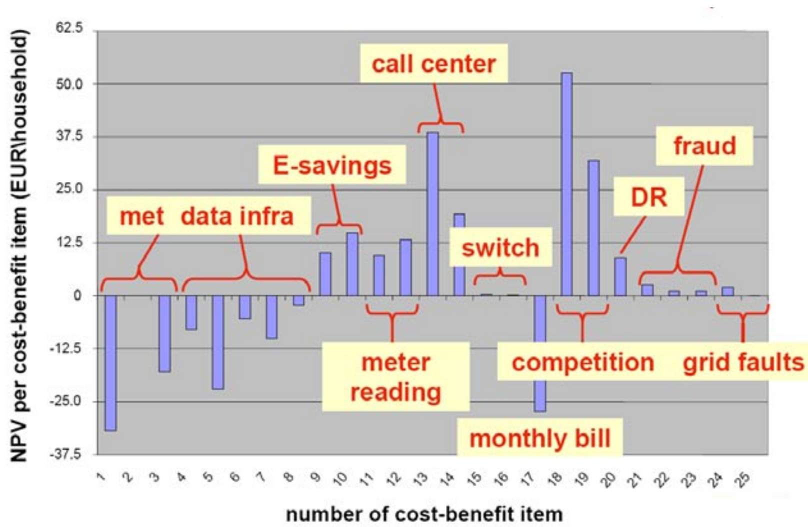

Figure 2.3 – Costs and benefits in Netherlands [13].

Figure 2.3 shows the extra costs and savings associated with the deployment of smart metering: the negative bars represent the costs of new meters, new infrastructures and new monthly bills while the positive bar indicate the expected winnings or savings that smart metering will allow with digital invoices, call centres, fraud detection and others.

The implementation of smart metering will also bring opportunities for a new market with increased retail competition. This will benefit both the actual market and the costumers, with lower costs and easier change of supplier. The financial benefits for the costumers aren't just lower prices. With a greater transparency and improved customer awareness there's a potential for cost savings on their electric bills.

Further benefits will be micro generation opportunities and the environmental gain enforced by a more efficient power grid and better integration of "clean" technologies. For example in the U.S. the transportation sector emits 20% of all carbon dioxide emitted and the generation of electricity emits 40% [3].

2.3. Different perspectives

After seeing the challenges and benefits of smart metering it is now time to see the different perspectives from the beneficiaries and/or contributors for the implementation of the system. There are three distinct perspectives to analyze: the energy networks, the regulators and the consumers.

2.3.1. Utilities

The energy networks look at smart metering as a revolutionary technology that can really change the energy supply market; however this has to be done properly. Proper planning with bold, brave and long-term decisions about how to develop and introduce this technology has to be made [8]. In order to summarize the utilities perspective regarding smart metering, the main conclusions from [10] are presented:

- Smart Metering could help Distribution Network Operators (DNO) to improve network utilization, increase penetration of distributed generation (DG) and facilitate active network management;
- There should be revenue / cash flow benefits from more accurate / timely consumption data and improved super-customer profiling;
- A Supply and Power Quality monitoring capability would provide opportunities for better network operational management;
- Subject to resolution of business separation issues, distributed systems management (DSM) could enable DNOs to improve load factor, reduce power losses and provide an important (distribution) system balancing ancillary service;
- DNO benefits will depend on a significant critical mass of smart metering – hence in terms of a roll-out program, the benefits may be back-loaded;
- DNOs could play an important role in providing a power line communication (PLC) service – but there is currently some uncertainty over the regulatory treatment of revenues.

2.3.2. Regulators

Regulators have as their duties and functions [12]:

- Protect interests of final customers;
- Secure license holders can finance their licensed activities;
- Promote competition in the generation and supply of electricity;
- Regulate tariffs;
- Secure that all reasonable demands by final customers for electricity are met;
- Promote safety and efficiency;
- Promote continuity, security and quality of supply;
- Promote the use of renewable, sustainable or alternative forms of energy.

These duties and functions allied with directives from EU that demand better meter reading, energy efficiency and management of peak demand among others (shown in section 2.1) make the regulators to look at the benefits and tariff opportunities as well as a cost-benefit analysis of smart metering. They concluded that there is merit in progressing with smart metering (refer to chapter 2.2). For advancing with smart meter deployment but recognize the need for a project that embraces all aspects of smart metering. Regulators from different countries have different proposals but they all embrace the general idea of section 2.1, implementing smart metering framework to guarantee interoperability [12].

“To an industry historically regulated for prior investment, the transformation to regulation for value delivery promises to stimulate substantial progress”. Regulators will continue to require that the value of the investments surpass the costs [3].

2.3.3. Consumers

Research, in the U.S. [3] and Norway [6], indicates that consumers are ready to engage into smart metering either by being exempted from reporting meter readings to grid operator or by wanting contact and control with their electrical box at home. But there are other factors to consider here, most costumers are not aware of the benefits and opportunities of smart metering, to a successful implementation of smart metering, and assuming most customers show interest in smart meters - 53% in Norway [6], there is a need to “provide information that in a simple and comprehensible manner presents automatic meter reading and the benefits this provides” [6]. They are driven by their desire to save money, but are not willing to pay a high enough premium to cover supplier cost [6]. Also smart metering interface has to be simple and accessible, with user-friendly units to increased understanding and tailored energy efficiency advice [3].

2.4. Architecture and Protocols

Two-way communications can occur between authorised parties and local devices, these are identified next [14]:

- A direct connection between the smart meters and the authorised parties;
- A dedicated intermediate communication infrastructure that works between smart meters and a concentrator;
- The usage of an existing intermediate communication infrastructure like the local internet available connected to the smart meters;
- A combination of the above; this would allow redundancy and different approaches to serve different implementation problems. Figure 2.5 presents an example of such a solution envisaged by EDP project InovGrid.

Other considerations for the communication architecture have to be addressed: for achieving the demand side management, real time constrains need to be satisfied [2]. This can imply support of broadcasting and broadband connection, if much data has to be transmitted [7].

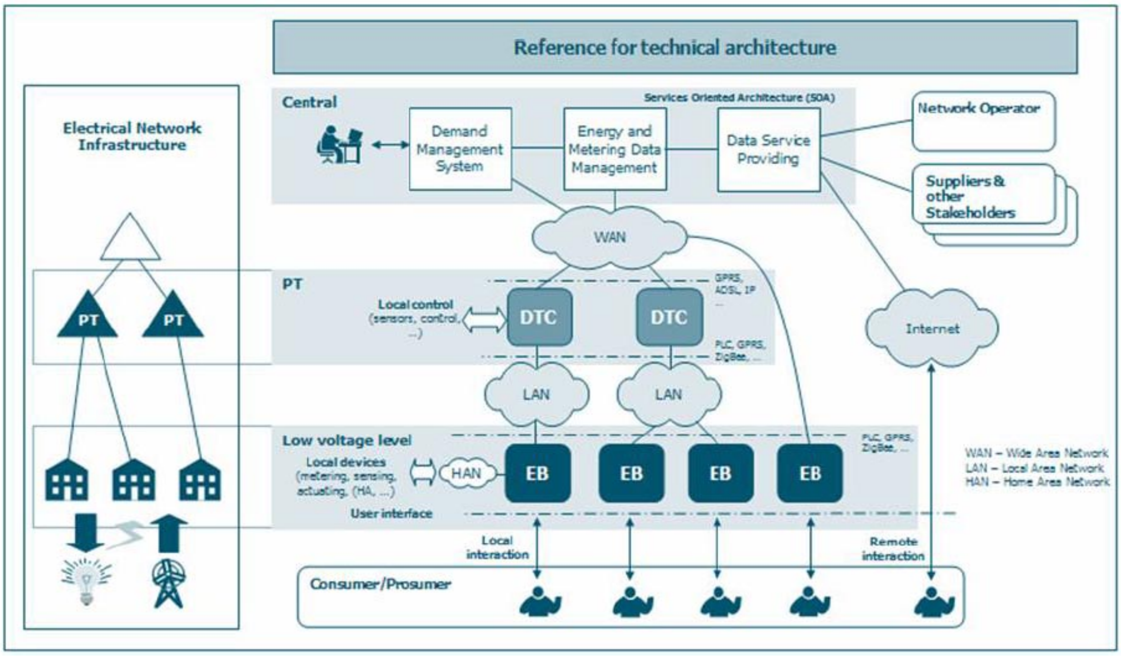

Figure 2.4 – Technical architecture of the InovGrid solution based on a multi-level hierarchical architecture [14].

In order to better understand the requirements posed by smart meters concerning communication capacity Table 2.1 summarizes the typical time and data size [7]. For each meter connected this will give an idea of how much data will need to be transferred. Flanders study [7] shows that just reading the measurements from the smart meter, from about 3 million meters, will result in 1,28 TB of raw data per year being transferred.

Considering communication means from utilities to smart meters, at least three categories are available: PLC, communication over telephone and/or cable infrastructure and wireless communication.

Power line carrier uses the power grid for data communication. It operates by modulating digital data on a carrier signal that is standardized and limited to a specific spectrum. The reserved spectrum in Europe lies between 3 and 148.5 kHz (EN 50065-1) [5]. The reserved utilities communication band, the A-band (3-95 kHz), only allow small band communication, with bandwidths reaching about 4 kbps [7]. Thus, in order to serve all meters the usage of concentrator will be required, while the usage of repeaters can improve reliability. PLC has some advantages compared to other solutions; since it uses the wires already installed it does not create dependency from third parties and does not require additional cabling and the meter is automatically connected to the communication medium. Nevertheless, it seems that European PLC-based deployments are not able to reach 1 to 5 % of the meters and if certain problems occur, e.g., interrupted distribution cable, the communication medium is also lost [7].

Regarding wireless communication, several possibilities include 2nd or 3rd Generation Mobile Telephony and Data, Non-licensed RF (i.e., ISM band) and Licensed RF.

Table 2.1 – Time and data size requirements per transaction type per meter [7].

Transaction type	Time critical	Response (min./typ./max.)	#times/year	#data (min./typ./max.)
Command Store measurement registers	Yes	Immediate/5min./1h	1	0,5KB/1KB/16KB
Send measurement registers (periodically + on demand)	No	Immediate/10min/2h	13 (12+1)	1KB/32KB/16MB
Command Reduce load	Yes	Immediate/5min/1h	1	0,5KB/1KB/16KB
Adjust parameters	No	Immediate/10min/2h	2	0,5KB/1KB/16KB
Upgrade firmware	No	10min/2h/1day	0,2	0,5KB/1KB/512KB
Send alarms	No	Immediate/10min/2h	0,2	0,5KB/1KB/16KB

The 2nd generation standards global system for mobile communications (GSM), general packet radio service (GPRS) and their variants or evolutions have almost full coverage and provide bandwidths of the order of tens of kbps. UMTS, the 3rd generation mobile is still being deployed around Europe, allows a shorter coverage but higher connection speeds than its previous generation, reaching several Mbps. In spite of their good outdoor coverage, reception in basements and alike is not guaranteed. Moreover, the use of mobile telephony implies a subscription fee to the mobile network operator without guarantees of availability for the expected 15 years corresponding to meters lifetime. Also their reliability is lower than (landline) telephone connections [7].

Non-licensed RF uses low-power radio on the non-licensed ISM band. A meter equipped with an RF transmitter allows communication directly to the concentrator or other meters that act as repeaters, as in a mesh network. The use of low-power radio also enables the connection between smart meters and smart appliances at home, for instance, with an overlapping network configuration with the connection to the AMI. RF offers high reliability when a large penetration is accomplished; this makes a better use of the repeater functionality, and provides a small band communication up to some kbps [7]. ZigBee, Bluetooth, Wi-Fi and Z-Wave are examples of technologies that can be used.

Professional Mobile Radio (PMR) is a group name for mobile radio systems that use licensed bands of the frequency spectrum. Walkie-talkies, PAMR and terrestrial trunked radio usually use these frequencies. It was built for group communications, but it is also standardised for utilities services [7]. No examples of usage of this communication means were found, but it is known that it has a very good coverage, broadcasting possibility and offers a medium bandwidth. This makes it well suitable for AMI and even provides a good reliability and responsiveness [7]. The new WiMAX is a technology using the licensed bands but can also use the non-licensed 5.8 GHz. It is standardized as IEEE 802.16a and allows a possible range of 50 km with broadband connection up to 100 Mbps [7].

For comparison purposes, Table 1.1 summarizes the communication means considered in this section.

The analysis of implementation costs as well as the communication costs per meter over time using different technologies can be found in figure 2.5 and figure 2.6 respectively.

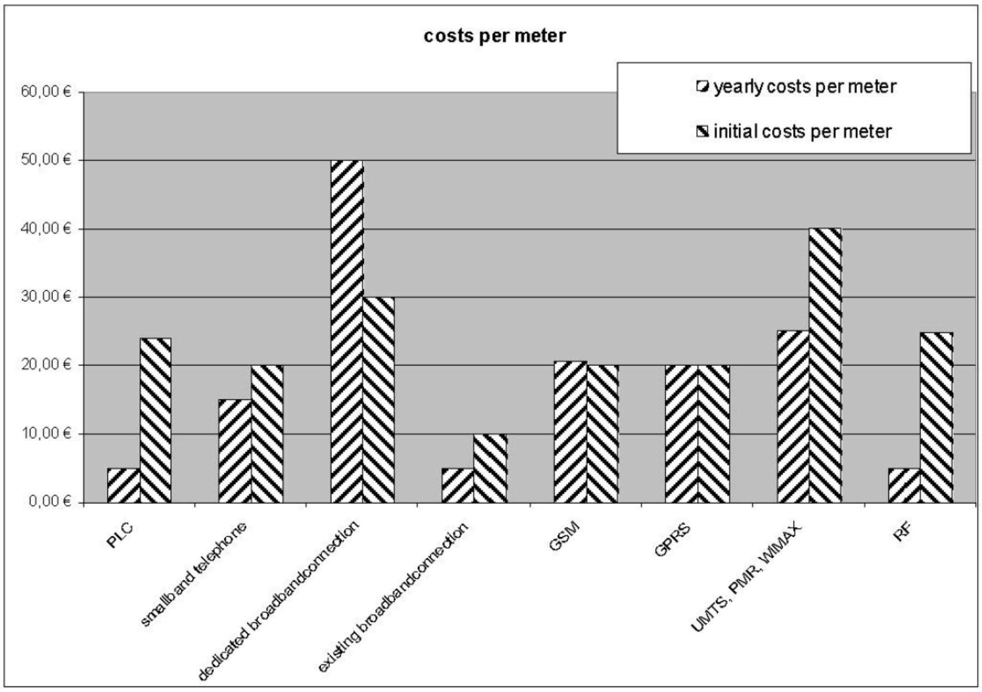

Figure 2.5 – Initial and yearly cost per meter [7].

Figure 2.5 is a comparison of the initial costs, such as meter communication module and meter to medium connection, plus recurring costs, such as connection cost and subscription fees, and installation costs [7]. The aggregation of these costs for a 15 year period – the expected life span of a smart meter - is shown in figure 2.6 [7].

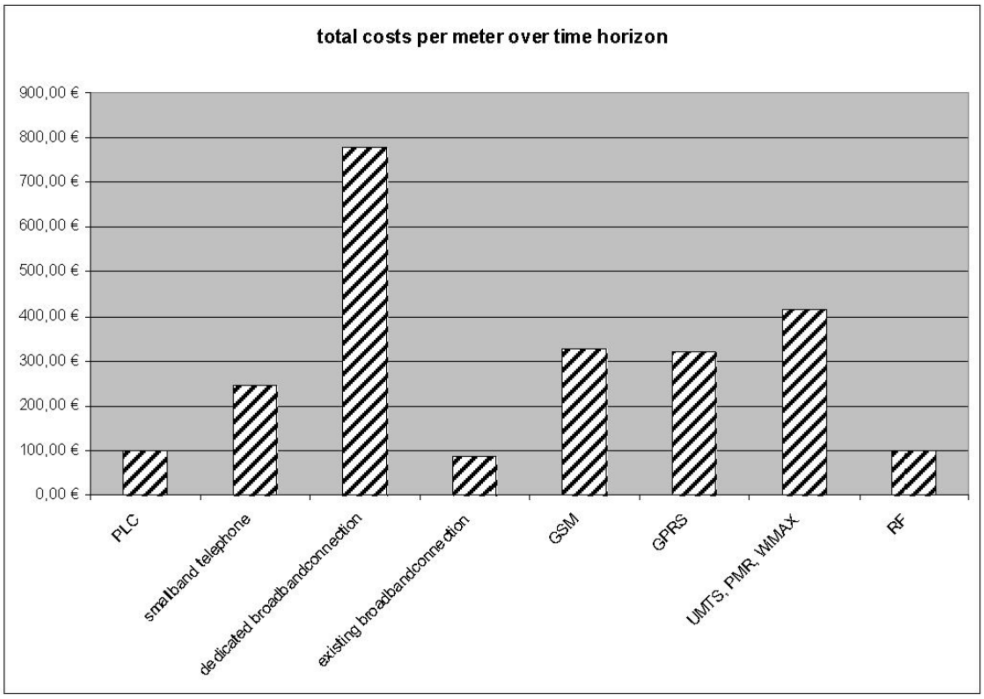

Figure 2.6 – Costs per meter over 15 year time horizon [7].

Figure 2.5 and figure 2.6 show that using an existing broadband connection is the cheapest solution to install and maintain but the problem is that users need to have this connection available at their households. Nevertheless, a single unified solution regarding the communication mean will be difficult to achieve, make existing broadband connection a strong candidate to be used.

Figure 2.5 and Figure 2.6 aim at giving an idea of relative costs of these solutions compared to each other, since these values were retrieved from one study made in Flanders – Belgium [7] and an analysis of the Portuguese case was not available.

2.5. HAN Technologies

The Home Area Network (HAN) is as extension of smart metering into the home itself, connecting the smart meter to a centralized home automation load centre with the major power consuming devices such as smart thermostats, air conditioners and washing machines. The usage of a HAN in a system like this allows homeowners to specify the consumption and efficiency according to their personal preferences.

The majority of the technologies that can be adopted for a HAN and here described are based on low power RF technology: ZigBee, Bluetooth, Wi-Fi and Z-Wave. Nevertheless, the usage of electric wiring is also possible with HomePlug. Each of these technologies addresses different targets [15]:

- Bluetooth (IEEE 802.15.1) was first targeted at consumer and communication applications, but soon started to be used to replace cables in basically all other applications. It is mainly used for point-to-point and point-to-multipoint-communications.
- ZigBee (IEEE802.15.4) addresses wireless sensor networks for several market areas such as: residential home control, commercial building control, industrial plant management, medical, energy management and automated meter reading. Key characteristics of ZigBee are low power and cost, and the need for networking devices as opposed to the point-to-point networks found for most Bluetooth and Wi-Fi applications.
- Wi-Fi purpose is providing an interoperable wireless access between devices and covers IEEE 802.11 standards including 802.11a, 80211b, 802.11g and 802.11n. It is mainly used for home networks, mobile phones and others. It permits the most flexible solution for connectivity.
- Z-Wave works with home automation applications, specifically to remote control applications such as home electronic devices.
- HomePlug AV aims to provide an entertainment oriented networking over AC wiring within the home [16] but can also be used for the home automation, but is restricted to wired devices. It has a bandwidth that can go up to 200Mbps [16], a much higher bandwidth when compared to all other HAN technologies addressed except Wi-Fi.

All these technologies define a complete protocol stack from physical layer through network layer, but all of them have incompatible interfaces with which other. The stacks vary in complexity depending on the different technologies, where Bluetooth and ZigBee follow the most open and flexible approach. ZigBee flexibility allows a small and simple stack like the one from Z-Wave [15].

Each technology implementing RF communication takes a different approach for its implementation [15]:

- “Bluetooth uses 2.4 GHz frequency band to achieve higher bandwidth and world-wide marketability”.
- ZigBee approach uses the 2.4 GHz and sub-GHz-frequency bands. This allows designers to make choices depending on the band that best fits their application. The

2.4 GHz frequency, as in the case of Bluetooth, is used to achieve higher bandwidth and world-wide acceptance along with the European Telecommunications Standards Institute (ETSI) 868 MHz and Federal Communications Commission (FCC) 900 MHz bands.

- Z-Wave uses ETSI 868 MHz and the FCC 900 MHz sub-GHz-frequency bands.
- Wi-Fi, depending on the standard, uses the 2.4 GHz (IEEE 802.11b and g) or 5 GHz (IEEE 802.11a and n) frequency band.

Each implementation uses a different technology implementation to avoid multi-path fading and to increase robustness. ZigBee and Bluetooth use spread-spectrum to improve signal immunity in presence of radio interference while Z-Wave uses narrow band for better bandwidth [15]. A comparison between range and bandwidth regarding several wireless technologies is presented in Figure 2.7. There are also other considerations regarding the coexistence with other RF systems using the same bands and decreased range in indoor applications.

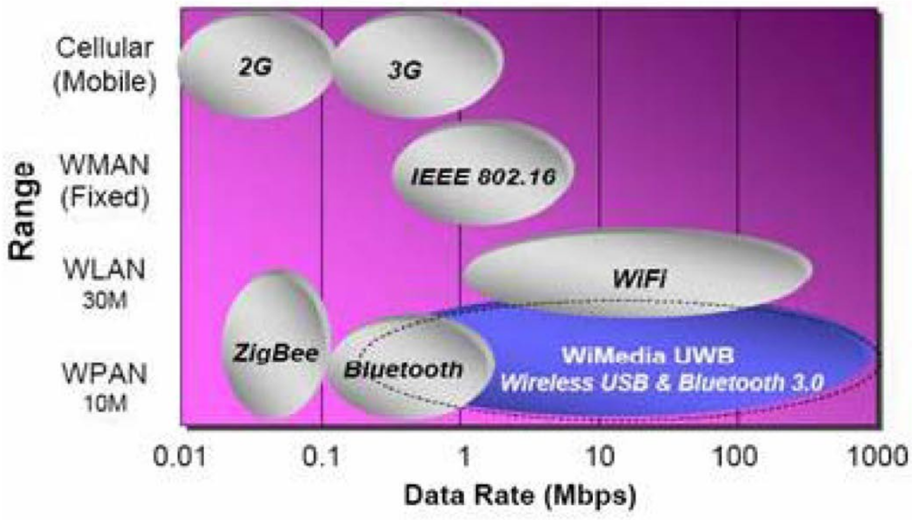

Figure 2.7 – Comparison between different wireless technologies regarding their bandwidth and range [5].

These RF technologies also differ on their medium access layer. Bluetooth uses master-slave system, whereas all others use carrier sense multiple access with collision avoidance (CSMA/CA) system [15]. Addresses for Bluetooth, ZigBee, Wi-Fi and HomePlug are IEEE compatible, whereas Z-Wave uses their proprietary addressing scheme.

ZigBee and Z-Wave have a pre-condition of battery-powered systems, so they include power-down modes. Bluetooth, Wi-Fi and HomePlug do not address this possibility [15].

Each technology follows a different approach to networking [15]:

- Bluetooth only needs point-to-point connectivity to target most of its applications. This does not provide a robust networking solution. Bluetooth does define a Scatternet but due to the large number of options in the specification and white spots makes it of impractical use.
- ZigBee offers a variety of routing algorithms, such as hierarchical tree, neighbour and table-based routing. The protocol automatically manages stray devices and shows a high degree of flexibility with functions for entering and leaving a network.
- Wi-Fi provides Ethernet compatibility and can be used in ad-hoc, access points and meshed networks.

- HomePlug brings back the ability to use Ethernet in bus topology. It has advanced network management functions consistent with new network standards and is also capable of supporting plug-and-play configuration as well as service provider set-up [16].
- Z-wave approach comes with source routing. The protocol does not support stray devices, automatic entering and leaving a network and lost network connectivity. But it provides a low complexity solution.

All technologies attempt to attain interoperability of different products through application profiles. Bluetooth has several profiles; however, most applications other than the standard voice or data communication use proprietary profiles or application based on the serial-port profile. ZigBee also specifies several profiles, which include: home automation, smart energy, building automation and others. The flexibility of ZigBee also permits original equipment manufacturers (OEMs) to create their own custom profiles. Z-Wave currently has defined approximately 20 profiles to be used on their home automation applications.

The application of RF technologies at home raises some security issues. The potential risk of someone gaining control of the HAN is high. For example, if a security system is part of the network, hacking the HAN may permit gaining control of this system. All technologies provide a full security approach with the exception of Z-Wave. Bluetooth implements its own cryptographic algorithm that, despite some minor flaws, has a good reputation when a proper implementation fulfills certain requirements [15]. ZigBee uses a layered approach to address security, providing advanced encryption standard (AES) encryption at the lower IEEE 802.15.4 level and a security toolbox on top, defined for key generation and distribution. This toolbox supports various modes for residential, commercial and industrial applications. Wi-Fi devices can be found in unsecure open mode, but some encryption standards are applicable. The most common protection method, WEP, has been shown easily breakable even in good implementations. The new WPA or WPA2 appeared to address the problems found in WEP and are considered secure. As with HomePlug, other security methods can be used to secure data, such as VPN or HTTPS. HomePlug is not an RF technology but also needs to addresses this problem. The link between HomePlug devices is encrypted by default with an encryption password. This can be changed by the users later by using the master password of the device. For a secure connection between HomePlug network with others network devices a secure higher-layer protocol is necessary because this connection is not encrypted. However, HomePlug provides, in a natural way, some level of security since the communication frequency used between each two devices has to be negotiated (by them) and this best frequency for two devices typically differs from other according to the medium characteristics [16].

Chapter 3

System architecture

The system architecture is formally described during this chapter. Starting by the functional specification of the system to meet the objectives is described in section 3.1, in order to support the reasoning done to define the strategy adopted to reach these objectives. The strategy adopted supports the decisions made by measuring the benefits against the drawbacks of the approach taken to achieve the objectives, also reasoning some of the technology choices presented in section 3.3. And finishing with section 3.4, where the overall system architecture is described.

3.1. Functional Specification

One of the main goals for the system being developed is the usage or compatibility with current meters, working as an upgrade to provide them with the necessary capabilities to work in a smart metering infrastructure. Figure 3.1 exemplifies a typical smart metering architecture as a visual aid to a better understanding of the smart metering operational requirements.

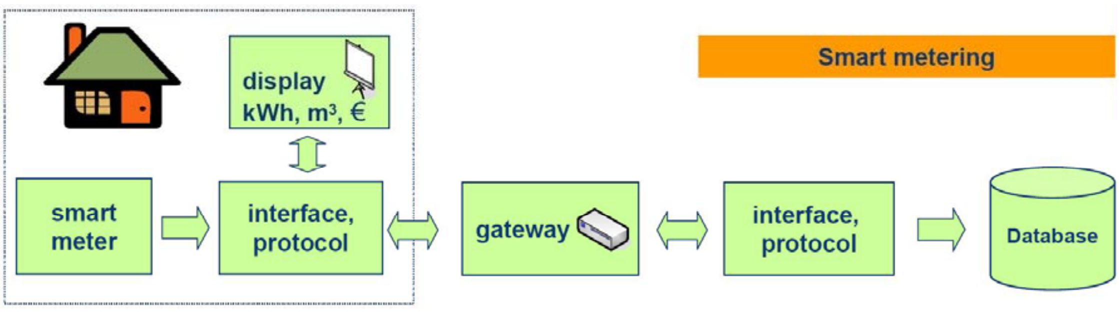

Figure 3.1 - A possible smart meter infrastructure [13].

There are some nuances, but at their core, the different architectures can be seen as in figure 3.1. Smart metering functional specification laid out next was compiled from different sources [1][9], [12], [13] and is as follows:

- Two-way communication with authorized parties and local device. This will deliver consumption information to customers and suppliers at a flexible and configurable level of detail;
- Two-way communication enables authorized parties to configure, monitor and manage the metering system without the need for physical visits to premises;
- Supports flexible tariff structures, including time of day, type of day and consumption based profiles for energy consumption. This will allow for innovative tariff structures to be introduced like lifestyle based;
- Electronic storage and display of data, including tariff and consumption;
- Meter Import/Export consumption, which will support micro generation;
- Include the necessary components to enable and disable supply of energy/gas at the metering system itself;
    - Easy to understand, prominent display unit which includes cost and an indicator of low/medium/high use,
- Comparison with historic/average consumption patterns,
- “Plug and Play”;
- Upgradeability;
- The ability to record and flag events such as tamper or loss/restoration of supply.

3.2. Strategy adopted

The approach taken to develop the project had to consider interoperability with different meters. This decision ruled out developing from scratch a smart meter application and directs the decision towards a system with high connectivity. By high connectivity it is meant that the system can interact with most of the energy meters already deployed, working as an upgrade in order for them to offer functionalities offered by smart meters and integrate an AMI. Beyond this upgrade function for current meters, the system should also allow integration of future meters.

The decision was to centre in the re-engineering of network equipment as a platform for smart metering with current and future meters. Network equipment can refer to any equipment that facilitates the use of a computer network: routers, switches, hubs, gateways, access points, cables among others; here it is referred to as a wireless router. A wireless router is a computer network device that includes functions of a router along with functions of a wireless access point. It is “low cost” and it is also widely available equipment that allows an easy integration with Wi-Fi enabled devices.

PC penetration in Europe, shown in figure 3.2, is expected to be higher than 60% by 2010 and 68% in Portugal [17]. Any other device with Wi-Fi or Ethernet connection with a browser can also be used to access, monitor and manage the system, for instance a mobile phone or PDA. Earlier, in chapter 2.5, HAN technologies were addressed as an extension of smart metering into the home, with a smart meter connected to a load centre together with major consuming devices while the focus done here is for data visualization, monitoring and control of the system being developed. Creation of a HAN was addressed as a way for allowing more control of energy usage from home appliances or other major loads and is only going to be addressed as future work. The use of Wi-Fi contributes to the flexibility and interoperability with high penetration home devices – computers or other Wi-Fi and browser enabled devices. Wi-Fi is capable of providing high data rates, which are expected to reach 600 Mbit/s in the new IEEE 802.11n. Security is provided through the use of WEP, WPA or WPA2 for data encryption.

Providing data visualization and system configuration with widely available devices allows a better user adoption. Moreover, providing the data through a web page, which is a widely used user interface, besides promoting user adoption also allows configuration and easy customization of the data provided: each customer can be given the choice to configure which data and how it is displayed to him. It is also a plug-n-play solution, as the integration with already available HAN is made seamless due to natural network connection of the wireless router.

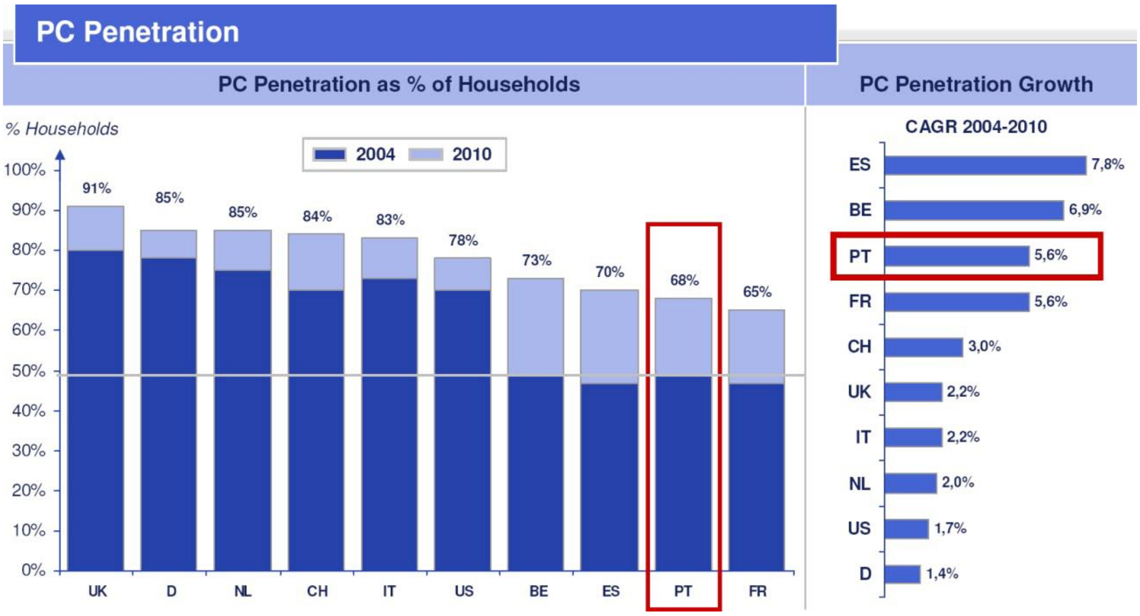

Figure 3.2 – Personal computer penetration in Europe [17].

Figure 2.5 showed that an already available broadband connection is the less expensive communication mean and also has the lowest maintenance cost if it is used for AMI, as observed in figure 2.6. The downside of using a broadband connection is the dependence on its availability, but cost is a major factor and figure 3.3 shows that it is widely available and growing, in some cases more than doubling in 6 years. Portugal is one of these cases. Portugal shows a growth of 35%, reaching a mature broadband development stage with 50% of penetration by 2010 [17]. These are reasons that justify using broadband as a suitable mean of communication between the meter and a central server. So the system will need to be able to access the broadband connection and the use of a wireless router will allow an easy integration. Broadband Internet connection is a global system of interconnected computer networks, the natural network interconnection where a wireless router is used. Usage of a wireless router will also allow for a backup connection, when no broadband is available, with the use of its Wi-Fi capabilities. The Wi-Fi connection can be explored in several ways, with the possibility of creation of a building ad-hoc mesh network or even city wide ad-hoc mesh networks connected with a concentrator with a broadband connection to upload readings, monitoring and management, and thus reducing dependency of available broadband connection. Or even use a drive-by car with a laptop to download readings from different meters but this method will not allow real-time monitoring. Data visualization and backup connection are both expected to function through the Wi-Fi connection. For security reasons, these different features should be available through separated Wi-Fi networks. The data being routed through the ad-hoc mesh network cannot be available in the HAN; data visualization can only be accessed by the system owner and authorized parties. Capacity to generate two different SSIDs is a requirement for the wireless router.

Usage of a wireless router will allow an easy integration of the chosen communication means for two way communication, between the meter and authorized parties, and visualization of data by the costumer. However, the integration of the meter with the wireless router and other functional requirements have to be addressed. Some meters already have a serial optical port or RS-232 to allow configuration and data acquisition but old legacy meters do not have any digital output from where data can be acquired and a different solution has to be developed (this case is considered in the future work). A mapping of available ports from the wireless router has to be made to know if the system allows inclusion of actual energy meters. Also the electronic data storage should be made available for the system. Wireless routers do have internal system memory for normal operation, but the availability and size of this memory typically are not enough to accomplish the desired life span for the system. Beyond that, the system has to be able to register events like tampering and loss of supply. Loss of supply is a problem since wireless routers are not designed for battery operation, so with the loss of energy supply the wireless router will also shutdown. This can be solved by checking the database for unknown values and register them as a loss of energy supply. These unknown values can also be due to other reasons like: lost connectivity with the energy meter or system shutdown by the user.

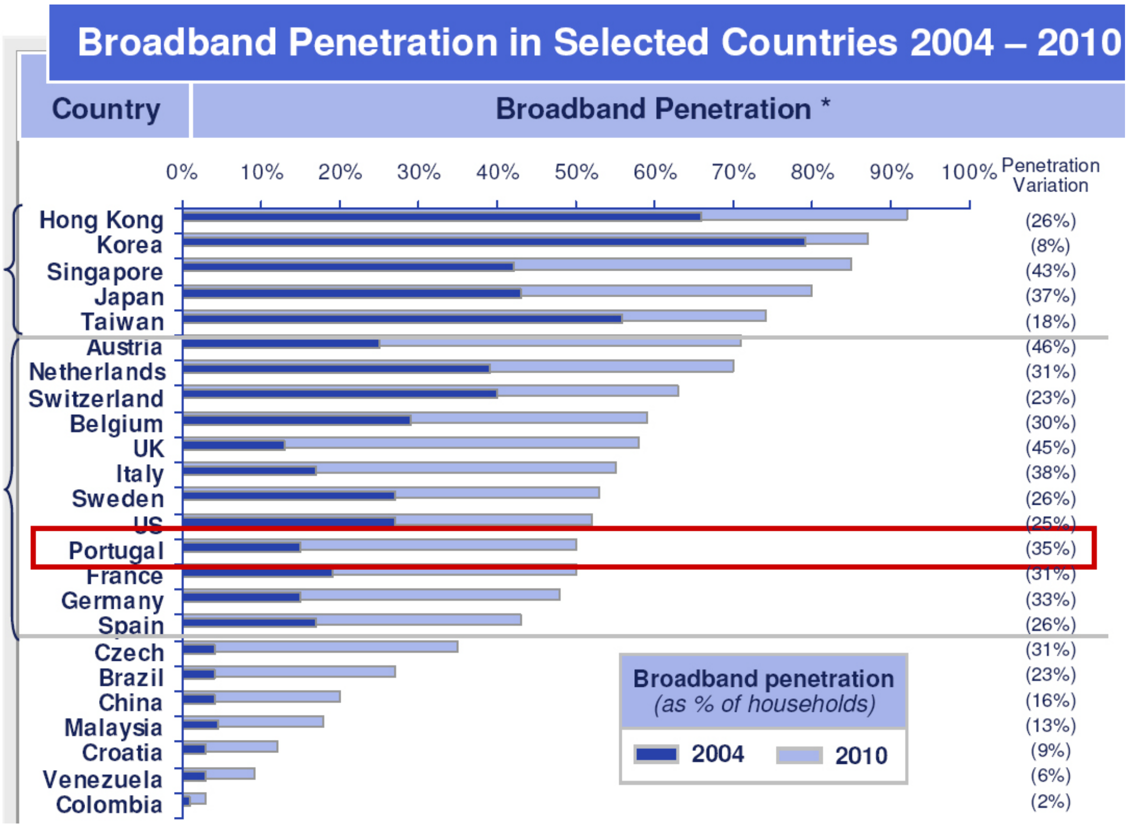

Figure 3.3 - Broadband penetration in selected countries from [17].

The choice of the wireless router came down in the use of the Wi-Fi router with the trade name La Fonera+ [18] as a base system for the project. This wireless router is based on the microprocessor without interlocked pipeline stages (MIPS) 4KEc Atheros AR2315 system-on-chip (SOC) running at 183 MHz and has 8MB of flash memory and 16MB of RAM memory and has the following characteristics:

- Antenna Connector: RP-SMA connector (reverse SMA);
- Antenna: External detachable antenna (1,5dBi);
- Network Standard Support: IEEE 802.11b / 802.11g (up to 54 Mbps);
- Ports: 2 Ethernet ports, by default one is used to connect to the WAN (10/100Mbps) for Internet access and the other port (10/100Mbps) is used for computer connections or other devices (network printer, storage, etc.);
- SSIDs: 2 available;
- Serial Port: 1 available.

This router meets the basic requirements of the functional specification previously described and has a “low cost” 29.95€ (at the time of the acquisition). Memory resource is low as predicted; therefore a persistent memory expansion will have to be added to achieve a life span of the system of 20 to 30 years.

3.3. Choice of technologies

For developing the project several tools were identified as necessary. The different technologies used during the project and the router hardware will be presented next.

3.3.1. Hardware

During the development of the system there were applied methods of reverse engineering. A quick overlook of the wireless router is going to be done to get acquaintance with the connectivity offered at factory state and search for potential new connections. The external aspect of “La Fonera+” can be seen in figure 3.4 a) and b) along with a detailed view of the available external features c) and d).

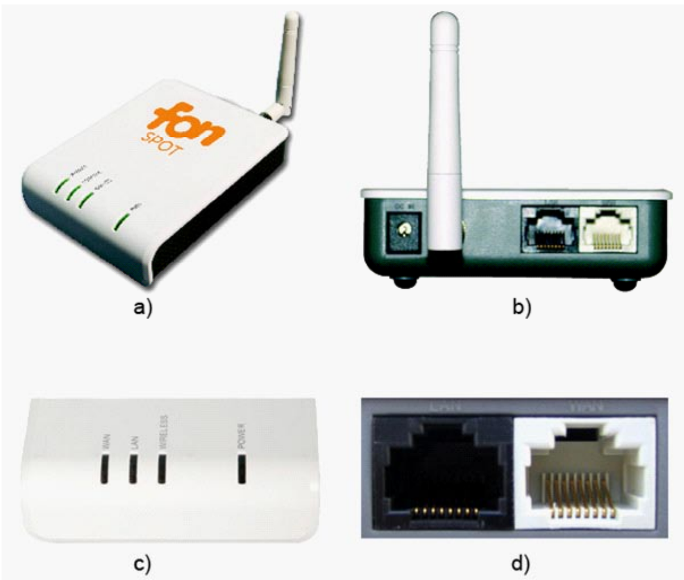

Figure 3.4 – Wireless router “La Fonera+”. a) General view. b) Back view. c) Information LED’s detailed view. d) Ethernet connections detailed view.

The external view shows two Ethernet ports, one for connecting to a LAN and the other for connecting to a WAN, and one power connector available at the back of the router. In the front of the device four LED can be seen for indication of power-on, wireless, LAN and WAN.

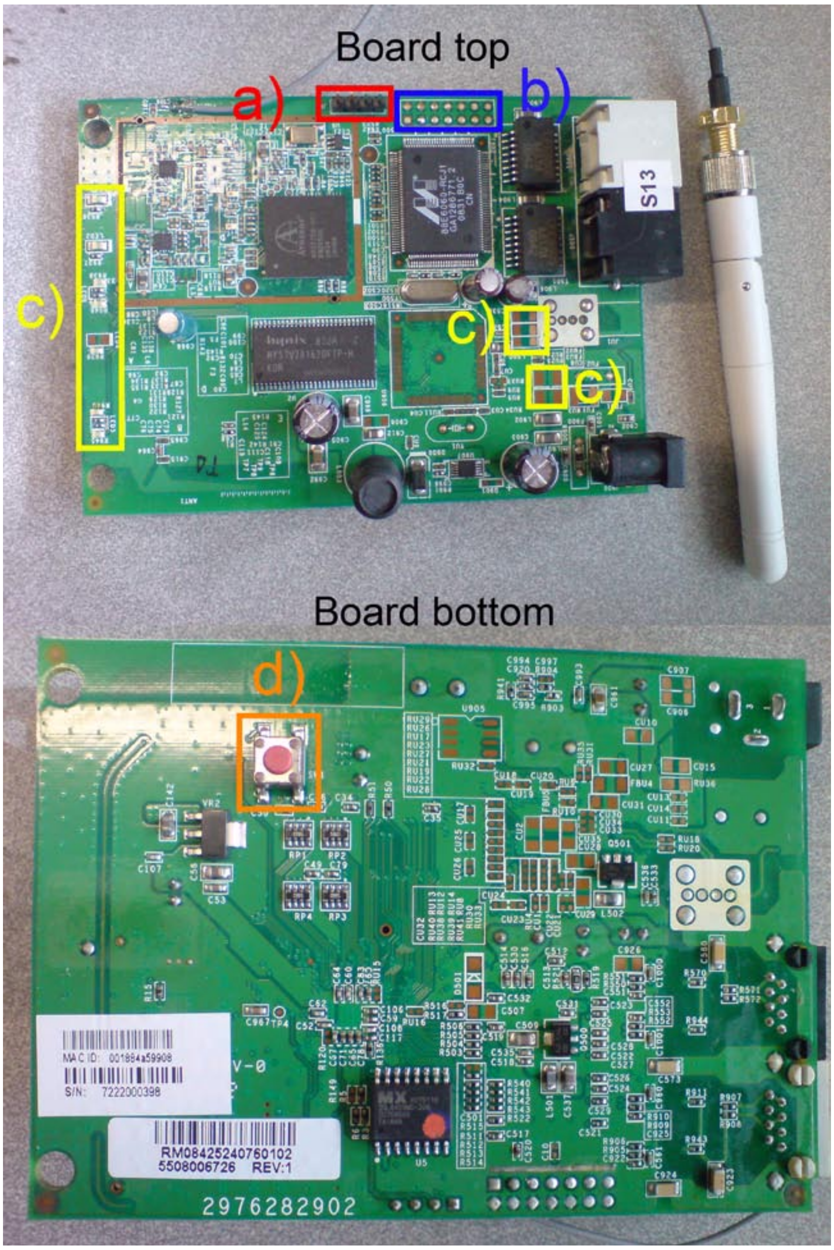

Figure 3.5 - Top and bottom perspective of the circuit board of the La Fonera+.

Looking at the circuit board in figure 3.5, the board top has four pins marked as a) belonging to the serial port that was present in old board revisions in a different connection, from right to left the pins are: the ground, RX, TX and Vcc. A JTAG connector is also available and is marked as b) and some of the general purpose input/output (GPIO) pins that seem to be available for the memory expansion are marked as c). On the bottom of the board the reset button is marked as d).

3.3.2. Firmware

The default router firmware does allow changes to the system, which is understandable since it was developed for other purposes and comes with a lot of pre-installed software. Thus, it is essential to find a new solution to be used as base firmware and develop the necessary applications on top of it, when necessary.

The firmware that came with the router is a striped down version of the open source Linux distribution OpenWrt, described as a Linux distribution for embedded devices. Originally designed for the Linksys WRT54G series, it was expanded to other chipset and manufacturers offering advanced features usually unavailable in consumer-level routers. The main feature offered by this firmware is a fully writable JFFS2 file system with package management via the ipkg system. This allows installing and developing packages to suit the needs of applications as required. It provides a framework to build a full firmware image and a framework for developing applications without the need to build the full firmware.

Since there are other firmware alternatives, the major projects that support the router chosen are:

- DD-WRT – a free version is available for private use and a paid version for commercial purposes. It has a development framework to build the full firmware image but does not have a package management like OpenWrt. It is a firmware solution designed to replace the pre-installed firmware version of several commercial routers and since version 22 is based on OpenWrt [19];
- Freifunk – another Linux distribution based on OpenWrt; its key feature is support for wireless mesh networks with OLSR [20];
- Gargoyle – it is essentially a web interface for OpenWrt, with emphasis on usability [21];
- X-Wrt – another web interface for OpenWrt [22].

A common characteristic of these projects is the usage of OpenWrt as basis. Some of these distributions simply replace the web interface while others add additional functionalities. These extra functionalities, mainly aimed at router enhancements, due to GNU general public license (GPL) license of OpenWrt are open and available and can be installed in OpenWrt through ipkg package management. Since the system being built can be used as a router, even if this is not its main focus, usage of OpenWrt was chosen. OpenWrt facilitates the usage of the devices in ways never envisioned for it by extending the functionality of the router with its flexible development framework and writable file system. This is a key feature for speeding up the development process of new applications and allows for an update feature for the system.

3.3.3. Data format and storage

The system will read instant power values to monitor the power consumption, so it is convenient to have these values read at constant time intervals and be associated with a timestamp. This information has to be treated by the system and saved in a format so it can be retrieved, presented and uploaded to a central utility as required in the functional specification.

Several formats can be used for storing the power values read from the energy meter. Among them is the simple comma separated value (CSV) file format or even XML, as they are often used for data exchange between disparate applications. CSV file format saves the records in a simple text file where each record is a new line and values are separated with commas. On the other hand, XML allows the creation of a custom markup language to allow sharing structured data. There is also the possibility of storing the data in a database. A database is a structured collection of records or data. The structure is achieved by organizing the data according to a database model. Database files can be saved in many forms, ordered/unordered flat files, ISAM, heaps, hash buckets or B+ trees. Each form has its advantages and disadvantages, but all of them benefit from indexing to increase their speed. These are general purpose databases used for storing persistent data. Round robin database (RRD) is based on a technique that works with a fixed amount of data, and a pointer to the current element. It can be seen as a circle with pre-defined points around its perimeter; one of these points works as start and end. This way, the dataset never grows in size, requiring no maintenance. It is specifically designed to store some sort of time-series data; in other words, it is designed to save some measured values at several points in time. From all the possible solutions presented, the choice felt into RRD since it is specifically designed for saving any sort of time-series data. Also, RRD data format maintains a fixed size over time, stopping data files from growing quickly and overwhelming storage space: this is performed by averaging and compressing data on the fly based on the parameters set during database creation. Controlling the file size requires less maintenance and more control over storage space. The only requirement posed by this solution is the definition of all parameters at the creation of the RRD. This can be seen as a downside of this solution; even though later modification of the parameters is possible, data can be lost during the process.

The use of RRD brings other benefits supported by the “RRDtool” application. RRDtool refers to Round Robin Database tool. “RRDtool is the Open Source industry standard, high performance data logging and graphing system for time series data” [23]. This tool allows the creation of the RRD, store data, retrieve the data stored and create graphics in the portable network graphics (PNG) format. Other special features associated with the inner works of the RRDtool, encompass:

- Data acquisition to be saved/updated at any time;
- Offers data consolidation functions with Round Robin Archives;
- The graphic tools allow generation of reports in numerical and graphical form based on the data stored in one or several RRDs. The contents of the graph can be defined freely with data calculation and/or transformation;
- Support for unknown data, for situations when it is not possible to retrieve the energy value from the meter for some known/unknown reason. Useful for acknowledgment of system failures;
- Allows exporting the saved data and/or numerical reports in XML from one or several RRDs;
- Supports the Holt-Winters time series forecasting that adaptively predicts future observations in a time series.

3.3.4. Memory expansion

The router default system memory is too low for allowing saving and archiving data for a considerable period of time as expected by the system life span. Therefore, it was necessary to add a memory expansion to the wireless router. The memory expansion has to be persistent, reliable, durable and big enough in order to meet these purposes. These requirements eliminated all volatile storage devices, i.e., random access memory (RAM) since they require power to maintain the data they store. Two other storage devices were considered due to their non-volatile nature: hard drive disks (HDD) and memory cards. The memory card offers an easy and reliable way for storing data offering several advantages over HDD because it is based on flash memory technology, so it has a small form factor and is a non-volatile solid state storage. This makes them more durable and reliable than HDD. Also, integrating an HDD as a memory expansion directly into the system hardware would not be possible due to the lack of available GPIO pins for the bus and lack of drivers for the system, so it would require extra hardware for providing the disk controller and the connection to the system would be made through an Ethernet port, removing the possibility of using the Ethernet port for other purposes, i.e. connecting to a meter. So the memory card was the memory expansion chosen, remaining the choice of the format.

There are many competing, incompatible memory card formats, almost one for each manufacturer; table B.1 of the Annex provides a technical comparison between the different memory cards. From the entirely different memory cards presented in table B.1 the chosen format was MultiMedia card (MMC). MMC require the lowest number of pins necessary for connecting to the card, and the router hardware does not have that many GPIO available. Also, by providing interaction with a MMC card, will allow connection of a Secure Digital (SD) card. This is possible because SD card is an evolution of MMC, both have the same card shape, even though the SD is a little bit thicker, and the SD card provides an serial peripheral interface (SPI) mode for compatibility, reducing the number of pins needed from 9 to 7, the same number as MMC.

3.4. System architecture

The system architecture was designed considering interoperability and re-use of the current energy meters present in households. It consists in a re-engineered wireless router acting as a central unit connected to the energy meter using a cable with a serial optical interface or directly using RS-232 in order to enable smart meter functions with current meters. It also serves as an interface with the personal computer or other browser enabled devices for data visualization, monitoring and configuration of the system, as well as a platform for an AMI. The central unit has two possibilities to connect to the HAN: Wi-Fi connection or one of the two available Ethernet connections, if the latter are not used for other purposes. The wireless router allows setting up two independent Wi-Fi networks; this feature allows exploring the possibility of creating an ad-hoc mesh network that consists of several central units acting as nodes and one/more of these nodes acting as a concentrator and/or gateway. This offers the possibility of efficiently sending/receiving data to the utility via broadband Internet connection or a drive-by car from the utility. This last possibility is discussed as backup communication means for data transfer to/from the energy meter. For a better understanding of the system the operating conditions can be seen in figure 3.6.

The connection between the central unit and the energy meter is vital for system interoperability: with several different manufactures, each one with many different versions of energy meters, offering different connections and proprietary protocols. Even when a connection is available these differences between different offers raise a serious obstacle for interoperability with current and future meters. Old mechanical meters do not provide any information available other than the visual mechanical display, which leaves only two options: use a camera to capture the visual information from the display completed with an Optical Character Recognition (OCR) algorithm to read the values or use a current sensor that along with the voltage value allow calculation of the power dissipated. Connecting with electromechanical meters using a current sensor to calculate energy consumption is the same as developing a new energy meter rather than providing a platform to upgrade current meters as intended in this thesis. Also, using this last solution, power consumption is based on an estimate, so it is necessary to guarantee an accurate estimate of the power consumption, otherwise this does not offer a suitable system alternative for replacing the methods used today for consumption reading. The option left is the use of a camera to capture readings from the displays present in the meters to provide a more wide interoperability to provide information to the costumer. Newer energy meters have a serial optical port and/or RS-232 port available to allow reading instant values or saved data and configuration of the meter. The central unit has to support an RS-232 port available for allowing connectivity with new meters through this connection in order to use the new capabilities present. The downside is the need to implement the different protocols, even though today most are migrating to the IEC/FLAG protocol and only the serial optical port is available which using a simple converter to RS-232 would solve these obstacles.

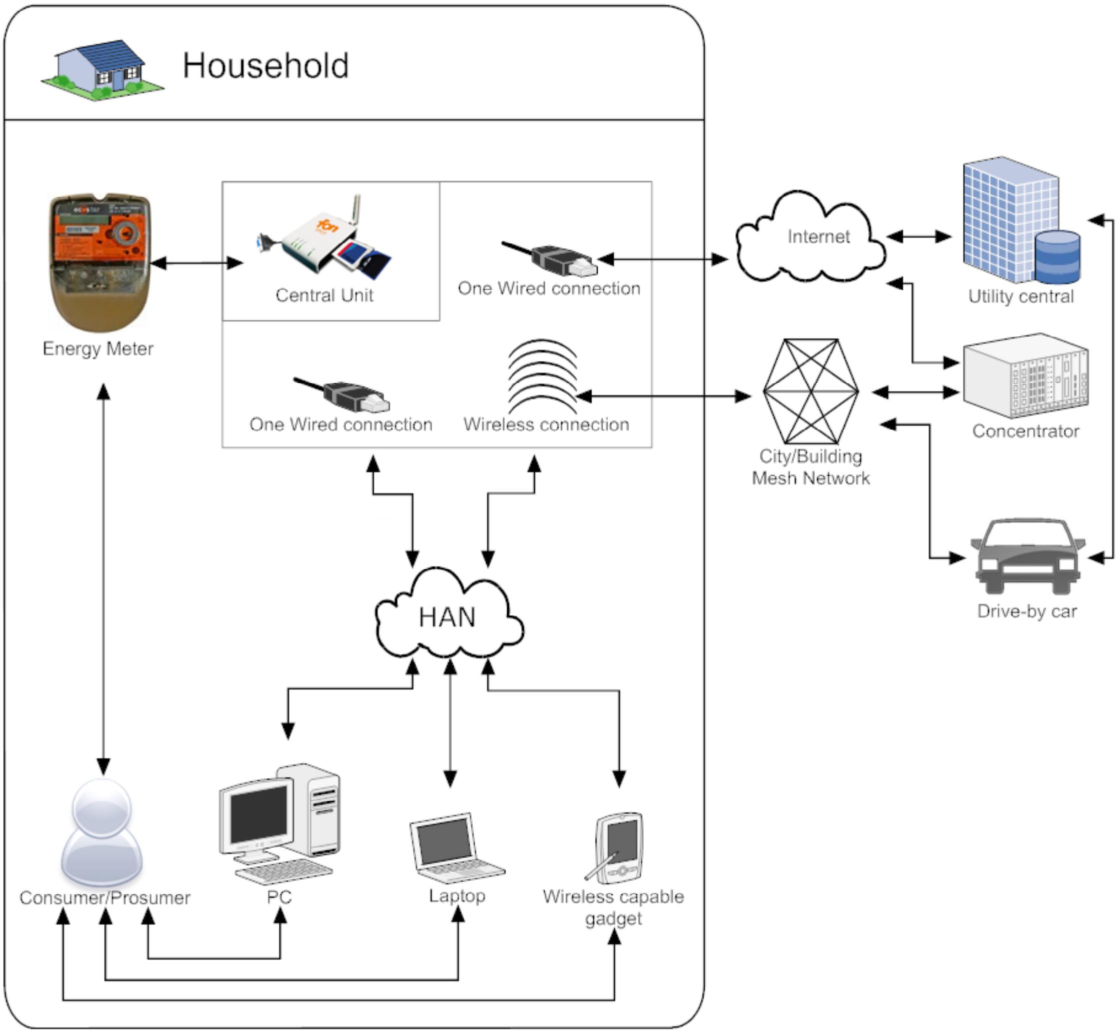

Figure 3.6 – System operating environment.

Data visualization and system configuration are done through a web interface; the user has to connect to the created HAN through the central unit using the Wi-Fi or Ethernet port, as it would in a normal wireless router, and access the web server located on the IP of the central unit to gain access to the services and configurations available by the system web page. Configuration and visualization of data through a web page provides a common way of access resulting in a plug-and-play feature to the central unity, due to consumer's acquaintance with web browsing and networking interaction. The Web page display of the data gives flexibility for creating an easy to understand display of cost, indicator of level of use (low/medium/high) and comparison of historic consumption patterns.

Two-way communications between the central unit and the Utility Central premises represented in Figure 3.6 is ensured by an available broadband Internet connection at the household and/or a wireless mesh network. The mesh network can consist of central units working as nodes, routers and gateways. It should be highlighted that using some central units as gateways should be accomplished with some compensation means for the users that provide the Internet broadband connection, but this issue is more related with the business model. It is also possible to create a building mesh network with a single concentrator for the whole building. The mesh network offers redundancy to the two-way connection when used with utility/building concentrators also providing a backup solution to the available broadband connection of households or in cases where the broadband is not available, reducing the dependability on their availability. As a last resource for remote areas where no broadband is available, a vehicle from the utilities can go to the location, connect to the mesh network created by the central units, and download the saved data and later upload the data to utility.

Figure 3.7 presents the system architecture of the central unit showing the main components of hardware and software necessary for achieving the proposed objectives.

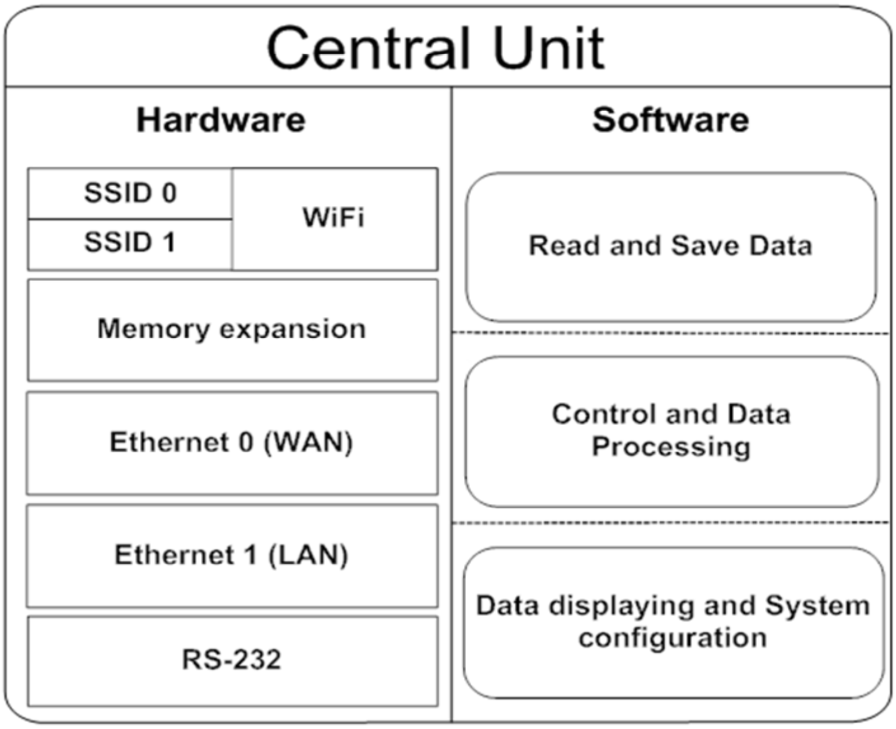

Figure 3.7 – Central unit system architecture.

The system will have a central software control responsible for initialization, preparation and data processing. This module will run in parallel with data display system available through the web server of OpenWrt along with data reading and saving processes. The communication between hardware and software will be made through the operating system so that all processes can have full access to the hardware resources.

Chapter 4

System development

This section describes the developments that were made in order to transform the FON router into a device that is able to retrieve data and, process, store and disseminate it to users through a Web Server that can be accessed using a wired or wireless connection.

The system developed is based on the architecture presented in chapter 3. Considering high-level development requirements, all the operations described in this chapter were made using a PC running Ubuntu Linux distribution 8.10 although Microsoft Windows ^{tm} could also be used. Adopting an open source operating system facilitates the access to a wide range of open source development tools that can be seamless integrated into the operating system, reducing the need for 3rd party software.

4.1. Firmware

For a full port mapping it is necessary to access the router's firmware, which can be made by enabling SSH on the original firmware. However, the original firmware has a stripped down version of some tools as well as pre-installed software to support the Fon network. As previously stated, in order to achieve all the desired functionalities and completely control the device operations and functioning principles, a fresh OpenWrt firmware was installed instead of trying to rework the original one.

Flashing the Fon is possible due to the boot loader RedBoot that comes with the wireless router. RedBoot is an acronym for "Red Hat Embedded Debug and Bootstrap", and is the standard embedded system debug/bootstrap environment from Red Hat. It provides an interactive command line interface for managing firmware images, enabling RedBoot configuration, image's download, etc. RedBoot is accessible from the serial port shown in figure 3.5 marked as a), or by the Ethernet WAN port shown in figure 3.5 d).

The original Fon firmware was substituted by a default OpenWrt image using the Fon Flash utility. This utility is especially designed for re-flashing FON routers; it basically automates the manual procedure. In order to use this tool, RedBoot has to be configured to accept Telnet connections, as in La Fonera+. It is also required to have the firmware file(s) stored in the PC. For OpenWrt firmware installation two files are necessary (both available at [19]):

openwrt-atheros-vmlinux.lzma – contains the OpenWrt image available at their website. This image contains pre-installed programs for basic functionalities, such as a wireless router for atheros chipset. It is also possible to build a full custom image for the system,

- however the router functionalities provided in the default image will be an integrating part of the system, allowing two-way communications.

- openwrt-atheros-2.6-root.jffs2-64k – creates the file system used by OpenWrt. JFFS2 is a log-structured file system specifically oriented for flash devices in embedded systems. It addresses the restrictions imposed by flash technology and operates directly on the flash chips, thereby avoiding the inefficiency of having two journaling file systems on top of each other.

In order for the Fon Flash application to be able to re-flash the router, the router needs to be connected to the PC through the Ethernet WAN port and be executed with the router in power off mode. After these initial steps, it is only required to supply the required information by Fon Flash graphical user interface (GUI) shown in figure 4.1 and click in the “Flash Router Now!” button. The program is prepared to connect to the router and perform the re-flashing, only requiring the user to turn on the router and wait for the report announcing that the flashing is over. After a successful re-flashing the chosen firmware is up and running.

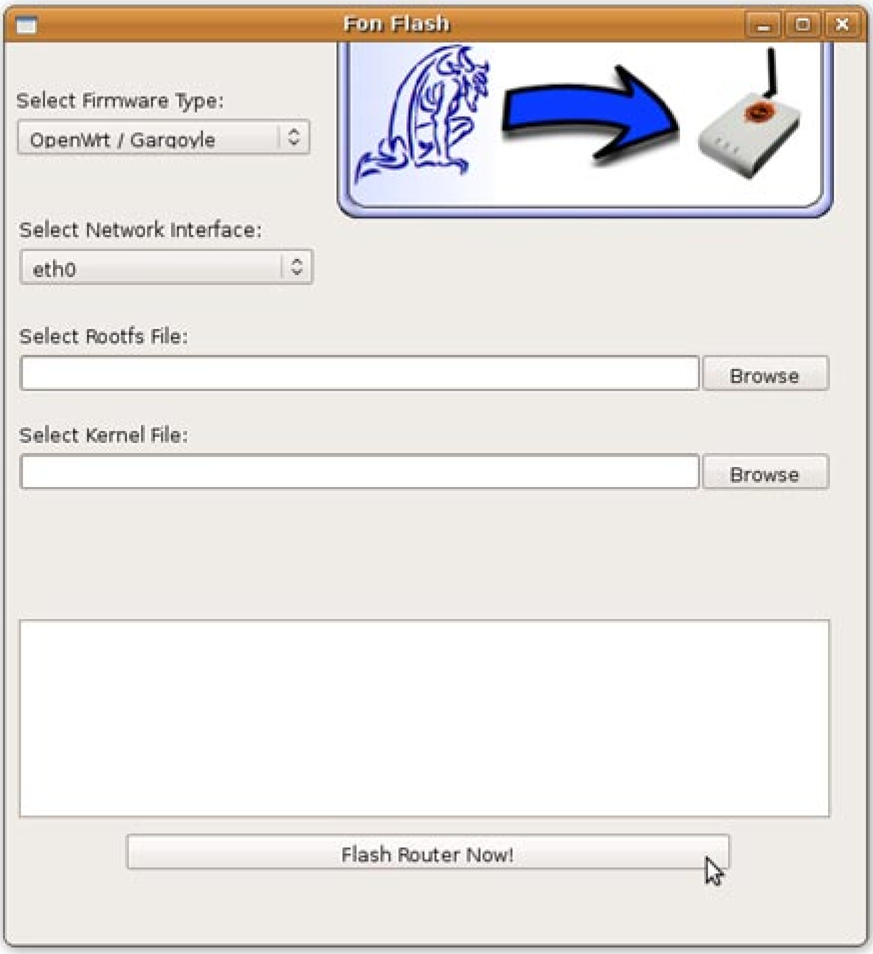

Figure 4.1 – Fon Flash graphical user interface.

The Fon Flash GUI is very simple; it requires a total of four inputs from the user in order to flash the router. The inputs are: 1) selection of the firmware type (note: only OpenWrt firmware is supported), 2) selection of the PC network interface connected to the LAN Ethernet port of the router, 3) and 4) selection of the firmware files described before. The selection of the firmware files will change according to each firmware type supported by the program; this is due to the fact that each firmware has a different number of files and formats.

Since the manual procedure of re-flashing is similar to the method used by Fon Flash, a description of this procedure will help to better understanding the re-flashing process. The manual procedure requires setting a server so that RedBoot is able to download the files and install them afterwards. Several server protocols can be used: HTTP, Xmodem, Ymodem and TFTP (Trivial File Transfer Protocol), but for example purposes TFTP is used to transfer the two files described earlier.

Using the manual procedure, the boot sequence needs to be aborted in order to access the RedBoot's command line interface. This can be achieved by establishing a Telnet connection to the router's default IP address (i.e., 192.168.1.1) and sending the interrupt signal "CTRL+C". This has to be done within the first 2 seconds after RedBoot started since after this period the normal boot is resumed. After successfully accessing the command line, the flashing process can start. The necessary commands to be executed are:

- fis init – initializes the Flash Image System (FIS) that formats the system image and root file system;
- load -r -b %{FREEMEMLO} openwrt-atheros-vmlinux.lzma – the execution of this command will download the firmware image from TFTP server into ramdisk;
- fis create -e 0x80041000 -r 0x80041000 vmlinux.bin.l7 – creates the flash image of the firmware image downloaded before. The values after –e and –r switches are the Kernel entry points and should not be changed;
- fis free – executing this command will print the first and last memory free blocks by subtracting the highest with the lowest remaining space available for the file system. Attention is required to the math because this values are in base 16;
- load -r -b %{FREEMEMLO} openwrt-atheros-2.6-root.jffs2-64k – same command as before, but this time the user controls the download of the file system;
- fis create -l 0xSPACE rootfs – flashes the root file system. The SPACE variable should be replaced with previously calculated space available for the file system.

All there is left to execute is the reset command and after the reboot the new firmware shall be up and running.

The installed OpenWrt image allows access either via Telnet or SSH to the 192.168.1.1 IP address. Telnet is by design very unsecure since connections are not encrypted and access control via username/password is not required to access the system. On the other hand, SSH requests username and password. However, by default, the user is "root" and no password is set which means that any password is accepted. After establishing the connection, interaction with OpenWrt is made through BusyBox, a small command line program with many of the common UNIX utilities present in x86 Linux distributions shells. For securing access, a "root" password can be set by running the "passwd" command and typing the new password when requested. The Telnet server shall be disabled for security reasons; this is done by removing the corresponding start-up using the command: rm /etc/init.d/S41Telnet.

4.2. RS-232

Connecting the PC to the system through the serial port requires a level shifter since the router logical levels "0" and "1" correspond to 0 and 3.3V respectively while the RS-232 standard defines the voltage levels for the logical "1" and "0" as ±5V, ±10V, ±12V or other values up to 25 V of open-circuit voltage – depending on the power supply. Thus, connecting the RS-232 from the PC directly to the router could damage the circuit of the router.

The level shifter used was the MAX3323EEPE from MAXIM [24], this is an RS-232 transceiver that allows multidrop applications with low power requirements, high data-rate capabilities and enhanced electrostatic discharge (ESD) protection. It provides control of the logical levels through the VL pin working from 1.65V to 5.5V to allow compatibility with a wide range of system's I/O voltages. Furthermore, it offers ±15kV ESD protection in all pins for industrial data acquisition applications and enables true RS-232 performance from a 3.0V to

5.5V supply [24]. All these characteristics make this level shifter suitable for supporting the RS-232 connection to the router.

The circuit developed for the level shifter is shown in figure 4.2. This is the typical operating circuit of the MAX3323EEPE with a 3.3V supply voltage [24]. The MAX3323EEPE allows different configurations but the lack of available control pins in the router does not allow the exploration of those configurations (specifically the power down feature for lower energy consumption from the system being developed).

In order to test the correct functioning of the circuit, a basic loopback test was done before connecting it to the router: by connecting the TX to the RX in the TTL side, the PC signal is echoed back rather than being sent to the receiver.

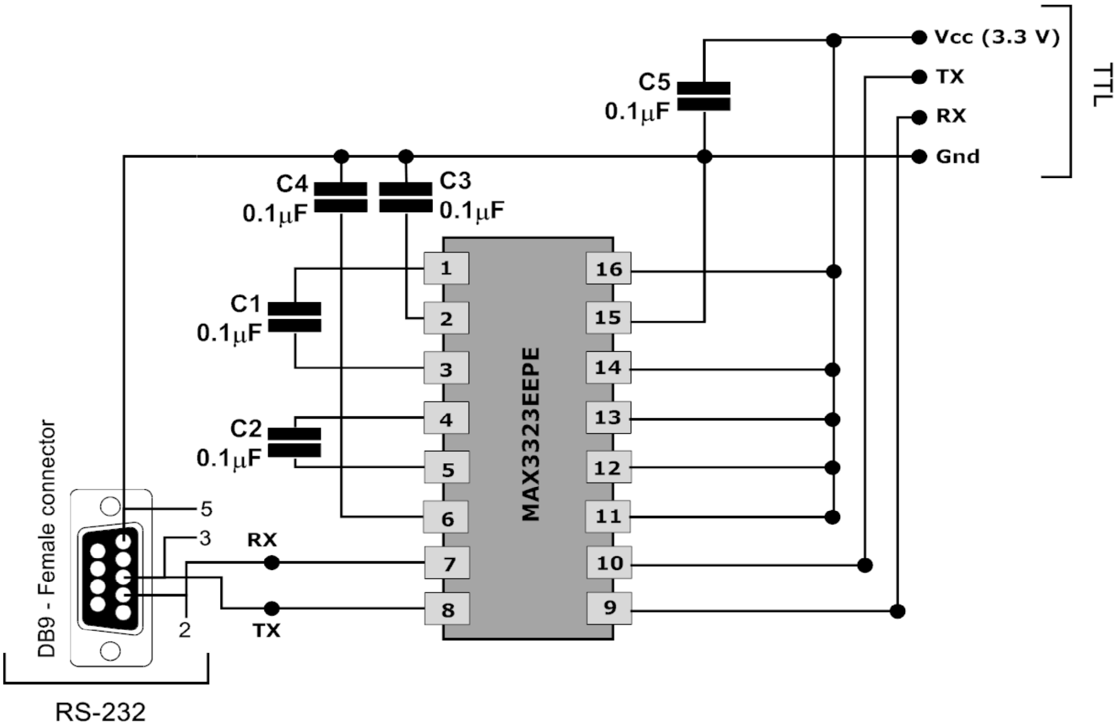

Figure 4.2 – TTL to RS-232 circuit.

Pins 16 and 15 are the power supply and ground of the integrated circuit, Pin 13 is the voltage reference for the logical values outputs on the TTL side, so the Vcc of the router is used as reference for the voltage level. Pins 11, 12 and 14 are connected to Vcc to enable the transmitter, receiver and normal circuit operation. If pins 11 and 12 are driven low the transmitter and receiver are put into high impedance. Driving pin 14 low will put the device in shutdown mode. For providing the output voltage levels of RS-232, the MAX3323EEPE uses a dual charge pump, where each pump needs a flying capacitor (C1, C2) and a reservoir capacitor (C3, C4). The values used in the capacitors C1 to C4 depend on the Vcc supply value and were chosen according to the table containing the minimum values required for the capacitors for the reference voltage level used [24]. Capacitor C5 functions as a bypass used for decoupling the power supply and its value is equal to C1 guaranteeing that the power-supply noise does not affect the system proper functioning. The pin description and tables used for implementing this circuit can be found in the datasheet of the MAX3323EEPE [24].

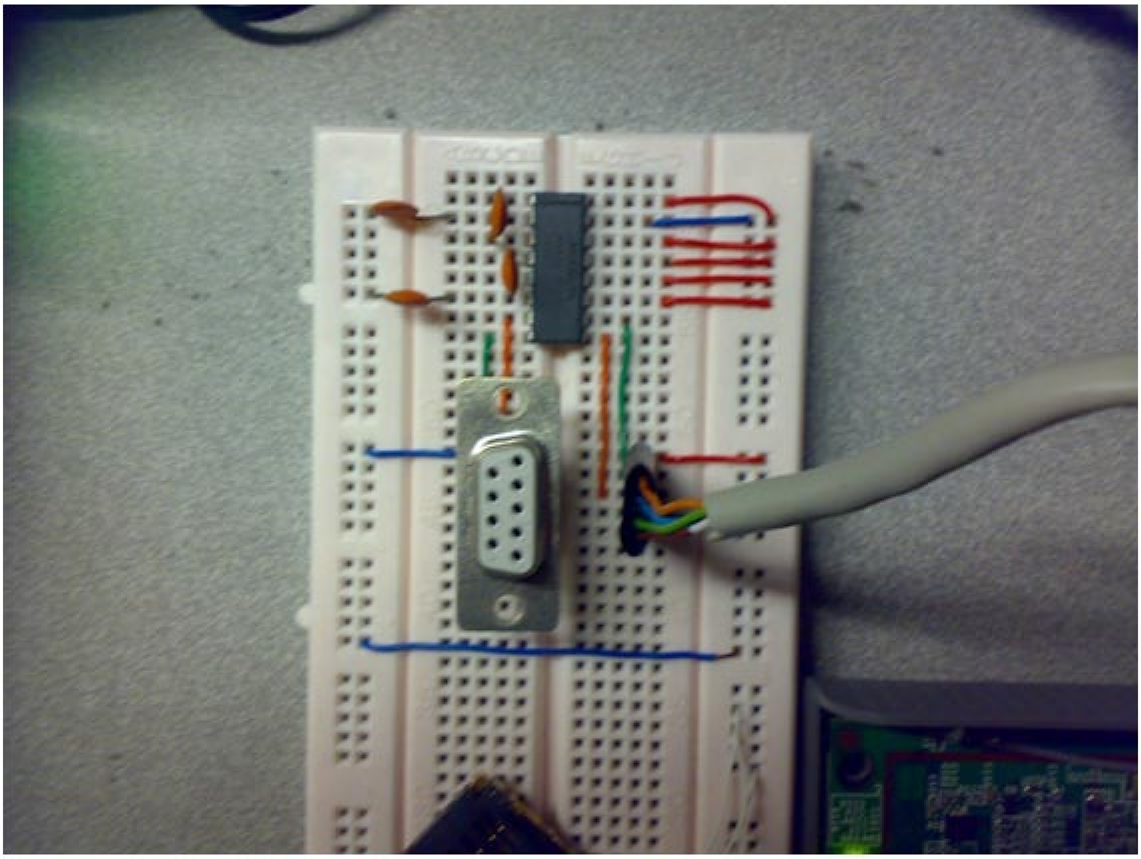

Figure 4.3 – Final RS-232 assembled circuit.

The RS-232 assembled circuit can be seen in figure 4.3.

4.3. Memory expansion

Achieving the desired life span of the proposed system requires the estimation of the storage space for the data that needs to be stored during the corresponding period, since the internal router memory space is only enough to guarantee its proper function. If a memory expansion is not included in the central unit (i.e., the router), it will limit the time the data archive can be saved before rewriting over old data. Before connecting the SD card, used for memory extension as described in section 3.3.4, it is necessary to find available GPIO ports in the router hardware that can be controllable through the firmware. This is necessary because internally the GPIO ports have their own registers and addresses that are used by the microprocessor to read or write to the GPIO ports. Moreover, these addresses have to be mapped in a header file so that the firmware, or program running in it, can instruct the microprocessor to access them.

The discovery of GPIO ports was done with the help of the gpioctl program, that allows reading and writing GPIO pins one by one, and an oscilloscope: a high state to a GPIO is forced using the gpioctl and the corresponding output is measured with the oscilloscope at free points across the board to note voltage levels; force the same GPIO to a low state and note any voltage changes at the same points previously measured. This method was applied repeatedly for finding available GPIOs. As expected, this method revealed to be very inefficient since the gpioctl utility only allowed checking 32 GPIOs, after which, even if a higher value number is used, it will redirect to one of the first 32 numbers (i.e., for instance, using GPIO 34 will correspond in fact to GPIO 2). Another problem is the hardware complexity, finding the board point controlled by a specific GPIO number is hard and actually a slow process. The mapping of the GPIO found is summarized in Table 4.1.

Table 4.0.1 – Available GPIO and respective hardware match

GPIO number	Description	Figure 4.5 match
1	Orange LED	a)
2	Green LED	b)
3	Marked resistor R940	c)
4	Green LED	d)
5	Reset	No match
7	Orange LED	f)

Table 4.1 shows the six GPIO pins found. These pins are enough for connecting the SD card through the SPI. It should be highlighted that the GPIO 5, when put in a high state, actually resets the system, which discourages its use for the desired purpose. Thus, only one of the GPIO pins is not used for any purpose (i.e., GPIO 5), while the remaining were used to integrate the SD card. The control over the router LEDs was lost, but they were not relevant for the desired system.

Using the SD card through SPI requires seven pin connections of the nine present; the other two pins left are in high impedance. SD card pins are shown in figure 4.4.

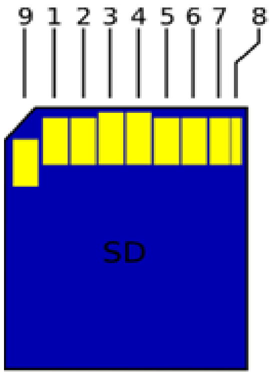

Figure 4.4 – SD card pin layout (bottom view).

A description of the SD card pins used and the corresponding mapping to GPIO connections are shown in Table 4.2.

Table 4.2 - SD card pinout description in SPI mode and corresponding GPIO connection.

SD card pin number	Description	GPIO
1	CS – Chip select	7
2	DI – Data in	4
3	Vss1 – Ground	Ground
4	Vdd – Power supply	Vcc (3.3V)
5	CLK – Clock	3
6	Vss2 – Ground	Ground
7	DO – Data out	1

After removing the LEDs, corresponding to GPIO pin numbers 1, 4 and 7, one SD card adapter was soldered to the router circuit board according to Table 4.2. The final result can be seen in figure 4.5.

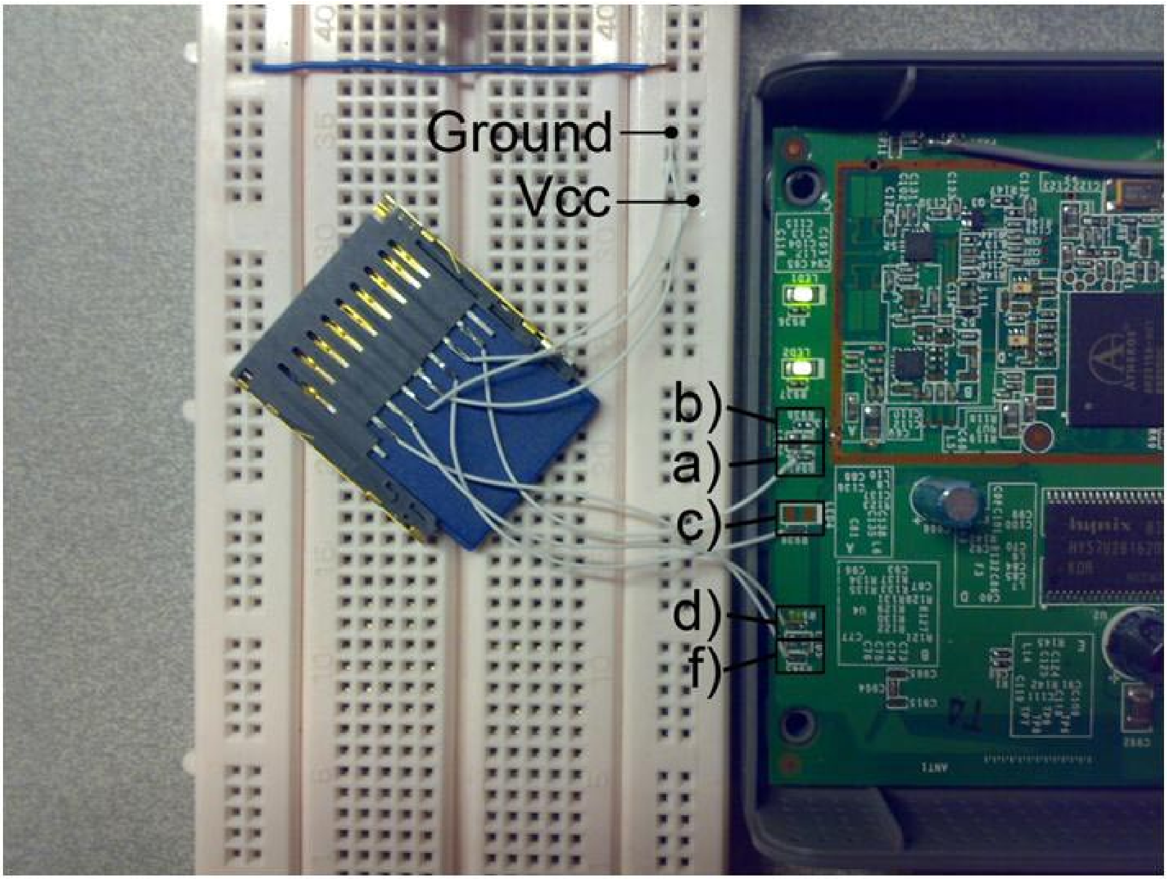

Figure 4.5 - The final SD card circuit soldered to the circuit board. Corresponce between the marked letters and respective hadware description is as follows: a) Orange LED, b) Green LED, c) Marked resistor R940, d) Green LED and f) Orange LED.

Figure 4.5 shows the final SD card circuit properly assembled, after which the following packages were installed on OpenWrt using ipkg system:

- Kmod-spi-bitbanging;
- Kmod-spi-gpio;
- Kmod_crc7:
- Kmod_crc_itu_t;
- Kmod-mmc;
- Kmod-mmc-spi;
- Kmod-mmc-over-gpio;
- Luci-app-mmc-over-gpio;
- Kmod-fs-ext3;
- Libncurses;
- Libblkid;
- Libuuid;
- E2fsprogs.

These packages are the drivers required to get the card working with OpenWrt. After installation it was necessary to configure the drivers to use the correct GPIOs, which was accomplished using the Universal Control Interface (UCI) of OpenWrt with the following commands:

1. uci set mmc_over_gpio.@mmc_over_gpio[0].enabled=1;
2. uci set mmc_over_gpio.@mmc_over_gpio[0].DI_pin=4;
3. uci set mmc_over_gpio.@mmc_over_gpio[0].DO_pin=1;
4. uci set mmc_over_gpio.@mmc_over_gpio[0].CLK_pin=3;
5. uci set mmc_over_gpio.@mmc_over_gpio[0].CS_pin=7.
6. uci commit mmc_over_gpio;
7. /etc/init.d/mmc_over_gpio start;
8. /etc/init.d/mmc_over_gpio enable;

The first command is used to enable the usage of the device, the following four commands define the connections between the system GPIOs and the memory card pins and the sixth command registers the configuration of the driver. Finally, the last two commands enable the start-up script for the driver: using this feature the driver will auto-start during the router booting making the memory available for usage.

As any UNIX system, OpenWrt requires the mounting of any storage devices to know that they are ready to be used. Mounting of the memory card was achieved via fstab with the following commands:

- uci set fstab.@mount[0].enabled=1 – This command enabled the memory card;
- uci set fstab.@mount[0].fstype=ext3 – This defined the file system used in the memory card to ext3;
- uci set fstab.@mount[0].device=/dev/mmcblk0p1 – This defined where the device memory card is available;
- uci set fstab.@mount[0].target=/mnt/mmc – This defined the mounting point of the file system of the memory card;
- uci set fstab.@mount[0].options=rw,sync,noatime – This defined the mounting options for read and write, with input and output done asynchronously and no time information update of files accessed.
- uci commit fstab – This is done for registering the changes made to fstab;
- /etc/init.d/fstab restart – This loads the changes made to fstab.

To get the memory card partition to be mounted automatically at boot, it was necessary to edit the fstab start-up script and change the “START” variable from “20” to “98” and execute: /etc/init.d/fstab enable.

The only requirement is the SD card to be formatted in ext3 file system before connecting, so that the system can recognise the card file system.

4.4. Software

The wireless router has MIPS architecture running only MIPS binaries. Since the development machine was based on an x86 architecture, it produced x86 binaries that are incompatible with the router hardware. To overcome this issue, a cross compilation method was used. OpenWrt offers a complete solution for cross compiling for its supported architectures. The system software was developed using the development environment provided by OpenWrt.

Reading energy consumption without a timestamp associated with the data is useless since it will not provide the consumer or the utility information regarding the moment or interval when that consumption took place. Associating the timestamp to the energy readout was achieved using the OpenWrt system clock. In fact, this clock was used to guarantee the system synchronization process. This decision makes the system software dependent on OpenWrt system clock, its set up value and accuracy but guarantees that a timestamp is available and does not depend on the energy meter.

As stated in section 3.3.3, it was decided to use an RRD database along with the RRDtool for saving the readings made by the central unit and enable the interaction between the software developed and the RRD databases, respectively. It should be highlighted that the RRDtool provides a C library for integrating its functions in any C program; however, since this library is still under development only some functions are provided and no guarantees are given regarding its correct functioning in a multi-threaded program. Therefore, interaction with the RRDtool was made through a system call instead of using the library provided. However, interaction with the RRDtool through system calls has its drawbacks, namely blocking the program until returning from the call. Overcoming this problem implied developing a synchronization mechanism to correctly use the RRDtool functions while providing constant energy consumptions, required by the RRD database.

The central control software flowchart is shown in Figure 4.6. The figure refers only to the control and reading procedures since data visualization was done apart from this software and using the web server offered by OpenWrt. Further details are provided in section 4.5.

From figure 4.6 it is possible to see that the software starts with an initialization procedure, during which the environment variables are set and the configuration values are loaded from a configuration file. The configuration file was created to allow adjusting the values used for the RRD database as well as the time interval between readings without being necessary to recompile the binaries. The configuration file is a simple text file located within the Linux system configuration folder at "/etc/config" with the program name "pomar". After initialization, the program checks if a database already exists for the actual month. If not, it will create a new one based on the configuration file and enters in a waiting state until reaching the time to read the energy consumption. The next time to make a reading is synchronized with the system clock and is based on the number of readings that can occur until the end of the month, according to the interval defined in the configuration file. These constraints enforce a constant data rate of values to be saved, as expected when the database was created. After the waiting state, the program launches a thread function with an infinite loop for reading and saving data. Afterwards, it enters an infinite loop to control the creation of new databases and process data for user visualization.

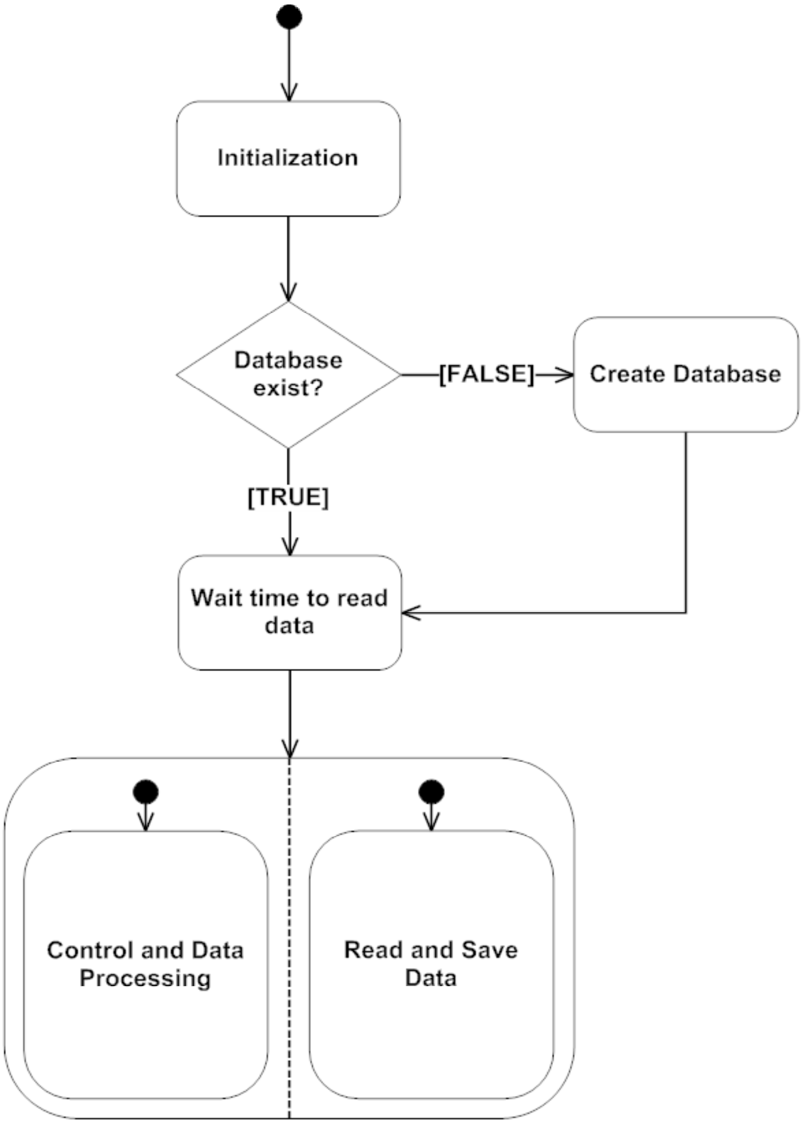

Figure 4.6 - Flowchart of the control software.

The system follows the principles adopted by utilities, which require energy consumption payment every month, by creating a new database each month. This way, the central unit can be used for providing smart metering readings simply by consulting the corresponding database. The RRD database requires that the data source(s), data archive(s), interval between readings of the sources, start and end time of the database are set in order for the database to be created. For this project, the above parameters were set having in mind meters that allow instant power consumption readings. The only data source used was the energy meter; as such, only two archives are used for saving the highest and lowest consumption values of each hour, the default interval between reads is 10 seconds, while the start and end times are defined at the beginning and end Unix time of each month, respectively. The control and data processing algorithm shown in Figure 4.6 manages this process. A detailed flowchart of this process can be seen in Figure 4.7.

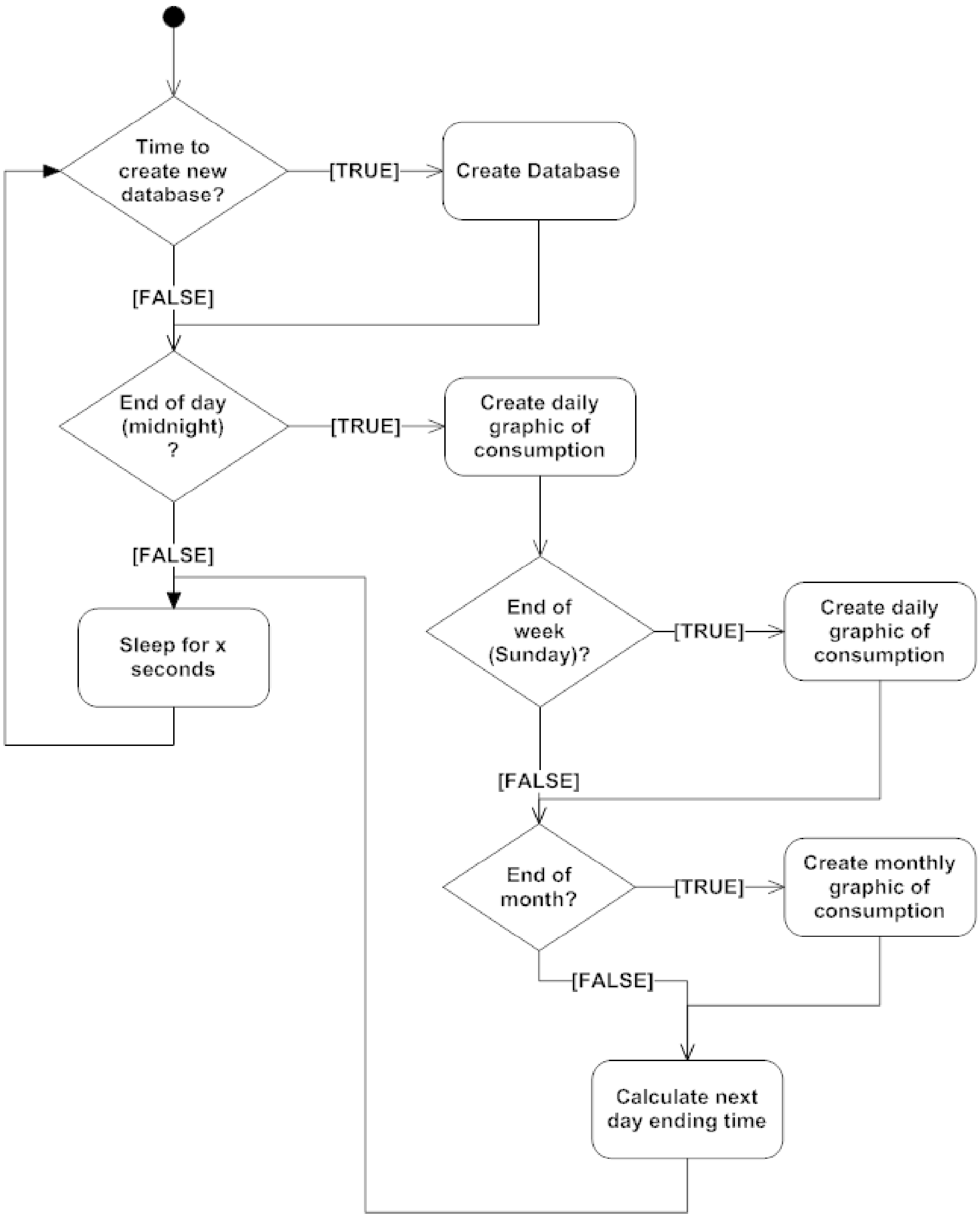

Figure 4.7 - Control and data process flowchart.

The main objective of the control and data process is to create the following month database before hand as well as “pre-defined” graphics for user visualization. Creation of these graphics reduces user input for data visualization providing a more plug-and-play system coping also with the system processing capabilities limitations. Creating the database takes some time; that is why its creation occurs a little before entering the next month enabling the system to achieve constant data rates.

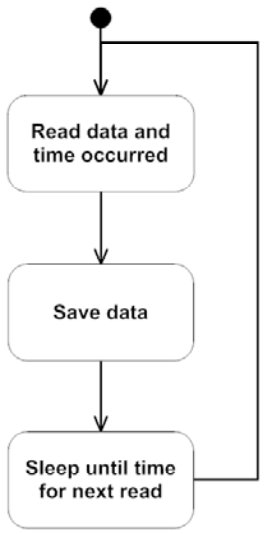

Figure 4.8 – Read and save data process flowchart.

The read and save data process presented in figure 4.8 is simple; it reads data from the meter and registers the time this reading occurred. These values are stored in the RRD database and the log file is updated. Since executing these steps takes some time, after them another reading of the actual system clock is performed to compensate the time for the next reading; otherwise the system would sleep for the time interval defined in the configuration file and desynchronized readings would occur. This process runs in parallel with the control and data processing due to the system calls to RRDtool for saving data; if they were running sequentially the system would freeze while creating the new database and no readings would be made.

4.5. Data visualization and system configuration

The data stored is a sequence of energy consumption values measured at successively equal time intervals. For a better exploration of this data, a graphical representation of the data series was used.

OpenWrt provides a web server running on the central unit IP address for allowing configuration of the wireless router networking settings and OpenWrt configuration. The web interface is provided by LuCi [25], a MVC-Webframework (Model View Controller - Webframework) that evolved to a collection of several libraries, applications and general purpose user interfaces for Lua [26] programmers with a web interface. The energy consumption visualization was developed to integrate the original web user interface of OpenWrt, taking advantage of the service already running and collaborating with one of the project goals: providing a web interface accessible through a common browser, such as the Internet Explorer or Mozilla Firefox.

LuCi web interface, besides allowing network configurations, also offers a wide range of advanced control and configuration options for the system such as installing/removing applications, killing processes, flash the router firmware, configuring services among others. However, for security reasons, these possibilities are not desirable in the developed system. Therefore, they should be closed/disabled so that no changes to the data stored can take place. In fact these features were removed and only the configuration pages associated with the device network configuration were left in the web interface.

OpenWrt was also designed to be a single user system; that is why only the “root” user exists in the system and both the web interface and Secure Shell Host (SSH) access control compare with the root username and password. However, having a system with a single user with root privileges is a security threat to the central unit. The central unit is designed to be a platform to support smart metering and allowing access to system also allows the manipulation of the data stored. To remove this threat a second user was added to the system without SSH access privileges, defined with default username: admin and password: admin. Applying these changes, the SSH service can remain active for configuration or maintenance by authorized parties while restricted access to the energy consumption visualization and system configurations are guaranteed.

The software described in section 4.4, generates daily, weekly and monthly graphics that were made accessible through the web interface using LuCi. LuCi's capacities supported the creation of the module developed for showing the pre-created graphics, customized graphics based on user input instead of the pre-created ones, and a live graphic feature for allowing real-time visualization of instant energy consumptions readouts, as seen Figure 4.9.

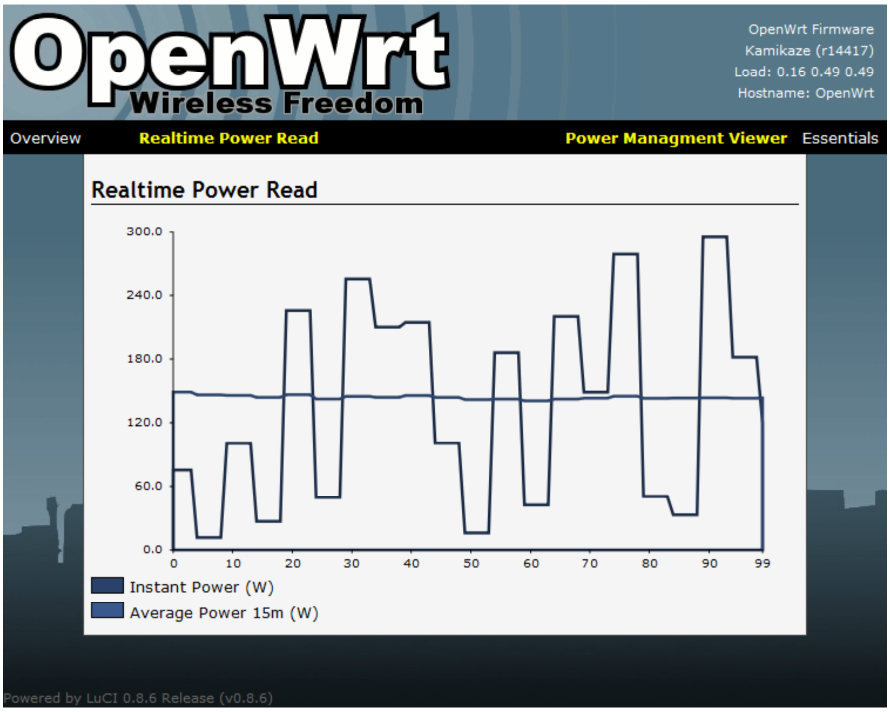

Figure 4.9 - Live graphic visualization feature on Mozilla Firefox.

Figure 4.9 shows the live graphic feature, the graphic auto updates every 2 seconds with the last instant power consumption read by the system. It also includes the average instant power for the last 15 minutes, providing a real time visualization of energy consumption and an average of the last 15 minutes for comparison.

Chapter 5

Results

The system developed has a specific operating environment that currently is not implemented, see Figure 3.6. Since not all system features were developed, some performance results cannot be provided. For instance, the system connection with a real energy meter was not established due to the lack of time to implement specific protocols (i.e., IEC 1107 Flag protocol mode C in Europe or ANSI C12.18 in North America). Also, the Utilities central server or system does not exist and no simulation was made. This was due to the several different implementations and approaches the Utilities can make regarding to aspects like the communication used, server type, file format among others.

The chapter starts with a resume of the implemented functionalities followed by the explanation of the tests done to validate each of the functionalities implemented. Last section, provides an insight of the system hardware cost, not considering any extra costs associated with hardware necessary for connecting with the meter or broadband fees, among others.

5.1. Functionalities

A simulation of the inputs was made to verify the correct functioning of the system functionalities. Table 5.1 shows the implemented functionalities.

Table 5.1 – Status of implemented functionalities.

Feature	Status
RS-232	Implemented
Memory card	Implemented
Control software	Implemented
Data visualization	Implemented
Mesh network	Not tested
Meter connection	Not implemented

5.1.1. RS-232

The RS-232 port was tested using a direct connection to the PC and using the screen utility. Screen program only requires setting which serial port to use and configure the data throughput. The test results are summarized in table 5.2.

Table 5.2 – RS-232 baud rate test results.

Baud rate	**Status**
2400	Working
4800	Working
9600	Working
19200	Working
38400	Working
57600	Working
115200	Working

The RS-232 port was tested in all standard baud rates and always worked seamlessly. Adopting a specific baud rate may depend on the target meter capabilities.

5.1.2. Memory expansion

The memory card, after being installed in the router hardware (and carrying out all the driver installation and configurations) appeared as an available device in OpenWrt. The file system of the card was configured in fstab to auto-mount during boot. The memory card adapter allowed testing it both with SD and MMC cards as well as different sizes and brands. In Figure 5.1 the system storage devices can be seen with two out of the three different memory cards mounted in the system, one at a time.

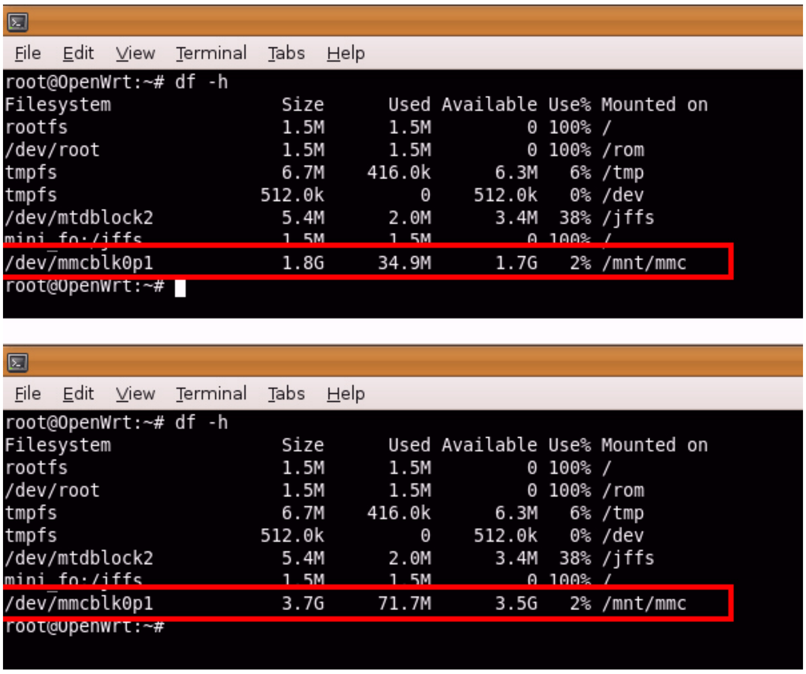

Figure 5.1 - Screenshots of the system storage devices with different memory cards.

Figure 5.1 also presents the output given by the command "df". The system worked with a 512 MB MMC card, 2 GB SD card and a 4 GB micro-SD card. Due to the unavailability of an SD-HC card no testing was made.

5.1.3. Control software

The control software developed comprises the reading of energy consumption from an energy meter; however the connection to the meter is not yet developed. Therefore, to simulate the data that should be collected through this connection, one function that generates a random number between and adds it to the last reading was developed. These generated numbers were first provided directly by a function implemented in the system software, to check if the database was properly updated and afterwards were sent to the system through the serial port by a test program running in a PC and were also printed to the system shell. Using this simulation scenario, it was possible to verify the software correct functioning, as demonstrated by figure 5.2.

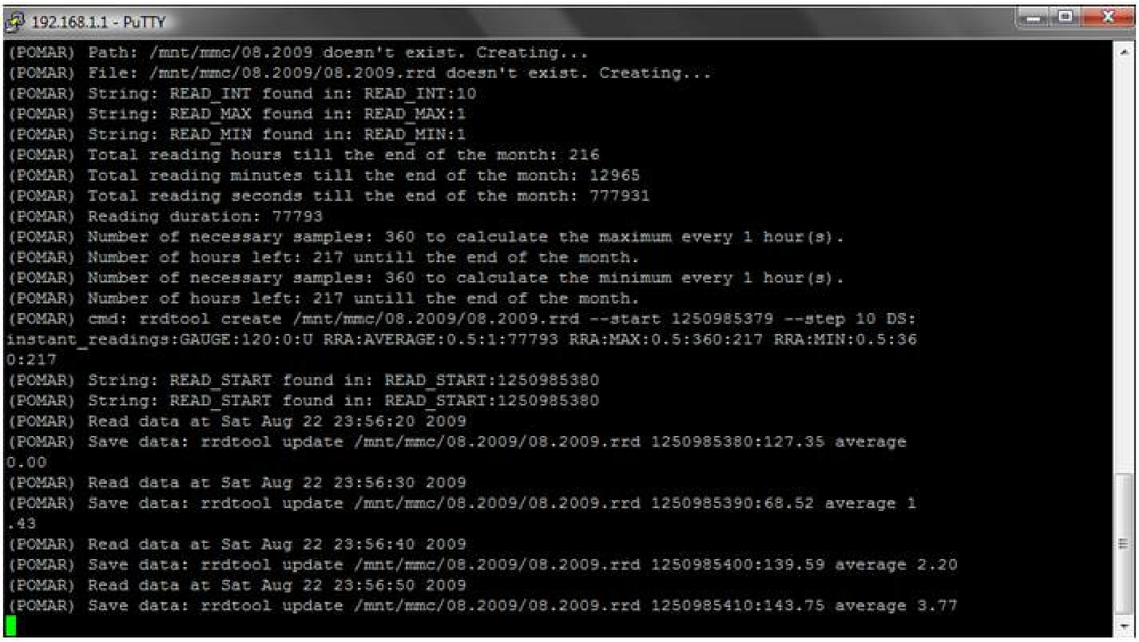

Figure 5.2 - Example of the control software outputs.

From Figure 5.2 it can be seen that the program maintains the 10 seconds time intervals between readings and that also saves the data to the RRD database, which includes the values and timestamp to be saved. By comparing the output of the command pair "timestamp:value" with the data fetched in the same database for the same time interval, data consistency can be verified. From the tests it was concluded that the system was able to deal with parallel tasks and data consistency was maintained.

For testing the automated process responsible for creating the pre-defined daily, weekly and monthly graphics, OpenWrt system clock was manipulated in order to test each graphic creation individually. For instance, forcing the end of the month would trigger the next month RRD database creation as well as the creation of all pre-defined graphics associated with the ending month. All the described functionalities worked as expected: the next month databases are created and operating correctly.

5.1.4. Data visualization

The data visualization features use the data collected and stored by the developed software. The software was designed having in mind a real application scenario where real-time data saving has to be made, i.e. gathering 1 month of readings would take 1 month and some graphics can only be generated at the end of this period. For speeding up the process of data collection, a test program was created to fill RRD databases and allow the generation of the corresponding pre-defined graphics. The different features of the data visualization were tested over different platforms and browsers, as depicted in table 5.3.

Table 5.3 – Data visualization test results.

System platform	Browser	Pre-created graphics	Real-time instant power visualization	User created graphics
PC	Mozilla Firefox	Working	Working	Working
	Internet Explorer 8	Working	Working	Working
	Google Chrome	Working	Working	Working
Mac	Safari	Working	Working	Working
iPhone	Safari	Working	Working	Working

According to the results shown in table 5.3, all data visualization developed is working in all tested platforms and browsers. A screenshot of the real-time instant power visualization working on the iPhone is shown in figure 5.3.

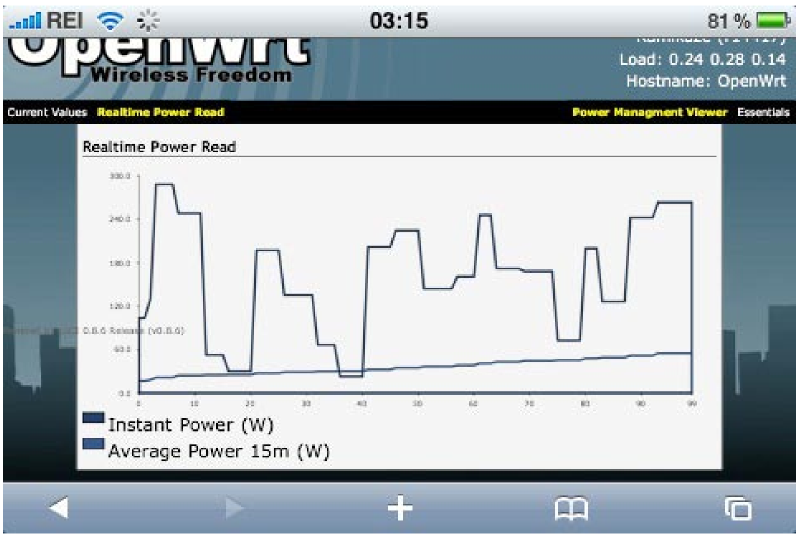

Figure 5.3 - Real-time instant power visualization on the iPhone.

The program created for testing the system data visualization also allowed performing an estimation of the amount of memory expansion required for archiving 20 years of data, corresponding to system's target life span. Every monthly RRD database occupies approximately 2MB and each pre-graphic size is around 150KB (approximately 0.15MB). So, the total amount of memory necessary for 20 years is approximately 20*12*(2MB+0.15MB) + 20*365*0.15MB + 20*52*0.15MB = 1467MB.

5.2. System cost

This project aimed to be a low cost system so it could be a different and cheap alternative to similar systems and promote/accelerate the introduction and adoption of smart meters. The total cost of the system developed is summarized in table 5.4.

Table 5.4 - Individual cost of the principal components and total system cost.

System component	Price
La Fonera+	29.95 €
MAX3323EEPE	5.82 €
SD card adapter	2.25 €
2 GB SD card	5.99 €
Others	1,00 €
Total cost	45.01€

Table 5.4 shows the system total cost with a SD card for 20 years (2GB). This is just an estimate because some prices can suffer variations due to the quantity of different resellers or/and brands, and only the main components are included in the total cost. The table row named "Others" includes an overestimated cost of all other material difficult to quantify like cables, soldering, etc.

All the components of the system developed passed all tests made to them individually and working together. The picture of the final system developed in shown in figure 5.4.

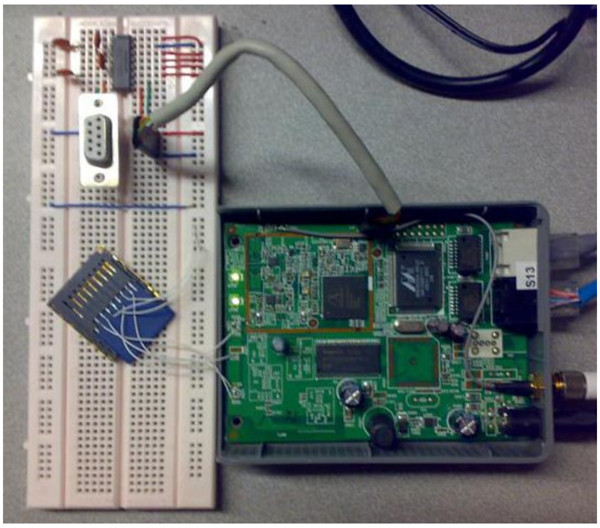

Figure 5.4 - Final system implemented (central unit showed in figure 3.7).

From figure 5.4 it can be seen that the system is still a prototype and more work and money have to be spent in order to redesign and integrate all the components inside the original box. Nevertheless, it is expected to continue as a low cost system and its final price (for the end user) can be lowered if sold as a package, for example with the Internet Operator, or other entities.

Chapter 6

Conclusion and future work

Power grids have evolved since its beginning but growth on peak demand, volatile prices costs, uncertain long-term supply of energy, new laws and environmental concerns among others require new and fresh approaches so that power grids can keep up the energetic sustainability. Smart grids and smart metering stand as the most promising approaches to help solving current and future energy problem.

There are some proposals of smart metering already being tested around the world; all have common goals and face similar challenges. This project proposes an alternative solution to these platforms based on a different approach that consists in offering a platform to support smart metering: the system developed provides smart metering functions with reduced communication costs to current and future meters while being easily expanded to support new added value services.

The results gathered from the developed system, prove that the strategy adopted supports the essential smart metering concept using current meters. The system, at this stage, is capable of meeting the following functional specification of smart metering:

- Two-way communication with authorized parties – using the broadband connection of the system and as a backup connection the Wi-Fi mesh network;
- Electronic storage of data – provided by the MMC/SD card memory expansion;
- Electronic display of data – provided through a web server, accessible through wireless or wired connection;
- Meter export consumption – the system uses RRD databases that allow exporting the saved data and/or numerical report in XML format;
- Plug and Play – configuration from the user is only necessary if he wants to;
- Upgradeability – the firmware is a Linux distribution with a package management system that allows installing new software or updating the existing one through the available SSH account; this update feature can be done locally and/or remotely.

This approach brings the following benefits to smart metering adoption:

- Reduction of stranded devices – the system developed serves as a platform for allowing smart metering functions with current meters;
- Low cost – re-engineering of a network device along with the use open source tools resulted in a total system cost around 45€.

- Low deployment cost - the system allows re-using current meters, removing their cost in the total deployment price. Also, providing the two-way communication through the less costly to deploy and maintain communications reduces the final invoice.
- Data visualization – The data visualization is provided through a series of devices common in most households today, removing the need to acquire new equipment.

As a summary of the system functioning results, it can be said that all implemented and tested features worked as expected. The RS-232 implemented allows all the software configurations, i.e. baud rate and parity bit. Memory card expansion is working with different MMC/SD card sizes providing the necessary extra memory for achieving the system objectives. The control software proved to be stable and robust, maintaining synchronization even when the router is under heavy load. And the data visualization tool implementation through the web server was verified to be compatible with different devices.

Smart metering promises to aid in the transition to a future sustainable energy system but achieving this goal requires the involvement from the relevant stakeholders (governments, regulators, consumers, etc). Thus, there are no guarantees that the deployment of such a system will help power grids face current and future challenges.

Nevertheless, the developed system has some open issues that have to be addressed in order to be a viable commercial alternative to smart metering. The system clock is provided via software, so whenever a reboot or power failure happens the system gets back to the default state. Updating the system clock can be done via Network Time Protocol (NTP) but this can cause the software developed to lose synchronization. Another alternative is to include a battery and an integrated circuit operating as the system clock. Also, due to lack of time to implement specific protocols, no communication to a real meter was implemented. These would be the next natural steps regarding the evolution of the system.

Still regarding the future work, reduction of stranded devices means interoperability between the system developed and a large number of different energy meters from different brands. This is a hard task to accomplish. One possibility could be the integration of a low cost web cam with image processing capabilities (i.e., to identify numbers) to cover the widest range of meters available.

The designed system architecture allow for a future implementation of a HAN, comprising the central unit connected with different sensors and controls through the home (or other premises) so that the central unit can act as load centre. This would allow a better configuration from the user, so that he could benefit from the chosen tariff, i.e. if the user has a bi-schedule tariff he could program when the major load appliances can operate for reducing the energy bill. One possible solution to integrate a ZigBee Coordinator could be through the utilization of Ethernet LAN port.

Future work can also incorporate improvement of the user visualization feature; access is done through a web browser and today web 2.0 technologies provide a wide set of tools to develop full feature web GUI. These improvements would enable creating a much more appealing interface – a fundamental point in order to increase user involvement. Old people may feel less motivated to use recent technologies; however, there are already some digital photo frames with wireless communications capabilities. Adopting one of these devices to work as an energy consumption display instead of burdening the router with more control requirements could also be studied.

Regarding communications improvement, developing the necessary features so that the system could also provide ad-hoc/mesh communications coupled with concentrator capabilities would be very interesting. This would enable the system to be installed in houses that do not have broadband connections and still benefit from all offered functionalities.

No simulation tests regarding the communication between the developed system and a Utility due to the different possibilities of the communication the Utilities can implement, future work should regard this simulation for better validating this alternative approach used.

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Annex A

Table A.1 - Summary table of suitable communication means [7].

	PLC	Cable		Wireless			
		internet	Telephone	GSM, GPRS	UMTS	RF	PMR/trunked radio
Costs	Medium	D: very high, E: medium	Medium to high	High	High	Medium	High
Operation	Own	D: telecom-provider E: ISP	Telephone operator	Mobile phone operator	Mobile phone operator	Own	Own or PMR - operator
Addressability of the meter	Via concentrators	Directly	Directly	Directly	Directly	Via concentrators	Directly or via concentrators
Suitability (BW - Bandwidth)	Functions with low BW	Function with high BW	Functions with medium BW	Functions with medium BW	Functions with medium BW	Functions with low BW	Functions with medium BW
Suitability for real time applications	Yes	D: yes E: No	No	No	Yes	Yes	Yes
Flexibility	Medium	High	Medium/high	Medium/high	High	Medium	Medium/high
Reliability	high	Medium / high	Very high	High/very high	Medium/high	high	Very high

Annex B

Table B.1 - Technical details of several memory cards [27].

Card	Varieties	Actual max. storage capacity (mebibyte, or MiB)	Theoretical max. capacity	Max. read Speed (MiB/s)	Max. write Speed (MiB/s)	Read/write cycles	Low-level access	Operating voltage (V)	Controller chip	# of pins
CompactFlash	I	65,536	128 GiB (137 GB; due to LBA-28)	133	133		NOR/NAND	3.3 and 5	Yes	50
	II	12,288	128 GiB (137 GB; due to LBA-28)	133	133					
SmartMedia		128		2		1,000,000	NAND	3.3 or 5	No	22
MMC	MMC	8,192	128 GB	20	20	1,000,000		3.3	Yes	7
	RS-MMC	2,048		2	2			3.3		7
	MMCmobile	2,048		15	8			1.8 and 3.3		13
	MMCplus	4,096		52	52			3.3		13
	MMCmicro	2,048						1.8 and 3.3		13
Memory Stick	Standard	128	128 MiB	2.5	1.8			3.3	Yes	10
	PRO	4,096	32 GiB	20	20			3.3		
	PRO Duo	16,000		20	20			3.3		
	PRO-HG Duo	16, 000		Actual: 30 Theoretical: 60	Actual: 30 Theoretical: 60			3.3		
	Micro (M2)	16,384	32 GiB	20	20			1.8 and 3.3		
Secure Digital	SD		4 GiB	20	20			3.3	Yes	9
	miniSD			12	12					11
	microSD			10	10					8
	SDHC	32,768	2048 GiB	20	20			3.3	Yes	9
	miniSDHC	4,096		12	12					11
	microSDHC	16,384		10	10					8
xD		512	512 MiB	5	3			3.3	No	18
	Type M	2,048	8 GiB	4	2.5					
	Type H	2,048	8 GiB	15	9					