Wireless Smart Grids for Smart Energy Management

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**Electrical and Computer Engineering**

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**November 2015**
To my family
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Lastly, but not less important, I thank my parents and sister for their help and love.
Abstract

Smart Grids are playing an increasingly important role in society, in one hand to improve client experience and make efficient distributed power by utility, on other hand by environment preservation, with a possibility of more efficient integration of renewable energies by users.

Thus, this dissertation addresses planning techniques of a smart grid system for energy monitoring purposes by customers and respective forwarded information to the provider entity. This network is implemented using wireless networks and radio link for communication, more properly, using intelligent measurement devices and devices to aggregate traffic from the meters. These planning techniques have the goal to optimize the network in order to minimize the cost associated with its implementation, which consists to put the minimum of concentrators in the network to reach high quality of service. For such, the evaluation of these techniques is studied using a MATLAB simulator in two different scenarios: synthetic, wherein the meters are placed in similar houses; and real, wherein the meters are in real houses, in an unpredictable scenario in terms of positions of dwellings and distances between meters. As a result it can be said that the final solution is heavily dependent on positions of smart meters.

Keywords

Smart grids, Wireless Mesh Networks, Smart Metering, Radio frequency, Network optimization, Concentrator placement
Resumo

Os sistemas de redes energéticos inteligentes estão a assumir um papel cada vez mais importante na sociedade, quer para melhorar a experiência do cliente e tornar eficiente a energia distribuída pela entidade fornecedora, quer pela preservação do meio ambiente, com a possibilidade de uma integração mais eficaz de energias renováveis por parte dos utilizadores.

Assim, esta dissertação aborda técnicas de planeamento de um sistema de rede inteligente, com o objetivo de monitorização de energia por parte dos clientes e respetivo envio da informação para a entidade fornecedora. Esta rede é implementada com recurso a redes sem fios e ligação rádio para comunicação, utilizando dispositivos de medida inteligentes e dispositivos para agregar o tráfego proveniente dos medidores. Estas técnicas de planeamento têm como objetivo otimizar a rede de forma a minimizar os custos associados à sua implementação, o que consiste em colocar o mínimo de dispositivos agregadores na rede de forma a alcançar um parâmetro de qualidade. Para tal, a avaliação das técnicas é feita com recurso a um simulador em MATLAB em dois cenários diferentes: um cenário sintético, em que os medidores estão colocados em habitações idênticas e equidistantes; e num cenário real, em São Paulo, no Brasil, em que os medidores estão colocados em habitações reais, num cenário imprevisível em termos de posições das habitações e distâncias entre medidores. Como principal resultado, verifica-se que a solução final é extremamente dependente das posições dos medidores inteligentes.

Palavras-chave

Redes inteligentes, Redes sem fios em malha, Medição Inteligente, Rádio frequência, Otimização de rede, Posição dos concentradores
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<th>Definition</th>
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<tbody>
<tr>
<td>AMI</td>
<td>Advanced Metering Infrastructure</td>
</tr>
<tr>
<td>AODV</td>
<td>Ad-hoc On-Demand Distance Vector</td>
</tr>
<tr>
<td>BI</td>
<td>Beacon Interval</td>
</tr>
<tr>
<td>BO</td>
<td>Beacon Order</td>
</tr>
<tr>
<td>BPLC</td>
<td>Broadband Power Line Communications</td>
</tr>
<tr>
<td>CAGR</td>
<td>Compound Annual Growth Rate</td>
</tr>
<tr>
<td>CAP</td>
<td>Contention Access Period</td>
</tr>
<tr>
<td>CFP</td>
<td>Contention Free Period</td>
</tr>
<tr>
<td>COST</td>
<td>COperation europenne dans le domaine de la recherché Scientifique et Technique</td>
</tr>
<tr>
<td>CSMA/CA</td>
<td>Carrier Sense Multiple Access with Collision Avoidance</td>
</tr>
<tr>
<td>DER</td>
<td>Distributed Energy Resources</td>
</tr>
<tr>
<td>DTC</td>
<td>Distribution Transformer Controllers</td>
</tr>
<tr>
<td>DSDV</td>
<td>Destination-Sequence Distance-Vector Routing</td>
</tr>
<tr>
<td>EB</td>
<td>EDP Boxes</td>
</tr>
<tr>
<td>EDP</td>
<td>Energias de Portugal</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>FAN</td>
<td>Field Area Network</td>
</tr>
<tr>
<td>FFD</td>
<td>Full Function Devices</td>
</tr>
<tr>
<td>FHSS</td>
<td>Frequency Hopping Spread Spectrum</td>
</tr>
<tr>
<td>FSK</td>
<td>Frequency-Shift Keying</td>
</tr>
<tr>
<td>GPRS</td>
<td>General Packet Radio Service</td>
</tr>
<tr>
<td>GTS</td>
<td>Guaranteed Time Slots</td>
</tr>
<tr>
<td>HAN</td>
<td>Home Area Network</td>
</tr>
<tr>
<td>HES</td>
<td>Head-End System</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, Ventilation and Air-Conditioning</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific and Medical</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>LV</td>
<td>Low Voltage</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MFR</td>
<td>MAC Footer</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
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</tr>
<tr>
<td>MHR</td>
<td>MAC Header</td>
</tr>
<tr>
<td>MPDU</td>
<td>MAC Protocol Data Unit</td>
</tr>
<tr>
<td>MSDU</td>
<td>MAC Service Data Unit</td>
</tr>
<tr>
<td>MV</td>
<td>Medium Voltage</td>
</tr>
<tr>
<td>NAN</td>
<td>Neighborhood Area Network</td>
</tr>
<tr>
<td>NTP</td>
<td>Network Time Protocol</td>
</tr>
<tr>
<td>PAN</td>
<td>Personal Area Network</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical</td>
</tr>
<tr>
<td>PHR</td>
<td>PHY Header</td>
</tr>
<tr>
<td>PPDU</td>
<td>PHY Protocol Data Unit</td>
</tr>
<tr>
<td>PSDU</td>
<td>PHY Service Data Unit</td>
</tr>
<tr>
<td>PIR</td>
<td>Passive Infrared</td>
</tr>
<tr>
<td>PLC</td>
<td>Power Line Carrier</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RFD</td>
<td>Reduced Function Devices</td>
</tr>
<tr>
<td>RREQ</td>
<td>Route Request</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
</tr>
<tr>
<td>SHR</td>
<td>Synchronization Header</td>
</tr>
<tr>
<td>SD</td>
<td>Super-frame Duration</td>
</tr>
<tr>
<td>SO</td>
<td>Super-frame Order</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multi Access</td>
</tr>
<tr>
<td>WAN</td>
<td>Wide Area Network</td>
</tr>
<tr>
<td>WiMAX</td>
<td>World Interoperability for Microwave Access</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Networks</td>
</tr>
<tr>
<td>WMN</td>
<td>Wireless Mesh Network</td>
</tr>
<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
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# List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>ALOHA time slot duration</td>
</tr>
<tr>
<td>$A$</td>
<td>Area of location of interest</td>
</tr>
<tr>
<td>$Q$</td>
<td>Available channel</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Average data traffic reaching the concentrator</td>
</tr>
<tr>
<td>$N_i$</td>
<td>Average number of retransmissions at node $i$</td>
</tr>
<tr>
<td>$C_i$</td>
<td>Concentrator point $i$</td>
</tr>
<tr>
<td>$P$</td>
<td>Data packet size</td>
</tr>
<tr>
<td>$d_i^d$</td>
<td>Downlink delay</td>
</tr>
<tr>
<td>$\bar{L}$</td>
<td>Expected path length</td>
</tr>
<tr>
<td>$r$</td>
<td>Fixed radio transmission range</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency</td>
</tr>
<tr>
<td>$\rho_H$</td>
<td>Housing density</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Incident angle to the normal of the outdoor wall</td>
</tr>
<tr>
<td>$L_{\text{in}}$</td>
<td>Indoor loss</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Loss coefficient for indoor propagation</td>
</tr>
<tr>
<td>$W_{G_e}$</td>
<td>Losses in parallel</td>
</tr>
<tr>
<td>$W_e$</td>
<td>Losses in perpendicular</td>
</tr>
<tr>
<td>$\lambda_{\text{max}}$</td>
<td>Maximum capacity available to each node (smart meter)</td>
</tr>
<tr>
<td>$R$</td>
<td>Maximum network depth</td>
</tr>
<tr>
<td>$\lambda_{\text{m-down}}$</td>
<td>Mean traffic (downlink)</td>
</tr>
<tr>
<td>$\lambda_{\text{m-up}}$</td>
<td>Mean traffic (uplink)</td>
</tr>
<tr>
<td>$q_{ni}$</td>
<td>Number of hops in the path of smart meter $n$ to concentrator point $i$</td>
</tr>
<tr>
<td>$M_i$</td>
<td>Number of meters aggregates to the concentrator point $i$</td>
</tr>
<tr>
<td>$X_i$</td>
<td>Number of nodes in $I_i$</td>
</tr>
<tr>
<td>$\varepsilon_i$</td>
<td>Number of shortest paths that contain the node $i$ as an intermediate</td>
</tr>
<tr>
<td>$L_{\text{out}}$</td>
<td>Outdoor loss</td>
</tr>
<tr>
<td>$\lambda_{\text{down}}$</td>
<td>Packet generation rate (downlink)</td>
</tr>
<tr>
<td>$\lambda_{\text{up}}$</td>
<td>Packet generation rate (uplink)</td>
</tr>
<tr>
<td>$d$</td>
<td>Perpendicular indoor distance</td>
</tr>
<tr>
<td>$p_i$</td>
<td>Probability of collision</td>
</tr>
<tr>
<td>$QP$</td>
<td>Quality parameter</td>
</tr>
<tr>
<td>$S$</td>
<td>Range</td>
</tr>
</tbody>
</table>
$P_{r-c}$  Sensitivity (concentrator)

$P_{r-SM}$  Sensitivity (smart meter)

$C$  Set of concentrators

$I_i$  Set of interferes of node $i$

$M$  Set of smart meters

$\text{dist}_{ni}$  Sum of distances of the smart meter $n$ to its neighbors connected to the concentrator point $i$

$t$  Time

$\text{Cost distance}_{c_i}$  Total distance between connected smart meters aggregated to the concentrator point $i$

$\text{Cost distance}_{\text{tot}}$  Total distance between connected smart meters in the network

$\text{Cost hop}_{\text{tot}}$  Total number of hops for every smart meters connect to respective concentrator point

$\text{Cost hop}_{c_i}$  Total number of hops for smart meters aggregated to the concentrator point $i$

$C_1$  Total one-hop capacity of the network

$L_{\text{tot}}$  Total propagation loss

$\bar{\lambda}_i$  Transmission rate of generic device $i$ considering the retransmission

$\lambda_i$  Transmission rate of generic device $i$

$P_{t-c}$  Transmitted power (concentrator)

$P_{t-SM}$  Transmitted power (smart meter)

$d_{iu}$  Uplink delay

$L_{lw}$  Wall loss
Chapter 1

Introduction

This chapter gives a brief overview of the work, focusing on important concepts. Before establishing work targets and original contributions, the scope and motivations are brought up. At the end of the chapter, the work structure is provided.
1.1 Overview

The global climate change and rapidly growing populations over the past decades have generated increasing demands for abundant, sustainable, and clean electric energy on a global basis. However, in most countries today, the increasing energy demand means an even heavier burden on the already overstressed, overaged, and fragile electricity infrastructure. The increasing electricity demand, together with the complex and nonlinear nature of the electric power distribution network, have caused serious network congestion issues. The network congestion and safety-related factors have become the main causes of several major blackouts that happened recently. In addition to the overstressed situation, the existing power grid also suffers from the lack of pervasive and effective communications, monitoring, fault diagnostics, and automation, which further increase the possibility of region-wide system breakdown. Furthermore, the global increasing adaptation of renewable and alternative energy sources in the 21st century also introduced new issues, such as power-grid integration, system stability, and energy storage, which also need to be addressed as additional challenges. To address these challenges, a new concept of next generation electric power system, a smart grid, has emerged [1].

The main goal of this thesis is to study and develop smart grid planning techniques to optimize a Field Area Network (FAN) to connect smart meters, in order to monitor client energy consumption and also for energy suppliers. This network is a bi-directional network called smart grid which is divided into two different networks:

- **Neighborhood Area Network (NAN)** - Multiple-hops “Mesh” network which ensures the connection between the terminals (smart meters) and aggregated by concentrators. The network planning involves the study of the transmission technology, clusters definition as a number of concentrators and optimizes its location which is intrinsically dependent on the propagation environment location and technical specifications of the devices.

- **Wide Area Network (WAN)** - Network which ensures the connection between the concentrators and control center, called backhaul. This connection can be implemented using different technologies like mobile communications, World Interoperability for Microwave Access (WiMAX), microwaves or guided transmission, means like optical fiber.

This work is focused on the NAN and proposes a methodology for locating concentrator points in a ZigBee Mesh network of smart meters, optimizing the performance of the network. The objective is to create a simulator which has as inputs: the number of smart meters and its location; the possible position to put the concentrators; all the variables related with the technology, like number of hops in the network and number of neighbors of each smart meter can have and the parameters of the propagation model. The outputs of the simulator are the number of concentrators and its position and the links between smart meters. To obtain these results the simulator executes the proposed algorithm to determine the concentrator position, i.e., the positions of concentrators that combine data from smart meters to send to the utility satisfying the quality requirements, minimizing costs, maximizing coverage, among others constraints. In order to validate the outcomes resulting from the algorithm, a synthetic and a real scenarios are simulated.
1.2 Motivation and Contents

Nowadays, smart grid is a term referring to the next generation power grid within the electricity distribution and management. This technology can control intelligent appliances at consumer’s home or building to save energy, reduce cost and increase reliability, efficiency and transparency. In this section, are presented the key motivations of implementation communication infrastructures in smart grid systems. As illustrated in Figure 1.1, the motivations are related to system, operation and environment features in emerging smart grid paradigm through communication infrastructures [2].

**Operation**

- Enhance customer experience

To improve service reliability and quality to customers, it is necessary to take into account communication infrastructures in smart grid systems. These services include reduced outage times when the power system is interrupted, improved notification of network problems and providing customers with proper options and tools to optimize their energy usage to curtail the peak-hour usage and to avoid power quality degradation or blackout. In this way, the system allows the costumers to control their consumptions, to avoid wastage of power and to reduce their energy costs.

- Adherence to regulatory constraints

New regulatory demands include provisions for increased levels of asset data tracking (cost justification), and greater reliability targeting the implementation of communication infrastructure in smart grid. Not all technology related activities must be regulated but regulation is needed to create the right environment for a market to be developed.

**Environment**

- Lower carbon fuel consumption/Greenhouse gas emission

One of the most concerns about the environment and power industry is the gas emission, and a smart grid system has the potential to reduce electricity losses in the network and limit growth in demand, due to embedded monitoring of the high, medium and low voltage networks through communication infrastructures, therefore, lower carbon fuel consumption and greenhouse gas emission.

- Facilitated renewable resource generation

Increased penetration of distributed and variable generation under the smart grid paradigm is expected to give rise to both operational challenges and market opportunities. A smart grid will enable options for renewable generation and provide customers with the awareness and capabilities to reduce their energy consumption on carbon fuel based power.

**System**

- Increase productivity

Intelligent performance information and tools allow customers or utilities to undertake their current duties and needs in a more efficient manner, with longer term benefits coming from automating the smart grid
system. In this way, these gains in productivity will help to reduce deployment costs and operational costs in managing the smart system.

- Improved utilization

The communication infrastructure in smart grid will provide detailed real-time data on distributed energy generation, electricity transmission, power consumption and market price. This information allows the utility operators to improve their decision making processes based on the relation improve/cost by identifying which components are likely to fail and the replacement strategy online [2].

![Diagram](image)

Figure 1.1 Diagram (extracted from [2]).

### 1.3 Work structure

This thesis is composed of 5 chapters. The first presents the introduction to the work. Chapter 2 contains the main system architecture necessary to understand the operation behind the functionalities, where an overview of smart grid systems, and more properly, the advance metering infrastructure, is given, as well a brief state of the art, either in Portugal or in the world.

Chapter 3 gives all the characteristics of the advanced metering infrastructure using radio frequency as technology, often referred to as RF systems for smart metering. It also provides technical information necessary prior to the design of the algorithm.

Then, chapter 4 includes the full description of the developed tool to solve the problem presented before. For that, the inputs, the metrics, the description and the extracted outputs are given. Additionally, the tool is applied to two scenarios in order to study the performance and the results are presented to provide clarification on some of the technical decisions made during the development of the algorithm.

Finally, chapter 5 concludes this thesis, recapping the main points and providing a critical analysis of the obtained results. Also, in order to improve the performance of this kind of system, future work is discussed.
1.4  Publications

The paper written on this thesis work was submitted and accepted for the 9th Congress of the Portuguese Committee of Union Radio-Scientifique Internationale (URSI), with the subject "5G e a Internet do futuro". As a result, the paper was selected for oral presentation and was named for the best student paper prize, being among the three finalists.
Chapter 2

Smart Grids

This chapter provides an overview of the Smart Grid systems, mainly focussing on the network design and applications. Also, a brief state of the art is provided.
2.1 The smart grid system

2.1.1 Introduction

The smart grid, as briefly referred before, is a modern electric power-grid infrastructure for improved efficiency, reliability, and safety, with smooth integration of renewable and alternative energy sources, through automated control and modern two-way communication technologies. In the smart grid, reliable and online information becomes the key factor for reliable delivery of power from the generation units to the end users. The impact of equipment failures, capacity limitations, and natural accidents and catastrophes, which cause power disturbances and outages, can be largely avoided by online power system condition monitoring, diagnostics, and protection. In this respect, the intelligent and low-cost monitoring and control enabled by online sensing technologies have become essential to maintain safety, reliability, efficiency, and uptime of the smart grid [3].

Grid is the electricity system that consists of electricity generation, transmission, distribution, and consumption. In traditional power grids, electric power is carried from a few central generators to a large number of load centers with electricity users or customers. A smart grid is a new type of power grid under development, which allows unconventional power flow and two-way information flow to create an advanced automatic and distributed energy delivery network. Table 2.1 shows a brief comparison between the existing grid and the smart grid [3].

The rapid deployment of smart meters to measure consumption of utility resources such as water, gas and electricity has presented a problem of scale. The huge amount of data thus collected is being used to make demand-response applications smarter as a part of the smart grid initiative. The wireless mesh architecture is a popular deployment method for smart utility networks and Advanced Metering Infrastructure (AMI), due to the low deployment costs offered by this method. Severe limitations are imposed on the scale of deployment by wireless environment parameters such as fading and path loss, differing widely from home and outdoor to industrial and in-building scenarios [3].

Usually, the smart grid is implemented through FANs, which can be seen as a superposition of a communication network and a power distribution network. In Figure 2.1 the smart grid functionality Cisco’s model is presented. In this figure, the AMI metering system is implemented through the Radio Frequency (RF) Mesh or PLC (Power Line Carrier) Mesh and the data is aggregated by a concentrator. Then, the concentrator sends the information to the AMI Head-End System (HES) through the mobile communications or any other means referred before.
Table 2.1: Comparison between the existing grid and the smart grid (extracted from [3]).

<table>
<thead>
<tr>
<th></th>
<th>Existing Grid</th>
<th>Smart Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromechanical</td>
<td></td>
<td>Digital</td>
</tr>
<tr>
<td>One-way communication</td>
<td></td>
<td>Two-way communication</td>
</tr>
<tr>
<td>Centralized generation</td>
<td></td>
<td>Distributed generation</td>
</tr>
<tr>
<td>Few sensors</td>
<td></td>
<td>Sensors throughout</td>
</tr>
<tr>
<td>Manual monitoring</td>
<td></td>
<td>Self-monitoring</td>
</tr>
<tr>
<td>Manual restoration</td>
<td></td>
<td>Self-healing</td>
</tr>
<tr>
<td>Failures and blackouts</td>
<td></td>
<td>Adaptive and islanding</td>
</tr>
<tr>
<td>Limited control</td>
<td></td>
<td>Pervasive control</td>
</tr>
<tr>
<td>Few customer choices</td>
<td></td>
<td>Many customer choices</td>
</tr>
</tbody>
</table>

Smart grid creates a new lifestyle for electricity consumers. In general, customers do not know how the energy they consume is produced and delivered to them. With smart grid technologies deployed all the way to the end user, consumers will be able to know exactly how much electricity they consume, for example, to roast a chicken or when lights are left on instead of being turned off. The customers pay for what they use at the end of the month, but there is no breakdown of how they used their energy. In-home energy management systems will enable interested consumers to keep track of how much energy
they are using and for what purpose. The costumers waste a lot of energy today, but with smart grid technology and information available at home or on our smart phones, they will become cognizant of what wasted and help to become more conscious of our environment [5].

![Smart Grid Infrastructure](image)

**Figure 2.2 Smart Grid Infrastructure.**

### 2.1.2 Smart Grid Applications in Portugal

The energy distribution network isn’t prepared to deal with constant oscillations between supply and demand of electricity because it’s not designed to go get new energy resources and management all the information in real time, optimizing energy fluxes which became necessary as far as the legal framework began to allow every citizen to take over the energy producer as an integrated part, using the sun, water or wind as raw material [6].

Therefore, in Portugal, in order to reply to these problems, the project Inovgrid was created. Inovgrid is Energias de Portugal (EDP) umbrella project for smart grids and presents an answer to several challenges, including: the need for increased energy efficiency; the pressure to reduce costs and increase operational efficiency; the integration of a large share of dispersed generation; the integration of electric vehicles and the desire to empower customers and support the development of new energy services. The project InovGrid started in the Portuguese municipality of Évora in October 2007, where the infrastructure spanned the entire municipality, reaching around 30 thousand electricity customers with an annual consumption of approximately 270 GWh. This project is associated with an investment of 70 million euros until 2010. Currently, the project is expanding to other portuguese cities, including Guimarães, Lamego, Batalha/Marinha Grande, Alcochete, Algarve and São João Madeira; reaching more than 150 thousand consumers at the end of 2014. Additionally, starting in 2015, all the new installations will use EDP boxes, making it the standard technology in Portugal [7].

From a technical perspective, the architecture of the system includes the following components:

- **EDP Boxes (EB),** installed in all low voltage customers, offering advanced smart meter functionalities, such as real time readings on demand, load diagrams, voltage monitoring and remote services (connect/disconnect, contracted power and tariff setup, tampering alarms, etc.);
- **Distribution Transformer Controllers (DTC) installed in every secondary substation, acting as**
data concentrators and local metering, monitoring and automation devices (power quality monitoring, medium voltage (MV) switching, local sensors, etc.);

- A communication network based on PLC and General Packet Radio Service (GPRS) technologies, linking EBs and DTCs to HESs;
- Electric Vehicle (EV) charge stations;
- Efficient public lighting systems, based on Light Emitting Diode (LED) luminaries with advanced control [7].

![Figure 2.3 EDP smart grid (extracted from [7])](image)

The project focus on the following features:

- **Active Demand response**: is stimulated by providing user-friendly interfaces for consumers with information on energy consumption, generated energy and management tools to react to external signals (e.g. price).
- **Integration with Smart Homes**: is achieved by providing energy management functions of home automation devices and smart appliances that stimulate energy efficiency.
- **Smart Metering Infrastructure**: includes the EDP Box to substitute the conventional meters at the consumer/producer premises and the DTC at the MV/Low Voltage (LV) substations. This equipment enables grid monitoring through data gathering at the consumer and substations level, data analysis functions and interface with commercial and technical central systems, enhancing grid automation and new market solutions.
- **Smart Metering Data Processing**: it is the functionality of the Smart Grid Asset Data Management System (Sysgrid). It includes all features related to the execution of commands and data gathering of the InovGrid infrastructure with the possibility to be integrated with commercial systems, management of communications and network settings.
- **Integration of Distributed Energy Resources (DER)**: it is achieved using advanced control and automation functionalities distributed over different levels of a hierarchical control structure that
matches the physical structure of the electrical distribution grid. This hierarchical control architecture enables the coordinated and synergistic management of DER, including distributed generation, responsive loads and distributed small-scale storage.

- Integration of EV: by anticipating an important future development, the project exploits the potential flexibility of actively managing electric vehicles battery charging at home premises. Additionally, the already existing Portuguese EV charging infrastructure energy flow is monitored and controlled by the InovGrid platform.

- Monitoring and control of LV networks. The EDP boxes and DTCs provide real-time information on the grid. That information will also be used to evaluate the impact of micro-generation on system voltages, currents, reliability and, of course, losses.

- Automation and Control of MV networks include the use of the control intelligence integrated in the DTC and automation mechanism. The possibility of remote control of MV devices reduces the need of intervention of work field teams and ensures short time failures. Additionally, electric remote controls and monitoring at the substation level are essential to anticipate problems.

- Integrated Communications Solution: the Device Language Message Specification/COMpanion Specification for Energy Metering (DLMS-COSEM) is used in InovGrid to enable a structured way of transmission of data currently from the Smart Meter EDP Box to the Systems. Supervisory Control and Data Acquisition (SCADA) application is used to collect data from the DTC and support remote control on the medium voltage. For communications, Prime PLC technology is being applied [7].

From a societal point of view, the business case for InovGrid is based on a set of benefits of the project accruing to several stakeholders, including: regulators, electricity users, energy services companies, electricity retailers, distributed generation promoters and vendors, electric vehicle owners and vendors and, considering the economic and ecological impact, society in general. The deployment in Évora provided ample evidence about many of these benefits, as shown in the diagram of Figure 2.4.

![Figure 2.4 InovGrid benefits diagram (extracted from [7]).](image-url)
The next goal of the project is due in end of 2017 the 6 million EDP’s clients should be covered by the change, gaining access to more accurate information on their energy consumption and the ability to act accordingly. As an example, the clients may have a possibility to change the contracted power, the kind of the contract or management their own devices reducing the operating hours of a more demanding consumer devices [6].

2.1.3 Smart Grid Applications in the world

According to the latest report by GTM Research, Global Smart Grid Technologies and Growth Markets, 2013-2020, the global smart grid market is expected to cumulatively surpass $400 billion worldwide by 2020, with an average compound annual growth rate (CAGR) of 8.4 percent, represented in Figure 2.5. China will be the largest smart grid market in the world, accounting for over 24 percent of the global market [8].

However, as smart grid implementations and applications begin to develop further in various geographies, the once-linear depiction of a smart grid roadmap is becoming increasingly multidimensional. There are, of course, common architectural, hardware and process components that will be deployed regionally; however, the deployment and maturity of applications will evolve differently depending on local drivers, requirements and technological appetites [8].

![Figure 2.5 Smart Grid Regional Forecast, 2013-2020 (extracted from [8]).](image)

Technology vendors for all aspects of smart grids should not underestimate their role and should ensure that they engage in the smart grid debate.

- Vendors are encouraged to bring the wealth of their experience to the policy table and ensure their requirements are reflected in new regulatory regimes and global standards.

- Modular design, forward compatibility and interoperability of smart grid equipment will be a key driver of how fast utilities and consumers adopt the technology. Vendors are encouraged to move rapidly towards de facto standards to help utilities re-risk investments.
As the industry moves rapidly towards standards for critical smart grid infrastructure, it is important that vendors continue to innovate with the end consumer in mind. The most successful vendors will create blended product and service offerings that make it easy for consumers to change their behavior. For smart grids to move towards mass adoption, consumers will need to embrace the technology [9].

In Figure 2.6 is presented a map with the major companies that are vendors of smart grid material, not only devices but also system solutions.

![Map of major companies for Smart Grid solutions](image)

Figure 2.6 Major companies for Smart Grid solutions (extracted from [10]).

### 2.2 Advanced Metering Infrastructure

#### 2.2.1 Introduction

For most of the history of the electricity industry, the area of metering has not seen major policy issues or developments. Those issues that did develop dealt with areas such as meter accuracy testing, frequency of billing, and other aspects of the meter reading function. In the 1990’s, competitive metering did not work very well. The costs of ad-hoc metering deployment (i.e. where meters are put in sporadically and with no geographic cohesion or proximity) proved to be 5 to 10 times the cost per meter as compared to a mass deployment by the utility. Competitive metering policy had even worse impacts on the deployment of advanced metering. Because such policy granted competitors the ability to take away the metering part of the utility franchise, utilities quickly became wary of making metering investments that could potentially become stranded [11].

Beginning in 2000, metering became a more important issue in the eyes of policy makers and the electricity industry. New metering and communications technologies brought forward new benefits. Most importantly, however, the rise in interest in demand response as a new policy and business component
of the electricity industry began to drive interest in advanced metering [11]. To solve this problem, it was introduced the concept of advanced metering infrastructure.

AMI is an integrated system of smart meters, communications networks, and data management systems that enables two-way communication between utilities and customers. Customer systems include in-home displays, home area networks (HAN), energy management systems, and other customer-side-of-the-meter equipment that enable smart grid functions in residential, commercial, and industrial facilities. AMI system components include an advanced meter or meter/module combination (often called a “smart meter”), a hierarchical or peer-to-peer communications network that is capable of delivering meter data and alarms in near real time called NAN, a network that collect the data from the smart meters and deliver to utility (backhaul) designed WAN, a suite of application software residing at the data center that manages customer read schedules, reads meters and transfers the meter interval data into a meter data management application or a meter data repository [11] [12].

AMI provides benefits to consumers, utilities and society as a whole. For the consumers, this means more choices about price and service and more information with which to manage consumption, cost and other decisions. It also means higher reliability, better power quality, more prompt, more accurate billing and, as members of society, consumers also reap all the benefits that accrue to society in general. For the utilities, AMI helps to avoid estimated readings, provide accurate and timely bills, operate more efficiently and reliably, and offer significantly better consumer service. AMI eliminates the vehicle, training, health insurance, and other overhead expenses of manual meter reading, while the shorter read-to-pay time advances the utility’s cash flow, creating a one-time benefit and consumer concerns about meter readers on their premises are eliminated. Society, in general, benefits from AMI in many ways. One way is through improved efficiency in energy delivery and use, producing a favorable environmental impact. It can accelerate the use of distributed generation, which can in turn encourage the use of green energy sources. And it is likely that emissions trading will be enabled by AMI's detailed

Figure 2.7 Typical AMI network architectures (extracted from [12]).
measurement and recording capabilities [11].

2.2.2 AMI Networks

2.2.2.1 Home Area Network

HAN is a dedicated network connecting devices in the home such as displays, load control devices and ultimately “smart appliances” seamlessly into the overall smart metering system. It also contains turnkey reference designs of systems to monitor and control these networks. Therefore, HAN is the backbone of the communication between smart meter and home appliances. These home appliances are beginning to become smart with connectivity features that allow them to be automated in order to reap benefits that smart metering and variable tariffs bring [13] [14].

In a HAN, multiple components interact to provide a wide range of capability. The basic components of a home area network are:

- The network portal or gateway that connects one or more outside information services to the HAN.
- The access point or network nodes that form the wired or wireless network itself
- The network operating system and network management software
- The end points such as thermostats, meters, in home display devices, and appliances.

The key challenge in implementing a HAN solution is to connect objects inside houses/buildings to offer smart interoperability features. One such example is connecting passive infrared (PIR) sensors to heating, ventilation and air-conditioning (HVAC) and lighting systems to turn off heating when windows are open, or turn lights off when no presence is detected. Summing up, the challenge in implementing a HAN solution is to interconnect different technologies to offer smart services for comfort, automation, security, energy management and health. Different technologies can be used to implement HAN such as ZigBee, Wi-Fi, Ethernet, Z-Wave, HomePlug, etc. In Table 2.2 is presented a comparison between
the technologies announced on different aspects as a connectivity, maximum speed per channel, reach, standards, adoption rate and security [13] [14].

<table>
<thead>
<tr>
<th></th>
<th>Zigbee</th>
<th>Z-Wave</th>
<th>Wi-Fi</th>
<th>HomePlug</th>
<th>Ethernet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connectivity</td>
<td>Wireless</td>
<td>Wireless</td>
<td>Wireless</td>
<td>Wired</td>
<td>Wired</td>
</tr>
<tr>
<td>Max speed per channel</td>
<td>250 kbps (2.4 GHz) or 40 kbps (915 MHz)</td>
<td>40 kbps (915 MHz)</td>
<td>11 Mbps or 300 Mbps</td>
<td>14 Mbps or 200 Mbps</td>
<td>10 Mbps – 1000 Mbps</td>
</tr>
<tr>
<td>Reach</td>
<td>10-100 m</td>
<td>30 m open-air, reduced indoor</td>
<td>100 m (indoor)</td>
<td>300 m</td>
<td>100 m</td>
</tr>
<tr>
<td>Standards</td>
<td>IEEE 802.15.4</td>
<td>Proprietary</td>
<td>IEEE 802.11</td>
<td>IEEE P1901</td>
<td>IEEE 802.3</td>
</tr>
<tr>
<td>Adoption rate</td>
<td>Widely adopted</td>
<td>Widely adopted</td>
<td>Extremely high</td>
<td>Medium</td>
<td>Extremely high</td>
</tr>
<tr>
<td>Security</td>
<td>128-bit AES encryption</td>
<td>128-bit encryption</td>
<td>802.11i (WPA2)</td>
<td>56 bit DES encryption technology</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2 HAN technologies (based on [14]).

2.2.2.2 Neighbourhood Area Network

In this section it is introduced the next component of the demand response system, which is the NAN. NAN is deployed within the distribution domain of the grid, i.e., it forms the communication facility of a power distribution system. Smart grid NANs offer distribution domain with the capability of monitoring and controlling electricity delivery to each household according to user demands and energy availability. NANs directly connect all the end users in regional areas, forming the most important segment in power grid that can determine the efficiency of the whole grid.

As one of the core technologies, an efficient, reliable, and secure communication network plays an important role in realization of all the goals of smart grid NANs. Communication network is required to connect smart meters in large distributed areas, and it forms a framework for real-time bidirectional information transmission and exchange in smart grid NANs. In order to upgrade the communication networks in the current power grid, many researchers started to find out the ways to apply advanced communication and networking technologies to power systems. These technologies include the up-to-date wired and wireless communication network technologies, such as broadband power line
communications (BPLC), wireless sensor networks (WSNs), wireless local area networks (WLANs), and wireless mesh networks (WMNs). Different communication and networking technologies are complementary in nature, and communication scenarios and characteristics of NANs in a power grid should be investigated.

Implementation of communication networks for smart grid NANs is a challenging issue. Smart grid NAN usually contains a lot of communication nodes deployed in a large and complex geographical area. Accordingly, the communication networks have to cover all power grid devices in the distribution domain, providing connections to all nodes. Considering the characteristic features of reliability, self-healing, and scalability of smart grid, it is understood that wireless communication networks offer smart grid a much larger degree of freedoms for information collection, dissemination and processing than any wired communication infrastructure. Especially, wireless communication technologies may be the only practical solution for smart grid network covering the last mile communications in the distribution domain, which offers the connectivity from smart meters to AMI concentrators.

Hereby, it is summarized the main design requirements for communication networks of smart grid, which are particularly essential for NANs designs.

- Reliability: Reliability is a basic requirement for communication networks in smart grid, which determines the availability of data transmission links. NANs should have an ability of self-healing via proper topology and routing design, so that abnormal operation of a single node or a few nodes will not affect the performance of the entire network.

- Scalability: Scalability is a critical requirement for smart grid communication networks, especially for NANs, which connect thousands of devices deployed in large and complex areas. It is required that a single node or a group of nodes can easily join and leave the networks while keeping topology stable and quality of services (QoS) at an acceptable level.

- Real-time capability: Bidirectional data transmission in smart grid must meet real-time requirements. The real-time data exchanges in a smart grid should ensure that all decisions are made by the control centers in a timely manner, and demand response can be realized in the customer domain. NANs involve many types of data which have different levels of time requirements.

- Security: Wireless communication network technologies can improve the efficiency and reliability of smart grid, but they may also create vulnerabilities which, together with inherent vulnerabilities of traditional power grid, make smart grid extremely vulnerable. NAN is the most complex segment in smart grid which contains a large number of smart meters, and thus security solutions must be provided to prevent outside attacks and privacy leakage.

- Throughput: Throughput is a valid indicator for evaluating data transmission ability of a smart grid. Different devices may have different throughput requirements. For instance, throughput of smart meters can be much lower than data concentrators in smart grid NANs. With an increase of data generated by smart meters, the throughput requirement of a smart grid also increases. Balancing throughput amongst main data aggregation nodes is very important.
• Economy: Under the promise of ensuring network performance, the number of concentrators, which work as gateways, must be minimized to provide a cost-effective smart grid deployment. For instance, to implement WMNs in a neighborhood area, a major factor that affects the cost is the number of these devices. In order to cover a large area, various concentrators are needed to provide reliable data transmission. If gateways are deployed in an optimized way, the number of these devices can be reduced significantly, while still keeping acceptable network performance. Thus, the entire cost for implementing a NAN can be substantially reduced [15].

2.2.2.3 Wide Area Network

Wide Area networks for AMI systems typically contain fewer “backhaul” components than NANs and can usually work with multiple NANs. Thus, WANs naturally can serve as a suitable networking choice which connects grid control centers and NAN data concentrators with long distances in very large areas, and transmits data in a very high-speed manner. The distribution domain includes distribution feeders and transformers to transmit electricity to customers. This domain provides two-way communications between smart meters and local utility centers (i.e., NAN data concentrators), forming so-called last mile communications in smart grid, to convey information of power usage, control and pricing.

Many AMI networks use multiple backhaul technologies (fiber, satellite, cellular, etc). As a result, shifts in WAN technologies are not as critical to avoid as shifts in NAN technology, as long as the data concentrators being installed have dual transport capability. Nevertheless, implementing WANs with sufficient bandwidth and reliability remains a critical design criterion, since system performance is highly dependent on end-to-end connectivity, availability and capacity. Systems with too much transport latency, for example, will degrade the performance of the AMI system to provide near real time on request reads, outage detection and other time sensitive AMI features [16].

2.2.3 AMI Devices

2.2.3.1 Smart meters

Smart meter is one of the most important devices used in the smart grid. The smart meter is an advanced energy meter that obtains information from the end users’ load devices and measures the energy consumption of the consumers and then provides added information to the utility company and/or system operator for better monitoring and billing. With smart meter, electrical data such as voltage and frequency are measured and real-time energy consumption information is recorded. Smart meter supports bidirectional communications between the meter and the central system. Also, smart meter has the built-in ability to disconnect-reconnect certain loads remotely and can be used to monitor and control the users’ devices and appliances to manage demands and loads within the “smart-buildings” in the future [17].

From the consumer’s perspective, smart meters are offering a number of potential benefits; for example consumers are able to estimate bills from the collected information and thus manage their energy
consumptions to reduce their electric bills. From the utility’s perspective, they can use the information collected from smart meters to realize real-time pricing, by which the companies can limit the maximum electricity consumption and try to encourage users to reduce their demands in the periods of peak load. System operator can terminate or re-connect electricity supply to any customer with proper mechanism remotely in order to optimize the power flows according to the information sent from demand sides [17].

Commonly, smart meter is expected to have the following functions:

- Two-way communication
- Data collection
- Data recording
- Data storing
- Load control
- Programming
- Security
- Display
- Billing

![Figure 2.9 Model of a smart meter (extracted from [17]).](image)

### 2.2.3.2 Data Concentrators

A data concentrator is the core of data and energy management in an AMI. It provides the technology to measure and collect energy usage data. The concentrator can also be programmed to analyse and communicate this information to the central utility database. Not only can the utility providers use this information for billing services, but can also improve customer relationships through enhanced consumer services such as real-time energy analysis and communication of usage information. Additional benefits of fault detection and initial diagnosis can also be achieved, further optimizing the operational cost. The data concentrators are the transition between NAN and WAN and support many technologies, as presented in Figure 2.10. In technical terms, the concentrator is equipped with 4 radio channels in order to handle the aggregated traffic of the whole network under its control and it is capable to support up to 25000 smart meters in a single network.

Data concentrators communicate information through the grid through aggregation of information from various meters. Additionally, its benefits include:

- Smart metering – instant read, load profile, billing information and remote management
- Inventory management – give utilities better visibility into its assets
- Optimization of network – real-time topology display, performance management and benchmarking [18].
Figure 2.10 Data concentrator functional block diagram (based on [18]).
Chapter 3
RF Mesh systems for Smart Metering

This chapter gives the characteristics of the RF mesh systems for smart metering, focusing on the main features and technical information necessary to use in the rest of the work.
3.1 Introduction

Several technologies can be adopted for AMI NAN but the RF mesh based system seems to be one of the most popular. RF mesh systems are mainly used for remote reading to capture interval data, advanced metering and for some other applications. This system requires reliable two-way communication between the metering end-points and the Utility’s HES that do not have strong requirements in terms of bandwidth and delay. However, utilities, that have spent millions of dollars installing such a widespread communication infrastructure, may want to exploit it for other types of applications that, in some cases, may require shorter response time [19][20].

RF mesh technology is uniquely suited for use in smart metering applications due to its ability to dynamically form ad-hoc communication links between neighboring network nodes. Furthermore communication range can be increased by performing multiple hops from one node to the next until the final destination is reached. Thus RF mesh systems are able to overcome variable propagation conditions, which are typically encountered in a NAN, by finding alternative paths through the mesh in the event that one path is blocked by an obstruction, e.g. a vehicle parked outside a house. Other RF solutions such as point to point or point to multi-point systems are constrained by the need to have consistent reliable links between each pair of communicating nodes [19].

3.2 Network architecture

Such RF mesh systems typically employ a layered system architecture in which electricity meters are meshed together at the lowest layer. An intermediate layer of network nodes or Routers interconnects with the meter mesh below and routes traffic to a data concentrator which connects to the upper WAN layer where the traffic is backhauled to the Utility’s HES. The backhaul, as referred before, is typically IP based using GPRS, 3G, WiMAX or a fiber network. The meter mesh, network nodes and concentrators are collectively referred to as the NAN.

![AMI common architecture](image-url)
The most adopted network architecture of the RF Mesh System follows the model shown in Figure 3.1. Metering end points (smart meters) transmit and receive data at a speed of 9.6 kbps whilst Router nodes and concentrators (or collectors) are able to transmit and receive at either 9.6 kbps or at double this speed, namely 19.2 kbps. Routers are typically mounted strategically on pole tops or on lamp posts and enjoy an improved high-speed line of sight communication to other Routers or ideally even the Collector itself. The Router mesh acts as a high speed communication highway for the meter traffic and are also used as range extenders to bridge areas where there are no meters or only scarce populations of meters which would otherwise lack mesh connectivity to a Collector. Collectors are deployed throughout the Utility’s service area to cover the entire population of meters. The number of Routers and concentrators required in a network depends on the distribution of end points [19].

However, most solutions are proprietary and not standardized for NAN, being part of the Smart Grid Networks architecture, established in Technical Standard for Smart Grid IEEE 2030. This new standard, launched in September 2011 by IEEE Standards Association (IEEE SA) defines Smart Grids standardized architectures, concepts, elements, connections and interoperability. A new standard specific to mesh networks based on IEEE Technical Standard 802.15.4g will attain the current and future requirements, functionality and interoperability of mesh networks with NAN topology of smart Grid Networks defined in IEEE 2030 [21]. So, the new topology and the topology used in this thesis is presented in Figure 3.2, where there are only two elements in the network, the smart meters and the concentrators.

![AMI new standard architecture](image)

Figure 3.2 AMI new standard architecture (extracted from [21]).

### 3.3 Main features

Many deployment AMI systems present proprietary features that not are easily disseminated to the public, hence in this thesis the most commonly features are used. The communication system in study
is a multi-hop mesh network made of smart meters and concentrators and one of the most commonly used network topologies. NAN considers the use of smart meters based on ZigBee Mesh IEEE 802.15.4 communication protocol and other backhaul technology for the concentrator which is connected directly with the utility HES. The communication channel is the unlicensed industrial, scientific and medical (ISM) band of 902-928 MHz. The ISM frequency band is divided into 240 discrete channels, each of which has a 100 kHz bandwidth. Transmissions from any given node occur on a different frequency channel for each time slot according to a frequency hopping sequence which is determined according to the nodes network identity. A transmission node selects a subset of channel frequencies from the 240 available and repeatedly hops between channels, as represented in Figure 3.3. The sequence is conveniently shifted in time in order to avoid that all the devices use the same channels simultaneously. Any node is able to determine the receiving frequency channel of its neighbors at any time; therefore, before transmitting a packet to a neighbor node \( j \), node \( i \) can tune its antenna to the frequency channel of node \( j \). The system uses Frequency Hopping Spread Spectrum (FHSS), which is a technique particularly efficient against low spectrum interference coming from other devices transmitting on the same band, generated by the transmission of multiple devices using the same frequency band, either within the same NAN or in different networks. The access to the medium is regulated by a synchronous ALOHA with 0.7 s time slots and each network node transmits its data using Frequency-shift keying (FSK) modulation in the allotted time slot. Device synchronization is achieved through the Network Time Protocol (NTP); collectors are equipped with high precision clocks (e.g. iridium) and provide a reference time for the other nodes. NTP can ideally yield good results in terms of synchronization of extended networks: unavoidable errors in synchronization are tackled by restricting the portion of time in which it is possible to transmit to only 400 ms out of the available 700 ms, thus leaving the remaining 300 ms intentionally idle as a safety margin [19] [20] [21] [22].

Figure 3.3 Example of frequency hopping sequence (extracted from [22]).

### 3.4 Communication Technologies

There are three basic types of smart meter system communication technologies: RF, PLC and cellular communications. In smart grid applications, there are different advantages and disadvantages associated with them. The utilities choose the best technology based on their business profits. Making the right decision to choose which technology requires a thorough evaluation and analysis of the existing needs and the future benefits for business. In table 3.1 is presented the main features of each technology.
applied in smart grid systems.

There are factors that impact the selection of the technology, such as:

- Evaluation of existing infrastructure;
- Impact on legacy equipment, functionality, technical requirements as well as the economic impact to the utility's customers [23].

<table>
<thead>
<tr>
<th>Technology</th>
<th>Spectrum</th>
<th>Data rate</th>
<th>Coverage range</th>
<th>Applications</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM</td>
<td>900-1800 MHz</td>
<td>Up to 14.4 kbps</td>
<td>1-10 km</td>
<td>AMI, Demand Response, HAN</td>
<td>Low data rates</td>
</tr>
<tr>
<td>GPRS</td>
<td>900-1800 MHz</td>
<td>Up to 170 kbps</td>
<td>1-10 km</td>
<td>AMI, Demand Response, HAN</td>
<td>Low data rates</td>
</tr>
<tr>
<td>3G</td>
<td>1.92-1.98 GHz; 2.11-2.17GHz (licensed)</td>
<td>384 kbps- 2 Mbps</td>
<td>1-10 km</td>
<td>AMI, Demand Response, HAN</td>
<td>Costly spectrum fees</td>
</tr>
<tr>
<td>WiMAX</td>
<td>2.5 GHz; 3.5 GHz; 5.8 GHz</td>
<td>Up to 75 Mbps</td>
<td>10-50 km (LOS); 1-5 km (NLOS)</td>
<td>AMI, Demand Response</td>
<td>Not widespread</td>
</tr>
<tr>
<td>PLC</td>
<td>1-30 MHz</td>
<td>2-3 MHz</td>
<td>1-3 km</td>
<td>AMI, Fraud Detection</td>
<td>Harsh, noisy channel environment</td>
</tr>
<tr>
<td>ZigBee</td>
<td>2.4 GHz; 868-915 MHz</td>
<td>250 kbps</td>
<td>30-50 m</td>
<td>AMI, HAN</td>
<td>Low data rate; short range</td>
</tr>
</tbody>
</table>

Table 3.1 Smart Grid Communications Technologies (extracted from [23]).

### 3.4.1 ZigBee (IEEE 802.15.4)

#### 3.4.1.1 Standard

IEEE 802.15.4 is a member of the IEEE 802 family, but it does not mean that all the features of all the other IEEE 802 standards are included or even desired for this low-rate, low-duty cycle standard. The mission for this standard was to empower simple devices with a reliable, robust wireless technology that
could run for few years on standard primary batteries [24].

The lack of a standard and protocol, the utility is “locked-in” to a particular vendor once they have selected their system solution and was seen as a major impediment to large scale manufacture. In early 2003 the IEEE 802.15.4 standard was ratified after many years of effort and represented a significant break from the “bigger and faster” standards that the IEEE 802 organization continues to develop: instead of higher data rates and more functionality, this standard was to address the simple, low-data volume universe of control and sensor networks [24] [25].

ZigBee offers a layered architecture based on the MAC (Medium Access Control) and PHY (physical) layers of the IEEE 802.15.4 standard. This design offers low power consumption and guarantees a longer battery life, which is one of the most important issues of wireless networks. Since ZigBee is based on IEEE 802.15.4 it inherits a low data rate, and a reception distance of about 100-150 meters, depending on environmental conditions. For the upper layers one of the most important characteristics of ZigBee is the possibility of using one of two types of routings: mesh and tree, explained in detail below. This gives the application designer much more freedom to get the maximum gain out of each option depending on the very own needs of the solution they develop [26].

The protocol also offers a framework application to make easier and faster the development of simple standard applications. Also, in order to promote the reuse of already existing functionalities, libraries and profiles have been created to facilitate the construction of the most frequently needed devices within the application environments that ZigBee has been created for. This is why ZigBee can not only be considered as a simple set of commands for the communication between sensor nodes, but as a whole framework that allows the creation of standard devices, assuring the interoperability between different manufacturers [26].

![Typical 802.15.4 Device](extracted from [24])

Figure 3.4 Typical 802.15.4 Device (extracted from [24])

Figure 3.5 shows the overall device architecture, with RF channel represented as the physical medium, the PHY layer controlling the RF channel characteristics, and the MAC layer controlling the PHY layer.
3.4.1.2 **Network Techniques**

The IEEE 802.15.4 specification provides guidance on possible network types; however, in terms of specification it codifies only tools that are necessary for formation of a network, but of unspecified topology or usage. Figure 3.6 shows two of the suggested types. The first, a star topology, is common to 802.11 and other host-client networks. The second type, the peer-to-peer, allows each device to communicate directly with peer devices and at its simplest defines direct communications between two devices. All messages from any client device must pass through the hub (Personal Area Network (PAN) coordinator), which is responsible for keeping the network running and managing other devices. Devices can have full function and are classified as Full Function Devices (FFD) or have reduced function and be called Reduced Function Devices (RFD). An FFD is a device that is capable of serving as the WPAN coordinator or a coordinator. An RFD is a device that is not capable of serving as either a PAN coordinator or a coordinator. An RFD is intended for applications that are extremely simple, such as a light switch or a passive infrared sensor; it does not have the need to send large amounts of data and only associates with a single FFD at a time. Consequently, the RFD can be implemented using minimal resources and memory capacity. However, this method also may be used to create a mesh network if a higher layer entity chooses to do so [24].
3.4.1.3 **PHYsical layer**

In recognition to create a standard for physical layer radio communications required for utility NAN, utility companies, smart meter vendors, semiconductor manufacturers, and research institutes worked together in the IEEE 802.15.4g task group within the 802.15 working group. The IEEE 802.15 is the body that has successfully standardized many wireless radio standards that are targeted for low data rate and low power applications with short range. With standardization effort of 802.15.4g, 802.15 expanded its portfolio to cover longer range applications.

The scope of IEEE 802.15.4g includes:

- Operation in available license exempt frequency bands, such as 700 MHz to 1 GHz bands and the 2.4 GHz band.
- Variable number of channels between 1 and 16 according to the respective bands.
- Bandwidth of at least 600 kHz until to around 5000 kHz.
- Data rates of at least 20 kbps but not more than 250 kbps.
- Symbol rate values from 20 to 62.5 kbps.
- PHY frame sizes up to a minimum of 1500 octets.

Ensure coexistence with other systems operating in the same band including IEEE 802.11, 802.15 and 802.16 systems [24] [25].
<table>
<thead>
<tr>
<th>Frequency Band (MHz)</th>
<th>868.3</th>
<th>902-928</th>
<th>2400-2483.5</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Channels</td>
<td>1</td>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>Bandwidth (kHz)</td>
<td>600</td>
<td>2000</td>
<td>5000</td>
</tr>
<tr>
<td>Data rate (kbps)</td>
<td>20</td>
<td>40</td>
<td>250</td>
</tr>
<tr>
<td>Symbol Rate (ksps)</td>
<td>20</td>
<td>40</td>
<td>62.5</td>
</tr>
<tr>
<td>Unlicensed Geographic Usage</td>
<td>Europe</td>
<td>Americas (approx.)</td>
<td>Worldwide</td>
</tr>
</tbody>
</table>

Table 3.2 IEEE 802.15.4 Frequency Bands and RF parameters (based on [24]).

As an example, the Data frame is depicted in Figure 3.7. Its structure is similar to the other 3 frame types. The Synchronization header (SHR) contains a preamble sequence (32 bits, or 4 octets) to allow the receiver to acquire and synchronize to the incoming signal and a start of frame delimiter that signals the end of the preamble. The PHY header (PHR) carries the frame length byte, which indicates the length of the PHY Service Data Unit (PSDU). The SHR, PHR and PSDU make up the PHY Protocol Data Unit (PPDU). The PSDU contains the MAC Header (MHR), which has two frame control octets, a single octet Data Sequence Number, good for reassembling packets received out of sequence, and 4 to 20 octets of address data. The MAC Service Data Unit (MSDU) carries the frame's payload and has a maximum capacity of 104 octets of data. Finally, the MAC Protocol Data Unit (MPDU) ends with the MAC Footer (MFR), which contains a 16-bit Frame Check Sequence [24].

There are three different PHYs specified in the 802.15.4g standard: MR (Multi-rate and multi-regional)-FSK, MR-OFDM, and MR-OQPSK. There are particular reasons for each of these PHYs. The MR-FSK PHY recognizes that the most of deployed systems in America are based on FSK modulation schemes, specifically those operating in the 902-928 MHz frequency band utilizing FSK modulation with FHSS. In addition to unlicensed bands, FSK is also used by sub GHz licensed bands that is deployed in some systems in America, while FSK PHYs are predominately used by existing systems, the 802.15.4g task group also defined an MR-OFDM PHY which will support higher data rates. The third PHY supported by the 802.15.4g work is an OQPSK PHY similar to the previous PHY defined by 802.15.4 based products have been widely used in wireless sensor networks, wireless remote controls and home area networks [25].
3.4.1.4 Medium Access Control layer

The sub-layer MAC protocol specifies beacon-enabled and beaconless modes of operation. In the beaconless mode, devices communicate asynchronously, requiring nodes to be constantly in the receive mode, awaiting reception of data transmission from other devices. Devices compete for channel access using an un-slotted non-persistent Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol and no QoS mechanism is used in this mode, hence, rendering it suitable for applications without QoS constraints [26].

In the beacon-enabled mode, devices are required to synchronize their actions and coordinate data delivery with each other. FFDs periodically transmit beacon frames to synchronize wakeup (or sleep) schedules with neighboring nodes. Channel access and data transmission are carried out using IEEE 802.15.4 standard super-frame structure (Figure 3.8). The main purpose of the beacon is to synchronize devices in the network, to identify the PAN coordinator, and to describe the super-frame structure. In order to reduce energy consumption, the coordinator introduces an inactive period by choosing Beacon Interval ($BI > Super-frame Duration (SD)$). During inactive period, all devices including the coordinator go into a sleep mode. $BI$, $SD$ and the $sd$ (slot duration which is one sixteenth of the active period) are determined by two parameters, the Beacon Order ($BO$) and the Super-frame Order ($SO$), and defined respectively, as [26]

\[
BI = aBaseSuperframeDuration . 2^{BO} \tag{3.1}
\]

\[
SD = aBaseSuperframeDuration . 2^{SO} \tag{3.2}
\]

\[
sd = aBaseSlotDuration . 2^{SO} \tag{3.3}
\]

\[
for \ 0 \leq SO \leq BO \leq 14 \tag{3.4}
\]
In the beacon-enabled mode, the PAN coordinator allows the other network nodes to reserve dedicated time slots to satisfy the bandwidth and latency requirements via a Time Division Multi Access (TDMA) method. These slots are branded as guaranteed time slots (GTS) and each node can assign up to two GTSs (one for receive and one for transmit), and one GTS may have more than one slot. The number of GTSs cannot surpass seven. These contiguous time slots form a contention free period (CFP) that is placed at the end of the active period of the super-frame as shown in Figure 3.8. To use the GTS, the node has to send a GTS request to the PAN coordinator in the contention access period (CAP) and when validated the coordinator will advertise in its beacon all the information related to the GTS allocation. The node has to keep tracking the beacon for any likely changes (de-allocation or reallocation). The node will be allowed to use its GTS only when the beacon is received otherwise it has to wait for the next beacon [26].

### 3.4.1.5 Routing Protocols

ZigBee network present some kind of routing packets methods, which are divided into three groups of protocols, the Table-Driven Routing Protocol (Proactive), the Source-Initiated On-Demand Routing (Reactive) and Hybrid routing.

In the Protocols using tables (Table-Driven Routing Protocol), each node can store routing information in the form of one or more tables, which contain information about all the network nodes. Thus, routes are computed and stored, even when they are not needed, incurring in a considerable overhead and bandwidth consumption due to the number of messages that have to be exchanged to keep routing information up-to-date. Proactive protocols may be impractical for large and dynamic networks. As an example of this type of protocol is Destination-Sequence Distance-Vector Routing (DSDV), which uses a well know packet routing implementation, the Bellman-Ford algorithm [21] [27].

In routing on-demand protocols (Source-Initiated On-Demand Routing) the establishment of the routes is made on demand, in other words, it only computes routes when they are needed. The process of finding a suitable route requires the transmission of route requests and the wait for replies with a path
to the destination. Due to the delays incurred in this process, this approach is not suitable for operations that require immediate route availability. The main representative type of this protocol is Ad-hoc On-Demand Distance Vector (AODV). This protocol is the established standard algorithm for packet routing in ZigBee networks. If the ZigBee devices configuration is not changed, this is the routing protocol that is running in the network. Once the protocol AODV relies on shortest path algorithms, it is considered the implementation of such algorithms, which minimizes the cost of routes in the meters of the mesh network. In order to calculate the best route, the procedure of the AODV is as follow:

- The source node sends to all its neighbors a packet called Route Request (RREQ);
- The neighbors will send to its neighbors successively until it finds the destination node.

It should be noted that once a node receivers a RREQ, and this is not a destination node, it stores in its routing table and address of neighbors in order to produce a reverse path. Thus, it is possible to dispose of repeated RREQ arriving at a node by different paths [21] [27].

Neither proactive nor reactive protocols provide an optimal solution for the hybrid WMNs. Ad hoc regions, the ones formed by clients, have some mobility and thus reactive protocols are most suitable because route updates are frequent. On the other side, the backbone has reduced mobility, thus proactive routing allows to maintain routes with low overhead.

Hybrid approaches aim at providing an optimal solution by combining the best properties of both proactive and reactive protocols. Hybrid routing uses different routing protocols in different parts of the hybrid WMN: reactive protocols for ad hoc zones and proactive ones in the backbone [27].

### 3.5 Geographical routing

The RF Mesh System supports peer-to-peer communication by employing a routing scheme which utilizes the geographical coordinates (latitude and longitude) of the communicating nodes. During commissioning, metering end points are automatically provided with the geographical coordinates of the concentrator which represents the target or destination for their upstream communication whilst the concentrator knows the coordinates of target smart meters for downstream communications. In each case the transmitting node discovers the geographical coordinates of its neighboring nodes and is therefore able to select a neighbor which is geographically the closest to the final destination node. Thus the communication path will have the minimum number of hops ensuring the lowest latency. The typical latency achieved using this approach is approx. 5–8 seconds for a round trip from concentrator to end point depending on the number of hops. In addition, a time to live mechanism is incorporated so packets are not repeatedly retried [19].
3.6 Retransmission protocol

Smart meters having established its neighbors a transmitting node sends its frame to the preferred neighbor according to the routing protocol and within its allocated time slot. The node then waits for an immediate acknowledgment and if this fails to arrive within the time slot it is assumed that the communication link to this neighbor has failed. An alternative neighbor is then chosen for a subsequent retransmission attempt. This process is repeated up to a configurable retry limit. In practice this proves to be more efficient than repeatedly retrying with the preferred neighbor because if that link is down due to an obstruction, for example, it tends to remain down for a time exceeding the retry limit whereas an alternative neighbor is immediately available [19].

3.7 Traffic characterization

Let’s suppose that the set of smart meters is representing by $M$ and the set of concentrators is representing by $C$. Let $\lambda_{m-up}$ be the mean traffic from each smart meter to the collector (uplink) and $\lambda_{m-down}$ the mean traffic from the collector to a single smart meter (downlink). In both cases, Poisson arrivals are assumed so that the aggregation of traffic streams at each node is also Poisson with a mean value equal to the sum of all sub-streams mean values. Let $\lambda_i$ be the transmission rate of generic device $i$. In order to characterize $\lambda_i$, the routing behavior of each device must be analyzed. Intermediate nodes are in charge of transmitting packets from the origin to the destination of the shortest paths they belong to. For this purpose, the variable $\epsilon_i$ is introduced, the number of shortest paths that contain node $i$ as an intermediate node. Then, a given smart meter $i \in M$ transmits its own packets to the collector at a data rate $\lambda_{m-up}$, packets from $\epsilon_i$ smart meters to the collector at a rate $\lambda_{m-up}$ and finally packets from the collector to the $\epsilon_i$ nodes at a rate $\lambda_{m-down}$. On the other hand, collectors transmit to each of the $|M|$ smart meters with a rate $\lambda_{m-down}$. These considerations can be summarized as follows [20]:

$$\lambda_i = \begin{cases} \epsilon_i(\lambda_{m-down} + \lambda_{m-up}) + \lambda_{m-up} & \text{for smart meters} \\ |M|\lambda_{m-down} & \text{for concentrators} \end{cases}$$

(3.5)

The actual transmission rate also depends on the number of packet retransmissions caused by collisions. In particular, if $N_i$ represents the average number of retransmissions at node $i$, the actual transmission rate can be defined as $\tilde{\lambda}_i = N_i \lambda_i$. The average number of retransmissions and the link with the collision probability is deeply analyzed in the next section [20].

Suppose there are $|M|$ smart meters in a given area as part of the AMI application, all connected to a concentrator. As the rate of data generation by smart meters are not necessarily synchronized, an average rate of data generation per second is a more useful value. Let each meter generate a data packet $P$ bytes long at an interval of $t$ minutes. Thus, the average data traffic rate reaching the concentrator from $|M|$ smart meters will be [28]:

---

36
\[
\lambda = \frac{|M| P}{60t} \text{ bytes/sec} = \frac{|M| P}{7.5t} \text{ bits/sec} \quad (3.6)
\]

Current standards specify that each smart meter sends a 512 byte packet every 5, 15, 30, or 60 minutes, but 15 minutes is the most common. Thus, henceforth it is used the interval of 15 minutes for evaluations. This translates to a data rate of \( \lambda = 4.55|M| \) bps arriving at the concentrator. This analysis can be further extended to include the concept of smart meter density. For example, assume that each house in a residential neighborhood has a smart meter, and the smart meter density (equivalent to housing density) per square meter, say \( \rho_h \), is known. So, given the area of the location of interest, \( A \), and the housing density, \( \rho_h \), the expected data traffic arriving at the concentrator would be [28]:

\[
\lambda = \frac{\rho_h A P}{60t} \text{ bytes/sec} = \frac{\rho_h A P}{7.5t} \text{ bits/sec} \quad (3.7)
\]

### 3.8 Probability of collision

One of the main issues in a wireless communication system is interference. If it is assumed that the interfering ray equals the covering ray, every node’s neighbors are its possible interferers. If it is neglected for the moment FHSS, it can be supposed that there is a collision at node \( i \) when at least one of its neighbors attempts to transmit during the same time slot. When a collision is experienced, the involved packets have to be retransmitted. The average number of times a packet at node \( i \) is retransmitted, \( N_i \), is related to the average collision probability \( (p_i) \) by [20]:

\[
N_i = \frac{1}{1 - p_i} \quad (3.8)
\]

As stated in section traffic characterization, the transmission rate of a set of nodes has a Poisson distribution with the sum of all \( \lambda_j \) as a mean value. Given \( I_i \) the set of interferers of node \( i \), the probability that none of the nodes \( j \in I_i \) transmits in a time-slot of duration \( r \) is:

\[
P(X_{t_i} = 0) = e^{-r \sum_{j \in I_i} \lambda_j} = e^{-r \sum_{j \in I_i} N_j \lambda_j} = e^{-r \sum_{j \in I_i} \frac{\lambda_j}{1 - p_j}} \quad (3.9)
\]

where \( X_{t_i} \) is the number of nodes in \( I_i \) that transmit during that time-slot. Then, the probability that collisions occur is:

\[
p_i = P(X_{t_i} > 0) = 1 - P(X_{t_i} = 0) = 1 - e^{-r \sum_{j \in I_i} \frac{\lambda_j}{1 - p_j}} \quad (3.10)
\]

On the other hand, if one take into account FHSS, the definition of collision changes: a collision occurs
at node $i$ when at least one of its neighbors is transmitting on the same channel as $i$. In FHSS modeling, each node randomly decides the transmission channel among the $Q$ available. Let us consider the event that at least one of the $k$ neighbors of $i$ chooses the same channel as $i$. This is the complement of the event in which all the $k$ nodes choose different from $i$. Therefore, the probability that at least one of the $k$ nodes chooses the same transmission channel as $i$ is given by [20]:

$$p^{(k)} = 1 - \left(1 - \frac{1}{Q}\right)^k \quad (3.11)$$

As a consequence, a collision occurs when there is at least one transmitting neighbor of node $i$ using the same channel as $i$. Therefore, the probability of collision is calculated as follow:

$$p_i = \sum_{g=1}^{+\infty} p(X_i = g)p^{(g)} = \sum_{g=1}^{+\infty} \left(1 - \left(1 - \frac{1}{Q}\right)^g\right) \frac{\lambda_i \tau \sum_{j \in i} \lambda_j}{(1 - p_j)^g g!} e^{-\tau \sum_{j \in i} \lambda_j (1 - p_j)} \quad (3.12)$$

This is a so-called fixed point equation, i.e., the problem of finding the values of $p_i$ that solve the non-linear equation in (3.12).

In [22] was done a study that shows how the probability of collision varies with the traffic with or without FHSS. It was assumed the same packet generation rate in uplink ($\lambda_{up}$) for all the smart meters and also the same packet generation rate ($\lambda_{down}$) from the collector to every smart meter. In multiple runs, the mean packet generation times ($1/\lambda_{up}$ and $1/\lambda_{down}$) vary in the interval between 0.5 and 4 hours in order to highlight the performance of the system at different traffic loads, representative of different smart grid applications.

In Figure 3.9, it is reported the variation of the maxima (dashed line) and the averages (continuous line) of collision probabilities with respect to packet generation rates in uplink and downlink. In particular, was used fixed values of the mean generation time in downlink ($1/\lambda_{down} = 1, 2, 3, 4$ hours) and drew the variation of collision probability according to $\lambda_{up}$. This figure shows that the collision probabilities do not undergo large variations as the traffic generation rate changes. For instance, the mean of the collision probability when $1/\lambda_{down} = 1$ hour is 0.22% at $1/\lambda_{up} = 4$ hour and 0.52% at $1/\lambda_{up} = 30$ minutes [22].

In order to highlight the impact of FHSS protocol on the performance analysis results, Figure 3.10 reports a comparison of the collision probabilities found with FHSS (in gray) and without FHSS (in black). For the sake of clarity in the comparison, traffic scenarios IDs represented in table 1 are used in this figure. A reduction of collision probability greater than an order of magnitude was found in all the scenarios; therefore it can be said with certainty that FHSS has a key impact on the performance of large scale RF-mesh system [22].
3.9 Delay and Bandwidth

A basic parameter in the analysis of the performance of a telecommunication network is delay. In a multi-hop random access system with small packets, such as Time-Slotted ALOHA, it is a standard practice to let the time slot duration include all other types of delay a packet can encounter. In the rest of the discussion, propagation, transmission and processing delays are included in the 0.7s time slot. In this first analysis, the queueing delay is considered negligible since it is to deal with very low data rates. In the light of these considerations, the average delay can be calculated based on the number of hops.
a packet makes in order to reach its destination only. The delay of a generic n-hop path such as the one displayed in Figure 3.12 can be calculated as follows [20]:

\[
d_{ij} = \tau \sum_{k=0}^{n-1} N_k
\]  

(3.13)

Note that in (3.13), delay depends exclusively on the length of the shortest path as well as the probability of retransmission of the system. It counts for two different types of delay: \(d_u\) is the uplink delay, the time necessary for a packet generated by a smart meter to get the concentrator; \(d_d\) is the downlink delay, the elapsed time for a packet to travel from the concentrator to a smart meter [20].

Assuming the typical packet delay as between 5-8 s as referred before, is possible to compute an additional constraint is the number of allowable levels (or hops) in the tree structure. Operators usually specify a maximum hopping depth for the system. "Hopping depth" does not refer to the number of packet hops being made between devices, but is related to the physical tree structure itself. Essentially, a device should only forward packets beyond itself to a certain tree depth, creating a system wide design constraint on what should be considered as reachable by the network. Without a limit on tree depth, a packet could be forwarded many levels via many routes increasing latency. In addition, each new route created by a hop increases the statistical chance of failure. And, each failure may require a retransmission all along a particular route (a chain), requiring additional system resources at every step of the way, thus consuming additional data bandwidth and reducing overall network capacity. Initially, AMI systems were designed for simple meter reading where data speed was not a factor. However, operators are now looking at adding support for Distribution Automation features and other emerging system operation/control features. These new features can require high data throughput with low latency. The requirement to optimally use system resources to improve available bandwidth and to meet latency targets is a critical factor in system design as well as affecting overall system cost [29].

Bandwidth requirements are of two forms. First, the total traffic inside is bounded by the capacity of the gateway collector, based on its connectivity to the internet and its processing speed, assuming that each smart meter generates an equal amount of traffic. Guaranteeing a throughput for individual flows in a multi-hop wireless network is more challenging. Since these systems work with multi-channel where interfering wireless links operate on different channels, enabling multiple parallel transmissions. The bottleneck on throughput is therefore reduced to the load of congested intermediate wireless links and its equal to the capacity of individual wireless links [30].
3.10 Security

As it turned out, IEEE 802.15.4 standard fits well with AMI networks. However, the security features provided by the MAC sublayer are not quite sufficient. Therefore, we propose a communication scheme which deals with potential security and privacy threats in the application layer. The following security requirements are considered for our scheme:

- **Device Authentication**: Any smart meter’s identity must be securely authenticated before it can join the AMI network and exchange data with other devices.
- **Data Confidentiality**: All data packets exchanged in the network, including meter readings and control messages, must be kept confidential so that only authorized entities, with corresponding credentials, are allowed to access specific sets of data.
- **Message Integrity and Authenticity**: When a message arrives at its destination, the recipient should be able to verify whether the message remains unaltered and if it comes from the sender it claims.
- **Privacy Protection**: Any sensitive data, which might be used to deduce private information, should only be known to their owner [31].

![Diagram of Device Registration Process](image)

**Figure 3.13 Device Registration Process (extracted from [31]).**

In terms of network device registration, the process is the following. Each newly installed smart meter should register with the utility before it can start to communicate. During the registration process, its identity must be authenticated, which is the very first step to ensure the security of the whole AMI system. In our scheme, Paillier cryptosystem, which is an additive homomorphic cryptosystem, this means that, given only the public-key and the encryption of $m_1$ and $m_2$, one can compute the encryption of $m_1+m_2$, is adopted at all smart devices. It is assumed that each smart meter holds its built-in private key while the authentication server of the utility knows the meter’s ID and public key, which can be provided beforehand by smart meter manufacturers. Figure 3.13 illustrates the data flow of the device registration process. Specifically, this process takes place in the following steps:

1) The newcomer smart meter initializes a registration request message. The message body consists of the smart meter’s ID and request content in a pre-defined format. The entire message is signed by the smart meter’s private key.

2) The smart meter passes the message to the collector with other smart meters possibly used on the way. The collector then forwards the message to the authentication server of the utility.
3) The authentication server finds the smart meter’s public key, according to the ID contained in the message, and verifies the signature. If the signature is valid, it replies to the collector with an “Accept” message and the smart meter’s public key; otherwise it replies with “Decline”.

4) The collector checks the received response. If the response is “Accept”, it sends an acknowledgement message and its own public key to the smart meter and adds a new entry to its registered device list. This list records the IDs and public keys of all successfully registered devices. Otherwise, it notifies the meter that the request is declined.

After registration completes, the smart meter and the collector know the public key of each other. Therefore, they are always able to set up a secure communication session later on. Also, by recording all information in the registration request message, the collector can gather all necessary topology information of this multi-hop smart meter wireless network when all smart meters are successfully registered [31].

3.11 Meter Readings and Data Aggregation

Smart meters typically capture metering interval data every 15 minutes. This data is transferred to the concentrator via the RF mesh network using a push mechanism. The traditional data aggregation method, in which each smart meter sends its data to the collector separately, is not applicable here, since the collector is able to access the data of any specific user. Instead, it is used an in-network aggregation scheme to protect customer privacy. In this scheme, the intermediate aggregation results are calculated along the way and the collector always receives a summation of all smart meters’ readings. Any sensitive data directly related to private information are only readable by their owners [19] [31].

First, it is needed to build an aggregation path that covers all registered smart meters in the neighborhood. If the smart meter network as a graph where all devices are vertices and available wireless links between any two devices are edges, then such a path naturally forms a spanning tree of the graph, which is called an aggregation tree. It is convenient to view the path in a top-down manner as a rooted tree, where the collector node is the root, as shown in Figure 3.14. The data are passed from the bottom to the top along the tree edges during the aggregation process. Since the collector is aware of the network structure as well as a routing backbone, it can construct an aggregation tree based on the routing backbone by simply connecting non-backbone nodes. When necessary, the collector can adjust the structure of the tree for better performance. When the aggregation tree is finally determined, the collector notifies each smart meter of the necessary information for aggregation, respectively. For a single smart meter, it only needs to know: 1) The IDs and public keys of its children nodes; 2) The ID and network address of its parent node.

The aggregation process is supposed to occur at a fixed frequency every day. It is assumed all smart meters are equipped with synchronized clocks such that they can initialize the aggregation
simultaneously when aggregation time arrives. The operations for each smart meter are essentially the same:

1) Encrypt its power usage data with the public key of the collector.
2) Wait for the data from its children (if any). When the data arrives, verify the integrity of the data received using public keys of the children.
3) Calculate intermediate aggregated result by multiplying its own data with the received data (if any).
4) Generate a digital signature with the intermediate aggregated result and current timestamp. The timestamp is a one-time bit sequence that indicates current aggregation time. It is unique and different for each aggregation process.
5) Send the aggregated result combined with the signature to its parent [31].

Figure 3.14 An example of aggregation tree (extracted from [31]).

3.12 Demand Response and Outage Detection

The concentrators are connected to the Utility HES via backhaul technologies connections which can either be maintained on a permanent basis or scheduled when needed for metering data transfer. The utility HES also transfers commands and demand response event messages downstream to the meters via the concentrator and RF mesh network. Such event messages may conduct to an immediate response from the smart meter such as a pricing confirmation message or a response to an instantaneous read request. These confirmation messages are prioritized by the concentrator and sent upstream to the HES [19].

Smart meters also detect any changes to the line conditions and are able to detect and report loss of power. These devices are equipped with super capacitors and concentrators are battery backed to ensure that such outage detection reports are successfully transferred to the utility HES [19].
3.13 Firmware Upgrades

Smart Grid standardization activities are still ongoing and it is likely that standards will evolve during the life time of the deployed meters and networking nodes. It is therefore important to allow the firmware protocol stacks to be remotely upgradeable over the air interface. The RF Mesh System supports such firmware upgrades in a secure and controlled manner. Only authenticated firmware images are accepted by the nodes and these must be provided via the Utility HES. New firmware is propagated or flooded across the metering population or network nodes requiring the upgrade. Switch over to the new protocol stack is achieved in a time coordinated manner across the network [19].
Chapter 4

Simulator Analysis

This chapter presents the simulator to solve the problem described. Also, is given the intermediate steps and final solutions of the simulations for the two scenarios.
4.1 Introduction

A great deal of research effort is currently being devoted to the performance study of RF-mesh networks. The importance of this theme is derived from the increasing interest in new smart grid applications. The main approaches that have been followed in literature can be grouped in two subcategories: stochastic simulations and real-field measurements. Both approaches have some strong points as well as some shortcomings. As a matter of fact, a well configured simulator can perform significant performance studies with great savings, and can be helpful in designing and testing new and not yet implemented features and solutions for existing systems. On the other hand, real-field measurements permit real systems analyses and not of a modeled version of these. Also, testing systems in a real environment can give deeper insights on their characteristics: some features (e.g. realistic propagating conditions) are very difficult to predict and model, and real field tests can cast light on inconsistencies of the model, which a simulator could hardly discover because of the ideal environment it works within.

A third approach, which I decided to follow, is totally analytic: known properties of wireless networks are used to find mathematical equations that allow analyzing the system’s performance. The analytic methodology can reduce the computational burden typical of simulations and can be easily extended to different scenarios and technologies [22].

4.2 Optimization problems for WMNs

With the emergence of wireless networking paradigm, several optimization problems are showing their usefulness to the efficient design of such networks. These problems are related, among others, to optimizing network connectivity, coverage and stability. The resolution of these problems turns out to be crucial for optimized network performance. In the case of WMN, such problems include computing placement nodes (gateways and distribution of mesh client nodes), so that network performance is optimized. However, most of these optimization problems for WMN are hard to solve in acceptable time. For instance, in the case of this thesis, mesh gateway node placement belongs to the family of node placement problems, which are known for their hardness to solve them optimally [30].

Different optimization problems can be formulated based on the objectives to optimize and set of different constraints, such as topological restrictions, battery restrictions, QoS requirements, etc. Some optimization problems are related to minimize the cost of WMN, such as minimizing the number of mesh gateway nodes to deploy, while others focus on the WMN performance, such as computing optimal placement of an a priori fixed number of mesh gateway nodes. The presence of many objectives is in fact a main challenge. These objectives include minimizing the number of mesh gateways, maximizing network connectivity, maximizing user coverage, minimizing energy consumption (especially in wireless and mobile networks), minimizing communication delay, maximizing throughput, minimizing deployment cost, etc. And, additionally, there could be certain constraints to take into account such as topological
restrictions of the geographical area, interference model, etc. It should also be noted that some of the objectives are contradicting, in the sense that trying to optimize some objectives goes in detriment to the optimization of another objective [30].

4.2.1 Wireless Mesh Networks

In most modern networks, links and nodes are interconnected (both logically and physically) in either a:

- star arrangement, with each node connected directly to a central switch, hub or server;
- bus configuration, with each node attached to a central line that is connected to a central switching component;
- ring topology, with each node connects to exactly two other nodes, forming a single continuous pathway for signals through each node - a ring;
- tree topology, which is essentially a combination of bus topology and star topology.

All of these configurations are well understood, inexpensive and generally reliable, but one broken link in either setup can isolate a node, cutting it off from the network [32].

![Network topologies](image)

Figure 4.1 Network topologies (extracted from [33]).

A newer arrangement, mesh topology, connects each node to at least two other nodes and potentially to each and every other network node, an arrangement referred to as "fully connected". This involves more cabling (or more wireless devices) and greater overhead, but it allows the network to heal itself automatically when a break occurs. Therefore, mesh network is a LAN (usually wireless, called WMNs) where each node is connected to many others, configured to allow connections to be rerouted around broken or blocked paths, with the signal hopping from node to node until it reaches its destination. The lack of a hub-and-spoke structure is what distinguishes a mesh network. Also, meshes don’t need designated routers; instead, nodes serve as routers for one another. Thus, data is passed from node to node in a process called hopping [32].

Wireless networking is an ideal vehicle for setting up a mesh network, because it can be done quickly and on an ad hoc basis. Wireless mesh nodes are small radio transmitters that function much like
wireless routers. For larger mesh networks, however, such as those designed for cities or large enterprises, certain nodes must be dedicated as backhaul nodes. The other nodes send all outgoing information to a backhaul node, which sends it to the utility without extra hops. The Table 4.1 shows the pros and cons of using mesh networks.

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>• They're self-healing: If any node fails, another will take its place.</td>
<td>• They're still in development.</td>
</tr>
<tr>
<td>• The network gets bigger and faster as more nodes are added.</td>
<td>• Wireless links are inherently unreliable. Since this problem gets worse with each hop, the size of meshes is currently limited.</td>
</tr>
<tr>
<td>• They're convenient in locations that don't have Ethernet connections, such as outdoor concert venues, warehouses and transportation settings.</td>
<td>• They're not completely seamless. Moving nodes (e.g., those in vehicles) may not establish new connections easily. When a network's topology changes, some transmission paths can be temporarily disrupted. Thus, voice and video don't work as well on meshes.</td>
</tr>
<tr>
<td>• They're useful where line-of-sight wireless signals are intermittently blocked.</td>
<td></td>
</tr>
<tr>
<td>• LANs can run faster than other networks because local packets don't need to run back to a central server.</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1 Pros and Cons of using mesh networks [32].

As referred before, in a WMN we have two types of nodes: mesh routers and mesh clients. Mesh routers are similar to normal routers but incorporate also additional functions to support mesh networking, and are usually equipped with multiple interfaces to work with different wireless technologies. Another feature of this type of routers is their ability to provide the same coverage with much less transmitter power through multi-hop communications. Also, mesh routers can be installed on a dedicated machine or on a general purpose machine. On the other hand, mesh clients have the necessary functions for mesh networking and could also be able to act as routers but do not have the functionality of a gateway or bridge and their single wireless interface with the hardware and software platform is much simpler than in the case of mesh routers [34].

Fast development of WMN is pushed by their low cost nature that makes them an economical alternative for providing wireless Internet connectivity, especially in development countries, avoiding costs of deployment and maintenance of wired Internet infrastructures. Applications of WMNs include WMNs for urban areas, community networking, metropolitan area networks, municipal wireless mesh networks, corporative networks, medical systems, transport systems, surveillance systems, etc. In all these applications, WMN provide cost-efficient broadband wireless internet connectivity to a group of users.
WMN have relatively stable topology except for occasional node failures or additions. Practically all the traffic flows either to or from a gateway, as opposed to ad hoc networks where the traffic flows between arbitrary pairs of nodes. Gateways would be connected directly to the fixed network, and therefore constitute traffic sinks and sources to WMN [35].

The analysis of WMN scalability is based on the following scaling relationships: traffic increases with the number of nodes, and traffic also increases with the distance over which each node wishes to communicate (i.e., due to packet forwarding). In [35], showed that $\lambda_{\text{max}}$, the maximum capacity available to each node (i.e. the rate at which packets are originated), is bounded by

$$\lambda_{\text{max}} < \frac{C_1}{\bar{L} \bar{r}}$$

(4.1)

where $C_1$ is the total one-hop capacity of the network, $\bar{L}$ is the expected path length, and $r$ is the fixed radio transmission range such that $\frac{\bar{L}}{r}$ is the minimum number of hops to deliver packets.

The inequality (4.1) shows that as the expected path length increases, the bandwidth available for each node to originate packets decreases. Therefore, the network scales better when the traffic pattern is local. That is, each node sends only to nearby gateways within a fixed radius, independent of the network size.

The expected path length clearly remains constant as the network size grows. Hence, for optimal performance, the WMN should be divided into disjoint clusters, covering all nodes, or at least almost all nodes. Within each cluster, the cluster head would serve as gateway, connected to the backbone [35].

### 4.2.2 Gateway node placement

In the gateway node placement problem, the objective is to find a placement of gateway nodes such that several parameters of WMN are optimized. Depending on the parameters to be optimized and the QoS constraints for the WMN, different versions of this problem can be formulated, such as optimizing communication delay and cost or maximizing the minimum flow throughput [30].

### 4.2.3 Client mesh nodes distribution

An important issue when formulating mesh node placement is whether the client nodes are stationary or mobile nodes. WMN with stationary nodes arise in many situations, for instance, in a neighboring community. In stationary nodes case, the positions of the clients are a priori known although the mesh client nodes can be arbitrarily situated in a given area. In the case of WMN with mobile nodes, the position of client nodes can change over time. It could as well be considered the case of a WMN where
we have both stationary and mobile nodes, for instance, in a neighborhood users inside the homes are stationary and users along the roads are mobile. In both cases, it is interesting, however, to consider concrete distributions of client mesh nodes [30].

4.2.4 Multi-objective optimization model

For optimization problems having two or more objective functions described above, two models are usually considered: the hierarchical and simultaneous optimization.

- Hierarchical model: In this model, the objectives are classified according to their priority. Thus, for a problem having k objectives sorted as follows

\[ f_1 \succ f_2 \succ \cdots \succ f_k \]  

means \( f_1 \) is the most important objective, \( f_2 \) the second most important objective and \( f_k \) the less important objective. The optimization procedure would first optimize according to \( f_1 \) until no further improvements are possible. Then, the algorithm optimizes according to \( f_2 \) subject to not worsening the value achieved for \( f_1 \), and so on. This model is useful when for optimize problems some parameters (objectives) are considered of more priority than others. It should be noted that the final solution computed by the optimization procedure need not to be optimal and could be far from optimal for the less priority objectives.

- Simultaneous model: In the simultaneous approach, all the objectives are simultaneous optimizing according the importance that the user attributes to the problem. Thus, for a problem having k objectives \( f_1, f_2, \ldots, f_k \), the optimization procedure tries to optimize at the same time all the objectives, which actually leads to a global cost function:

\[ f = \alpha_1 f_1 + \alpha_2 f_2 + \cdots + \alpha_k f_k, \quad \sum_{i=1}^{i=k} \alpha_i = 1, \quad 0 \leq \alpha_i \leq 1 \]  

means \( f \) the global cost function and higher the value of \( \alpha_i \), higher the priority of the objective.

4.3 Inputs

- Smart Meters positions – The simulator receives as inputs the geographic coordinates of smart meters.
- Possible positions to put the concentrators – The simulator receives as inputs the geographic coordinates of possible positions to put the concentrators.
• Device Parameters – To discover possible links between devices it is necessary to know their transmitted power ($P_{t-SM}$ for smart meter and $P_{t-C}$ for concentrator) and their sensitivity ($P_{r-SM}$ for smart meter and $P_{r-C}$ for concentrator). This information was extracted from documents available in section 1 and section 2 of the annex D.

$$P_{r-SM} = -108 \text{ dBm} \quad (4.4)$$

$$P_{t-SM} = 26 \text{ dBm} \quad (4.5)$$

$$P_{r-C} = -105 \text{ dBm} \quad (4.6)$$

$$P_{t-C} = 30 \text{ dBm} \quad (4.7)$$

• Propagation model parameters – These parameters are location dependent. Once the band frequency is between 902-926 MHz, the model of propagation used is Extended Cost231 Walfisch-Ikegami. For this model, we need information as a frequency ($f$) used, which is 926 MHz, the maximum frequency in the band; the loss coefficient for indoor propagation ($\alpha$), which is assumed the value 2 dB/m (typical); the perpendicular indoor distance ($d$) is 2m (typical); incident angle to the normal of the outdoor wall ($\theta$) has a proximally a mean value of 30° and it is the value used for all links in the network; and losses in parallel ($W_G$) and perpendicular ($W_e$) penetration, with the value 20 dB and 12 dB, respectively. The model is fully described in annex A. With the devices and propagation model parameters it is possible to compute the link range between smart meters and between smart meter and concentrator. For the first, it is necessary to have in consideration the signal through the source and destination walls. Therefore the attenuations $L_{tw}$ and $L_{in}$ are the double than the values used in smart meter to concentrator link and is necessary to solve a following equation (variation of Friis formula):

$$P_{r-SM} = P_{t-SM} - 2L_{tw} - 2L_{in} - L_{out} =$$

$$= P_{t-SM} - 2(W_e + W_G(1 - \sin(\theta))^2) - 2ad - 42.6 - 20 \log(f [GHz]) - 26 \log(S[km])) \quad (4.8)$$

On other hand, in order to solve the concentrator range problem, it is necessary to have in consideration that the network is a two-way communication, and for this feature the concentrator range $S$ is the minimum of smart meter- concentrator link and concentrator-smart meter link.

$$P_{r-C} = P_{t-SM} - L_{tw} - L_{in} - L_{out} \quad (4.9)$$

$$P_{r-SM} = P_{t-C} - L_{tw} - L_{in} - L_{out} \quad (4.10)$$

Solving equation (4.8), the link range between smart meters is 0.340 km and solving the problem: $\min_s \{ (4.9), (4.10) \} = \min_s \{ 3.3998, 1.8290 \} = 1.8290 \text{ km.}$
• Minimum Quality parameter (QP) – This parameter means the relation between the smart meters connected to the network and the total number of smart meters. The standard value for this work is 0.99.

\[ QP = \frac{\text{smart meters covered}}{\text{total smart meters}} \]

• Network Parameters - For operational considerations the gateway placement problem should take into account the QoS requirements such as delay and bandwidth. In a multi-hop network, significant delay occurs at each hop due to contention for the wireless channel, packets processing, and queuing delay. The delay is therefore a function of a number of communication hops between the source and the gateway, presented in equation (3.13). The delay constraint is translated into a maximum depth \( R \) of the spanning tree rooted at the gateway. If we considering a delay of 7 s (5-8 s typical) and probability of collision tending to zero due to the FHSS, the variable \( R \) can be calculated with the equation (4.11):

\[
d_{ij} = \tau \sum_{k=0}^{R-1} N_k \Leftrightarrow 7 = 0.7 R \Leftrightarrow R = 10
\]

For bandwidth requirements, it is necessary to guarantee a throughput in concentrator and first order smart meters, because if there is a limit in first order smart meters, the smart meters with lower orders also meet the requirements, for instance, if a first order smart meter have in its chain 500 smart meters is guarantee that the second order smart meter have less than 500 smart meters in its chain.

As was referred before, the data rate of the concentrator for transmission is 19.2 kbps and for smart meters is 9.6 kbps. This information allows to calculate the limit of the capacity in concentrator and first order smart meters through traffic characterization:

\[
|M|\lambda_{m-down} = 19200 \Leftrightarrow |M| = 4219.78 \rightarrow 4219
\]

As seen in the section 3.7, the traffic characterization for concentrator is the given in the equation (3.5), and it is assumed that the traffic for each smart meter is the same for uplink and downlink (\( \lambda_{m-down} = \lambda_{m-up} = 4.55 \text{ bps} \)). The same method can be used to determine the number of smart meters that can have the chain into the first order smart meter.

\[
\varepsilon_i(\lambda_{m-down} + \lambda_{m-up}) = 9600 \Leftrightarrow \varepsilon_i = 1054.44 \rightarrow 1054
\]

To avoid interference, the maximum number of first order smart meters connect to the concentrator is equal to the number of frequency channels of the system, which is 240.

To facilitate the comprehension of the constraints, Figure 4.2 is introduced. The green set is composed by all smart meters connected to concentrator, which has a limit of 4219, the red set
is the number of first order smart meters which is limited to 240 and the blue set is the chain of first order smart meter that has the limit of 1054.

Figure 4.2 Network limitations.

4.4 Metrics

For optimizing this problem, the hierarchical model was chosen. The objectives are described below:

- Minimizing the number of concentrators – The concentrators are the most expensive device due to its complexity and functionalities. Therefore, the minimization of these devices leads to a minimized cost of the project, which is the major requirement of the energy utilities to implement this type of solutions.

- Minimizing hops in the path of smart meter to concentrator – The hops of the packet is the main responsible for delay, and therefore it is fundamental to guarantee delay and packet loss minimization and also to increase the network reliability. This variable can be calculated solving the equation (4.14):

\[
\text{Cost hop}_{\text{tot}} = \sum_{i=1}^{c} \text{Cost hop}_{c_i}, \text{Cost hop}_{c_i} = \sum_{n=1}^{N} q_{ni} \tag{4.14}
\]

where \(\text{Cost hop}_{\text{tot}}\) is the total number of hops for every smart meter connected to the respective concentrator point, \(c_i\) is the concentrator point, \(\text{Cost hop}_{c_i}\) is the total number of hops for smart
meters aggregated to the concentrator point $i$, $M_i$ is the number of meters aggregated to the concentrator point $i$ and $d_{ni}$ is the number of hops in the path of smart meter $n$ to concentrator point $i$.

- Minimizing the distance between connected smart meters – By minimizing the distances between smart meters, the signal strength increases. This means that the lower the distances between connected smart meters, the higher is the entire network reliability. Therefore, is presented the equation (4.15):

$$
Cost \ distance_{tot} = \sum_{i=1}^{C} Cost \ distance_{C_i}, Cost \ distance_{C_i} = \sum_{n=1}^{M_i} dist_{ni}
$$

(4.15)

where $Cost \ distance_{tot}$ is the total distance between connected smart meters in the network, $Cost \ distance_{C_i}$ is total distance between connected smart meters aggregated to the concentrator point $i$, and $dist_{ni}$ is the sum of distances of the smart meter $n$ to its neighbors connected to the concentrator point $i$.

### 4.5 Simulator Description

In this section, the simulator is presented. For a better understanding, is presented a flowchart in the Figure 4.3 and the Table 4.2 which contain the description what it is done in each phase of the execution.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>For each concentrator’s possible position ($N_t$), build mesh network with the constraint R only, i.e., the maximum order in the mesh network is R. Furthermore, if there are more than x smart meters with the possibility to connect directly to the concentrator, the simulator gives priority to smart meters that haven’t any neighbour and after connecting to smart meters that have a strong power signal (lower distance).</td>
</tr>
<tr>
<td>2</td>
<td>In this phase, it is determined all the hypothesis using $N_a$ concentrators, where $N_a$ is the number of concentrators in evaluation. This hypothesis is calculated through combinations in the following way: $C_{N_a}^{N_t}$ or “$N_a$ choose $N_t$”. The set of these combinations is represented by C.</td>
</tr>
<tr>
<td>3</td>
<td>For each element in set C, it is calculated the number of smart connected to each concentrator and in total. The element or elements of C that have the higher number of connected smart meters form the new set C. The maximum number of connected smart meters is represented by $SM_C$. In this phase, a table (Cp) is created that orders in decreasing</td>
</tr>
</tbody>
</table>
way the elements that have the higher covered smart meters.

<table>
<thead>
<tr>
<th>4</th>
<th>For each element in the set C, it is created a mesh network considering the $N_a$ concentrators. Smart meters that are connected to more than one concentrator, are connected to concentrator that connects with the lower order, or in case of equal order, to the concentrator that connects with the lower distance.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>For each element in the set C, the simulator calculates the number of smart meters connected to each concentrator, represented by $SM_{C_n(N_a)}$. For instance, the number of smart meters connected to the concentrator 1 of the element 2 in the C set is represented by $SM_{C_2(1)}$. In case of concentrator have connected more than $L$ smart meters, the simulator tries to connect the exceeding smart meters (started with higher order) to another concentrator in order to meet the network requirement, given priority to concentrator that have the possibility to make lower order link, and in case of equal order, to lower distance. If it is not possible, the higher order smart meters are discarded.</td>
</tr>
<tr>
<td>6</td>
<td>The element or elements of C that have more smart meters connected and meet the previous requirement form the new set C. For each element in set C, calculate the number of smart meters connected to first order smart meters, in the other words, the number of paths have the first order smart meters in their chain. The first order smart meter is represented by $N_b$. Therefore, the number of smart meters connected to the chain of $N_b$, to concentrator 1 of the element 2 in the set C, is represented by $SM_{C_2(1)(N_b)}$. In case of this number exceeds $F$ variable, the simulator tries to connect to another chain in the same concentrator or, in case that not possible, to the chain of another concentrator, fulfilling all the previous network requirements.</td>
</tr>
<tr>
<td>7</td>
<td>The element or elements of C that have more smart meters connected and meet the previous requirement form the new set C. In this phase, for all elements is calculated the number of hops in the path from smart meters to the respective concentrator with the equation (4.14). The elements with the minimum hops ($Cost_{hop_{tot}}$) form the new set C.</td>
</tr>
<tr>
<td>8</td>
<td>In this phase, for all elements in set C are calculated the distances between connected smart meters using equation (4.15). The element that minimize the variable $Cost_{distance_{tot}}$ is the final solution.</td>
</tr>
</tbody>
</table>

Table 4.2 Simulator phases description.
Figure 4.3 Simulator flowchart.
4.6 Outputs

- Clusterization – As a result, the simulator discovers the clusters (set of smart meters connected to each concentrator) and represents this information in a figure. In this figure it is represented the clusters differentiated by colors and the non-connected smart meters, in decimal coordinates.
- Number of hops – In the final solution, also it is represented a table that gives the number of hops that each smart meter need to reach the concentrator differentiated by clusters. Additionally, a figure that has the orders of smart meters differentiated by colors is presented.

4.7 Cases of study

In this section, it is detailed presented the two scenarios to consider, and for each one, it is specified the geographical area, the execute iterations of the algorithm and the final solutions.

4.7.1 Synthetic scenario

4.7.1.1 Geographical Area

In this subsection, the simulator is applied to a synthetic case and the results are analysed. This scenario has the following characteristics:

- The total number of smart meters (red points in Figure 4.4) are 4400.
- The total number of concentrator’s possible positions (black points in Figure 4.4) are 20
- Each smart meter represents a dwelling, in other words, the simulator considers one point as a single smart meter, despising the z axis.
- The scenario is composed by groups of 40 dwellings and the distances between has the configuration presented in Figure 4.2 These parameters are, (see Figure 4.5):
  - A=50 m
  - B=75 m
  - C=125 m
4.7.1.2 Results

In this section, are presented the results of simulation for the case described in section 4.7.1.1. The outputs for the first iteration are illustrated in Figures 4.6 and 4.7, and in the Table 4.3. For this case, the concentrator that covers the largest number of smart meters is number 8, covering exactly 3504
smart meters. This information allows to compute the QP, which leads a result of 0.7964, or in other words, only 79.64% of total smart meters are covered using only one concentrator. Due to the symmetric scenario, it is expected that the coverage has a circular shape, because its range is equal for any directions. This result is illustrated in Figure 4.6. Furthermore, as one can see in Figure 4.7, the smart meters order increases when these deviate from the concentrator, creating “rings”. For this reason, as indicated in Table 4.3, the number of smart meters per order remains approximately constant, in fact, there is a growing tendency when the order of smart meters increases.

![Figure 4.6 First iteration for synthetic scenario.](image1)

![Figure 4.7 First iteration discriminated by number of hops (synthetic case).](image2)
Table 4.3 Number of smart meters per order in first iteration (synthetic case).

In the first iteration, the simulator has not achieved the QP parameter. Therefore, it is necessary to add another concentrator. The QP parameter in this case is equal to 0.9766 and the selected concentrators are numbers 10 and 12. As one can see in Figure 4.8 and 4.9, the clustering is approximately symmetric, and for this reason, the distribution of smart meters is balanced between the two concentrators. In Table 4.4 it is possible to notice that the number of smart meters in each hop is practically equal for two concentrators, which evidences the symmetric relation.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>1-Hop</th>
<th>2-Hop</th>
<th>3-Hop</th>
<th>4-Hop</th>
<th>5-Hop</th>
<th>6-Hop</th>
<th>7-Hop</th>
<th>8-Hop</th>
<th>9-Hop</th>
<th>10-Hop</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>240</td>
<td>189</td>
<td>260</td>
<td>303</td>
<td>384</td>
<td>426</td>
<td>459</td>
<td>434</td>
<td>429</td>
<td>380</td>
<td>3504</td>
</tr>
</tbody>
</table>

Figure 4.8 Second iteration for synthetic scenario (synthetic case).

Figure 4.9 Second iteration discriminated by number of hops (synthetic case).
Table 4.4 Number of smart meters per order in second iteration (synthetic case).

<table>
<thead>
<tr>
<th>Cluster</th>
<th>1-Hop</th>
<th>2-Hop</th>
<th>3-Hop</th>
<th>4-Hop</th>
<th>5-Hop</th>
<th>6-Hop</th>
<th>7-Hop</th>
<th>8-Hop</th>
<th>9-Hop</th>
<th>10-Hop</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>240</td>
<td>183</td>
<td>260</td>
<td>278</td>
<td>334</td>
<td>247</td>
<td>235</td>
<td>159</td>
<td>149</td>
<td>92</td>
<td>2177</td>
</tr>
<tr>
<td>2</td>
<td>240</td>
<td>184</td>
<td>261</td>
<td>279</td>
<td>330</td>
<td>243</td>
<td>214</td>
<td>139</td>
<td>136</td>
<td>94</td>
<td>2120</td>
</tr>
</tbody>
</table>

Again, the QP parameter does not achieve the quality value of 0.99, and in this way it is necessary to simulate with another concentrator. The concentrators that were chosen were numbers 5, 6 and 19. With this combination the QP parameter is equal to 1, in another way to say, all the smart meters are covered by network. Notice that the simulator attempts to divide the smart meters for all concentrators, in order to relieve the links and avoid traffic congestion. The results are presented in Figure 4.10, 4.11 and in the Table 4.5.

Figure 4.10 Final solution for synthetic scenario.

Figure 4.11 Final solution discriminated by number of hops (synthetic case).
Table 4.5 Number of smart meters per order in final solution (synthetic case).

<table>
<thead>
<tr>
<th>Cluster</th>
<th>1-Hop</th>
<th>2-Hop</th>
<th>3-Hop</th>
<th>4-Hop</th>
<th>5-Hop</th>
<th>6-Hop</th>
<th>7-Hop</th>
<th>8-Hop</th>
<th>9-Hop</th>
<th>10-Hop</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>240</td>
<td>185</td>
<td>233</td>
<td>230</td>
<td>213</td>
<td>134</td>
<td>91</td>
<td>38</td>
<td>11</td>
<td>0</td>
<td>1375</td>
</tr>
<tr>
<td>2</td>
<td>240</td>
<td>126</td>
<td>154</td>
<td>204</td>
<td>216</td>
<td>240</td>
<td>124</td>
<td>92</td>
<td>31</td>
<td>16</td>
<td>1443</td>
</tr>
<tr>
<td>3</td>
<td>240</td>
<td>189</td>
<td>219</td>
<td>233</td>
<td>251</td>
<td>205</td>
<td>133</td>
<td>77</td>
<td>31</td>
<td>4</td>
<td>1582</td>
</tr>
</tbody>
</table>

4.7.2 Real scenario

4.7.2.1 Geographical Area

In this subsection, it is presented a real case study in order to execute the simulator with this data. The scenario is illustrated in Figure 4.12. The smart meters are situated in São Paulo, Brazil, with the following characteristics:

- The total number of smart meter is 1774.
- Each smart meter represents a dwelling, in other words, the simulator considers one point as a single smart meter, despising the z axis.

Figure 4.12 Representation of smart meters in real scenario (extracted from Google Earth).
In order to input in the simulator the concentrator’s possible positions, it was necessary to discover light poles in strategic places to cover the greater number of smart meters and to meet the quality parameters requirements. To find the light poles coordinates, it was made a visual search through Google Earth Street View mode and were selected 70 points. As an example, the Figure 4.13 represents a process to nominated one of the 70 light poles and the coordinates of all concentrator’s possible positions are defined in Table 4.6.

Figure 4.13 Example of possible position to put the concentrator (extracted from GoogleEarth Street View mode).

<table>
<thead>
<tr>
<th>Point</th>
<th>Longitude(decimal)</th>
<th>Latitude(decimal)</th>
<th>Point</th>
<th>Longitude(decimal)</th>
<th>Latitude(decimal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-23.479903</td>
<td>-46.806125</td>
<td>36</td>
<td>-23.548661</td>
<td>-46.890614</td>
</tr>
<tr>
<td>2</td>
<td>-23.483267</td>
<td>-46.806753</td>
<td>37</td>
<td>-23.507706</td>
<td>-46.890408</td>
</tr>
<tr>
<td>3</td>
<td>-23.480586</td>
<td>-46.806208</td>
<td>38</td>
<td>-23.509506</td>
<td>-46.892958</td>
</tr>
<tr>
<td>4</td>
<td>-23.480006</td>
<td>-46.804825</td>
<td>39</td>
<td>-23.508336</td>
<td>-46.897456</td>
</tr>
<tr>
<td>5</td>
<td>-23.484508</td>
<td>-46.806311</td>
<td>40</td>
<td>-23.511606</td>
<td>-46.895708</td>
</tr>
<tr>
<td>6</td>
<td>-23.485394</td>
<td>-46.808408</td>
<td>41</td>
<td>-23.512944</td>
<td>-46.897547</td>
</tr>
<tr>
<td>7</td>
<td>-23.487053</td>
<td>-46.807319</td>
<td>42</td>
<td>-23.515336</td>
<td>-46.899697</td>
</tr>
<tr>
<td>8</td>
<td>-23.489375</td>
<td>-46.810839</td>
<td>43</td>
<td>-23.516897</td>
<td>-46.901619</td>
</tr>
<tr>
<td>9</td>
<td>-23.487169</td>
<td>-46.816144</td>
<td>44</td>
<td>-23.512922</td>
<td>-46.904078</td>
</tr>
<tr>
<td>10</td>
<td>-23.505408</td>
<td>-46.809319</td>
<td>45</td>
<td>-23.476406</td>
<td>-46.886317</td>
</tr>
<tr>
<td>11</td>
<td>-23.504881</td>
<td>-46.810981</td>
<td>46</td>
<td>-23.481689</td>
<td>-46.878819</td>
</tr>
<tr>
<td>12</td>
<td>-23.509233</td>
<td>-46.810881</td>
<td>47</td>
<td>-23.488794</td>
<td>-46.884522</td>
</tr>
</tbody>
</table>
The next step was to put the data in MATLAB software. Figure 4.14 represents the smart meters and the concentrator’s possible positions in decimal coordinates. The conversion from the coordinates in degree to decimal presented in the following. Informally, specifying a geographic location usually means giving the location’s latitude and longitude. The numerical values for latitude and longitude can occur in a number of different formats:

- Degrees minutes seconds: 40° 26’ 46” N 79° 58’ 56” W
- Degrees decimal minutes: 40° 26.767’ N 79° 58.933’ W
- Decimal degrees: 40.446° N 79.982° W

There are 60 minutes in a degree and 60 seconds in a minute. Then to convert from a degrees minutes seconds format to a decimal degrees format, one may use the formula

\[
\text{decimal degrees} = \text{degrees} + \frac{\text{minutes}}{60} + \frac{\text{seconds}}{3600}
\]  

(4.16)
To convert back from decimal degree format to degrees minutes seconds format:

\[
\text{degrees} = \lfloor \text{decimal degrees} \rfloor \tag{14}
\]

\[
\text{minutes} = \lfloor 60(\text{decimal degrees} - \text{degrees}) \rfloor \tag{4.18}
\]

\[
\text{seconds} = 3600((\text{decimal degrees} - \text{degrees}) - \frac{\text{minutes}}{60}) \tag{15}
\]

where the notation \(\lfloor x \rfloor\) means take the integer part of \(x\) and is called a floor function [32].

![Real Scenario - Smart Meter and possible concentrator positions](image)

Figure 4.14 Representation of real smart meters and possible position of concentrators.

### 4.7.2.2 Results

After a brief scenario description, the results are presented. Notice that the more the number of possible positions to place the concentrators, the closer the solution to the optimum.

In the first iteration, there are 1105 smart meters covered, what corresponds a QP value of 0.6229. The concentrator selected is the 54, because it offers the most coverage complying with restrictions. One interesting aspect in this situation is the fact that the capacity for first order smart meters is not fully occupied. This happens because the concentrator cannot connect to more than 223 smart meters directly and the signal from smart meters are not strong enough to be captured by the concentrator. The outputs are represented in Figures 4.15 and 4.16, and in the Table 4.7.
Figure 4.15 First iteration for real scenario.

Figure 4.16 First iteration discriminated by number of hops (real case).

<table>
<thead>
<tr>
<th>Cluster</th>
<th>1-Hop</th>
<th>2-Hop</th>
<th>3-Hop</th>
<th>4-Hop</th>
<th>5-Hop</th>
<th>6-Hop</th>
<th>7-Hop</th>
<th>8-Hop</th>
<th>9-Hop</th>
<th>10-Hop</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>223</td>
<td>131</td>
<td>137</td>
<td>122</td>
<td>135</td>
<td>124</td>
<td>97</td>
<td>60</td>
<td>37</td>
<td>39</td>
<td>1105</td>
</tr>
</tbody>
</table>

Table 4.7 Number of smart meters per order in first iteration (real case).
As expected by the geographical dispersion of smart meters, the second concentrator is required. The results are represented in Figures 4.17 and 4.18 and in the Table 4.8, where the chosen concentrators were numbers 15 and 40. The QP parameter in this case is 0.9273 because the smart meters covered by the two concentrators is 1645, still far from the desirable value. However, it is notorious a convergence for the final solution, such that the solution covering the main groups of smart meters in the scenario. The same synthetic scenario behaviour can be observed on the topic of the smart meter orders, where the “ring” shape is applicable also in this case despite the random distribution of smart meters. As with the first iteration, it is represented the positions of connected smart meters distinguished by orders and the number of smart meters connected in each order per concentrator, in Figures 4.17 and 4.18 and in Table 4.8.

Figure 4.17 Second iteration for real scenario.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>1-Hop</th>
<th>2-Hop</th>
<th>3-Hop</th>
<th>4-Hop</th>
<th>5-Hop</th>
<th>6-Hop</th>
<th>7-Hop</th>
<th>8-Hop</th>
<th>9-Hop</th>
<th>10-Hop</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>240</td>
<td>57</td>
<td>79</td>
<td>72</td>
<td>71</td>
<td>57</td>
<td>44</td>
<td>28</td>
<td>20</td>
<td>8</td>
<td>676</td>
</tr>
<tr>
<td>2</td>
<td>240</td>
<td>87</td>
<td>98</td>
<td>112</td>
<td>99</td>
<td>65</td>
<td>72</td>
<td>95</td>
<td>66</td>
<td>35</td>
<td>969</td>
</tr>
</tbody>
</table>

Table 4.8 Number of smart meters per order in second iteration (real case).

The same situation happens when using three concentrators, the numbers 15, 22 and 37. Thus, the QP parameter has the value of 0.9899 and despite being very close, it is not enough to find the final solution. The results are represented in Figures 4.19 and 4.20, and in the Table 4.9.
Figure 4.18 Second iteration discriminated by number of hops (real case).

<table>
<thead>
<tr>
<th>Cluster</th>
<th>1-Hop</th>
<th>2-Hop</th>
<th>3-Hop</th>
<th>4-Hop</th>
<th>5-Hop</th>
<th>6-Hop</th>
<th>7-Hop</th>
<th>8-Hop</th>
<th>9-Hop</th>
<th>10-Hop</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>240</td>
<td>57</td>
<td>79</td>
<td>72</td>
<td>71</td>
<td>57</td>
<td>43</td>
<td>23</td>
<td>13</td>
<td>8</td>
<td>663</td>
</tr>
<tr>
<td>2</td>
<td>240</td>
<td>38</td>
<td>18</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>306</td>
</tr>
<tr>
<td>3</td>
<td>240</td>
<td>103</td>
<td>119</td>
<td>88</td>
<td>67</td>
<td>58</td>
<td>60</td>
<td>28</td>
<td>13</td>
<td>11</td>
<td>787</td>
</tr>
</tbody>
</table>

Table 4.9 Number of smart meters per order in third iteration (real case).

Figure 4.19 Third iteration for real scenario.
Finally, with four concentrators it is possible to find the final solution. The concentrators are the 13, 22, 37 and 65. The network designed with these concentrators would be able to connect 1772 smart meters, which means that only just 2 are left out to connect. The Figure 4.21 represents the solution with clusters discriminated by colours. Notice that the concentrators are working well below capacity due to the general shallowness of the network, which, on the other hand, increases the performance of the network. The reason for this is the dispersed distribution of smart meters and the tight values for parameters of the constraints. This results an increase of QoS because, as referred before, the QoS depends on the delay and in turn the delay depends on the number of hops in the network. The remaining results are presented in Figure 4.22 and in the Table 4.10.
To evaluate these results, it is necessary to make a cost analysis to clarify if the final solution is, in fact, the best solution from utility’s view point. To answer this question it is required to know the final cost of the project, which is dependent only on devices prices.

Let’s assume that the maximum delay imposed in the network by utility is 5 s and the rest of parameters are the same. In the same way applied in previous situation, the maximum number of hops in the network is 7. In this case, it is expected that the number of concentrators increases due to less coverage range, and probably the concentrators using are different than used before. On the other hand, for sure that

<table>
<thead>
<tr>
<th>Cluster</th>
<th>1-Hop</th>
<th>2-Hop</th>
<th>3-Hop</th>
<th>4-Hop</th>
<th>5-Hop</th>
<th>6-Hop</th>
<th>7-Hop</th>
<th>8-Hop</th>
<th>9-Hop</th>
<th>10-Hop</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>219</td>
<td>49</td>
<td>51</td>
<td>24</td>
<td>10</td>
<td>10</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>365</td>
</tr>
<tr>
<td>2</td>
<td>240</td>
<td>38</td>
<td>18</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>306</td>
</tr>
<tr>
<td>3</td>
<td>240</td>
<td>103</td>
<td>104</td>
<td>63</td>
<td>45</td>
<td>23</td>
<td>42</td>
<td>19</td>
<td>12</td>
<td>11</td>
<td>662</td>
</tr>
<tr>
<td>4</td>
<td>240</td>
<td>77</td>
<td>74</td>
<td>37</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>439</td>
</tr>
</tbody>
</table>
the QoS increases due to the delay constraint. This comparison analyzes the effect of reducing the number of hops and evaluate the advantages and disadvantages.

Figure 4.23 First iteration for real scenario (R=7).

As was done in the case before, the analysis starts at the first iteration. In Figure 4.23 it is illustrated the result using just one concentrator. The concentrator that offers the higher coverage is the 54 and the QP parameter is equal to 0.5462. As this resolution points out, the concentrator used is the same than previous case but is much fewer in terms the percentage of smart meters coverage, as would be expected.

Figure 4.24 Second iteration for real scenario (R=7).
In the second iteration, presented in Figure 4.24, it was observed that the concentrators that provide the higher coverage were the 13 and the 37. For this network design, the QP parameter is 0.7982. Again, this value did not reach the minimum quality requirement and is much less than the case which has 10 s as a maximum delay.

The next step is to insert a new concentrator. The tendency is that the peripherals smart meters to be connected lastly because, as the priority is to connect the greater number of smart meters, the center of mass is the more likely place to put the concentrator.

In the third iteration, the selected concentrators were the 13, the 29 and the 70. This set a value of 0.9453 to the QP parameter. As initially expected, the selected concentrators in both cases are different to reach the same QP and the maximum delay defined by utility has higher influence in the final solution.

In the following, another case is presented. This time, the parameter that was changed was the maximum number of smart meters connected to the concentrator, the input L, changing for the value 900. Using just one concentrator, it’s obvious that if this constraint is exceeded, the higher order smart meters will be discarded because there is no other concentrator in the network.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>1-Hop</th>
<th>2-Hop</th>
<th>3-Hop</th>
<th>4-Hop</th>
<th>5-Hop</th>
<th>6-Hop</th>
<th>7-Hop</th>
<th>8-Hop</th>
<th>9-Hop</th>
<th>10-Hop</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>223</td>
<td>131</td>
<td>137</td>
<td>122</td>
<td>135</td>
<td>124</td>
<td>28</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>900</td>
</tr>
</tbody>
</table>

Table 4.11 Number of smart meters per order in first iteration with L=900 (real scenario).
As one can see in Figure 4.15 and in Table 4.7, the capacity of the concentrator 54 is exceeded. Therefore, the higher order smart meters are disconnect from the network and are represented in the Figure 4.26 in blue. In fact, there are other solutions that satisfies QP value because it cannot exceed the value of 0.5073 but, in order to compare with the case of L=4219, only this selected concentrator is presented. In second iteration, the concentrator 40 exceed the maximum smart meters connected permitted. However, it is possible to connect some of them to the concentrator 15 (in green in Figure 4.27), and the rest are inevitably discarded from de network (in blue in Figure 4.27).
<table>
<thead>
<tr>
<th>Cluster</th>
<th>1-Hop</th>
<th>2-Hop</th>
<th>3-Hop</th>
<th>4-Hop</th>
<th>5-Hop</th>
<th>6-Hop</th>
<th>7-Hop</th>
<th>8-Hop</th>
<th>9-Hop</th>
<th>10-Hop</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>240</td>
<td>57</td>
<td>79</td>
<td>72</td>
<td>71</td>
<td>57</td>
<td>44</td>
<td>32</td>
<td>40</td>
<td>34</td>
<td>726</td>
</tr>
<tr>
<td>2</td>
<td>240</td>
<td>87</td>
<td>98</td>
<td>112</td>
<td>99</td>
<td>51</td>
<td>54</td>
<td>79</td>
<td>63</td>
<td>17</td>
<td>900</td>
</tr>
</tbody>
</table>

Table 4.12 Number of smart meters per order in second iteration with L=900 (real scenario).
Chapter 5
Conclusions

This chapter concludes the dissertation, recapping the main goals of the development simulator, the analysis of the algorithm and providing the more important obtained results. Also, is presented the possible improvements for future work.
The main motivation of this thesis is to facilitate the communication between users and energy suppliers for energy monitoring proposes using smart grids systems. In this way, from a supplier’s point of view, it is possible to reduce the operation costs, reduce the gas emissions and facilitate the renewable resource generation. On the other hand, on the user’s perspective, this system allows the costumers to control their consumptions to avoid wastage of power and to reduce their energy costs.

The current thesis intended to analyse and study planning techniques to implement a smart grid system, more properly, a NAN. The smart grid system is divided into two networks: NAN and WAN. NAN ensures the connection between the smart meters and are aggregated by concentrators. On the other hand, WAN ensures the connection between the concentrators and control centre, called backhaul. NAN can be implemented through WMNs, mainly focussing to guarantee the QoS with the lowest possible project cost, which is dependent on the number of smart meters and number of concentrators. WMN is a LAN where each node is connected to many others, configured to allow connections to be rerouted around broken or blocked paths, with the signal hopping from node to node until it reaches its destination. In this way, the main advantages of these kind of networks are to increase coverage range and their ability for self-healing.

Due to their complexity and flexibility, WMNs are difficult to plan. Furthermore, there are specialized companies that provide this service to energy suppliers. The service included not only provides all the hardware but also offers the network control software. In order to create a standard for these proprietary solutions, it was established the Technical Standard for Smart Grid IEEE 2030 on smart grids architectures, concepts, connections and interoperability.

To design an efficient NAN, a MATLAB simulator was created that optimizes performance based on smart meters geographical positions and possible positions to put the concentrators. As it has been evident along the written assignment, the final result is extremely dependent on the inputs. Besides, the development tool is programmable for all others requirements, such as:

- Devices parameters (power transmission and sensitivity);
- Propagation model, which is chosen depending on the conditions of validation and simplification;
- QP, which is the stop condition that permits determining if the pre-defined percentage of covered smart meters was reached;
- QoS constraints, which is composed of four variables. The first is the maximum number of hops, which was determined in relation with the maximum delay for the packets arrives to concentrator from any smart meter and the probability of collision, or in other words, the probability of at least two packets try to access the concentrator at the same time in the same frequency channel. The second variable is the maximum number of smart meters which can be connected to one concentrator, and such value is limited by the maximum data rate of the concentrator. The next parameter is the maximum number of paths that contain a first order smart meter, also limited by data rate, but in this case, it is considered the maximum data rate of the smart meters. In order to avoid interference, when this network was planned, the number of links available in each device is limited to the number of frequency channels.
In terms of metrics, the main goal is to ensure that the network satisfies its purpose, in other words, it is to guarantee, at least, a minimum QoS. As such, the construction of the mesh network is made trying to minimize the number of hops to reach the concentrator, in order to reduce the delay of the transmission packets. In case there are no differences in connection order, the smart meters chosen to connect the closest neighbour smart meter, in theory, it would be the smart meter that receives a stronger signal because there is higher probability that links don’t fail. However, in this project, an insertion of a new concentrator depends exclusively on the network not reaching the minimum QP or don’t meet the requirements. In this way, it is possible to minimize the number of concentrators, and consequently the cost of the project.

As outputs, it is represented the scenario divided by clusters, one for each concentrator and the non-connected smart meters, if that is the case. Also, it is illustrated the scenario with smart meters discriminated by orders and, in this way, it is possible to identify the levels of the mesh network. Lastly, it is provided a table which contains the number of smart meters in each hop for each concentrator.

To demonstrate the simulator operation two scenarios were used, synthetic and read. The synthetic, wherein the meters are collocated in houses that have each other always the same distance and are symmetric; and the real, wherein the meters are in real houses, in an unpredictable scenario in terms of positions of dwellings and distances between meters.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Synthetic</th>
<th>Real</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 concentrator; R=10; L=4219</td>
<td>0.7964</td>
<td>0.6229</td>
</tr>
<tr>
<td>2 concentrators; R=10; L=4219</td>
<td>0.9766</td>
<td>0.9273</td>
</tr>
<tr>
<td>3 concentrators; R=10; L=4219</td>
<td>1</td>
<td>0.9899</td>
</tr>
<tr>
<td>4 concentrators; R=10; L=4219</td>
<td></td>
<td>0.9989</td>
</tr>
<tr>
<td>1 concentrator; R=7; L=4219</td>
<td></td>
<td>0.5462</td>
</tr>
<tr>
<td>2 concentrator; R=7; L=4219</td>
<td></td>
<td>0.7982</td>
</tr>
<tr>
<td>3 concentrator; R=7; L=4219</td>
<td></td>
<td>0.9453</td>
</tr>
<tr>
<td>1 concentrator; R=10; L=900</td>
<td></td>
<td>0.5073</td>
</tr>
<tr>
<td>2 concentrators; R=10; L=900</td>
<td></td>
<td>0.9166</td>
</tr>
</tbody>
</table>

Table 5.1 Value of QP in different situations
As previously stated and observing the results in the Table 5.1, there are significant differences between the two scenarios, which leads to the conclusion that the chosen scenario strongly influences the final results. These characteristics are demonstrated in the presented results, in such a way that, for the synthetic scenario, three concentrators are needed to connect all the 4400 smart meters, while in real scenario composed by 1774 smart meters, to reach a percentage of 99% of these covered devices, is needed four concentrators. In other words, to connect more than twice of smart meters, the synthetic scenario needs less one concentrator, which exemplifies well how the position of smart meters effects the network.

Also, according to Table 5.1, the insertion of more concentrators in the network increases the number of connected smart meters. However, not always the insertion of a new concentrator stands for a significant improvement in the system, like when to insert the fourth concentrator in the real scenario. Thus, with this insignificant improvement, it becomes necessary to analyse whether this development compensates the investment from energy supplier’s view point. An alternative for this situation is to use another technology to cover the remaining smart meters that are not already connected.

Furthermore, by reducing the maximum delay of the packet transmission, which will result in reducing the maximum number of hops allowed in the system. In this way, it is possible to confirm that, for the same QP, it is necessary to insert news concentrators.

Finally, by reducing the maximum number of smart meters allowed to connect to one concentrator, a decrease of QP for the same number of concentrators in the network was noticed.

In terms of future work, based on this study, it is possible to implement the optimum WAN that combines with this NAN implementation. Also, is interesting to applied the same principles to the WSNs based on this work, more properly, in the internet of things subject.
Annex A

Smart Grids Radio Propagation Models

The annex presents the propagations models applied to the smart grid systems, offering various alternatives for different conditions and precisions.
A.1 Introduction

In this annex, is presented 4 propagations models and smart meter position scenarios for smart grid applications, more specifically, for Advanced Metering Infrastructure. To perform the system, is extremely important have a propagation model which closely as possible to the case of study. As described above, the technology used to plan this network is wireless, and the usage of digital cellular radio networks provide advantages compared to wire technologies, like well-established infrastructures, lower installation costs, and sufficient QoS and data rates especially for subsequent or dedicated integration of distributed energy components. As part of the release of lower frequency ranges for new services, like the reuse of television broadcast radio spectrum for Smart Metering, a promising frequency range is available in order to overcome the coverage lack caused by the prevailing in-house installation of the communication components. There is a lot of parameters to have in consideration as a smart meter position, frequency, house walls and position of the concentrator, among others [37].

Figure A.1 a) Deployment Scenarios Front b) Deployment Scenarios Back (extracted from [37])

A.2 COST 231 path loss model for building penetration

A basic approach has been developed within the COST (COperation europenne dans le domaine de la recherché Scientifique et Technique) project. Based on measurements of Okumura, urban and suburban environments are analyzed. The model assumes isotropic antennas, in the other words, the antennas issues the same radiation in all directions, carrier frequencies in the range of 900-1800 MHz and base station height below 30 m, or in case of AMI system, the concentrator height below 30 m.

The propagation loss is divided into three parts:

\[ L_{tot} = L_{out} + L_{tw} + L_{in} \]  

where represents the total propagation loss, \( L_{out} \) the outdoor loss, \( L_{in} \) the indoor loss and \( L_{tw} \) the wall loss. Thereby the outdoor loss is given by a corresponding approximation of the free space loss.
\[ L_{\text{out}} = 32.4 + 20 \log(f[\text{GHz}]) + 20 \log(S + d) \]  

(A.2)

where \( f \) is the signal frequency and \( S \) is the distance from external wall to concentrator. The indoor loss is determined by

\[ L_{\text{in}} = \max\{pW_i, \alpha(d - 2)(1 - \sin(\theta))^2\} \]  

(A.3)

where \( p \) is the number of penetrated indoor walls, \( W_i \) the loss per wall, \( d \) the perpendicular indoor distance, \( \alpha \) the loss coefficient for indoor propagation and \( \theta \) the incident angle to the normal of the outdoor wall. In contrast, the wall loss on condition of an arbitrary incident angle can be determined by the special cases of perpendicular \( (W_e) \) and parallel \( (W_G) \) penetration.

\[ L_{tw} = W_e + W_G(1 - \sin(\theta))^2 \]  

(A.4)

As can be seen the model determines the path loss by a superposition of free space loss between the outdoor transmitter and indoor receiver and the wall losses by the external and internal walls [37].

### A.3 Extended COST 231 Walfisch-Ikegami model

In order to allow higher frequencies than 1800 MHz and to be more accurate, in [37] the authors extended the basic COST 231 model. Two modifications are made, one for the indoor loss and one for the outdoor loss. The loss by the external wall is untouched. For more realistic modeling the outdoor path loss is replaced by the Walfisch-Ikegami model

\[ L_{\text{out}} = 42.6 + 20 \log(f[\text{GHz}]) + 26 \log(S[\text{km}]) \]  

(A.5)

As this model only uses the path loss between the concentrator and the external wall \( S \), it’s more accurate than basic COST 231 building penetration. To further improve and simplify the model a change was made in indoor attenuation

\[ L_{\text{in}} = \alpha d \]  

(A.6)

This modification is equivalent to a scenario where the indoor walls are separated each time by 10 m. A further advantage of the simplification made in (A.5) is, that no detailed information is needed about the location of the receiver. In summary, the Extended COST 231 Walfisch-Ikegami model is valid for frequencies between 800 and 2000 MHz, concentrator heights of 4 to 50 m and distances between 0.02 and 5 km. This model is also referred as COST 231 wi [37].
A.3.1 Practical example

Based on the study in Dortmund in Germany, the Figure A.3 illustrate an example of coverage analysis for large-scale smart grid scenarios. The percentage of supplied houses is shown in dependency of the housetype and used frequency. Therefore, a minimum receive strength, or in the other words, the receiver sensitivity is assumed by a threshold of -90 dBm. The outdoor installations (housetype 1 and 3) show the best performance result compared to the basement (Housetypes 2 and 4) and indoor deployments (Housetype 5) as well as the lower frequencies, the lower the frequencies higher the percentage of number of the supplied houses in all the housetypes scenarios. In order to provide connectivity to the basement receiver, the usage of lower frequencies, offer a sufficient enhancement. Still the problem remains that due to the pessimistic threshold and the variation of the incident angles only a maximum of 52 % are supplied [37].

A.4 Winner II B4 LOS model

In the context of Winner II (Wireless World Initiative New Radio) many channel models for outdoor,
indoor and transition scenarios are developed. An interesting transition model assuming LOS conditions between the concentrator and the incident point of the incoming ray at the external wall is Winner II B4. This model requires frequencies between 2 and 6 GHz, mobile stations height of 1 to 2 m over floor and base stations heights of 5 to 15 m below rooftop. In the same way as previous models the path loss is divided into three parts. In contrast to COST 231 and COST 231 wi the outdoor and indoor loss is modified while the through wall attenuation \( L_{tw} \) is unchanged

\[
L_{out} = \max\{41 + 20 \log\left(\frac{f[\text{GHz}]}{5}\right) + 22.7 \log(S + d), L_{free}\} \quad (A.7)
\]

and

\[
L_{in} = pW_i \quad (A.8)
\]

Herein \( S \) is the outdoor distance (cf. Figure A.2) and \( L_{free} \) is the free space loss between the outdoor base station and indoor receiver or vice-versa without considering the walls of the house. The indoor path loss is modeled as a stepwise attenuation, which makes the model more realistic for irregular houses, i.e. for spacing between the interior walls not always the same. It has to be noted that the specified path loss is reciprocal, i.e. the same is true for an indoor-to-outdoor transition.

A.5 Winner II C4 NLOS model

Winner II C4 represents another transition model for outdoor-to-indoor propagation proposed within the Winner II project with respect to for non-line-of-sight (NLOS) outdoor scenarios. NLOS conditions mainly occur in urban scenarios which increase the path loss compared to Winner II B4 and reduce the coverage area of one concentrator. Assumptions for Winner II C4 are distances between concentrator and smart meter of 50m to 5km, concentrator position higher than 30 m and frequencies between 2 and 6 GHz. Equally to the approach of the other channel models the path loss is described as a superposition of three parts. Compared to the COST 231 wi, the indoor loss \( L_{in} \) and through wall attenuation \( L_{tw} \) is unchanged, while the outdoor path loss \( L_{out} \) have to be replaced due to the changed outdoor scenario:

\[
L_{out} = [44.9 - 6.55 \log(h_{BS})] \log(S + d) + 26.465.83 \log(h_{BS}) + 20\log\left(\frac{f[\text{GHz}]}{2}\right) \quad (A.9)
\]

A general disadvantage of all present channel models is, that are only valid for positive mobile station height. Therefore they cannot be applied for receivers below ground, i.e. smart meters which are located in the basement [37].
Figure A.4 Winner II C4 scenario (extracted from [37]).
Annex B

Frequency Hopping Spread Spectrum vs Direct Sequence Spread Spectrum

The present annex leads to understand the difference between the two methods and what their impacts in the network performance.
Spread Spectrum modulation techniques are defined as being those techniques in which the bandwidth of the transmitted signal is much greater than the bandwidth of the original message and is determined by the message to be transmitted and by an additional signal known as the Spreading Code [38]. A spread-spectrum transmission offers main advantages over a fixed-frequency transmission:

- Spread-spectrum signals are highly resistant to narrowband interference. The process of re-collecting a spread signal spreads out the interfering signal, causing it to recede into the background [39].
- Spread-spectrum signals are difficult to intercept. A spread-spectrum signal may simply appear as an increase in the background noise to a narrowband receiver. An eavesdropper may have difficulty intercepting a transmission in real time if the pseudorandom sequence is not known [39].
- Transmitted energy is spread over a wide band, and therefore, the amount of energy per specific frequency is very low. The effect of the low power density of the transmitted signal is that such a signal will not disturb (interfere with) the activity of other systems’ receivers in the same area and that such a signal cannot be detected by intruders, providing a high level of intrinsic security [38].
- Spread-spectrum transmissions can share a frequency band with many types of conventional transmissions with minimal interference. The spread-spectrum signals add minimal noise to the narrow-frequency communications, and vice versa. As a result, bandwidth can be used more efficiently [39].
- The message is (or may be) present on different frequencies from where it may be recovered in case of errors. The effect of redundancy is that Spread Spectrum systems present high resistance to noises, being able to recover their messages even if noises are present on the medium [38].

Two main Spread Spectrum modulation techniques are defined: Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS).

When using FHSS, the frequency spectrum is divided into channels (Figure B.1a). Data packets are split up and transmitted on these channels in a random pattern known only to the transmitter and receiver. Because collocated networks follow different random patterns, or hop code tables, multiple networks can operate in close proximity without interfering. If interference is present on one channel, data transmission is blocked. The transmitter and receiver ‘hop’ to the next channel in the hop table and the transmitter resends the data packet. Frequency hopping technology works best for small data packets in high interference environments. As an example, the Figure B.1b represents the frequency spectrum divided into 27 channels, this means that the transmitter have 27 channels to transmit data.
On the other hand, the DSSS encoder spreads the data across a broad range of frequencies using a mathematical key (Figure B.2a). The receiver uses the same key to decode the data. While narrowband use the same total power to send data, DSSS uses a lower power density (power/frequency), making it harder to detect (Figure B.2b). DSSS also sends redundant copies of the encoded data to ensure reception. Narrowband interference appears to the receiver as another narrowband transmission. When the total received signal is decoded, the wider band transmission (DSSS encoded data) is decoded back to its original narrowband format while the interference is decoded to a lower power density signal and is ignored by the receiver (Figure B.2c). When broadband interference is present, however, the resulting decoded broadband interference can give a much higher noise floor, almost as high as the decoded signal. For this reason, DSSS works best for large data packets in a low to medium interference environment, but not as well in higher interference industrial applications. As a general rule, FHSS can resist interference from spurious RF signals ten times better than DSSS, and for this reason is used for RF mesh systems for smart metering where the higher number of smart meters and their transmissions results in a lot of interference [40].
Annex C

Network Time Protocol

This annex explains the definition of Network Time Protocol and how it works.
Network Time Protocol (NTP) is a networking protocol for clock synchronization between computer systems over packet-switched, variable-latency data networks. In operation since before 1985, NTP is one of the oldest Internet protocols in current use. NTP was originally designed by David L. Mills of the University of Delaware, who still oversees its development [41].

NTP uses Coordinated Universal Time (UTC) to synchronize computer clock times to a millisecond, and sometimes to a fraction of a millisecond. UTC time is obtained using several different methods, including radio and satellite systems. Specialized receivers are available for high-level services such as the Global Positioning System (GPS) and the governments of some nations. However, it is not practical or cost-effective to equip every computer with one of these receivers. Instead, computers designated as primary time servers are outfitted with the receivers and they use protocols such as NTP to synchronize the clock times of networked computers. NTP uses a hierarchical, semi-layered system of time sources. Degrees of separation from the UTC source are defined as strata or “stratum”. A radio clock (which receives true time from a dedicated transmitter or satellite navigation system) is stratum-0; a computer that is directly linked to the radio clock is stratum-1; a computer that receives its time from a stratum-1 computer is stratum-2, and so on [42]. A brief description of strata 0, 1, 2 and 3 is provided below.

- **Stratum 0** - These are high-precision timekeeping devices such as atomic (cesium, rubidium) clocks, GPS clocks or other radio clocks. They generate a very accurate pulse per second signal that triggers an interrupt and timestamp on a connected computer. Stratum 0 devices are also known as reference clocks. In the Figure C.1 is represented a stratum 0 for NTP, the U.S. Naval Observatory Alternate Master Clock at Schriever AFB (Colorado).

![Figure C.1 Stratum 0 for NTP (extracted from [41]).](image)

- **Stratum 1** - These are computers whose system clocks are synchronized to within a few microseconds of their attached stratum 0 devices. Stratum 1 servers may peer with other stratum 1 servers for sanity checking and backup. They are also referred to as primary time servers.
- **Stratum 2** - These are computers that are synchronized over a network to stratum 1 servers. Often a stratum 2 computer will query several stratum 1 servers. Stratum 2 computers may also peer with other stratum 2 computers to provide more stable and robust time for all devices in the peer group.

![Diagram of strata relations](image)

**Figure C.2** Relations of strata (extracted from [41]).

- **Stratum 3** - These are computers that are synchronized to stratum 2 servers. They employ exactly the same algorithms for peering and data sampling as stratum 2, and can themselves act as servers for stratum 4 computers, and so on.

The Figure C.2 presents the relations between the various strata, which the yellow arrows indicate a direct connection and the red arrows indicate a network connection.

The upper limit for stratum is 15; stratum 16 is used to indicate that a device is unsynchronized. The NTP algorithms on each computer interact to construct a Bellman-Ford shortest-path spanning tree, to minimize the accumulated round-trip delay to the stratum 1 servers for all the clients [41].

The term NTP applies to both the protocol and the client/server programs that run on computers. The programs are compiled by the user as an NTP client, NTP server, or both. In basic terms, the NTP client initiates a time request exchange with the time server. As a result of this exchange, the client is able to calculate the link delay and its local offset, and adjust its local clock to match the clock at the server's computer. As a rule, six exchanges over a period of about five to 10 minutes are required to initially set the clock. Once synchronized, the client updates the clock about once every 10 minutes, usually requiring only a single message exchange. In addition to client/server synchronization, NTP also supports broadcast synchronization of peer computer clocks [42].
Annex D

Devices Datasheets

This annex illustrates the main characteristics of the devices used in this work, the smart meter and the concentrator.
D.1 Endpoint Datasheet (Landys + gyr)

Figure D.1 Smart meter datasheet (extracted from [43]).
D.2 Concentrator Datasheet (Landys + gyr)

Figure D.2 Concentrator datasheet (extracted from [44]).
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