MASTER THESIS

- Towards Automated Fault Management in Smart Grid Communication Networks -

Master thesis

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STUDENT REPORT

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"Dans les champs de l'observation le hasard ne favorise que les esprits préparés"
"Where observation is concerned, chance favours only the prepared mind"

Louis Pasteur

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Abstract:

This master thesis deals with automated fault management in communication systems, with a particular interest on smart grid networks.
Smart grid is the upcoming way to manage the electricity grid, using modern communication technics and a decentralized architecture.
Due to the criticality of the data, smart grid systems use a two-networks solution, one primary and a backup one. Such configuration has been emulated in the simulator OMNeT++, using ADSL and LTE as a first and secondary network.
A fault detection algorithm based on probe's metrics such as end-to-end delay and inter-arrival time of probes, has been implemented. The results of the simulations show that the detection process is functional. However, the best performances are obtained using high-frequency probes, which can reduce the scalability of such systems.
some future works could focus on the use of other principal networks such as Wireless Mesh, or simulations working on test beds.

Acknowledgements

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Finally, I would like to express my gratitude to my parents. Their support and affection throughout my years of studies was invaluable. Their package of French food during the year strongly helped me support the scandinavian winter.

Contents

Nomenclature

AMI Advance Metering Infrastructure

DIX Danish Internet Exchange Point

DSLAM Digital Subscriber Line Access Multiplexer

FTTx Fiber To The x

ISP Internet Service Provider

LTE Long Term Evolution

M2M Machine to Machine

NED Network Description

PGW Public Data Network Gateway

PLC Power Line Communication

PMU Phasor Measurement Unit

PRNG Pseudo Random Number Generation

QOS Quality of Service

SCADA Supervisory Control And Data Acquisition

SGW Service Gateway

SG Smart Grid

UE User Equipment

WAN Wide Area Network

WMN Wireless Mesh Network

xDSL Digital Suscriber Line

Preface

This thesis concludes my Master of Science education in the field of Networks and Distributed systems at Aalborg University. The thesis was performed throughout my 9th and 10th semester, year 2013/2014, at the Department of Electronics.
the thesis deals with the study automated fault management in smart grid communication systems.
Citations will be shown as the number of a specific reference within brackets like this: [1] which will link to the source list at the end of the report.
Simulation data are obtained using the network simulator OMNeT++. It is assumed that the reader may not be familiar with it and therefore, the way the simulator operates is detailed in chapter 4.
All schematics or flowcharts are obtained using Microsoft Visio, while the plots are from Matlab.

Aalborg University, June 4, 2014

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Reading guide

The sections described are referred as (number of section). The **Chapter 1** contains an introduction regarding the current electric grid, and why the smart grid is needed. At the end of this introduction is stated the motivation of the thesis, and a problem is formulated.

The first part of **Chapter 2** describes the different tiers composing the communication systems of smart grids (2.1). It is followed by an overview of different technologies (2.2) that can be used at every level of the network. Finally, the last section highlights the various applications that can be used in smart grid systems, among with the quality of service requirements (2.3).

The **Chapter 3** focuses on the dependability of a system. The initial part defines the attributes of a dependable system, and the different steps of fault management(3.1). The second part defines the anomalies a network can encounter (3.2), while the last one is narrowed down to the detection process, and how faults can be detected in a communication network (3.3).

The **Chapter 4** is about the model used during the simulation. The first section describe the network architecture used (section 4.2). It is followed by the description of OMNeT++, from the general functioning (4.1), to the specific modules used for the experiments (4.3). The section 4.5 describes the algorithm designed for the thesis, while section 4.6 focuses on the implementation in the simulator.

Finally, **Chapter 5** will be used to discuss the results of the experiments, while **Chapter 6** and **Chapter 7** will conclude and open the path to future work.

Chapter 1

Introduction

NB: *Part of this introduction has been written in collaboration with group 921 (Mohammed Seifu Kemal and Alexandru Ceocea) during the Autumn semester 2013.It is therefore normal that an important number of paragraphs in this introduction may be exactly the same as in their report : "Integration of General Fixed Tele-Infrastructure in Smart Grid Communication Systems"*

We use energy, and lots of it. However there are going to be some big changes in the way we use it. The world is running out of oil and natural gas. Denmark has the vision of becoming politically independent of fossil fuels and so, the energy systems will be transformed in the years to come.

In the near future, energy will be produced, transported and used in a very different and far more efficient manner than that the one for which the power system was originally designed.

Until recently, electricity was produced in large central coal plants close to the cities and industrial areas, and then transported on to the consumers. Although this has already changed, when thousands of new wind turbines, photovoltaic plants and heat pumps have appeared all around Denmark. Simply put, energy today is produced everywhere and it is transported in all directions in the power system. This trend will most certainly intensify in the future.

The houses and commercial buildings in the future will be intelligent, which means that automated intelligent systems will control the energy consumption. A/C units, freezers, refrigeration units, heat pumps and other appliances will all be controlled in such a way as to increase efficiency and decrease costs.

In the coming years, electricity production and consumption will change considerably. Energy generation will be based more on renewable energy sources and less of fossil fuels and consumers will change the way they use this energy.

In the traditional sense of a power grid, the consumers (household and commercial consumers) have mostly been passive components, with predictable and regular consumption patterns. [1]

In an intelligent power system, namely a Smart Grid, new opportunities and

perspectives emerge. Such as the ability for the consumers to interact with the power system and generate energy which can be distributed in the grid, thus becoming *resources*.

1.1 Historical Overview

Different studies show that there is a causality between the increase of the Gross Domestic Product, and the consumption of energy and particularly electricity [2]. After World War II, and especially with the reconstruction of Europe, most of the developed countries acknowledged a strong growth until the first oil chock in 1973. This period also created a lot of knew habits for people, bringing inside homes a lot of brand new electrical objects to make their lives easier. These new needs in electricity lead the different states to design and build a powerful and broad electric grid, in order to supply the demand. Although, the needs of electricity growth over the years (the consumption of electricity in the world was doubled since 1965 [3], but the grid has almost not changed since 1960's. This is explained by the long procedures, time and money consuming plans in order to build high voltage overhead power line, and sometimes the opposition of the population leaving nearby. So, the current grid is ancient, and the current consumption is higher than for what it has been designed. Moreover, this grid has been designed by each state on a country scale, with some interconnection between other countries in order to provide some mutual assistance. Nevertheless, from the past decade, this approach is no longer valid, and the cross country connections are used to shift growing power volumes over the whole continent.

Furthermore, the grid has been designed according to a vertical service: a power plant produces the electricity, and it is delivered through the grid.Those power plants were rare and placed at some strategic point(close to primary resources) and were designed to produce a large amount of electricity and be able to provide for the whole grid. Yet, with the implementation of renewable energy sources, such as windmills or solar panels, the production of energy is more distributed all over the grid. Beside, the production of energy is also random: indeed, renewable energies are more subject to external factors (wind, sun, etc.) than traditional power plants such as nuclear or charcoal are. The main consequence to that is the load on the power lines is very variable, but the absence of proper sensors & a communication network that belongs with the electric grid, in order to control the grid, implies that the regulation has to be human based. And despite an already existent coordination throughout the different actors of the grid, the high power volumes over the grid plus the instability of the grid which is not designed for the current need, and also the lack of automated regulation can lead to major failure in the system. This was the case, for example, in November 2006, where a planned power cut in Northern Germany introduced a blackout for more than 15 Millions people for 40 minutes, and introduced disturbances in all electric lines (e.g frequency shift) in Europe for a bit less than two hours[4]. To avoid these kinds of major failures, smart grids are

needed.

1.2 Smart Grid Power components

A power system may be viewed as a network of Electrical Systems working together for Generating, Transmitting and usage of Electrical Energy. This system is responsible for supplying Electric power to homes, industries, business, schools and various application areas. A modern power system can be viewed as a system with multiple main components:

- Power Plant
- Transmission lines
- Substations
- Distribution lines
- Transformers
- Distribution Substations
- Distributed Energy storage

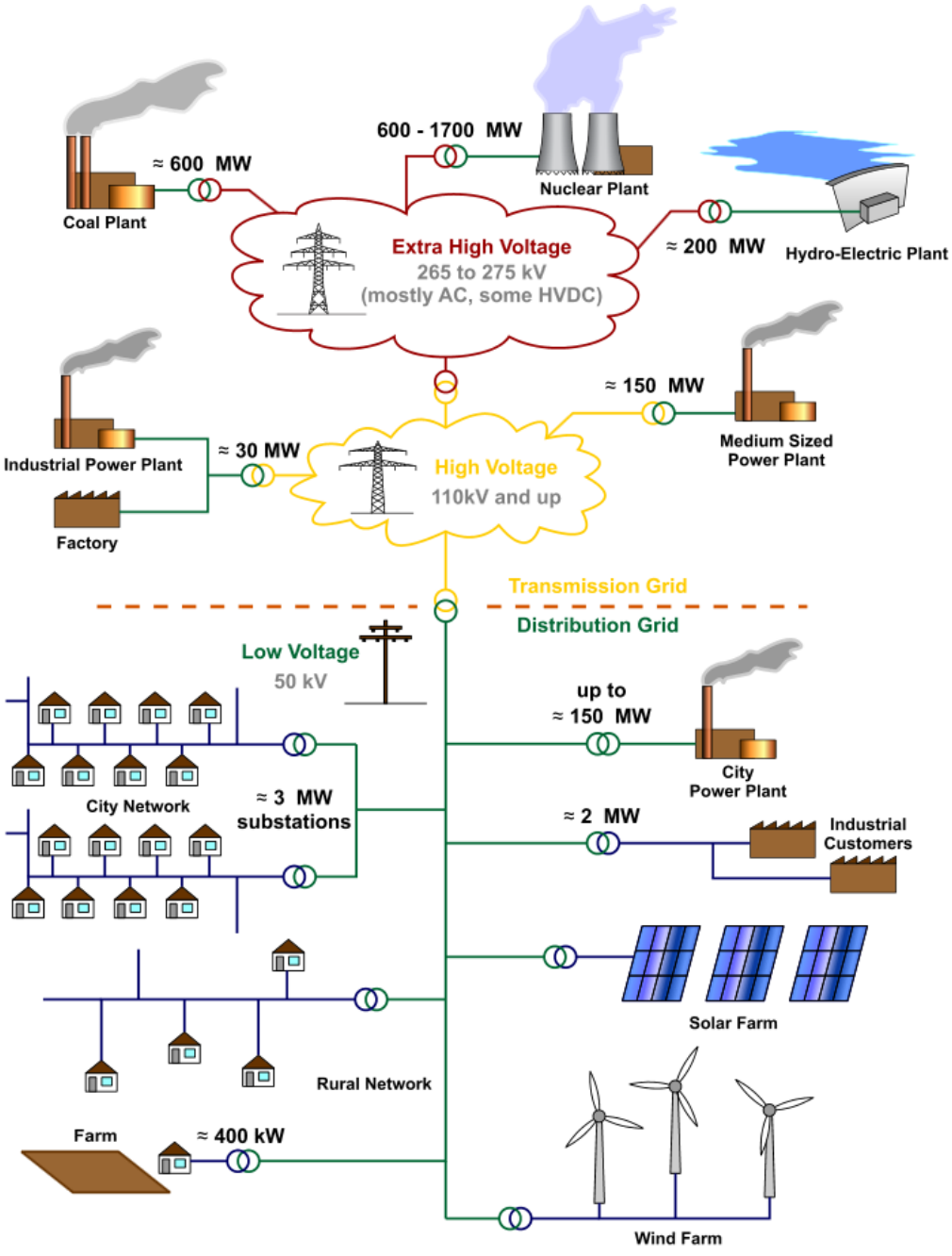


Figure 1.1: *Electricity grid schematic and components*

Power Plant - A power generating plant is an industry which generates electrical power by means of conversion from mechanical energy to electrical energy. The main component of this major subsystem is the electric generator, which converts this mechanical power to electrical power through a rotating motion between an electric conductor and magnetic field. Electrical Energy sources can be broadly categorized as Renewable energy sources and non-renewable energy sources.

Non-Renewable Energy - Electricity that is produced at an electric power plant by using fuel sources such as coal, oil, natural gas, or nuclear energy produces heat energy. This heat energy is used to boil water which changes its state to steam. The high pressure created by the steam spins a turbine which interacts with the electric conductor and magnetic field to produce electricity. Another non-renewable source is Uranium. By splitting the atoms through nuclear fission, heat energy is created and used for producing Electric energy.

Renewable Energy Sources - Renewable energy sources can be categorized as follows:

- Solar Energy, which can be turned into electricity and heat;
- Wind Energy - use wind turbines to create mechanical motion;
- Geothermal Energy - use the heat inside Earth's crust;
- Biomass - plants, firewood, ethanol obtained from corn, bio-diesel;
- Hydro-power - Hydro turbines in hydroelectric generation plants.

The Danish government has set a target which states that 50% of the electricity consumption should be supplied by wind power by 2020. As shown on the chart below, the major sources for electric power now, are non-renewable energy generation plants that use coal. The aim by 2020 is for renewable wind energy to be the dominant source of electric generation.

Transmission line - Electric power transmission is concerned with transmitting the generated Electrical energy from distributed renewable or non-renewable plants to areas where demand centers are located. In practice, transmission lines operate under circumstances where each are connected to other transmission lines creating A network of transmission lines (a transmission network). The term Grid is used to describe transmission lines, Together with substations and electric power distributions .The voltage levels reach as high as 500kv.

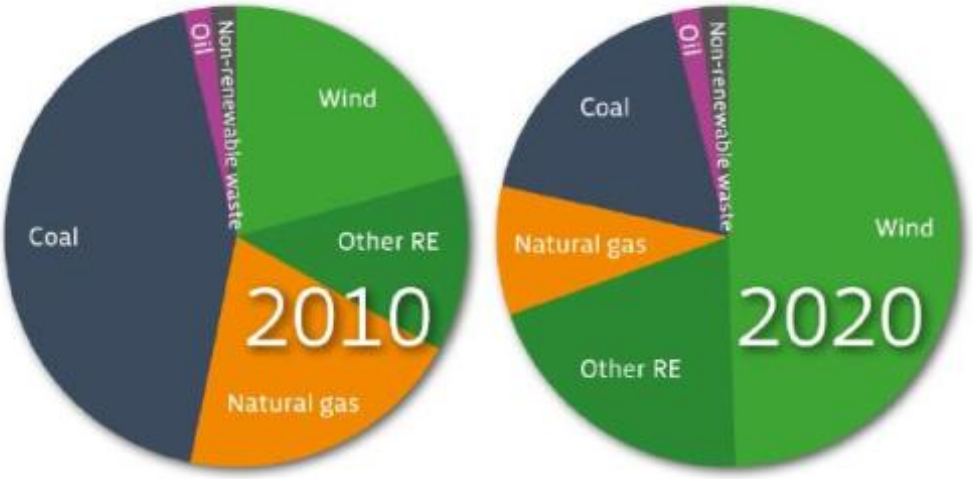


Figure 1.2: *Danish Energy generation*

Substations - An electrical substation which is familiar sight on highways and cities is responsible for changing high voltage power of the electricity from power plants and transmission lines to lower voltage. The task of supervision and electricity distribution is undertaken here .The other main task of substations is to make sure that the distribution network is working safely and efficiently. Some of The components found in substations are power transformers, switching devices, Circuit breakers for cutting power in case of outages. Control devices, protection devices and other components used for measurement are also part of substation. Power from Generation may pass/flow through several substations at different voltage levels.

Transformers - A transformer is basically defined as a static machine used for transforming the power to the desired level. Electric power is generated in low voltage because of its cost effectiveness but to decrease the cost of transmission, we have to step up the power. For high voltage transmissions, the current reduces significantly causing a low I2R losses which in-turn requires a low cross-sectional area conductor. Because of this reason, the voltage is stepped up at generation and stepped down for distribution circuits using transformers. Step up transformers and step down transformers are used accordingly.

Distribution substations - Distribution substations are type of step down transformers which are the closest to consumers. Usually distribution substations transform the electricity of low voltage distribution lines to 220v or 400v which are supply voltage for homes. They are easily recognized mounted on poles especially in

rural areas.

Phasor Measurement Unit - The phasor measurement unit is one of the keystone of smart grid unit.When old meters were only able to monitor the voltage magnitude every few seconds, the Phasor Measurement Unit (PMU) can measure the magnitude but also the phase with high precision at a rate between 20 and 120 Hz. All the PMU on the system can be synchronized using a GPS clock system.

In conclusion, the electric grid used nowadays is not as hierachical as it was before, but geographycally distributed over diver components. In order to manage this grid, it is then primordial to have measurement everywhere over the grid in order to be able to monitor the state of the grid.

1.3 Motivation

The Smart Grid concept has been used widely in the recent years in different contexts and with different definitions. [1]

In this thesis, we treat the Smart Grid as a network between the consumers, power generators and also the equipment necessary to establish and ensure this connection.

The future of energy systems will be highly dependable on power systems that rely on a variety of new electricity generation sources with added consumption mechanisms. This will drive an Electrical Power System to be flexible and be able to integrate a very high level of alternative energy sources. A Smart Grid will enable the power system to collect, exchange and take action to ensure that the reliability, security and efficiency coefficients are maximized and to ensure sustainability of the system and the services it provides. [5]

Given the rising demand for energy and also its effect on the cost of electric power, energy companies are competing to take advantage of the new opportunities and to cope with the situation. It is thus, desirable to balance the supply and demand with additional alternative energy sources and with smarter ways of using the generated power. In this case, Wind and Solar Energy play an important role as alternative energy resources and need efficient mechanisms to integrate them in the existing power grid. Although there is a very high demand for the deployment of Smart Grids, their costs and complexity are hindering the faster growth of this technology around the globe, but some countries like Denmark and the United Kingdom, are mandating plans for the deployment. In 2011, the smart grid network set up by the Danish Ministry for Climate and Energy, published a report that points to 35 recommendations which contribute to establish a Smart Grid in Denmark. [6]

Smart Grid components, by nature, are spread over different geographical locations, with the generation points and consumption locations being spread almost everywhere, it is obvious that there is a need for a proper management of *location intelligence*. Location intelligence provides information that is essential for smart, efficient and self-healing systems. For the upper management, it provides information which is used for making strategic decisions, mapping of the customers, prospects

and suppliers. In the operations part, it provides information regarding different smart grid components such as smart meters, aggregators, substations, transformers and alternative energy sources.

st In a smart grid situation, metering systems send data, under certain time constraints, to the control centers. Consequently, if the data are not properly sent to those management centers, it is more difficult for the power source company to regulate the grid. On the electric grid, a small fault can have unpredictable repercussions on the network leading into a series of other faults, and thus, it is crucial to be able to detect it quickly in order to prevent a general failure.

In this thesis, my aim is to examine and study the Smart grid communication infrastructures, requirements and technologies and use this to design an agent capable of analyzing the dynamics of the network to detect faults and correct them, in order to maintain all the time a link between each component of the grid.

1.4 Problem Formulation

A smart grid network is ubiquitous, with heterogeneous means of communication, and also geographically distributed on a large scale. The organization followed by power companies is: end-users have smart meters sending data to a control center Due to the criticallity of metering data, a solution to prevent a breach of communication in case of failure, it is desirable to provide a backup network that will be used on those case.

To maintain connectivity between these end-users and the management center in case of a failure the link is maintained using an other backup network performing on a different mean of communication.

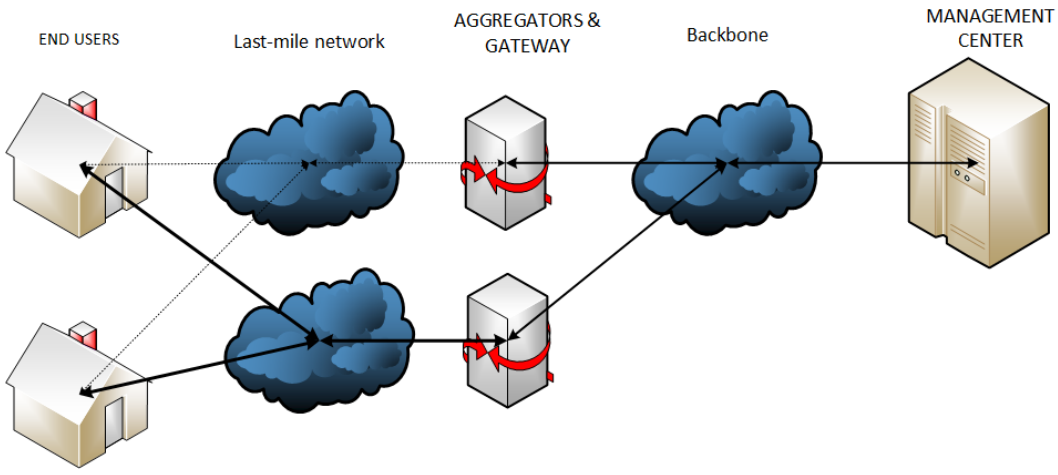


Figure 1.3: Main and backup network in Smart grid

It is then important for management consideration, to be able to detect any failures that are happening in the primary network in order to ensure an interrupted

service. Moreover, the handover of many users at the same time, must not impaired the performance of the backup network and lead to an other failure.
This leads to the principal axes that will be followed on this project:

- How to dectect dynamically detect faults on a network using quality of service metrics?
- What is the influence of the automated switch of mean of communication on the network?

Chapter 2

Smart Grid Communication Systems and Applications

2.1 Network architecture

To understand the stakes of the Smart grid communication network it is important to detail it architecture, from the end-user to the management and control center.The global communication network in a smart grid is composed of different heterogeneous tiers of communication networks, the same way the electrical network is divided in three levels of voltage (High,medium,low).

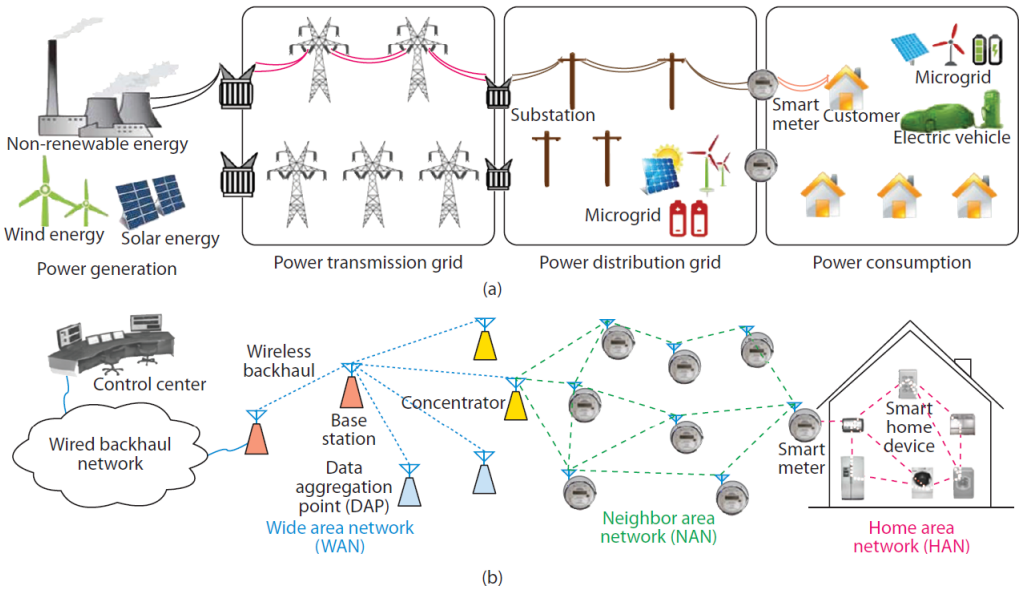


Figure 2.1: Architecture of Smart Grid Electric and Communication network [7]

The National Institute of Standards, and Technology defines the different tiers of

the network as follows [8]

2.1.1 Customer premise

This is the customer side of the network. According to the type of customer, three different terms are used: Home Area Network (HAN) for all the network inside houses with few sensors, Business Area Network (BAN) for buildings with more sensors and Industrial Area Network (IAN) for industries with the higher need in voltage. This side of the network can also be connected to auxiliary renewable power source or electric vehicle. Those networks use smart-meters as gateways to the last mile network.

2.1.2 Last Mile

This is a two-way communication network that is coupled on top of the power distribution system. According to its characteristics, topology, and service offered, the literature has three terms for the Last Mile access: Neighborhood Area Network(NAN),Field Area Networks(FAN) or Advanced metering infrastructure (AMI). This network allows the communication with different renewable-energy generation farm, connected to the distribution system. This network is also used to make a link between meters in the customer premise, and the data aggregators of the back-haul.

2.1.3 Back-haul

Data from customers' meters are aggregated at the end of the Last mile Network through aggregators. From there, aggregated data go through a back-haul network, then contains aggregates, but also substations automation parameter's data, mobile workforce information from the last mile network. Those data are directed to the major point of presence of the Wide area network.

2.1.4 Wide Area Network

The Wide Area network (WAN) is composed any different technologies such as fiber optics, Power Line communication, DSL, and various Wireless communication. The is designed to support critical application and operation on electric utility infrastructure: relay of High voltage, SCADA, physical security, etc. Typically, the network is a private network, in order not to rely on public communication due to the criticality of the operation, that possess a high-bandwidth backbone/core network The following section will then present what are the technologies mostly used in order to assure the communication in those unusual tiers.

2.2 Smart Grid communication technologies

In a Smart Grid network, the importance of real-time and reliable information

becomes paramount and can be considered a key factor in the delivery of power to end-users.[9]. Thus a real-time monitoring is necessary in order to detect any failure. The impact of down-times caused by equipment failures, constraints due to capacity or caused by natural accidents thus becomes much greater than before, but can be controlled by constant and real-time monitoring.

In the smart grid paradigm, one of the key factor to assure the availability of the electric grid, is to have real-time information of the grid using communication networks. It is then primordial to have a reliable communication system covering the overall system, in order for the energy companies to have a real-time monitoring of the electricity grid. Any failure on the communication networks can have serious repercussion on the overall system.[10]

In a Smart Grid system, data from end-user sensor will go through three different networks before going to the control center of the energy company. Therefore, multiple technologies,wired or wireless, can be used for Smart Grid networks and the following sections will be an overview of the pros and cons for the most notable technologies that may be used.

2.2.1 IEEE 802.15.4 (Zigbee & 6loWPAN)

The IEEE 802.15.4 is a standard used for Low Rate Wireless Personal Area Network, and specifies the physical layer and the MAC layer. This standard allows the uses of a low cost, power efficient and low datarate wireless networks. However, because of the lack of definition of the network layer in IEEE 802.15.4, some other's standards on top of it are necessary to build the network.

The Zigbee standard, defined by the Zigbee Alliance, specifies the network layer and also the application one. The standard allows the creation of mesh network, with inherent redundancy, self-configuring, and self-healing capabilities within the range of 10 to 100 meters.[11]

Another standard using as basis the IEEE802.15.4 is the 6loWpan from the Internet Engineer Task Force, which allows the use of the IPv6 protocol for low power protocols. Because IPv6 requires higher bandwidth than IEEE 802.15.4 can give, the 6loWpan protocol reduce the overhead by fragmenting and compressions the headers.But, one of the key advantages of the 6loWpan is its complementarily with the Zigbee protocol. Indeed, as the figure 2.2 shows, it is possible to use both protocol at the same time, allowing then Zigbee network to have gateways to other Internet-based networks.

However, Zigbee and Zigbee over 6loWPAN have also some disadvantages. The main one is the uses of the 2.4GHz bands, and therefore, it is subject to interference from other devices using, for example, the IEEE 802.11 (WiFi), or IEEE 802.15 (Bluetooth) standards. Furthermore, because of the low-power aspect, the signal is sensitive to the environment, especially with concrete walls, reducing considerably the range of application.

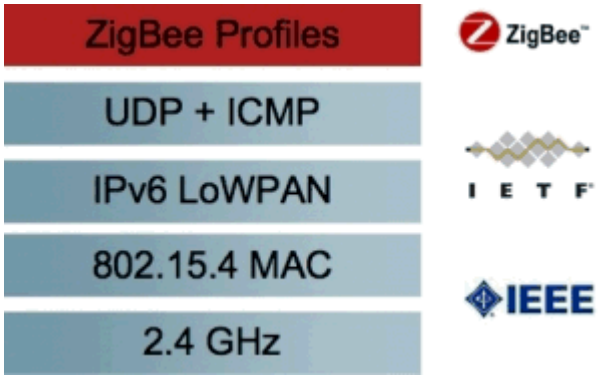


Figure 2.2: Zigbee over 6loWPAN

2.2.2 Wireless Mesh Networks

Wireless networks have been proposed recently, by the NIST as an important networking technology to be employed in the smart grid [12]. Because of the constant decrease in price for the networking equipment, and growth in performance, it has become feasible from an economical and technological point of view to deploy advanced data networks in the power systems.

Wireless Mesh Networks (WMN), are flexible networks, which consist of groups of nodes, with each node acting as an independent router.[13]

Mesh networks represent a dynamic solution that is both cost-effective from an implementation point of view and also easily scalable, which can be very useful in the Smart Grid environment. It can as well offer and provide good coverage by means of multihop routing, in an urban or suburban environment, and it can support the addition of multiple new nodes without the need for complicated reconfiguration.

A disadvantage to WMN, can be the fact that in urban areas, interferences and fading can have a major effect on the quality of services offered. According to [14], because every node acts as an access data point and data passing through each one has to be encrypted for security purposes, loop problems could appear that can cause unwanted overheads in the communication channel. This can lead to a decrease in the available bandwidth.

2.2.3 WiMAX

WiMAX (Worldwide Inter-operability for Microwave Access) is a broadband access using IEEE 802.16 standard. Current version of Wimax achieve transmission rate op to 72Mbps symmetrically, and can use a mesh or a point to point topology.

WiMAX has been designed to be an alternative to DSL, especially in rural areas. Indeed, one of the main advantages of WiMAX is the coverage, going from few kilometers in a non line of sight situation, up to 75 kilometers in a line of sight[11].

Because Wimax has at been seen only as a wireless DSL alternative, it has been mainly deployed in rural areas without wire access. However, because of the evolution of IEEE 802.16, WiMAX offers data transfer speeds close to the LTE standards seen above, and may be installed more inside cities.

2.2.4 Cellular Networks

Cellular networks are a good option due to the already existent network used by communication companies. This means that the energy companies can rely on the existent infrastructure and therefore, will not have to build their own, reducing de facto the time of deployment for the Smart Grid. The different generations for cellular networks will be described.

2G/2.5G

One of the main advantages of the 2G/2.5G is the existing coverage: in Europe, almost 100% of the civilised area are under a 2G/2.5G cell.[11]. It is possible to reach a speed up to 118 kbps in uplink using 2.5G network. However, GSM networks use among other the 900Mhz band, which penetrates houses but have troubles to reach basement, where is often located the meters. A solution is to install the antenna above the ground level, but this would reduce the cost efficiency of cellular networks uses.2G technology are packed based, low bandwidth, and because it uses IP technology, it suits for TCP/IP applications where latency and bandwidth are not the main issues.

3G

The 3G and its evolution are perfectly able to provide data services, based on IP and packet oriented, the same way 2G does. It is possible to reach around 14Mbps in uplink using 3G, up to 23Mbps in 3G+. However, the 3G coverage is inferior to 2G, especially in rural area, because of the frequency of 2GHz used in Europe. Nevertheless, this may change over the years, due to the reuse from the communication companies of the 900Mhz band used by 2G. This will, de facto, increase the coverage.

LTE

LTE technology is the latest standard used in mobile communication networks. One of the main goals of LTE was to reach at least two to three times the 3G+ levels in uplink (50Mbps). LTE has a high spectral efficiency, a low latency and support variable bandwidth. Nonetheless, because the LTE needs a new radio access network, and because it is a recent technology, the actual coverage is limited and concern, mainly big cities.

To sum up, Cellular Networks could be an interesting solution knowing that the energy companies will use already existing infrastructure, and so reduces the cost of deployments. However, to use the network the fees for 3G use can be elevated in the long term.Also, except for LTE, the latency of cellular is high, which will alter the

performance of the network. Moreover, cellular networks are not dedicated, meaning that all the resources are shared with all the users, leading to a decrease of the network performance. Moreover, if an equipment breakdown appears, a substantial amount of data can be lost, which is not acceptable in case of real-time monitoring.

2.2.5 Digital Subscriber Lines

Digital subscriber Line is a data communications technology allowing fast transmission over the telephone network lines. In cities, the use of Very high speed Digital subscriber Line can support data rates up to 100 Mbps.

Telephone wire networks are widespread over-all territories, so this solution would reduce the implementation cost. However, DSL services can be use just More... only over a few kilometers (less than 5km), meaning that this solution would fit purely for dense area. Moreover, it is impossible for the end user to split bandwidth with a second modem, meaning that the customer shares the connection with his regular internet access, to bandwidth issues.

2.2.6 Power Line Communication

Power Line Communication(PLC) is a technique allowing the transmission of data using electric power lines. Since most of the devices are already connected to the power grid, the uses of PLC seem to be a privileged technology. There are no proper open standards for communication over power lines, but most of the time two different approaches are distinguished: the use of narrowband PLC, which perform on a band below 148.5kHz, or the Broadband PLC which is operating between 2-30Mhz.

The obvious advantage of use of PLC in a smart grid system, is that the wired network is already there. However, PLC has also many disadvantages: In order to make the communication possible, some expensive infrastructures are needed. Moreover, parts of the power in the lines are converted into electromagnetic radiation, leading to a high noise on the medium of transmission. And, PLC is not properly adapted to a mesh network, including the change of the load over the transmission line.

2.2.7 FTTx

Optical fiber is currently the fastest medium for data transmission, with a 100 Mbps in average. Optical fiber is a serious option, due to many advantages: a low latency, a high bandwidth, high reliability, a better cost for maintenance than copper. Optical fiber can be put directly inside the end user house (Fiber To the Home, FTTH), or to a building(Fiber To The Building, FTTB) where another technology (most of the time, VDSL) ensure the connection.

, However, the fiber network is far from being entirely deployed, and it's mainly in major cities, and the objective in Europe is to have 50 per cent of the population with

fiber access in 2020. So the direct consequences would be the cost of this deployment, around 202 billions to meet the agenda.

The principal attributes of each technologies are summarized in tables 2.1 and 2.2.

2.2.8 Choice for simulation

Whatever technology is used as an infrastructure for a smart grid project, each has its advantages and disadvantages based on the implementation and application. While wired technologies offer good capacity, security and reliability, the costs associated with implementation and deployment might favor wireless technologies. Because of the geographic distribution, all those technologies may respond to local constraint and therefore be used, leading to a network heterogeneous. However, all the means of communication used must fulfill some traffic requirement according to the application they have been designed for, which will be the topic of the next session.

According to Erhvervsstyrelsen(Danish Business Authority) [15], in 2012, 98% of the Danish households are connected to an xDSL connection with at least 2MBps data rate, and have the biggest share of user in Denmark. Therefore, it seems reasonable to assume that energy company may choose this existent network as primary network, in order to reduce their costs of deployment. The purpose of a secondary network, is to handle some of the communication from the primary network that cannot be transmitted properly. The idea is also to use a wireless mean, in case of a power outage, to be capable to maintain communication using a battery. In Denmark, the main operator TDC has announced a plan have a coverage of 4G , of almost 100% more than 200 cities. Therefore, the simulation in this thesis will use the LTE as a backup network.

Table 2.1: Summary of Wired Technologies in Smard Grid [7]

Technologies	Datarate	Coverage	Stength	Weakness
PLC	Narrowband: 1-500Kbps Broadband: 1-10Mbps	NB PLC : 150km BB PLC : 1.5km	– Infrastructure already established – Physical separation from other networks – Low operational cost	– Multiple non-interoperable technologies and standards – High attenuation and channel distortion – High noise from other electromagnetic source – Complex routing
FTTx	AON: 100 Mbps symetrical BPON: 155-622 Mbps symetrical EPON: 1Gbps symetrical	AON: 1-10km BPON: 20-60km EPON: 10-20km	– Long distance communication – High bandwidth – Robustness against interference	– High deployment cost and terminal equipment, – Difficult to upgrade
xDSL	ADSL:8Mbps down 1.3Mpbs up ADSL: 2+ 24Mbps down 3.3 Mpbs up VDSL2: 200Mpbs symmetrical	ADSL :4km ADSL2+ 7km VDSL2 300-1km	– Communication infrastructure already established, – Broadband technology used	– Ressource shared – Distance limited – Telco companies fees

Table 2.2: Summary of WirelessTechnologies in Smard Grid [7]

Technologies	Datarate	Coverage	Stength	Weakness
Wifi	IEEE 802.11e/s: up to 54 Mbps IEEE 802.11n: up to 600 Mbps	Indoor: 50-70m Outdoor: 100-300m	– Low-cost – Unlicensed spectrum – Flexible	– High Interference – Energy costful.
Wimax	802.16: 128Mbps down, 28Mbps up 802.16m: 1Gbps symetrical	802.16: 0-10km 802.16m:5-30km	– Can handle thousands of users simultaneously – high distance coverage – Sophisticated QoS mechanisms	– Complex network managment – Cost of equipment – Licensed spectrum
WPAN	IEEE 802.15.4: 256 Kbps	10-75m	– Energy efficient – Low cost – IPv6 ready	– Low datarate – Short range – Don't support complex networks
Mobile	2G/2.5G:100-300 Kbps symetrical 3G: 84Mbps down, 22Mbps up LTE: 326 Mbps down, 86 Mbps up	2G/2.5G: 3-10km 3G: 0-5km LTE: 0-5km, up to 100km	– Large scale infrastructure already build – Broadband technology used for	– Ressource shared among users – Not suitable for backhaule/backcore – Telco companies fees

2.3 Applications and requirements

Automatic meter reading: The Automatic meter reading (AMR) refers to the methods using the communication systems in order to collect meters' data or to send to the control center some event-based alarms, or send electricity pricing to the customer. This is the principal application for smart grid system, and is defined by many standards such as ANSI C12.1-2008, IEC 61968-9 and the IEEE 1337. Because this application is responsible for sending alarm message, it has to have a short delay response. On the other hand, because of the wide spread of the meters at every node of the network, the data rate of a reading report is small, around 100-200 bytes.

Synchrophasor: Synchrophasor is the direct application of the different PMU inside the network. In order to have an accurate estimation of the load on the network at a given time, all the PMU units needs to be perfectly synchronised. Being synchronised allow a better managment of the electrical grid.

Demand response: The Demand-response is one of the main applications of the Smart Grid paradigm: it consists for the operator to balance in an optimal way the difference between power generation and consumption. To do so, the operator can involve the customer in two ways: Through a dynamic pricing, so the customer will use less power during a peak period, and by using remote load control programs, for example, to reduce the load used by a thermostat or air-cooler during the peak. The bandwidth requirement for those kind of command is quite low (few kb)

Electric Vehicle charging: In the future, Electric vehicle will become more and more common, especially in big cities. However, this will introduce also some challenge for the grid management. Indeed, electric vehicles will be, for most of them, plugged around 6p.m, which is as well the time of the evening peak of the load, leading to an aggravation of the peak. The development of "'smart charging"' application will be critical then. On the other hand, the other hand, when the car is plugged during the peak, if it battery is not empty, the operator could use the remaining power as an alternative power source to feed power back in the grid. This is called a Vehicle to grid application.

Substation Automation : The substation automation is a direct consequence of the Demand response problem. By dynamically producing the power generated by distributed substation power plants, the delta between energy power consumption and production can be efficiently be reduced.

Regarding the traffic requirement, in terms of bandwith and delay, the table 2.3 show the information from the paper [7] which regrouped the different requirements that can be found in litterature for many applications.

In conclusion, all those example's applications may have completely distinct traffic patterns, and must coexist at the same on the network.

Information Types	Delay	Bandwidth
In-Home Communications	2-15s	10-100kbs
Advanced Meter Reading	2-15s	10-100kbs
Demand Response (DR)	500ms	few tens of kbps
Synchrophasor	20-200ms	600-1500kbs
SCADA	2-4s	10-30kbs
Fault Location, Isolation, and Restoration for Distribution Grids — FLIR	-	10-30kbs
Distribution Automation	25-100ms	2-5Mbs
Workforce Access for Distribution Grids	150ms	250kbs

Table 2.3: *Traffic requirements in terms of delay and bandwidth of different SG's applications [7]*

The communication pattern of smart grid is completely different than the usual telecommunication systems. Smart grid communication networks have to support a lot of traffic from distributed meters, but without any human-made interaction, only from Machine to Machine(M2M). De facto, this traffic is mainly periodic or event based, and each application has different packet inter-arrival rate, burst size, latency. Because of the difference in priority, criticality some QOS differentiation will be necessary, in order to ensure the coexistence of protection, control monitoring, repartition of the traffic on the grid.

The European Telecommunications Standards Institute, has defined 5 main classes of application in different classes and defines the typical max response time and the range of the data burst associated :

To conclude this chapter, Smart grid will be an ubuquitous computing system,with of specific applications, and in an heteregenous network. Because of the criticality of certains applications, the network must be the most reliable possible, which lead us to the next part, about Performance and monitoring.

Application Data	Typical maximum response time	Data burst size
Protection	1-10ms	Tens of byte
Control	100ms	Tens of byte
Monitoring	1s-15min	Tens to hundreds of bytes
Metering/biling	Hours	Hundred of bytes
Reporting/Software update	Days	Kbyte to Mbyte

Table 2.4: Traffic and delay requirement for Application class of Smart grid [16]

Chapter 3

Network performance and Monitoring

This chapter is relative to the evaluation of the system performance. In the first section will be explored how any system's performances is evaluated. Then, a focus will be made on communication systems, where the type of anomalies an IP network can encounter. Finally, the last section will focus on how to monitor a communication network.

3.1 Systems and Faults

This first subsection is a generic description about the probability of failure of a system.

3.1.1 System components & Failure probability

As seen in section 2.1 , end-users send their data through different tiers, until the managment center.

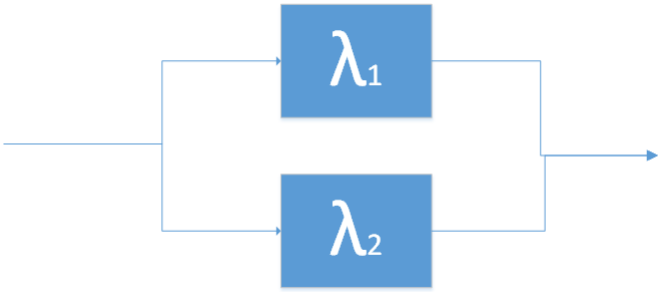
In communications network systems it is commonly assumed that each component are statistically independent and that they have a lifetime following an exponential distribution with a certain failure rate that is called in the litterature λ.
Two types of relationship between components can be distinguished :

- 2 components are linked in series In this case, if one of the two components

fails, subsequently the overall system fails. So, the failure probability of the two components in series can be defined as:

$$\begin{aligned} F(T) &= Pr[Failure\ of\ 2\ components\ in\ series] \\ &= Pr[Failure\ in\ C1] \cup Pr[Failure\ in\ C2] \\ &= Pr[Failure\ in\ C1] + Pr[Failure\ in\ C2] \end{aligned}$$

- 2 components are linked in parallel



In this case, in order for the system to fail, it is necessary that both components fail at the same time. Then the failure probability of the two components in parallel can be defined as

$$\begin{aligned} F(T) &= Pr[Failure\ of\ 2\ components\ in\ serie] \\ &= Pr[Failure\ in\ C1] \cap Pr[Failure\ in\ C2] \\ &= Pr[Failure\ in\ C1] * Pr[Failure\ in\ C2] \end{aligned}$$

It is then easily proved that the probability of failure for components in parallel is lower than the ones in series. This subsection was used to prove the necessity of having two different networks, using two different gateways to internet in order to reduce the probability of a failure in the system.

3.1.2 Dependability of the system

A service provided by a system can be defined using a binary relation as shown in following figure.

The idea behind this thesis is avoid service's failures that are more frequent and more severe than acceptable, meaning to have the most dependable service as possible. In this section, will be presented the necessary attributes to be a dependable system and distinct threats a system can encounter.

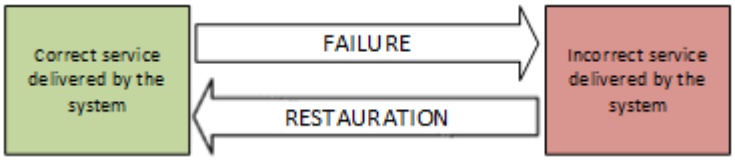


Figure 3.1: Relationship between correct/incorrect service

Attributes

For the attributes of a dependable system, article [17] provides the following definitions:

- Availability: It defines the readiness for delivering a correct service by the system. In other words, it verifies if at a certain instant t, the system can deliver a correct serve.
- Reliability: It defines the continuity of the services to provide a correct service
- Maintainability: It is the ability for the system to undergo repairs and modification.
- Integrity: It defines the ability of the system to avoid possible alterations of the system.
- Safety: It defines the absence of dramatic consequence for the user and/or the environment.
- Confidentiality: This defines the absence of unauthorized disclosure of information.

It is possible to define the Availability, Reliability and Maintainability in a more quantitative way.

For common smart grid applications (seen in 2.3) applications, the required availability is in the 99–99.99 percent range. However, some critical applications such as Synchrophasors or substation automation, require even better reliability,approximately 99.99995 percent, which equates to being out of service for 16 seconds in one year.

Threats

A system can encounter three different threats:

- Fault: It is an event that is the cause of an error. Many different types of fault can occur, the article [17] distinguished more than 256 different combined fault classes.
- Error: An error is a deviation for the system from a correct service state, and may lead the system to a failure.

- Failure: A failure is an even when the delivered service is not acceptable or fails to conform a specification of the system.

In the case of multi-component or distributed system, failure in one part can therefore lead to a fault in another part of the system, and consequently, provoke a cascading failure off the overall system.

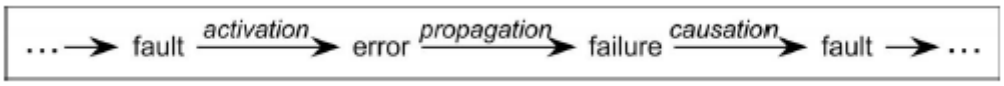


Figure 3.2: Propagation of failures [17]

3.1.3 Concept of Fault Management

Network management tasks must follow by the OSI/ISO network management model FCAPS (Fault,Configuration,Accounting,Performance,Security), that defines five fields for network management as stated in [18]:

- **Fault management**: This is the process from the recognition to its resolution of an abnormal operation of the OSI environment.
- **Accounting management**: It enables the uses of statistical means in order to identify the cost of the use of resources
- **Configuration management**: it identifies, collects and provides data to initialize and start continuous operation of services.
- **Performance management** : It evaluates the behavior of resources and the effectiveness of communication activities, to ensure performance remains at the sufficient level. The performance management can gather relevant statistical information for the network.
- **Security management** : It supports the application of security policies, but also reports any security events that might threaten the integrity of the system.

In this thesis, a particular care has been taken on the fault management aspect of the FCAPS framework. In real life, it is impossible to have a system that will never encounter any errors. However, those errors must stay at a reasonable level, in order not to lead to failures. It is then important to design a system capable of being resilient when a fault occurs, in order not to have a or many failures as seen in section 3.1 Instead of the two-state service as seen in figure 3.1, the fault management concept is divided into five different steps as follows :

- Detection: A fault is detected on the system, without knowing where on.
- Diagnosis: This is the capacity of determine which component lead to a fault

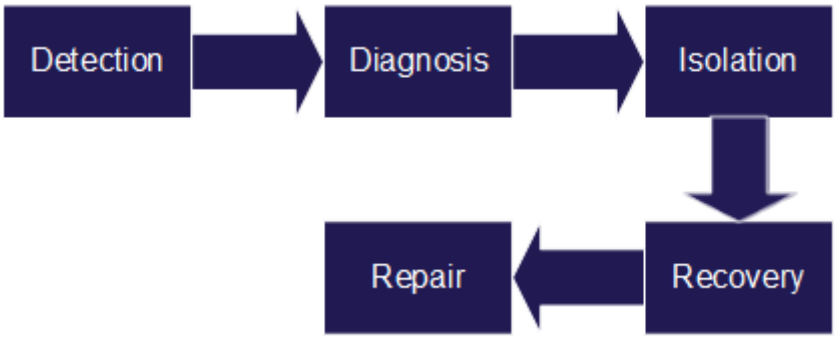


Figure 3.3: Fault managment steps

- Isolation: It's the way of make sure that the diagnosed fault will not propagate, leading to a cascading failure.
- Recovery: This is the function restoring the component to its normal state
- Repair: Restoring the system to its expected state.

This thesis will focus only on the detection, diagnosis and isolation steps, and with a specific care for the two first. The detection and diagnosis procedures will be more detailed in the following sections. The isolation function has been designed in the problem formulation. Indeed, when a fault is detected and can lead to a failure, then the smart meters will switch the mean of communication allowing the data to be send through the backup network.

3.2 Anomalies in the network traffic

In the scope of this project, my goal is to try to prevent any failures in the communication link between an end user and the control center. To do so, the approach where the network traffic is monitored to see any anomaly in it has been chosen.

The first step for this way, is to define clearly what is the normal traffic in the network so when an anomaly occurs, there will be a deviation from this regular state.Those events may be detected while or before a failure of a part of the system, and therefore, are needed to prevent them.

It is assumed the network is using only the IP protocol from the Smart meters to the control center, and consequently, a close attention is payed on two kinds of anomalies IP systems may encounter.

The first category is all the different types of failures that can happen in an IP-system and the performance problems. This category of an anomaly could be really broad and, without being exhaustive. The most familiar ones can be described as :

Link corruptions: This refers to a physical damage to the connection, that could be a broken cable, a fiber span, etc.

Electrical noise : It refers to instability of the link because of a high electromagnetic radiation, for example, close to high-voltage devices.

Power outage: It refers to a power problem of a device in the network, that could be locally situated, or more global. In the case of a power outage for an antenna or a router, this can affect a large number of devices.

Interface damage: This is probably the most common hardware failure, that affect for example a router or a switch, leading to a disconnection of a certain area in the network.

Software issue: When the internal software of a device encountered a bug, and no longer communicates.

Routing Misconfiguration This refers to incorrect routing table, than can lead the traffic not to be routed in optimal paths, or even in loops.

Packet over-flooding This refers to situations were the bandwidth is occupied by unwanted traffic, for example in the case of broadcast storm

In the litterature, those failures are mainly regrouped in 4 distinct classes

- IP-Connectivity issues
- Physical issues
- Network misconfiguration
- Software issues

The second category of anomalies, is this time human based, and concerns security-related issues. Because the network will be extremely complex due to its open and distributed architecture, an IP network can be attacked from inside or outside. Mainly, this concerns denial of service attacks, but also virtual shutdown of the network or flooding by unwanted traffic due to worms.

All the failures in those two categories have a clear impact on the metrics of the network, such as the throughput, the delay, the bandwidth, but also will induce the fragmentation of packet, retransmission, collisions.Thus, by getting the network performance data, it is possible to detect any *transient changes in measured network data that occur prior or during an abnormal event* [19]

The following part will explain what are the different paradigms and strategies in order to monitor the network, and get the performance data.

3.3 Monitoring and Fault detection

The monitoring of a network concerns mainly two fields of the FCAPS framework described previously in section 3.1.3:

- Fault Monitoring
- Performance Monitoring

The fault monitoring concerns problems in the network. As seen in 3.2, faults can happen in various layers of the OSI layers, thus, it is important to know which one is abnormal.
The Performance monitoring can measure performance of a network. By observing the network during non faulty situation, it is possible to establish some efficient performance "model". Therefore, a faulty situation can be then detected when the performance of the network tend to be too different from this faultless model.

The way of monitoring a network can be separate into two distinct kind: Passive and Active monitoring.

Passive monitoring does not generate any additional traffic on the network, and only listen what transit on the specific point(e.g a router), and derive from it metrics.According to thoses, the probing station may decide if there is a faulty situation or not. Some alarm may be also inherent to the protocol used, such as a wrong packetsize, number of retransmission packets. More generally, the article [19] defines somes relevant metrics and what should be the alarm condition inherent and are transcribed in figure 3.1

Among others, common passive monitoring are, for example, Wireshark, Fiddler, or Tcpdump.

Active monitoring involves sending traffic in the network in order to sample its behavior. One of the principal advantages of active monitoring is that there is a direct choice of which traffic to send, and the probes (i.e the traffic sent) can be designed in order to measure a specific quantity like average delay, the route, available bandwidth. It is then possible, by observing the network to localize fault, and diagnose it.

Some monitoring standards have been defined and are commonly used, such as the Simple Network Management Protocol [20], Netflow [21] or the Remote Network monitoring [22]. These methods are qualified as *Router-Based* monitoring techniques. The idea is that the probes stations are localized on certain node of the network, and monitor the nodes around them. A unique central management center send probing request to the stations, that transmit the results afterward. Therefore, as explain in [23], in order to to have a real time monitoring of a highly distributed system, a high processing load on probing station along with a high bandwidth consumption must be expected. Thus, this may lead to flooding the network due to high frequency management request. Thus, they may behave well in the small-scale network, their

Network Metrics	***Alarm Condition***
Out-of-order sequence packets	First Appearance
Jumbo or Runts frames	First Appearance
CRC error frames	First Appearance
TCP Checksum error	First Appearance
Collision frames	Threshold-based
Fragment packets	Threshold-based
Retransmission Packets	Threshold-based
Broadcast packets	Threshold-based
Packet interarrival time	Analysis over monitoring period
Throughput	Analysis over monitoring period
Packets per second	Analysis over monitoring period
Packet size	Analysis over monitoring period
TCP window size	Analysis over monitoring period

Table 3.1: Metrics and their Alarm condition in IP networks

performance decrease with the complexity of the network, while flooding the network with management requests. Some example of monitoring framework using this centralized, or "router-based" approached can be found in [24],[25].

The other approach of active monitoring is to use a decentralized way. There is no more one central management center which collect results from stations, but instead, different nodes send for themselves probes and can derive directly the network dynamics. Therefore, the node does not have an overall vision of the network, but only of the path the probes took.

One of the inconvenient shared by both approaches is the impact of the probes on the network. The goal is to send enough packets in order to have a relevant monitoring, but not too much in order not to flood the network and induce congestion. Two different probing techniques is then possible:

Pre-Planned Probing: This involves a preplanned selection of probes that are send periodically, and the network state can be determined with probe's results. This

implies that a large management traffic is generated, that can induce delay, and de facto a certain inaccuracy.
Moreover, active probing suffer from a limitation: The probes set are defined in advance and in an "offline" situation, it is mandatory for it to be able to detect all potential problems.
Two problems arise from that: The first one, is that it cannot be proven that the designer of the probes select a complete set of probes all problems imaginable, leading to potential weaknesses. The second is the possibility that probes have been designed to detect faults which are unlikely to occur, flood the network for nothing. Furthermore, most of the time, once a fault is detected, the diagnosis may need more information, not available with defined probes[26].

Active Probing: Active Probing is based on an interactive mode, where the most likely diagnosis is determined using the probe's results. Once a diagnosis has been established, extra probes are selected in accordance, and send to get more information and de facto to refine the diagnosis, this operation is repeated until the determination of the problem.

By this way, active probing would be a solution for the preplanned probing limitations: The probes are sent to occurring problems, and are dynamically designed for that problem. Furthermore, the probes can directly focus on the localization of the fault, reducing the impact of monitoring the network.

The technical report [26] give a hint about the steps to follow in order to diagnose faults:

1. A small probe set must be pre-selected, so that when a problem occurs, it is possible to detect something has gone wrong
2. The probe results must be integrated and analyzed, to determine the most likely network state
3. The "'most-informative"' probes to send next must be selected based on the analysis of previous probe results
4. this process must be repeated until the problem diagnosis task is complete

In both active or pre-planned probing, the selection of the probe is then an important step in order to localize a fault. Various different types can be found in the literature[27]. Those probes have different ways of interaction in the network, by the number of packets sent, or the frequency of sending. The principals methods are the following:

- **1-packet**: The pathchar tool describes by V. Jacobson used the 1-packet method, to estimate link bandwidth from round trip delays of different packet

size, on the assumption than the transmission delay grows linearly with the packet size

- **Packet pair** The method use *minimum inter-departure time* of successive packets sent back-to-back on a link to estimate the bottleneck bandwidth. Some methods estimate available bandwidth based on the observation of inter-departure time of consecutive probe packets.

- **Packet train** A Packet train is simply a sequence of multiple packet pairs. As an example, the Pathload tool uses this method. train.

- **Packet tailgating** These methods use packet trains, using large packet and small packets. Because of their limited TTL, large packet will be discarded midway, and only the small one will capture timing information. However, if the probing bit rate is higher than the bandwidth, this will cause a congestion. Therefore, by knowing the minimum probe rate, it is possible to know the available

  bandwidth.

As examples, the most common probing tools are ping, pathchar,iperf, Cprobe, Skitter, pathrate,PatchChirp,NetTimer.

3.3.1 Choice for the simulation

To sum up, two categories of monitoring are possible : the ***passive*** one, which consist in listening the network at certain important point, or the ***active***, that provide metrics by the use of probes send in the network.

In the scope of this thesis, the monitoring must collect data such as end-to-end delay or the jitter. Therefore, the passive monitoring cannot provide such metrics for each link between houses and the management center.

For the active monitoring, as described, the probes stations can be placed following two different approaches : the router based, or the decentralized one. Two problems arise with the first approach: as explained in section 3.1.1, the simulation will use as primary and secondary network respectively an ADSL connection and a LTE one. This means that data will transit throughout internet, and therefore, the management center does not have the capacity of pulling probing command.
Moreover, Router-based techniques implies that only the network management center will get the monitoring information.Yet, in the thesis scenario, both ends need to estimate the network dynamics, which is not the case here. In conclusion, Router-based approach seems th
en non compatible within the scope of this thesis. Therefore, the decentralized active probing seems to be the best way of to obtain end-to-end metrics. However, a particular attention to its scalability and the probes' impact on the network dynamics must be paid.

Chapter 4

Simulation Model

As explained in the previous sections, the general idea of monitoring a smart grid network, is to have a smart meter in each house, sending data periodically, between one and fifteen minutes. In a concern to have a more scalable system, the smart meters send data actually to an aggregator, which then report to the management center. Due to the low frequency of updates, it is important that the messages are well transmitted between the two end of the network. Therefore, one of this thesis' goals of is to detect if any faults happened inside the network between two messages send, and if those faults lead to a possible failure of communication, use a secondary network to transmit the data.

Each meter will probes in between the real messages, in order to be sure that the data can be received properly. If, from the probes results, the primary network is considered as faulty, then the message will be send through the secondary network, that has a different aggregator, until full recovery of the first one. This means that the main and the secondary aggregator must have a coordination system, to ensure that if one has a failure, the other handle the connection. If for the same house, the two concentrators conclude there is a failure, then the management center must be notified.

As seen in section 2.3, the size of the packets of actual data for smart grid application is small: the maximum is around hundred of kilobytes. As seen the report [28], such packet are more sensitive to delay than the bandwidth itself. Therefore, in the simulation, the probes will be used to derive the end-to-end delay of packets, but also the interarrival time of the probes. In the following section, the architecture of the primary and secondary network will be described, and how can the delay be characterized based on that:

4.1 Networks description

As detailed in section 2.2 the primary and secondary network used are respectively ADSL and LTE. The ADSL network can be simplified as follow :

From 4.1, it is etasblished that one of the main weakness point of the network

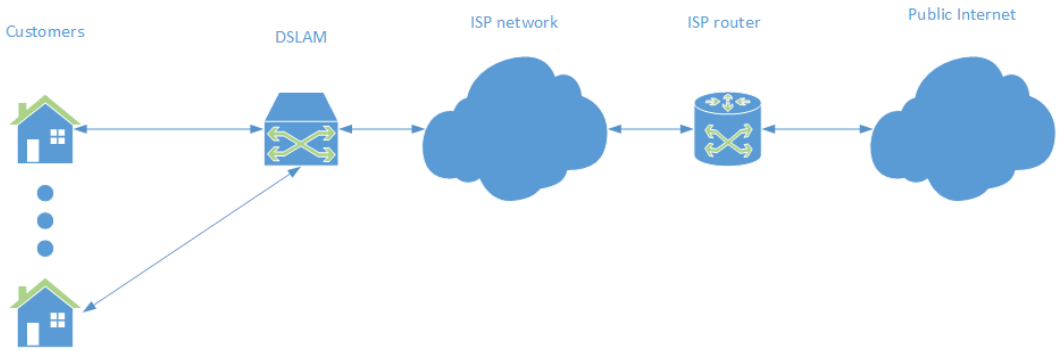


Figure 4.1: ADSL Architecture

is at the DSLAM, which multiplex the data of many users to connect it to the ISP network. Indeed, if many users use intensively the network at the same time, this might be a typical point for a bottleneck to be formed.

Regarding the LTE network, due to the lack of mobility for the houses, all the components responsible for the handover managment will not be taken in consideration. The architechture of the network can be schematised as :

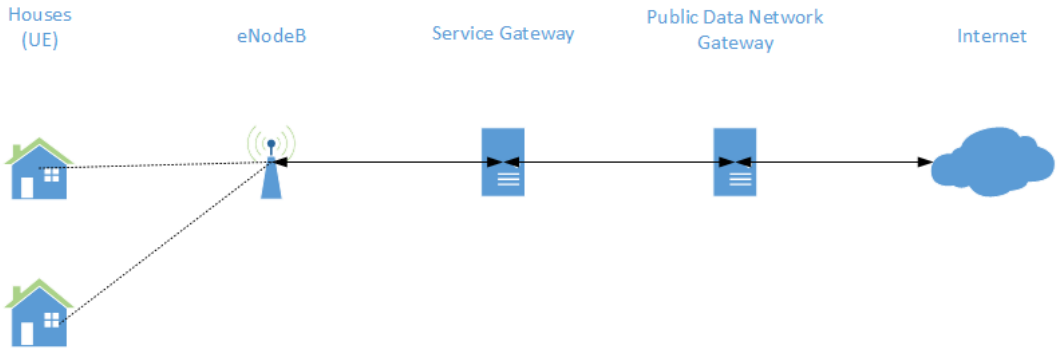


Figure 4.2: LTE network representation

The LTE network is composed by :

- User Equipment : It is modem requirement to connect to the network
- eNodeB : It is the evolution of the UMTS base station, it has the role to connect the users to the core network of LTE
- Service Gateway : the S-GW allows the users to communicate with other users of the LTE network but also 2G/3G network. It is also responsible for routing the packets to the correct eNodeB from the P-GW
- PDN Gateway : This gateway provide the connectivity between the UE and external packet data network, such as Internet.

A new feature of the LTE compared to 2G/3G network is the use of ALL-IP connectivity. This means that all kind of utilisation (voice,voip,data) is treated the same way. This feature reduce the number of steps necessary to connect the user to internet. This lead to a important improvement of the latency, with usual latency below 30ms for data smaller than 1Kilobyte.
LTE use as coding the Orthogonal Frequency Division Multiple Access. This modulation is at the same time a frequency and temporel multiplexing. The use of orthogonal frequency reduces the interference caused

In conclusion, the final system architecture that will be used during the simulation can be seen in figure 4.3

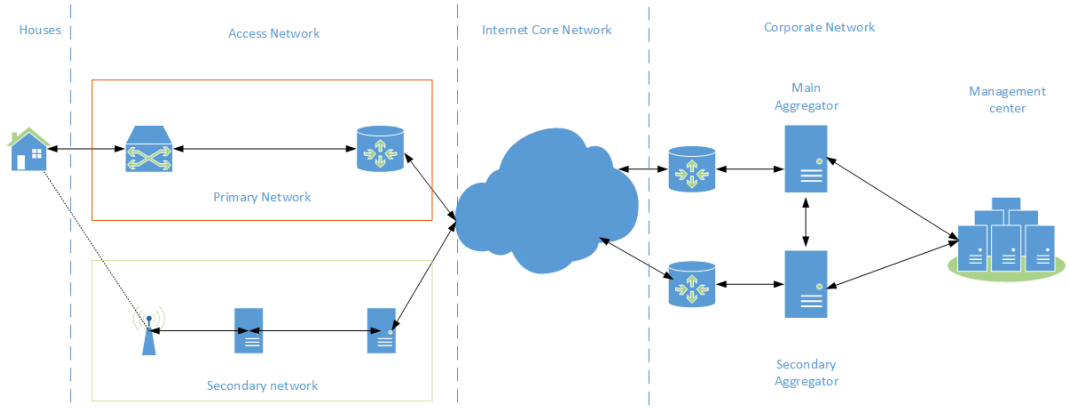


Figure 4.3: Simulation system architechture

From this definition of the network model used in the thesis, the following section will focus on the implementation in the network simulator OMNeT++.

4.2 Simulator description

4.2.1 OMNeT++

OMNeT++ is an open source discrete event simulation package written in C++. OMNeT++ has been designed to enable large scale simulation, with hierarchichal, and customizable modules.

OMNeT++ use a modular language named NEtwork Descrption (NED), which allows the modelisation of complex systems by assembling several elementary modules together. The architechture of the network is described following a hierarchichal organistation, with the following components:

- Simple Module: It is a single component that allows us to define the algorithmic coportement
- channel: It is the link that ensure the liason between modules

- Compound module: a structure composed by simple modules connected t

Active modules, also named *simple modules* are derived from a framework base class, cSimpleModule. Those active modules, can be regrouped in a hierarchichal way in order to form compound modules. Unlimited different hierarchichal layers of compound modules can be created in order to make a system module. Modules communicate between each others using messages; those are send either by direct connection between modules(input/output gates) or directly to the destination modules.

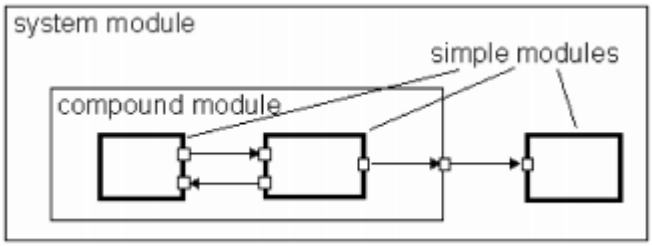
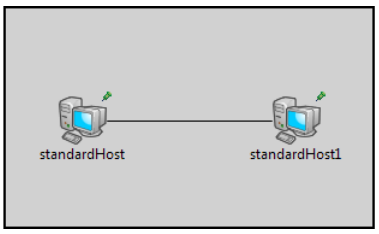


Figure 4.4: Model Structure in OMNeT++ [29]

Once modules different modules are built, the network model can be defined using the NEtwork Description (NED) language particular to OMNeT++. NED language is used to described which module are used, to define the topology of the network, the interconnections between the modules, and the parameters of the compounds. The Topology of the network can also be defined using the user interface of OMNeT++, which translate automatically into code the different modules. The figure 4.5 show as example the way two host are connected together, using the graphical interface, or the ned language.




```
network Rapport
{
    @display("bgb=293,262");
    submodules:
        standardHost: StandardHost {
            @display("p=64,93");
        }
        standardHost1: StandardHost {
            @display("p=195,93");
        }
    connections:
        standardHost.ethg++ <--> DatarateChannel <--> standardHost1.ethg++;
}
```

Figure 4.5: Graphical (left) and Ned-based (right) Network description

Once the simulation model described in NED or the module behavior written in C++ are completed, the simulation parameters are stored using INI files. While the "backbone" of the simulation (NED and C++ files) is assumed to stay unchanged, some parameters vary according to the experiment. Therefore, all parameters are saved seperately in an INI file. Using this differientation allows us to have multiple scenarios, to observe how the simulation behave according to different inputs withouth having to change the models files.

OMNeT++ is a simulation environment, where the standard modules are generic to fit in any basic scenario. However, due to its modularity each module can be easily reused in any other module, which has lead to the developpement of diverse framework on top of the simulation environment.

4.2.2 INET

The INET framework for OMNeT++ is the keystone of the simulator : while OMNeT++ only implement generic modules, the INET framework add up a full library of standards use in an internet networking. On top of protocols issued from the OSI layers, INET also implements several applications models, mobility support, routing protocols and is responsible for the configuration of the IP network (IPv4/6). Therefore, this framework is essential in order to have realistic simulation. The figure 4.6 show for example the difference between a regular OMNeT++ host and one using the INET Framework.

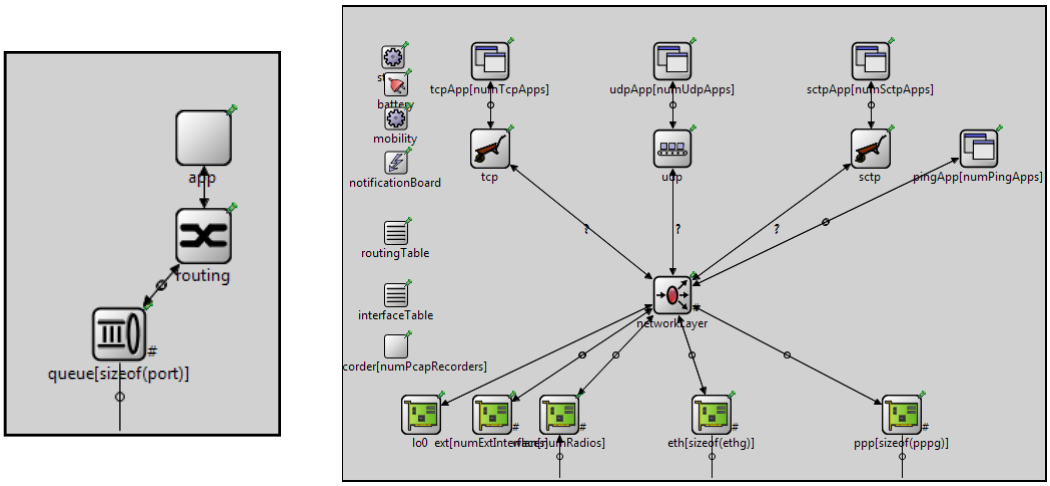


Figure 4.6: Comparision between OMNeT++ Host(left) and INET-extended Host(right)

4.2.3 SIMULTE

The SimuLTE is a framework developped to evaluate the performance of LTE and LTE-Advanced networks. The framework implements the core network of 4G networks as described in section 4.1, but also the eNodeB, and the physical and Mac layer for the Users Terminals. Regarding the rest of the OSI layer for the Users terminals, SimuLTE is based on the INET framework, insure a full compatibility with other INET modules.

4.3 Network description in OMNeT++

From the OMNeT++ point of view, the network described in 4.1 can be seen from the simulator interface as:

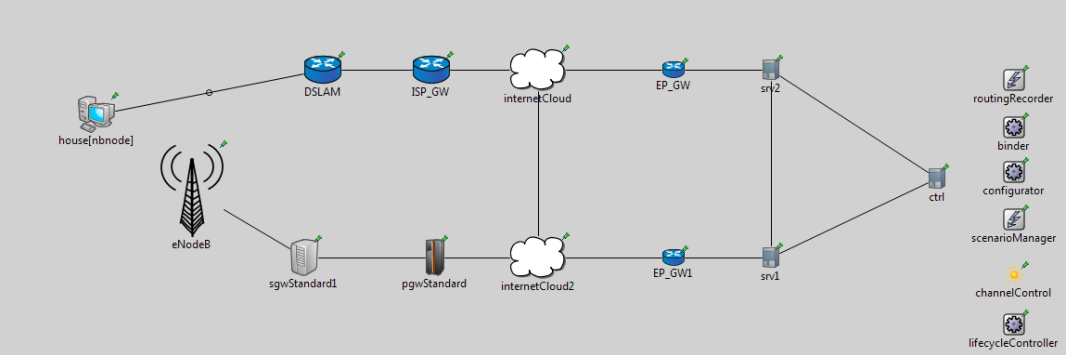


Figure 4.7: Omnet++ Representation of the network

This section will cover the different OMNeT++/INET/SIMULTE modules used in order to reproduce this network.

4.3.1 IP Adress attribution

To function properly, each nodes of the network must have an defined IP adress. To do so, OMNeT++ implement two modules: IPv4NetworkConfigurator and IPv6NetworkConfigurator. The role of this configurator is to assign each interface a unique adress, and to define static routes. The attribution can be either done automatically by the module, or can be configure manually. In this case, the configuration file must be store in an XML file. This XML file must contain one <config> element, and then may contain multiple parameters elements from :<interface>,<wireless>,<route>,<multicast-route>.

The <interface> provides configuration attribues for one or many interface of the network. These are :

- hosts: Selector that specifies the hosts that must be affected by the interface element
- name: Selector attribute that specifies the name or a list of interface name. By default, it is set to "*" (All names)
- towards: Selector specifing a list of host names connected towards the specified host
- among: Selector specifing a list of host names to whom the specified host is connected
- address: Parameter limiting the range of assignable addresses. Possible to leave unspecified part such that the configurator fill it automatically eg:"10.0.x.x"

- mtu: Parameter to set the MTU in the interface
- netmask: Parameter limiting the range of assignable netmask. Possible to leave unspecified part such that the configurator fill it automatically eg:"255.255.x.0"
- groups : Parameter to assigned a list of IP address to add in the multicast group of the interface

The <multicast-group> is used to provide multicast network addresses for the interface of the network.

The <wireless> is used to described any wireless network, with the following attributes:

- id: Parameter to identify the wireless network
- hosts: Selector that specifie a list of host names
- interface: Selector that specifie a list of interface name that will be affected

The <route> allows to provide manual routing table for multiple node. The scope of those route are delemited by the following attributes :

- hosts: Selector that specifies the hosts that must be affected by the interface element
- destination: Selector attribute that specifies the destination adress in the route.
- netmask: Parameter that specifies the netmask in the route.
- gateway: Paratemer specifiying the next hop adress in the route

The <multicast-route> defines the multicast routing tables, by specifying from which interface multicast packets are expected (parents), and to whom those packets are send (children).

As example, considering the following test-network:

The configutation file may contains the following (but not exhaustive) xml code:

```
<config>
<interface hosts="host1" towards="router1" address="172.0.0.1" netmask="255.255.255.0" mtu="1500"/>
<interface hosts="host4" towards="router3" address="172.0.1.1" netmask="255.255.255.0" mtu="1500"/>
<interface hosts="router2" towards="router1" address="172.1.0.1" netmask="255.255.255.0" mtu="512000"/>
<multicast-group hosts="host1 host2 host3" towards="router1" address="225.0.0.1"/>
<route hosts="host1" destination="*" netmask="/0" gateway="router1" metric="0"/>
<route hosts="router1" destination="host1" netmask="/32" metric="0" interface="ppp0"/>
<multicast-route hosts="router1" groups="225.0.0.1" children=">host1 >host2 >host3"/>
<\config>
```

At the network initialisation, the configurator will first take the configuration file and apply it. If some interface or routes, are not defined, it will assign it automatically. Once the network is configured, each node in the network must have inside the network layer a module named IPv4NodeConfigurator (or IPv6NodeConfigurator) that actually set the node's interface table and routing table based on the information defined by the IPvxNetworkConfigurator.

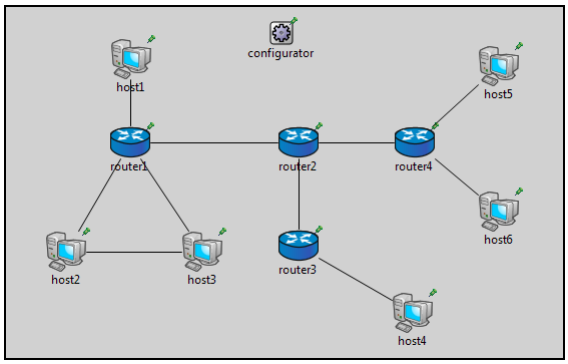


Figure 4.8: Test network for IPv4NetworkConfigurator

4.3.2 LTE BINDER

The LTE BINDER is a similar module as the IPvxConfigurator seen previously used with SimuLTE. It has only one instance in the whole network, and is called at the initialisation of the network. The Binder stores the mapping tables with other OMNeT++ module (not part of SimuLTE). First, the binder assigned the IP and mac Addresses for lte modem, then bind the User equiments to an eNodeB and define what is the next hop for each eNodeB in case of Handover. During the simulation, the Binder is used by the eNodeB to acces the nexthop table, by any module to access the others OMNeT module's ID, and to get the map of already deployed User Equipments in order to have some Adaptive Modulation & Coding (AMC).

4.3.3 Channel Controler

The Channel Controler is a mandatory module in OMNeT++ if the simulated networks use wireless communications. The controller is responsible to locate every moving node in the network, and determine which nodes can interfere with others. Then, the radio interface of the node reuse this paramet during the transmission. The Channel Controler is also responsible to enable and set up the radio tranmission channel parameters. In the case of a LTE network, the channel parameters are :

- Shadowing
- Pathloss scenario
- Height of eNodeB
- Carrier Frequency
- Target Block error rate
- Harq reduction
- Antenna Gain: UE and eNodeB

- Thermal Noise
- Noise figure : UE and eNodeB
- Fading type
- InCell and Inter-cell interference

SimuLTE provide different XML scripts implement those parameters with different values, or model type.

4.3.4 Hosts

The aggregators and the managment center are defined as Standard Host, while the houses are defined as a Standard Host with an LTE interface added. The internal structure of an host has been shown in figure 4.6.

The host is composed in 4 layers disposed in a hierarchichal way, which correpond to the OSI layer.

- The first layer is for the interfaces such as ethernet, point to point or LTE.
- The second is the network layer, using either IPv4 or IPv6
- The third correspond to the transport layer, and implements TCP, UDP and SCTP
- The last correspond to the Applications using protocols of the transport layer.

The 3 first item cited are used in a "transparent" way for the user, meaning that no configuration is necessary prior the simulation. However, the application layer is defined in a generic way, assuring only the interconnection to the transport layer. Each application must inherit from this generic application. This way, many application can run at the same time. Inet provide as examples different types of applications

INET UDP Applications :

- Basic Client: An application sending periodically packets
- Burst: Same as the Basic client, but packets are send in a bursty way
- Echo: Send back any incoming packet
- Video Streaming client: Send video stream request
- Video Streaming server: Send a video after receiving a request

INET TCP Applications :

- Basic client : A simple request-response application over TCP
- Echo: The server Echo incoming message
- Telnet: A telnet session
- Sink: Any incoming packet are dropped
- Session: Opens a connection, sends a number of byte and closes
- Server: Server to handle TCP-based application

Those examples are a nice introductory way to design further advanced application.

4.3.5 Internet Core Network

To emulate the internet core network, the INET framework has a specific module named "Internet Cloud". This module allows to have a more accurate representation of the core network. This component takes many different parameters as input

- src : It is the source of the packet
- dest : Destination of the packet
- delay: the time the packet will wait before reaching the destination
- datarate: the throupghut of the link
- drop: the probability that the packet is dropped.

The internetCloud module allows to have different routes with different delays and drop probality. In order to have a clear input, those routes can be stored in a Xml file. An example of xml file is given below

```
<traffic src="router1" dest="router2" delay="10ms+truncnormal(5ms,5ms)"
 datarate="uniform(10Gbps,100Gbps)" drop="uniform(0,1) &lt; 0.01" />
```

From this example, it can determined that the Cloud network is located between two router, the delay between the two router is following a normal distribution with a mean of 15ms with a deviation of 5ms. The datarate is uniform between 10Gbps and 100Gbps, and the probability that a packet is dropped is les than 0.01. Regarding the drop probablity, the term "<" correspond to the sign "$\leq$" (less or equal) in xml language.

4.3.6 Scenario Management

According to the experiment, users may want a change of parameters,eg. a route supression, an increase of the bit error rate of a connection, in order to examine the transient behaviour of the network. To do so, the user may want to do it manually through the graphical interface. However this is a long process, and in the case of many experiments to run in a row, it can get a fatisdious task. Therefore, OMNeT++ implement a module named ScenarioManager in order to automatize the scheduling of certain events. The ScenarioManager executes a set of built-in commands that accept parameters. Those commands are:

- <set-param>: Select and modify a parameter's value for a specific module.
- <set-channel-attr>: Modify an attribute of the channel connected to the gate of a module
- <connect>: Connect two gates of two modules with a channel defined with <param>
- <param>: Used inside the <connect>, to fix the channel attributes.
- <disconnect>: Disconnect the gate of a module

For each command in the script, a time "t" must be specified so that the Manager can schedule the events. For a same time, either one or many event can be schedule. The following example show a script with 7 events at 4 different times.

```
 <scenario>
<set-param t="10" module="host[1].mobility" par="speed" value="5"/>
<set-param t="20" module="host[1].mobility" par="speed" value="30"/>
    <at t="50">
        <set-param module="host[2].mobility" par="speed" value="10"/>
        <set-param module="host[3].mobility" par="speed" value="10"/>
        <connect src-module="host[2]" src-gate="ppp[0]"
                 dest-module="host[1]" dest-gate="ppp[0]"
                 channel-type="ned.DatarateChannel">
<param name="datarate" value="10Mbps" />
<param name="delay" value="0.1us" />
        </connect>
     </at>
     <at t="60">
        <disconnect src-module="host[2]" src-gate="ppp[0]" />
        <disconnect src-module="host[1]" src-gate="ppp[0]" />
     </at>
 </scenario>
```

The ScenarioManager allow to schedule event in order to modify parameters. However, it is incomplete regarding any failure a node can experience. To correct that, a module named LifeCycleController has been developped in starting INET-2.2.0. The LifeCycleController introduce three type of commandes scriptable by the scenario manager : NodeShutdownOperation, NodeCrashOperation and NodeStart-Operation.

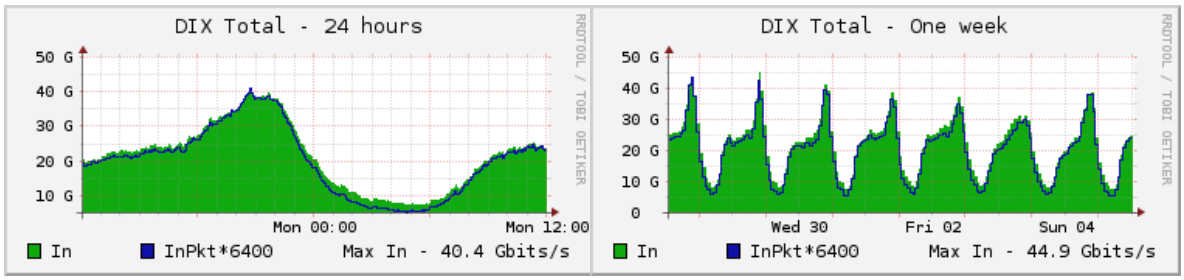
The way those operations are scripted are slightly different from other scenario events: The script first indicate that this is a lifecycleController operation, then which operation is used and finally in which node the event occurs.

```
<at t='3s'><tell module='lifecycleController' operation='NodeShutdownOperation' target='Router1'/></at>
<at t='6s'><tell module='lifecycleController' operation='NodeStartOperation' target='Router1'/></at>
<at t='10s'><tell module='lifecycleController' operation='NodeCrashdownOperation' target='Router1'/></at>
<at t='11'><tell module='lifecycleController' operation='NodeStartOperation' target='Router1'/></at>
```

4.4 Internet Traffic Description

4.4.1 Periodicity of the Traffic

It has been proven that the internet traffic follows a weekly and daily periodicity. The Danish Internet Echange Point (DIX)[30] provides the following graph for the daily and weekly traffic graph at the beggining of may 2014:



Because the internet traffic, but also the electricity consumption, is similar for each day of the week, the simulation will only cover 24 hours cycle. Unfortunately, simulate a 24H hours cycle would need too much ressources, and even more capacity of storage for the results that are not possible.
It has been seen from the network description in section 4.1 that a possible bottleneck is at the gateway between the access network and the core network. If a congestion may occur, it is therefore most likely that it happens at the end of the day. Therefore, the simulations will focus on that specific timeframe of the day, simulating the equivalent of four hours during the spike of consumption.

4.4.2 Delay characterisation

As stated previously, the principal metric this thesis focus about is the delay.Using the network architecture, it is possible to have an estimate of what will be the delay in a regular case.

As seen in the figure 4.9, the delay can be decomposed in 3 types:

- $\Theta(\tau_n)$: The delay for a message within a link
- $\Theta(\text{CN})$: The delay of packet within the internet Core Network
- $\Theta(q_n)$: The delay a message spend in a queue
- $\Theta(p_n)$: The processing time at the meter/server level.

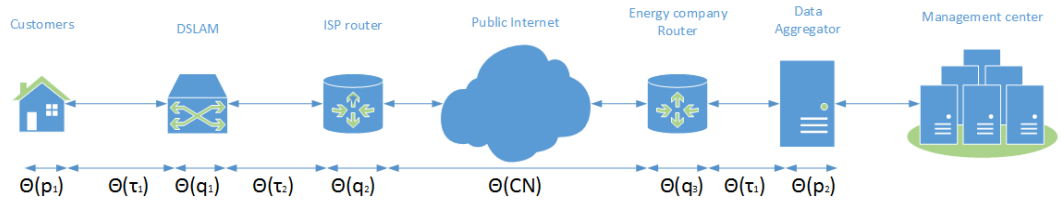


Figure 4.9: Decomposition of the delay

The values of $\Theta(\tau n)$ are assumed to be following a normal distribution, with a small variance. The processing time at the house and the aggregtors are assumed to tend to zero. The article [31] estimates that the access network as a delay around 20ms, the delay in the internet core network is between 10ms to 20ms. It is assumed that the time at the corporate network is small, less than 5ms. The time each packet spend in a queue depend on the load of the queue. When it is empty, the time is zero, and, a contrario, tend to infinity when it's congestionned.

From those metrics it can be assumed that the delay of packets using the primary network from one house to the main aggregator will follow a uniform distribution. The following graphs show different example distributions the measured delay from the probes will likely follow, in the case of en empty queue.

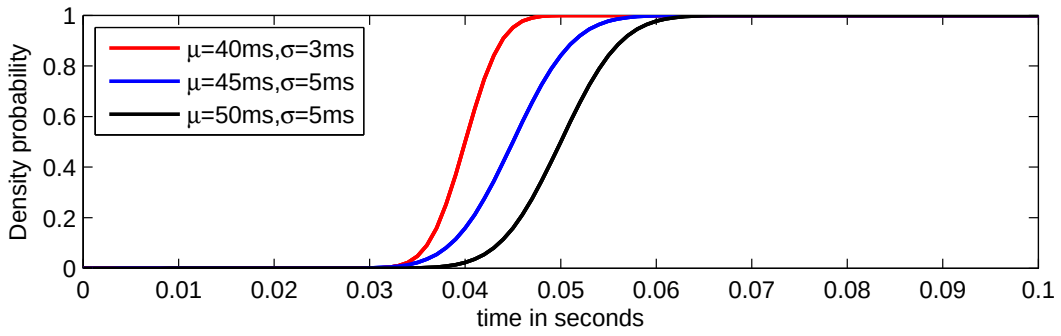


Figure 4.10: Cumulative density function of theoretical end-to-end delays

The same reasoning can be applied for the secondary network : the technical report [28] stated that theoretical delay between an user equipment and the PDN gateway is between 20 to 30ms.

4.4.3 Queue description

From the previous subsection, it can be seen that the time each packet send in the the queue of the DSLAM or routers is the main unknown variable for delay calculation. In the simulation, two type of queue will be used, and are described in the following paragraphs.

Tail Drop:

The tail drop is the most simplistic queue model running the following algorithm:

Algorithm 1 Tail Drop Algorithm

```
1: for all New Packet incoming do
2:     if Queue size ≥ Queue Capacity then
3:         Drop Packet
4:     else
5:         Store Packet
6:     end if
7: end for
8: test
```

The idea is that the queue is serving the packets according to a First In First Out (FIFO) scheduling and has a limited storage capacity. Any new packets are accepted in the queue until being full, where any new incoming packet are dropped.

In case of congestion, all host using the TCP protocol, whom packet are in transiting through this queue will enter in a slow-start, reducing therefore the throughput of all host (TCP global Synchronisation) . This queing management does not differentiate any packet, and therefore are all traited the same way.

With this type of queue, a congestion can be detected only when the queue is full and the packet are dropped, and therefore it is too late to prevent congestion. This process is done when the average queue is higher than a fixed threshold.

Random Early Detection

The Random Early Detection (RED) is a queuing management widely usef, designed to avoid congestion at the gateways level. The goals of RED is to control the average queue size in order to prevent congestion, TCP global synchronisation (as seen for the Tail Drop), and biais again any bursty traffic.

The principle of RED is that the gateway can detect congestion using the computation of the average queue size. This average is kept as low as possible in order to be able to have fluctuation in the actual queue size, and accomodate with bursty traffic. The idea is to pro-actively try to reduce the throughput of some connection, using congestion mechanisms that transport layers may have, to avoid the congestion. Therefore, RED algorithm works well in presence of TCP flows.

The general algorithm for the RED can be defined as :

The average size of the queue is calculated using an exponential weighted moving average and the result is compared with two fixed thresold: the minimum and

Algorithm 2 General RED algorithm

```
for all New incoming packet do
    Calculate average queue size avg
    if min_thresold ≤ avg ≤ max_thresold then
        Calculate marking probability p_α
        According to p_α, drop incoming packet
    else if max_thresold ≤ avg then
        Mark packet
    end if
end for
```

maximum. If the average is below the minimum, no packet are marked. A contrario, if it is above the maximum, all packet are marked.
When it is in between the two boundaries, each packet is marked with a probability p_α, where p_α depend on the average. The probability p_α correspond to the probablity of being droped. By dropping packet before the queue if full, the RED algorithm try to trigger congestion mechanism of transport layer, in order to avoid the overflow of the queue.

The detailed algorithm of the Random Early Detection can be found in the article [32] One of the option of the RED gateway is to measure the queue in byte instead of packets, which influence the Using this principle, the p_α calculation. This way, a large packet has more chance to be marked than a smaller one.

The Random early Detection method is more "fair" regarding the use of the avalaible bandwidth and allowing a better treatment for bursty traffic using only few ressources. This protocol effiency rely on transport layer's congestion avoidance mechanisms. However, protocol such as UDP does not have those mechanism, which lead to a reduction of the performance of this queuing management [33] [34].

For the simulation, both of this queue management will be implemented, to see the influence of the queuing time on the delay.

4.5 Faults detection Algorithms

In section 3.3, it has been explained that the fault detection system will use active probing techniques. This implies that the host send probes to a target in the network, derive metrics from those probes, and can evaluate the situation of the network. The fault detection process are separated in two : First the collection of network data and the fault detection process itself.

In this experiment, two type of metrics are collected : The one-way delay and the interarrival time of the probes.

As seen in section 4.4.2 the delay follows a normal distribution with a certain mean. Using a moving average process to calculate the mean delay for a link, it is

possible to observe any variation in the distribution. Furthermore, due to the small variance of this distribution, even two distribution with a smal difference in their mean can be easily distinguised.
Furthermore, because the smart grid application must fulfill certain delay requirement, as seen in section 2.3, it is easily possible to dinstinguish faulty and faultless situation.Therefore, a thresold decision based algorithm can been chosen as fault detection system.
The following figure shows an example of this threshold process. In this case, the delay for a faultless case has a mean of 42ms. Then, a failure leading to an increase in delay on a link has happened, and a shift of the distribution is noticeable. When the distribution cross the 70ms mean threshold, then the system consider this distribution as the result of a failure.

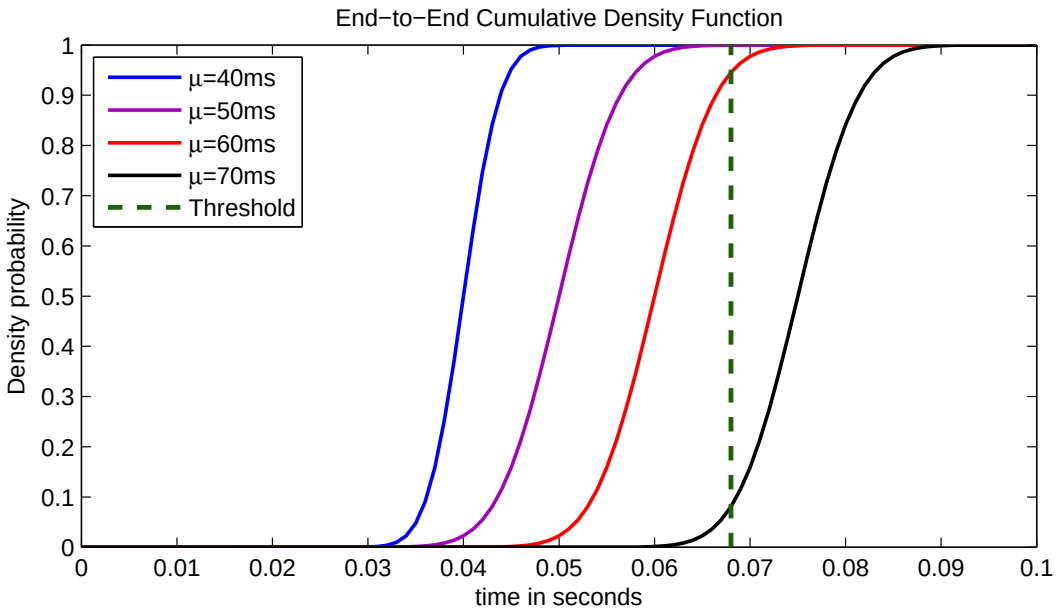


Figure 4.11: Distribution shift after a failure and Threshold

Because the incoming and outcoming traffic is not the same at both end of the network, two similar faults detection algorithm has been designed, one from the Houses' point of view, the other from the aggregators point of view. The process for each end will be descrined in the following section:

4.5.1 Fault detection - House's Point of view

Data Acquisition

The data collection and metrics derivation from the house point of view follows the step presented in figure 4.15.

The calculation of the delay and the Interarrival are based according to the following formula:

$$Delay = Current\ Time\ -\ (Timestamp\ of\ the\ packet)$$

$$InterArrival = (Time\ of\ arrival_{Current\ packet}) - (Time\ of\ arrival_{Previous\ Packet})$$

In a communication network, some packet may exceptionnaly have a high delay while the connection itself is faultless. In order to prevent false positive errors, the fault detection process will use average values for the delay and the interarrival time rather than instantaneous value. Therefore, the sample size determination has a crucial importance on the outcome of the average calculation process. The importance of this parameter will be explored during the simulation phase.

Timeout Process

Despite the good efficiency of these algorithms to detect faults using the probes data, one problem arise when a failure leads to an absence of probes. If the average delays and interarrival time are collected for a server are collected just after receiving a probe from the server, then when no probes are received, the averages remain unchanged and the fault cannot be detected.

This is why a Timing process has to be implemented.

After each probes, the current time is saved along the other metrics. By this way, the system can know when the last probe from the server is received. The process will inspect for the server the last time a probe was received. If the time difference is higher than the threshold fixed for the interarrival time, then a timeout routine is launch, and a new average is calculated. Doing this way, it prevent the possibility of false positive in case of one timeout, and emulate the data acquisition with a new interarrival time input that increase the average. Therefore, the value of the data add into the average, and the sample sized used have an influence the delay between the fault and its detection. The following figure shows the number of Timeout routine needed to detect a fault, according to the new value added to the moving average calculation, and by the fault threshold that has been fixed in order to detect a fault.

One of the direct consequence of the previous figure, is the actual time needed to detect the fault, that this time will depends on the frequency of the timeout routine, but also the frequency of the probes. If probes are sent periodically every five seconds, then even with a threshold equivalent to four times the mean value after the initialisation (which is the basis for the threshold decision) is equal to a time close to twenty seconds. A contratio, with probes sent every fifteen seconds, such a threshold is not possible, because equal to the period of actual smart grid data (every minutes). The time required to detect a fault can be derived as

$$Time =\ Threshold\ +\ (number\ of\ steps) * frequency_{update}$$

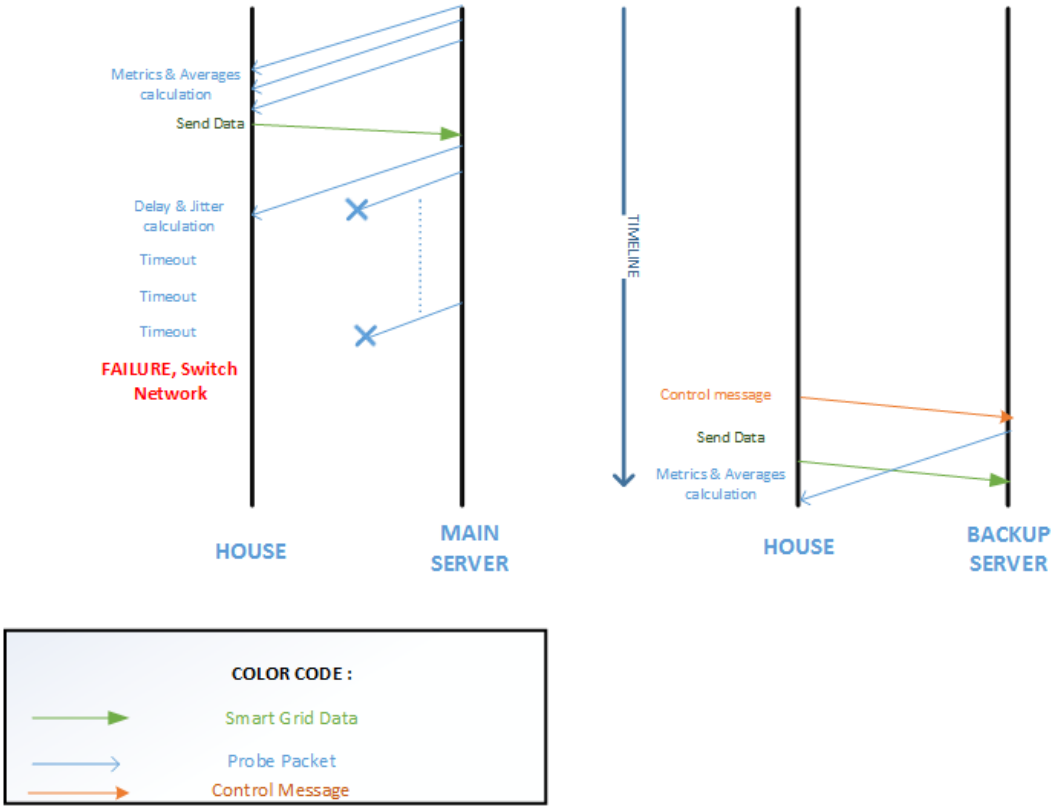


Figure 4.12: Timeline of a Timeout scenario, House point of view.

Restauration Process

When a fault is detected among the primary network, the house decide to switch the network and start sending the data to the secondary network. However, the use of the backup network must be limited in time and therefore, the house must be able to detect when the main network is back to a faultless situation. The figure 4.14 show an example timeline of events that will lead to restaure the communication with the house and the main server.

Therefore, the fault detection process must also detect when the network become faultless again. This will be described in the next subsection.

Fault detection process

Unlike the data collection that is called everytime a new probes packet is incoming on the socket, the fault detection process run in an independant way and periodically. From this periodicity, it can be concluded that the time period used is a critical aspect in the process. This process works as described by the figure 4.15. As explained earlier, a thresold decision has been chosen in this case. After the data from the probes is acquired, the average delay and interarrival time for the last N packets

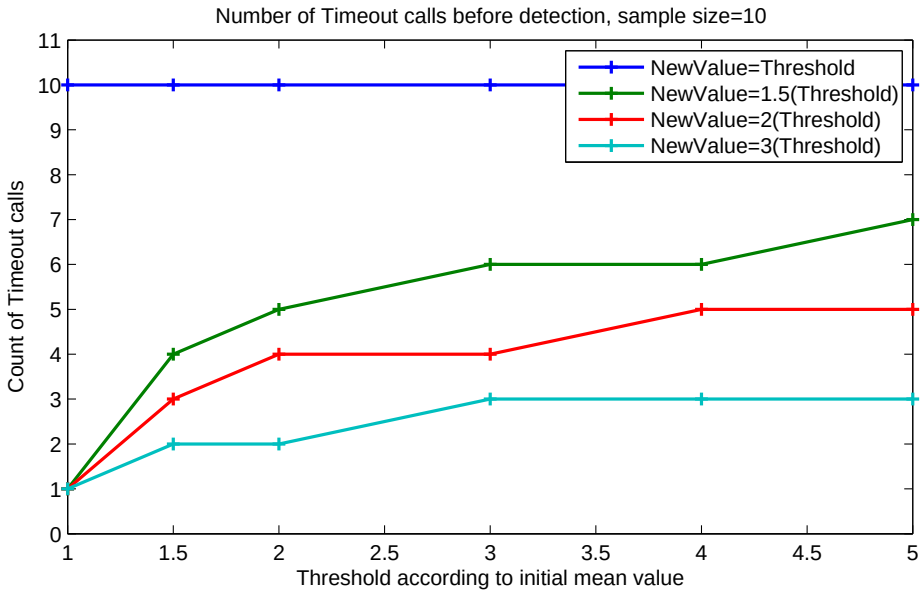


Figure 4.13: Number of Timeout routine needed to detect a fault

(N being the sample size) is calculated. Then, these averages are compared to the thresold, and a decision is made. However, according to the destination server (Main Server or Backup), the number of steps for the process differs. If the destination server is the main server, the house will not verify if the Backup server is functionnal. Indeed, it is assumed that as long as there is no connection between the house and the backup server, this server does not send any probes. This decision has been made considering that the backup server use a telecomunication network that does not belong to the energy providers and that the amount of traffic need to be minimised in order to reduce the fees.

This conclude the description of the fault detection from the Houses' point of view, and the following part will be dedicated to describe the algorithms used in the simulation from the aggregator's one.

4.5.2 Fault detection - Aggregator's Point of view

While the House must consider only two concentrators (primary and backup), the aggregators must handle the connection of all the houses at the same time. This has an influence on the processing time of the packet, but also can provide a more accurate view of the network. Furthermore, it allows the management center to locate the point of weakness in the network when a failure happens. The timeout process being the same as for the one used in the House's, it wont be discussed.

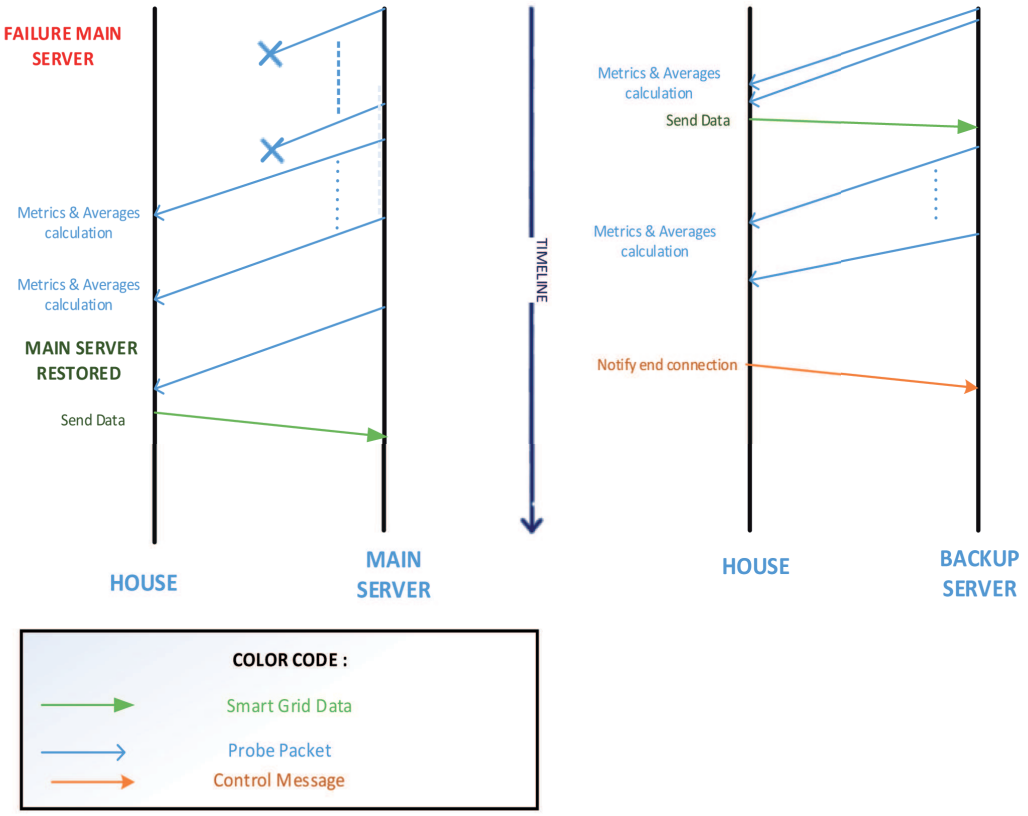


Figure 4.14: Timeline of the restauration process from House point of view

Data Acquisition

The data collection and metrics derivation from the aggregator point of view is rather similar to the House's one, but one step is added as show in figure the step presented in figure 4.16 :

The collection of data is then the same except the last step which consist on having an average of the mean delay and interarrival time for each link. This overall average is used to have an idea of where the fault is located, and will be discussed afterwards.

Coordination Process

When an aggregator detect a fault for a link, it does not know what kind of fault it is, and if at the other side, the house send data to the backup aggregator. Two scenarii arise :

- The house has detected the fault, and send message to the backup network
- The house has not detected the fault, and still tries to send the data through the primary network

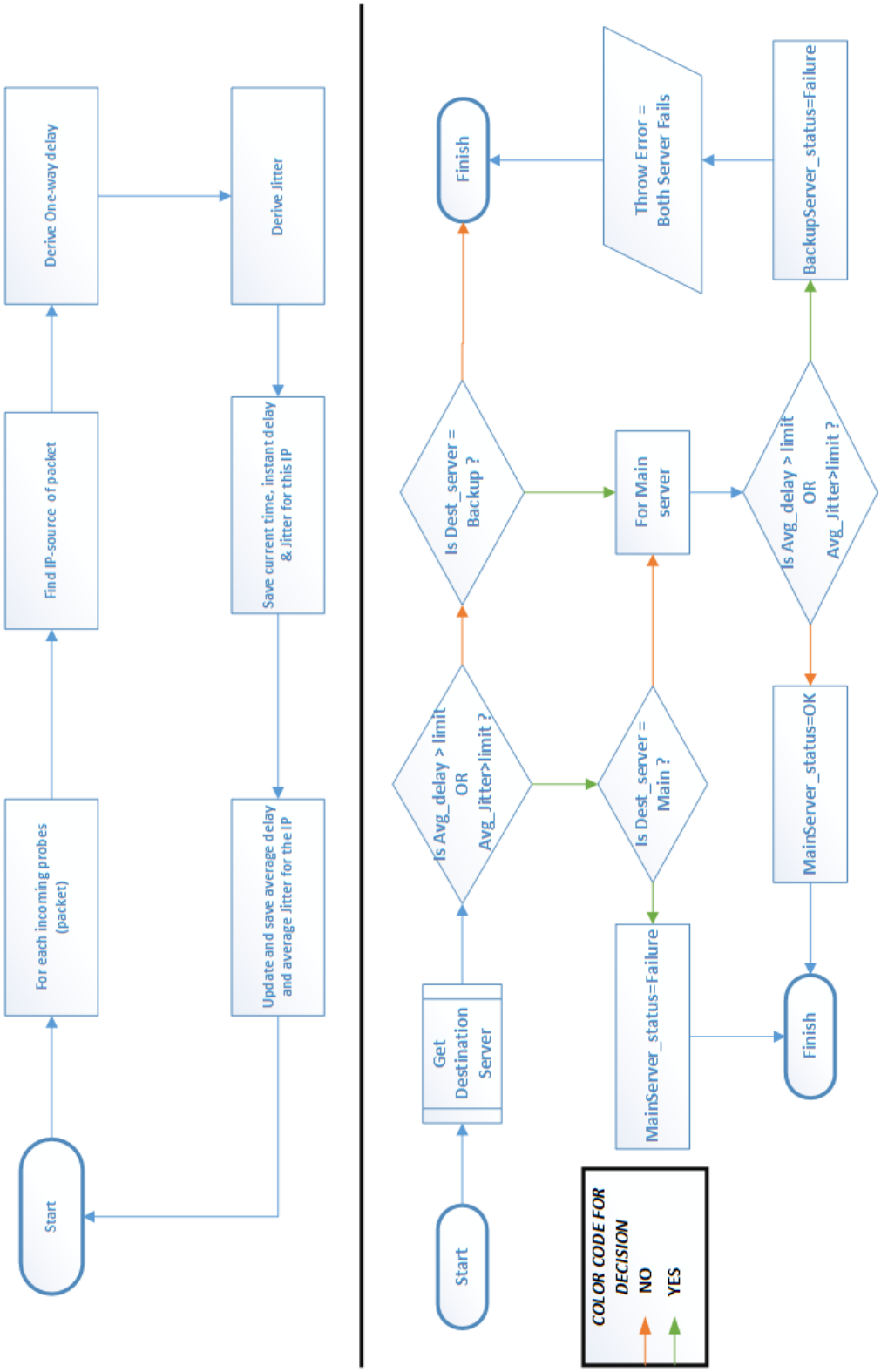


Figure 4.15: Data collection (up) and Fault detection (low) algorithm

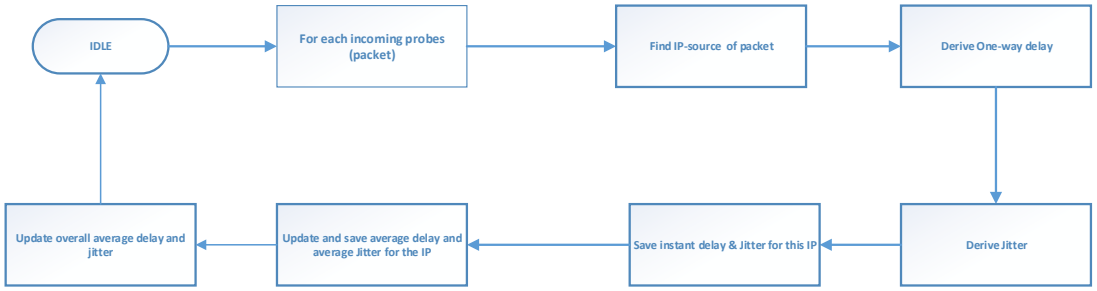


Figure 4.16: Data Collection and Derivation at the Aggregator level

Therefore, the first thing the server has to do when a fault is detected is to check with the backup aggregator if it has the data from the failing house. From there, two scenarii:

- The backup aggregator has received message from failing house, the main concentrator acknowledge that and do not consider the house as faulty.
- The backup aggregator has not received message from failing house, the main concentrator warn the management center that one house is failing.

Fault location process

Regarding the overall average that has been calculated during the data acquisition. The idea is that the aggregator has an overview of the network using those averages and can approximate the location of the fault. For example, considering a set of two hundred houses communicating with the aggregator, with a delay following a normal distribution between 50ms and 60ms and a 10ms variance 4.17

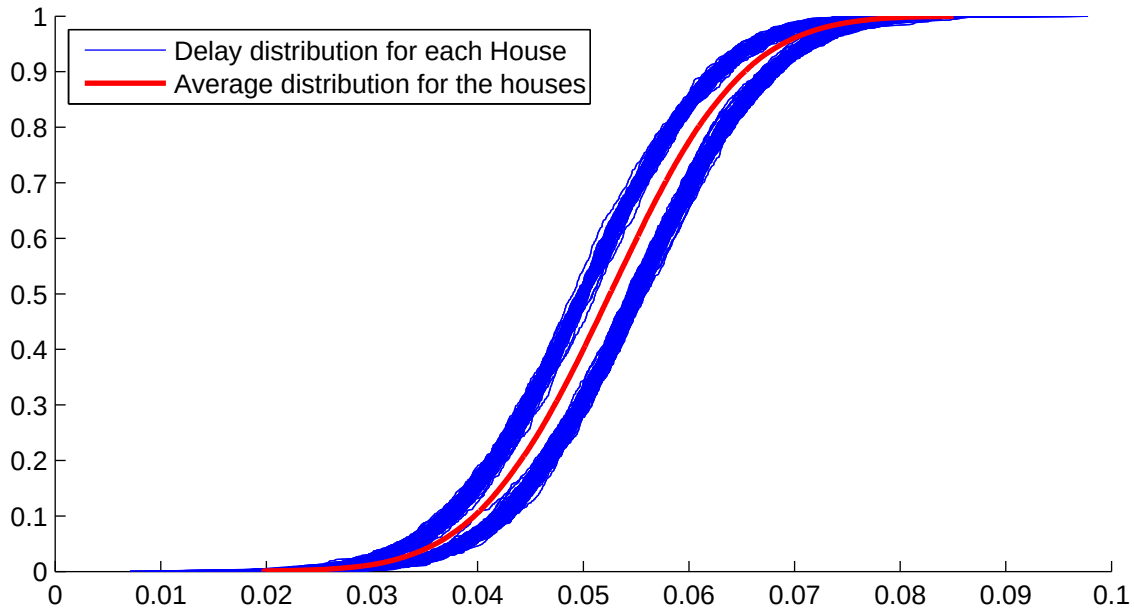


Figure 4.17: Distributions of houses and mean distribution, Faultless situation

This set of house are in a faultless situation , and the aggregator has an overview of the all set. If one or a few house are failing and the others are normal this should have a little influence on the global average.If the aggregator detects a failure for a house, but the overall average looks normal, then the failure is considered as inherent to the house only. On the opposite, in case of a major failure is happening, but only a few houses are considered as failing during the fault detection process, the overall average will be irregular and the aggregator can conclude that this is a global phenomenon and inform the control center.

By using this process, if the aggregator detect that a large failure is happening, the management center can remotely inform the houses to switch the network, even though the houses themselves hae not detected any fault.

4.6 OMNeT++ Implementation

In this section, the main part and key component to design the fault detection system will be discussed. To implement this process in OMNeT++, it was necessary to design an module at the applicative level. Considering that the probes are sent over the UDP protocol, but the actual smart grid data are sent over TCP protocol, an application implementing both protocol was needed. However, a multi transport protocol application does not exist in OMNeT++, and therefore it was necessary to design it entirely.

The mandatory step to implement a new type of application, was to produce a generic interface, through a module implementing one input/output gate with the

UDP implementation, one input/output gate with the TCP implementation.

```
moduleinterface IUDPTCPApp
{
    parameters:
        @display("i=block/app");
    gates:
        input   udpIn @labels(UDPControlInfo/up);
        output  udpOut @labels(UDPControlInfo/down);
        input   tcpIn @labels(TCPCommand/up);
        output  tcpOut @labels(TCPCommand/down);
}
```

Figure 4.18: UDP-TCP generic interface

Then, during the definition of the application using the NED language, the inheritance from this generic interface must be stated, along with all the parameters required to have an UDP application, and a TCP application.

```
simple TCPUDPBasicApp like IUDPTCPApp
{
    parameters:

        // UDP APP
        int udplocalPort = default(-1);  // local port (-1: use ephemeral port)
        string udpdestAddresses = default(""); // list of IP addresses, separated by spaces ("": don't send)
        int udpdestPort;
        volatile int udpmessageLength @unit(B); // length of messages to generate, in bytes
        double udpstartTime @unit(s) = default(this.udpsendInterval); // application start time (start of the first packet)
        double udpstopTime @unit(s) = default(-1s);  // time of finishing sending, -1s means forever
        volatile double udpsendInterval @unit(s); // should usually be a random value, e.g. exponential(1)
        int udptimeToLive = default(-1); // if not -1, set the TTL (IPv4) or Hop Limit (IPv6) field of sent packets to this value
        int udptypeOfService = default(-1); // if not -1, set the ToS (IPv4) or Traffic Class (IPv6) field of sent packets to this value
        string udpmulticastInterface = default("");  // if not empty, set the multicast output interface option on the socket (interface name expected)
        bool udpreceiveBroadcast = default(false); // if true, makes the socket receive broadcast packets
        bool udpjoinLocalMulticastGroups = default(false); // if true, makes the socket receive packets from all multicast groups set on local interfaces

        // TCP APP
         string localAddress = default("");
        int localPort = default(-1);  // local port
        bool active = default(true);
        string connectAddress;
        int connectPort = default(1000);
        string dataTransferMode @enum("bytecount","object","bytestream") = default("bytecount");
        double tOpen @unit(s) = default(1s);
        double tSend @unit(s) = default(1s);
        int sendBytes @unit(B) = default(1MiB);
        string sendScript = default("");
        double tClose @unit(s) = default(2s);

    gates:
        input udpIn @labels(UDPControlInfo/up);
        output udpOut @labels(UDPControlInfo/down);
        input tcpIn @labels(TCPCommand/up);
        output tcpOut @labels(TCPCommand/down);

}
```

Figure 4.19: NED implementation of the meters application

One the ned file is described, then the way the application behave must be written in C++. After the initialisation of the application, the paramaters are handed from the configuration ini file and saved in memory.

The next step to build an application is to create and parameter UDP and TCP sockets from the application. The following figure show the configuration configuration for the UDP socket, the initialisation of the TCP sockets follows a similar process.

Once those two steps are completed, then the application itself can be designed.

4.7 Data collection- Signal mechanism

OMNeT++ has two way to do gather data from the simulation modules:

- The Collectors
- The Signals

The collectors are a classic approach of gathering data. The collector need to be hardcoded in the C++ code, and a collector can only describe one type of statistics(vector, scalar or histogram).

The Signal is a softer way to collect statistics. This mechanism allows us to collect a temporal serie of information $S = x_t$ where x_t is the information at time t of the signal S.

This information is collected using fuction named emit(S,value),where value correspond to x_t. One of the advantages of the signal is the that any modules can suscribe to a signal, and be notified when the signal is emited. For example, when the aggregator's fault detection module emit a fault signal, the module responsible for the coordination with the backup network is notified and start sending message to the second aggregator.

```
@signal[delayPk](type="double");
```

Moreover, diverses types of statistics(mean,variance, histogram) can be collected to do post-mortem analysis of the simulation.

```
@statistic[endToEndDelay](title="end-to-end delay"; source=delayPk; unit=ms; ...
record=histogram,vector; interpolationmode=none);
```

The signals are stored after the simulation in two files, one that contains the scalar results, and the other the vectors results. Those files can be handled directly using the statistical software R, or by exporting by hand the vector desired into a CSV file.

Chapter 5

Results

In this chapter, the experiments conducted will be presented, and discussed.

5.1 Parameters and variables

In this first section, the different scenarii's parameters and variables used for the experiments will be detailed.

5.1.1 Random Number Generation

The generation of random numbers is a important step in any simulation : the quality of the random variables influence directly the quality of the results. In OMNeT++, the pseudo random generator by default is the Mersenne Twister. This PRNG is used in many tools and language and has the following propriety:

- The periodicity is $2^{19937} - 1$
- It can produce 623 indepent sequence of 32bits numbers, uniformly repartited

It is also possible to use others PRNG such as the L'Ecuyer generator or the Linear Congruantial Generator.

The seed is responsible for the suite of generated number. It is then primordial parameter to select. In OMNet++, the seed of each simulation can be specified in the ini file. Therefore, in this thesis, for each simulation a different seed is selected. This make possible to have a different simulation every time instead of a repetition of a previous simulation. Moreover, in order to discard the data produced during the transient phase of the PRNG, OMNe++ include a parameter named Warmup period, which correspond to the time no results will be stored. Finally, in order to have more statistically accurate results, each experiment is repeated 10 times, and the results stated are average of all the replications.

5.1.2 Simulation parameters

The parameters used in the experiment defined the different scenarii and help to make the distinction between experiments.

The first parameter is the number of houses. The primary network is an emulation of an ADSL network, and DSLAM is composed by several aggregation cards. Those usually contains 24,48 or 72 ports. The simulations will therefore use 72 houses.

The Smart Grid application emulated in the experiment is a metering application. This means that the size of the data send are in the order of X and the frequency of data send is between 1 and 15 minutes. In the simulation, the actual data are send every minutes.

5.1.3 Simulation variables

In the previous chapter, five parameters used in the fault detection algorithm and having a direct influence on the simulations' results have been defined:

- Frequency of the probes
- Frequency of the fault detection routine
- Samples size for the average calculations
- Threshold definition
- Timeout process

Therefore, the first experiments realized are how does the variation of those parameters affect the fault detection process.

In order to first verify that the fault detection process is fuctionning correctly, experiments are made with a network under a light load (no dropped packet at the gateways), but with scenarized faults. This way, the performance of the algorithm can be evaluated. The scenarized faults are

- Gateway shutdown for one minute
- Increase of latency for one link (House to Gateway)
- Increase of latency for several links
- Increase of latency for all links

5.2 Fault Detection

5.2.1 Caracterisation of the Delay and Inter-arrival rate

The fault detection algorithm used in the thesis stands on the assumption that the distribution of the probes would be normally distributed, and the decomposition

of the delay in section 4.4.2 was indicated the delay would be between 40ms and 45ms. The first step of the experiment was therefore to analyse the delay in the simulation, to verify this assumption. To do so, the data of 3 hours simulations have been collected , where the network is in a light load.

The empirical cumulative distribution is shown in figure 5.1, along with theoretical distributions.

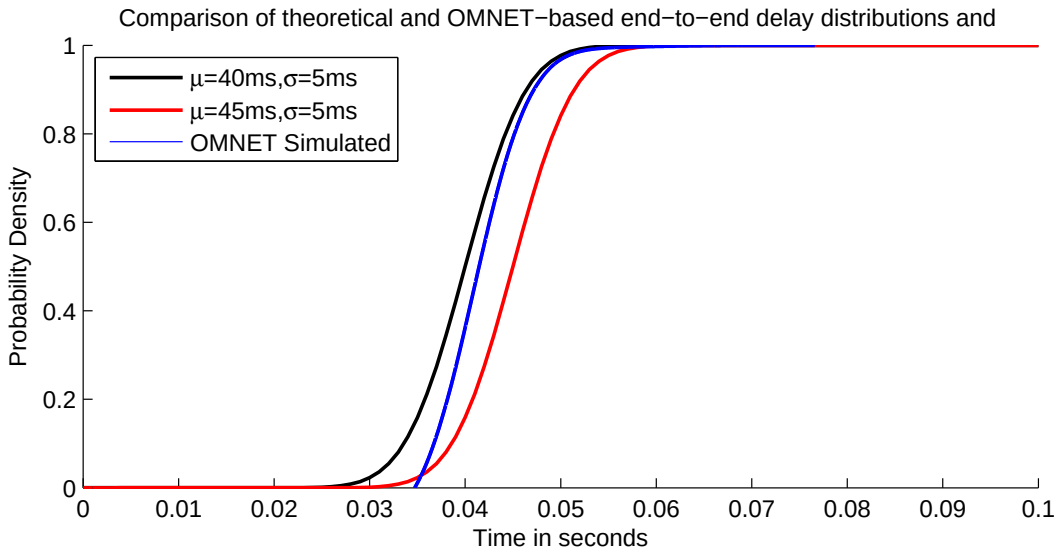


Figure 5.1: Comparision of theoretical and Results for end-to-end delay

It can be seen from the distribution that the end-to-end delay seems to follow similar to what was described in section 4.4.2. This result was predictable, and is used here as a confirmation. The delay among links is a parameter in OMNeT++, so it was expected to be around 42ms. This shows also that the assumption that the delay will be following a normal distribution, used in the detection algorithm, is correct.

5.2.2 Router Shutdown

The first step in the experiment was to verify that the algorithm was functionning. To do so, the first experiment conducted was in the case of a router failure, at the gateway level. This failure was simulated using the lifeCycleManager component in OMNeT++, and the operation used was a "NodeShutDownOperation". This means that the router interface was at some point turned off, and all incoming packets were dropped. The failure of the router implies that the interarrival time will increase, and the timeout routine will be called until the failure detection.

The following sets of plots will shows the performance of the algorithm with different values for the variables detailed previously in subsection 5.1.3.

Probes interarrival

The first variable used to the evaluation the delay between the failure and the detection, from both end point of view, according to the frequency of the probes. Five sets of experiments has been realized, with probes varying between one and 10 seconds. The others parameters are fixed as:

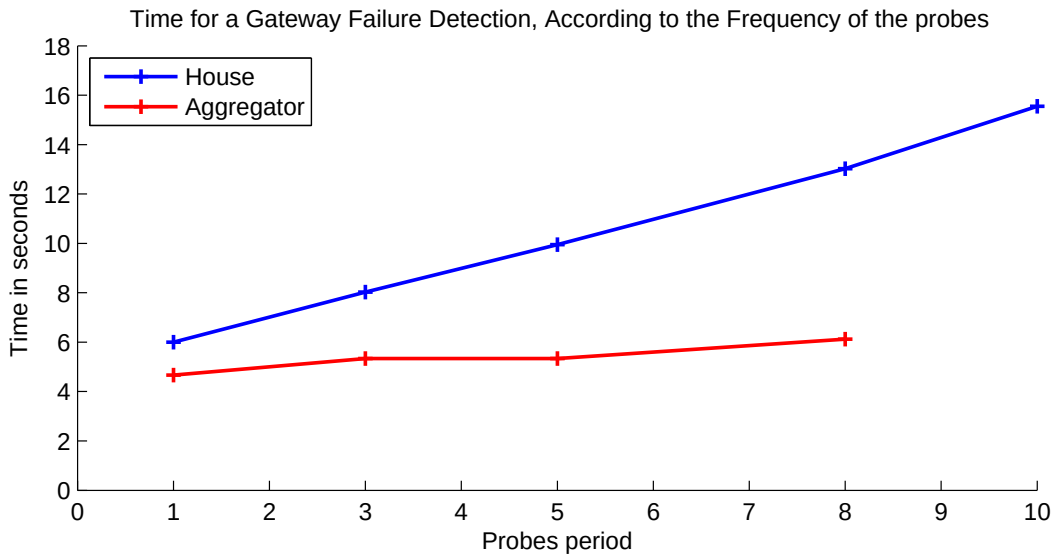


Figure 5.2: Time required to detect a fault, according to the interarrival of probes

The first observation that can be made, is that the performance from the server side are better from the aggregator side than from the individual house point of view. For the best performance (probes frequency = 1s), the aggregator is 22% time faster to detect the fault than the house. For the worst performance, the aggregator is on average 115% times faster to detect the fault.

It is also interesting to observe that while the difference between the house extrema (from minimum to maximun) increase by 159%, the aggregator remains almost constant with an increase of 2.5

However, this good results for the aggegator side can be tempered by noticying that for the aggregator side, when the probes are send every 10 seconds, the number of false positive is too high, and it is not possible to properly distinguish the proper detection with the false positives.

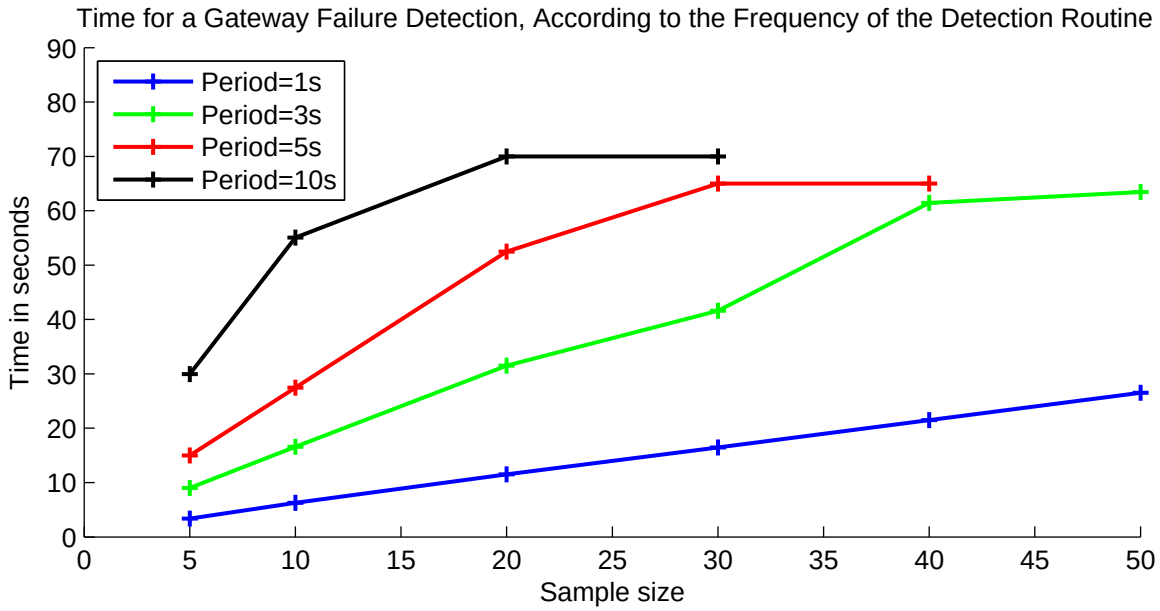
Sample size and update frequency

Once the probe frequency is fixed, two remaining variables are to set: the sample size used in the moving average calculation, and the frequency update. In this experiment, the probe period is set to 2 seconds. The experiments have been conducted where for each period for the fault detection routine, a different value of sample size has been chosen.

Detection routine frequency=[1 3 5 10]
Sample size=[5 10 20 30 40 50]

The two next plots shows the performance of the algorithm, from each point of view.

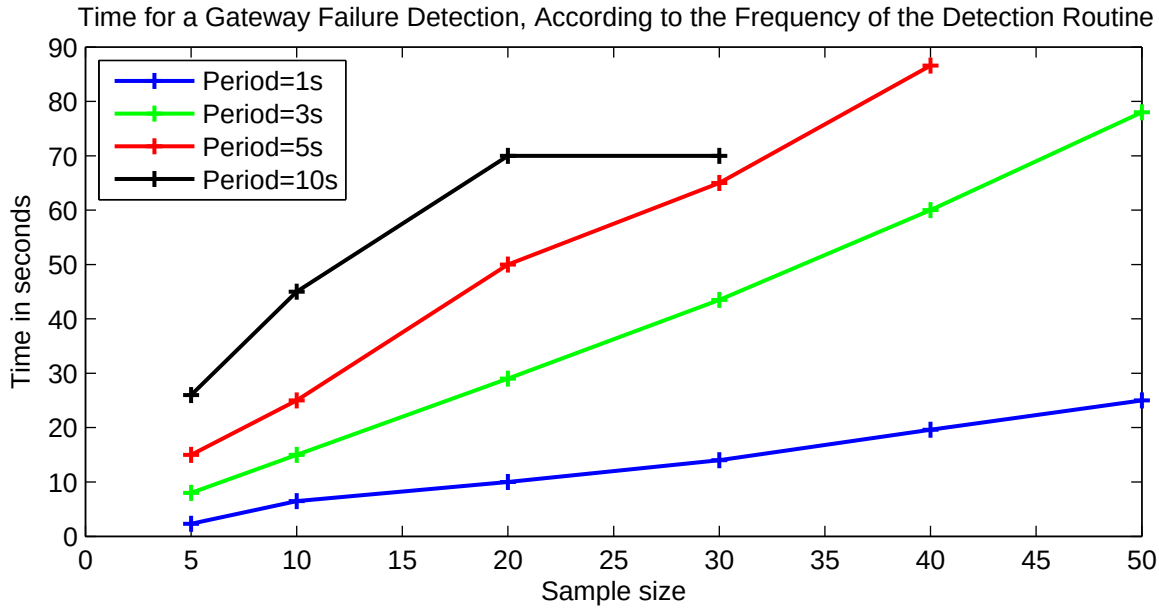
House Point of view



Different observation can be done from this graph. The more important one, is that the two variables have a bigger impact on the performance than the probes' period. for the best case, the time need on average is 3.5 seconds (sample size = 5, period=1s), .

It can be noticed that when the frequency of update is higher than 5 seconds with a sample size higher than 30 samples for the moving average, the fault is not detected anymore. This can be explained because, the timeout process needs a certain number of steps before signaling a failure. After 60 seconds, the gateway is back in his functionning state, and the house does not call the timeout failure. Therefore it is the case of a false negative.

Aggregator Point of view



In this case, it can be seen that, like for the probes' period comparison, the error are detected faster by the aggregators rather than the houses.

It can be noticed that for certains configurations, the delay between the failure and the detection is higher than 60 seconds. Yet, the failure duration is 60 seconds, leading to a false positive.

5.2.3 Latency Increase

In this second set of experiments, the faults simulated induce an increase of latency on different links. The first scenario is the increase of latency of only one house, while the rest remains intact. The second scenario is the latency increase on all the links simultaneously.

	1 link	**10 links**	**All links**
House	4.0	3.7143	3.5370
Aggregator	3.0	2.0	2.0

Table 5.1: Time of detection in case of latency increase failure

It can be noticed that once again, the aggregators detects the fault slightly faster than the house. In addition, the more houses are failing simultaneously, the faster it

gets. The other observation, is that the time required to detect a fault caused by a latency increase is faster than a hard failure.

5.2.4 Restauration Process

As detailed in section 4.5.1, the restauration process happens when the primary network goes back to a faultless situation while the house is communication on the backup network. The house must monitor this situation to reduce the time of utilisation of the backup network. In the case of a hard failure,using the parameters where the algorithm best performs (probe period=1s,sample size=5), the average delay between the restauration of the link is 4.18 seconds In the case of a latency increase,the average delay between the restauration of the link is 8.96 seconds. This difference can be explained by the variability of the data observed. Indeed the difference between the values of fault and faultless situation is higher in the hard failure than in the soft failure case. Therefore, when the system goes back to normal, the average value will tend faster to his faultless state in the case where a hard failure happened.

5.2.5 Effect on the LTE network

The second problem formulated at the beginning of the thesis was to evaluate the impact the sudden apparition of a set of houses on the backup network.

To do so, three different experiments were conducted where the number of houses using simultaneously the network varies:

$$Number\ of\ houses=[1,10,72]$$

The first plot is the reprensentation of the end-to-end delay for the two first experiments

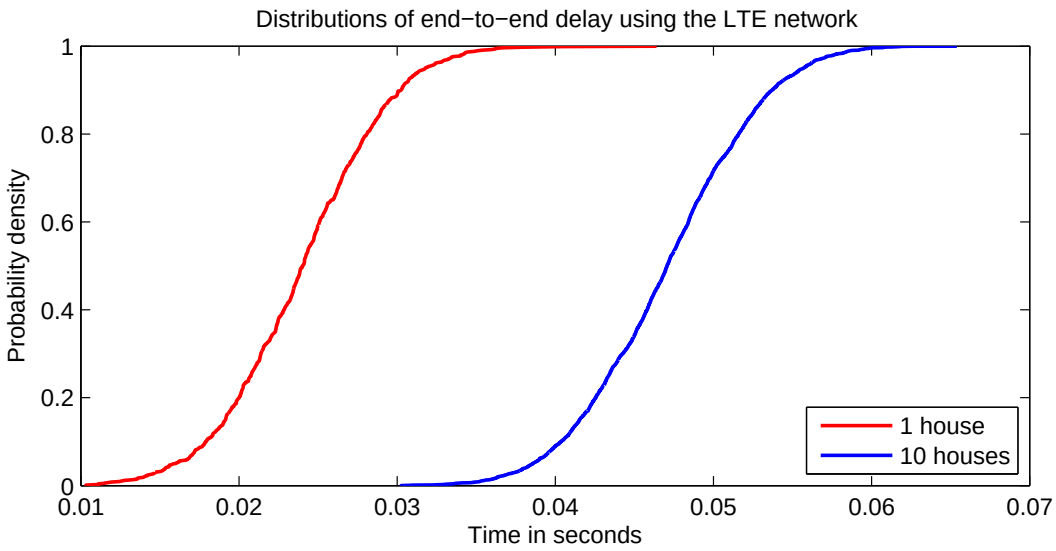


Figure 5.3: End-to-end distribution of the houses

The first remark is that the each house of the second experiments follows the identicle distribution, and the plot represent the average. The first observation is that the latency for one house is really low, the average time being around 25 ms. The second observation is the gap between the distributions, the second plot has an average around 46ms. It seems that by increasing the number of houses, the delay increase also. This lead to the last experiment, when all the house start using the network around the same time, shown in figure 5.4

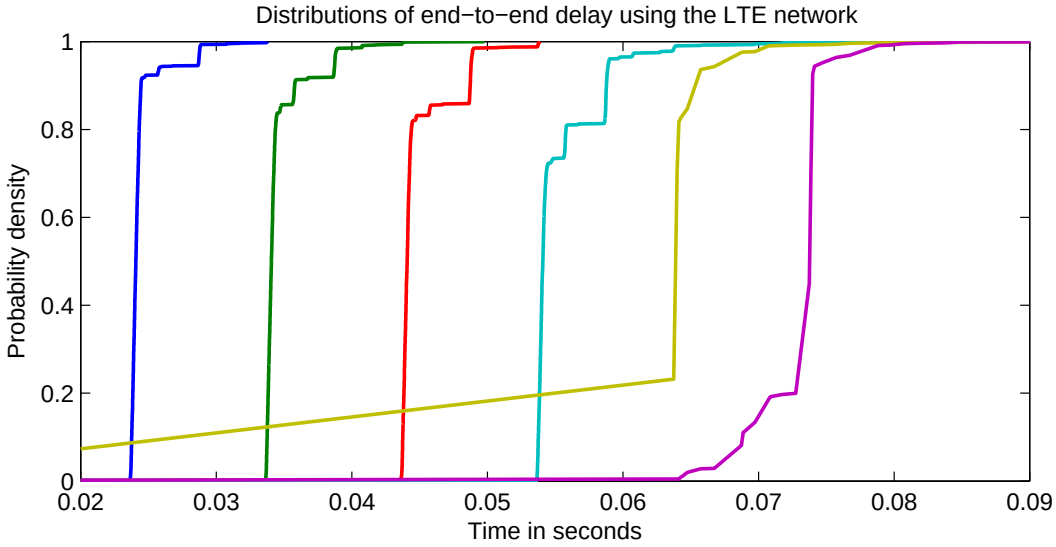


Figure 5.4: End-to-end distribution of the houses

In this case, the houses does not all follow the same distribution, but instead are separated into different groups following the same distribution. It can be noticed that the distributions are less smooth than was the two first one on figure 5.3. Those distribution shows that in most of the case, a large set on the data are distributed close to the mean value, but a certain set of data, higher than the mean, deviate from the distribution. It can also be noted, that each distribution are separated by approximately 10ms. This deviation may be caused by the fact that an LTE frame in the time domain is 10 ms.

In this case, the inter-cell interferences have a clear impact on the delay. However, it was expected that the interferences would cause some packet loss, but the simulation has shown a packet loss count of zero. It seems that the number of house using simultaneously the network has only an impact on the delay.

5.3 Discussion

The previous experiments have shown that the primary objective of the fault detection algorithm is fulfilled. The best performances are obtained when the probes' frequency and the frequency of the algorithm.
However, in the decision process to tune the parameters of the algorithm, the overall scalability and the CPU utilization must be taken into consideration.
Therefore, it may be wise, to have an algorithm that perform a bit less, but with an important reduction of the number of probes, or calculation needed. For example, using the data shown in the figure 5.2, by sending probes every three seconds instead of one seconds, the detection time increase by 25%, (from 6 seconds to 8). But, it allows a reduction of 300% of the amount of probes.

The previous results of the experiments have shown that the fault detection algorithm performs in the case of a hard failure. It has been shown that the aggregators are able to detect faster the faults than the house are. This feature can be considered as optimum, so the control center can then decide how to manage the network.

However, in the way the detection and coordination algorithm has been designed, it may be problem : When the aggregator detect a fault for a house, the coordination routine is called. This means the main aggregator will query the backup one in order to decide if the house is indeed failing or not. Although, because the house has not detected the failure yet, it has not switch the network to use, and so the backup network does not receive messages at this time. This will lead to the decision of declaring a failure.
A possible implementation can be that, when the backup aggregator is queried for a failing link, it waits a certain time before answering to the main server, and terefore give the time for the house to detect the failure and start sending messages through the backup network.

One of the weaknesses of the simulations may be the amount of houses emulated. Indeed, only 72 houses are used for the simulation to fit the DSLAM characteristic. This has been chosen because of a limitation of OMNeT++ and its implementation of the TCP protocols. Indeed, the TCP applications use a function named activity() to handle messages. This function call a certain number of others coroutine, and have a limited size. When trying to simulate a higher number than 80 TCP connection at the same time, the simulation automatically refuses to run. This limitation has a clear impact on the amount of packet that are dropped. Actually, the simulations did not shown any case were packets were dropped, and it has not been possible to see what is the impact of congestioned network on the detection process.

Regarding the LTE network, the experiments have shown that the number of houses using the network has a significant impact on the delay.
However, those results must be put into perspective. The simulation was not taking into consideration the spatial organization of the houses, and all the modems were located approximately at the same place.
Yet, any wireless communication depends on the spatial organisation, that cause fading and scattering of the signal. By being situated at the same location, the devices may have caused a higher level on interference that cannot be reproduce in real situations.
Furthermore, as explained previously, the number of end nodes emulated was 72. While this number is accurate regarding the ADSL configuration, it is not for a LTE one. Indeed, the LTE network is not dedicated to the smart meters. Therefore, users other than meters must be taken into consideration.

Chapter 6

Conclusion

The first problem stated at the beginning of the thesis was: **How to dectect dynamically detect fault on a network using quality of service metrics?**

The analysis and the experiments showed that fault in communication networks systems can be detected by sending probes in the network and analysing metric derived from them.

The experiments have been conducted under the hypothesis that actual data are send to the management center at a period of sixty seconds, and a good detection rate has been shown for hard failure like a gateway shutdown. All experiments has been repeated several times with various parameter in order to optimise the detection rate. However, this methods implies the use of a large number of probes, which can be an issue when the network is under a heavy load. Moreover, the presence of a certain number of false positive, shows some weakness in the solution.
Furthermore, the simulations were based on the assumptions that the application (monitoring) requires to send data every minutes.
However, other applications requires a more smaller frequency, and the use of ISP networks and internet does not seem to be the most appropriate for a this task.

The second question of the thesis was: **What is the influence of the automated switch of mean of communication on the backup network?**
The first observation, is that the results show that the use of the backup network with the coordination process can be feasible for detection faults and ensuiring the continuity of the service.
Regarding the use of LTE, it has been demonstrate that theorithically, that this mean of communication, by it low latency and high bandwidth, is suitable for smart grid technologies.
Although, the results obtained have shown that the higher the number of users on the network, the more the performance were degraded. However, as discussed in the results chapter, the simulation of the LTE network had many weakness and incertainty, and the results may be only the artifacts of those parameters.

Chapter 7

Future Work

The experiments in this thesis have been made under two main assumptions:

- The application chosen was the metering system, and will send data every minute.
- The primary network corresponds to the actual internet access of the user

The use of two networks that does not belong to the energy company itself seems to be a non optimal solution regarding the fault detection using probing techniques. Indeed, the management center does not have all the tools and access to important point of the network, reducing its ability to use different probing approaches.

Another field of study could be the use of wireless mesh networks, belonging to the energy company, as primary network. Using a mesh network would allow the utilisation of a hierarchichal topology, where each aggregator is located at the access network level, and would send to the management center an agglomerate of data. This approach seems the more suitable for smart grid system and its scalability issues.
Furthermore, an interesting field of study would be to consider the houses as a wireless sensor network, and to develop an efficient cooperative fault detection process. By delegating the fault detection process to the house, the concentrator would need only to concentrate the data, reducing the CPU utilization needed by each aggregator.

Future works can also concern the use of the LTE for smart grid. Indeed this thesis has just focused on the use of the LTE without being too narrow on the property of LTE, the number of meters than can be used in the cell, but also the resource scheduling.
It can be interesting to have simulations using proper network planning of the LTE users in cells, to have accurate simulations regarding the use of the network by the meters.

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