Planning and design of a Smart City Metro-Access network

Master Thesis

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Abstract:

The Smart City concept consists of a new urban environment, capable of managing itself in a sustainable way, for the benefit of its citizens, through the use of communication technologies. Smart City's applications will require a new network infrastructure, able to satisfy their demands in quality of service. This project analyses these requirements in order to propose a hybrid optical-wireless network architecture acting as the Smart City Metro-Access network, mainly focusing on the network design and planning. The Aalborg commune in Denmark is used as a case study for implementing the proposed architecture. Optimization algorithms are used in the radio and fibre planning for maximizing the architecture efficiency.

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Preface

This report is the work of 2 students on the 4th semester of the "Network and Distributed Systems" master at Aalborg University.

The report structure is divided in 6 chapters. In the first chapter *Introduction* the motivation behind this project is presented as well as the problem statement and the expected outcome. Secondly, three different applications of the Smart City are introduced in the chapter 2 *Pre-analysis* as well as well-known Metro-Access network architectures. The third chapter *Case Study* describes the Aalborg municipality, used as a scenario for this project and the GIS data of this area. The *Design* chapter presents the design of each of the applications as well as the access and metro network architecture and the assumptions made to delimit the problem in each case. Radio and fibre planning are described in the following chapter *Network panning* in parallel with their results and a discussion on them. Finally, in *Conclusion* the initial question is answered by presenting each step take to accomplish it. This thesis report concludes with the *Future Work* section proposes possible future improvements of the project.

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Chapter 1

Introduction

More than half of the world's inhabitants live in cities, and it is expected that the urban population will double by the mid-century [15]. Although each city is unique, city's officials are facing many similar challenges like gathering and analysing data for taking better decisions, efficiency in coordinating resources and the need to resolve problems in a proactive way. All these issues call for solutions that require creativity and innovation out of the ordinary. Moreover, because of economic pressures, budgets for providing services are constantly shrinking. Furthermore, ageing and inefficient infrastructures paralyse resources and generate waste in all activities of the city.

Today, new perspectives are made possible in order to solve these problems. The evolution of wireless technologies, multimedia communication and intelligent systems offers nowadays the possibility to explore new opportunities and aims at improving human life [7]. As a result the Smart City concept is now being developed. It consists of a new urban environment increasing the quality of life of its citizens through the use of advanced and innovative services. As a centre for business, culture and life, it is natural that most of the innovations for a smarter planet should begin to be applied to cities, especially the ones concerning education, health, water and energy distribution, police, transportation and administration. Therefore, cities will be able to manage their growth and development in a sustainable and profitable way for all citizens.

The Smart City idea may require a new infrastructure that will accommodate all these innovations [15]. As the Internet of Things (IoT) suggests [5], the future network will not only interconnect the existing networked terminals like computers, smart devices, mobile phones, but also daily life objects, which were considered until now as "un-networked ". Consequently, the number of ubiquitous communication devices will increase [7]. Therefore, a well – considered network infrastructure must be provided in order to support not only existing applications, but also future ones. The design of this infrastructure is a complex task as it must provide different services anytime and anywhere while satisfying their quality requirements.

1.1 Motivation

Despite the fact that there is no robust definition of the Smart City concept, experimental applications are realized towards this direction. Such applications target to achieve a degree of sustainability in a increasingly urbanized environment as well as to provide services for the well-being of the citizens.

The information and communication technologies (ICT) are already holding a key role to the development of modern societies and economies, acting as their nervous system. In a Smart City environment, ICT infrastructure sticks to this role, and at the same time should be able to accommodate the traffic of the additional underlying heterogeneous networks as defined by the Internet of Things (IoT) and Internet of Services (IoS). Hence, many challenges are introduced to the design of the future metropolitan and access area network (Metro-Access) that must handle the heterogeneous traffic disseminated by all kinds of sensors and actuators deployed in order to turn the urban environment into a Smart City.

While there is no final standardization of the Smart City communication network infrastructure, many companies provide fragmented implementations that lead citizens to the overall concept. As an example, "Libelium" [20], a company that operates in this field, features over 50 applications through a set of different sensors. The lack of concrete infrastructure designed for this purpose arises as a major issue, thus setting numerous limits to the applications and the quality of service that can be delivered. Considering how critical ICT is for a Smart City, infers that the design of a dedicated network is imperative. Therefore, during this project the challenges of network planning and dimensioning for such scenarios will be addressed.

1.2 Problem formulation

A dedicated and high performance network infrastructure is crucial for the implementation of the Smart City concept. Using a bottom-up approach, this project will be focussed on the planning and the design of the Metro-Access network, that will provide the desired connectivity for the Smart City applications. The future-proof aspect is one of the key requirements for this network, as it will host several existing and new applications and services. This project can be summarized as the following question:

How to design a Metro-Access network that satisfies the application requirements for the Smart City of the future?

The contribution of this project can be described as following:

- Investigate the actual state of the art of metropolitan area networks and heterogeneous access networks and the different technologies used in such networks.
- Consider different applications with distinct quality of service (QoS) requirements. This will ensure that the proposed network will satisfy demands of various types of applications in a Smart City environment.
- Estimate the traffic produced based on the aforementioned applications and their distribution in the metropolitan area. To achieve more realistic results, the traffic of the nodes (running applications) will be acquired through the exploitation of real Geographic Information System (GIS) data.
- Propose a Metro-Access architecture that meets the Smart City requirements.
- Planning and dimensioning of this architecture in a real life scenario.

The implementation of the Smart City concept will need a proper network infrastructure capable of supporting heterogeneous technologies and applications. In this project, different architectures accommodating heterogeneous networks will be considered, to finally propose one architecture that is suitable to the Smart City concept. The overall expected outcome of this project is the proposal of a specific Metro-Access network and its implementation in a real life scenario, focusing mainly in the network design and planning.

Chapter 2

Pre-analysis

The pre-analysis chapter contains a brief description of the investigated technologies towards the realization of the Smart City (SC) network. First step is to delimit the problem in order to clarify it further and simplify it without compromising the generality. The bounds of the delimitation consist of defining SC applications with different QoS requirements as well as the network domain (e.g. Metropolitan Area Network) that can accommodate these applications in the future Smart City. The last part argues on technologies found to be the most relevant to provide access to the SC nodes. Thereafter, the necessary background will be there in order to define the design of the overall system in the next chapter Design.

2.1 Delimitation

2.1.1 Backbone

The main scope of this project is to propose and plan a network that will serve as the Metro-Access for the Smart City ICT. The nature of such infrastructure introduces some challenges related to the interoperability of the diverse underlying technologies that that are already there or will be deployed in the future.

Before making choices on the design of any network, all the major parameters that may have an impact on it, have to be considered. The most obvious among them at this stage of the pre-analysis, are the city wide size, as well as the backbone role of the network. Then, the need of incorporating and pairing diverse applications over a shared medium highlight the necessity of a packet-switched network. Combining, these delimitations leads to an initial assessment of a Metro-Access network to act as the Metropolitan Area Network (MAN) and at the same time to provide access to the scattered nodes of the underlying networks.

We define the Metro-Access network as the combination of the MAN and the access network. The Metro part consists of a number of MAN nodes dispersed throughout the city and interconnected according to a topology. The access part's role is to reach every SC node, meaning that each of the access nodes has to be equipped with appropriate additional interfaces to accommodate the underlying networks. It can be a wireless interface in the case of a wireless network or an optical transceiver module when the connection is implemented by fibre. The Metro-Access network architecture is depicted in figure 2.1. Furthermore, considering the fact that the proposed network might as well be required to provide wireless and wired access at the same time, a solution based on the Next Generation Access Networks will be examined.

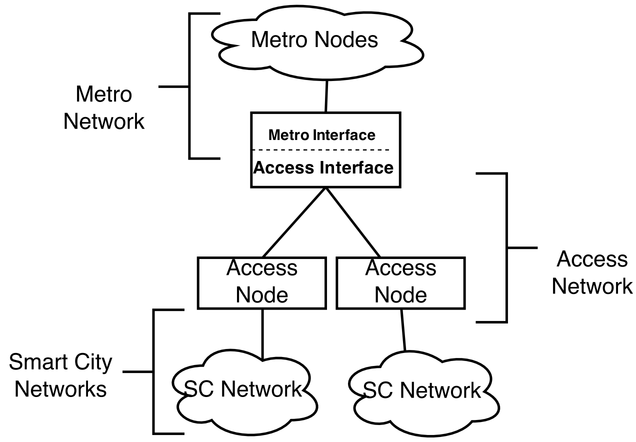

Figure 2.1: The Metro-Access architecture for a Smart City

2.1.2 Applications

The idea of the Smart City project from the ICT point of view is to offer to its citizens applications and services that will ameliorate their quality of life. Among these applications, three were chosen to be studied more deeply. This selection was based on their distinct demands in the network performance metrics. More particularly: Smart Grid, smart parking and traffic monitoring will be considered for the planning and the design of the Metro-Access scale network. As quality of service is crucial in order to provide satisfaction to the end user, these application were chosen as they have different QoS requirements, like reliability, latency, bandwidth, network throughput etc.

Smart Grid

The Smart Grid (SGrid) application intends to improve consumption - production relation of the current power grid. Nowadays, the power produced and offered to the grid is much higher than the actual needs of the specific moment due to lack of prompt information on the available power and consumption. This leads to great waste of resources in order to prevent power outages. Mainly for this propose, new architectures are proposed for the SGrid which will be able to support non only the energy flow, as practised up until now, but the information flow as well in order to know in real time how the energy network is working [12]. Using the information technologies, SGrid will be able the improve the overall energy grid, aiming for more efficiency in delivering energy and controlling in real time its production. Therefore, a smart information infrastructure is crucial for the SG implementation.

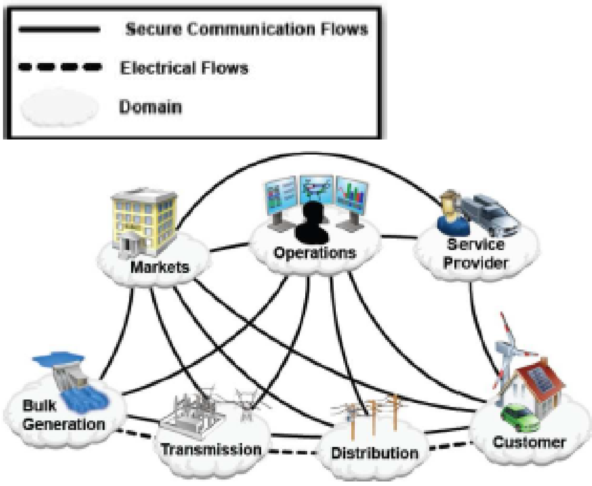

Figure 2.2: Smart grid architecture [21]

In [12] the SGrid system is divided in 3 subsystems, each one responsible for a particular function in the SGrid environment. The first one is the Smart Energy Subsystem, responsible for a better production, transmission and distribution energy system. Secondly, the Smart Information Subsystem in charge of collecting the information and its management. As an example, Smart metering is part of this Subsystem. Smart meter, the most important application of this class, provides real-time information about consumption of gas or electricity for the users and for the energy firms as well [32]. It is believed that the use of smart meters will reduce considerably the energy consumption [21]. The third subsystem in the SGrid architecture, is the Smart Communication Subsystem, responsible for supporting the two-way flow of information.

Wireless sensor networks (WSNs) are used in order to manage a smart power system and to detect failures. The use of this sensors has many requirements in quality of service, resource demands, remote maintenance and configuration or even more in security issues and environmental conditions [12]. Among all these constraints, this project will be focused only in the quality of service requirements as they will condition the design of the SC Metro-Access network.

The information generated from the sensor networks may be associated with QoS requirements such as reliability, latency and network throughput [12]. Firstly, the latency is an important factor for SGrid as the information about a problem in the grid must be provided in real time and delivered promptly. The reliability is a second important factor because of the large number of devices connected, using different technologies. The network throughput is another parameter to be considered since the number of devices connected to the SGrid may be increasing really fast in the future. Moreover, high coverage and constant availability must be provided given that SGrid must be capable of responding to an event in real time. Finally, the security is another issue to be considered in future investigation as privacy must be guaranteed.

The investigation of this project did not conclude in any results of widely deployed SGrid examples. Regardless this fact, a wide variety of applications are proposed and realized on test beds. Following are examples of applications destined for the SG as they were proposed by several companies in response to the state of Washington request for comments on the communications requirements of electric utilities.

- Automatic Meter Reading (AMR):
  AMR for the power grid refers to the automatic transmission of data containing information of the per house power consumption. It is usually periodic, but can also be triggered on request.

- Direct Load Control (DLC):
  DLC is the application that enables smart meters to dictate other smart appliances in the house to turn on or off. This can prevent power outages when power consumption reaches its peak, but also store energy when consumption is low (e.g. charge electric vehicles batteries, lower the freezer temperature, control hot water heater).

- Real Time pricing:
  The billing of the power consumption in a SGrid can be based on the instantaneous supply and demand of that specific moment. Given the fact that the SGrid will enable the reduction of power production the dynamic billing will be more fair and in favour to the customer.

- Distributed Generation:
  Lately there is a continuous struggle to achieve sustainability through renewable energy sources such tidal, solar and wind power. Despite the availability of stochastic models to predict their fluctuation, it is almost impossible to have exact values. Moreover, on such scale the fault tolerance has to be very small because even a tiny fluctuation causes very big increase of the power produced and subsequently instability to the power grid. The task of distributed generation service is to provide a continuous flow of information on the power

production of the renewable energy sources or even control the means of production (e.g. stop some wind turbines).

The technology used in the Smart Communication Subsystem is defined in a latter stage, as depicted in the Design chapter. There is a general agreement that this subsystem must fulfil all the aforementioned QoS requirements [28]. Different possibilities about the technology used in the Smart Communication Subsystem exist, including wireless or wired technologies. In this project,the wireless technologies are going to be used to connect the SGrid application to the Metro-Access network since the SGrid demands a complete coverage of the city. Moreover, wireless technology is easily deployed and has a low installation cost [28] The choice of the wireless technology will be discussed in the subsection 2.2.2

Smart Parking

The parking system is facing many problems as the number of vehicles in the city is increasing rapidly [24] [29]. The Smart Parking (SPark) system is being deployed as a solution for those problems [24]. The widespread use of wireless technologies such as WSNs and in general the improvements in wireless applications may be a solution for the parking challenges. WSNs seem to be the best alternative because of their low cost of deployment in the existing parking spaces and low energy consumption. In a smart parking environment, wireless sensors will be put in every parking slot, and will be able to collect and transmit data to the parking sink.

In [24] this system is described with a three tiered approach as shown in the figure 2.3. The lowest level is the sensing function. Through the use of sensors distributed in the parking space it will be possible to know in real time the free spaces left. The second level is the data transmission and the upper level is data processing, data storage and the client interface.

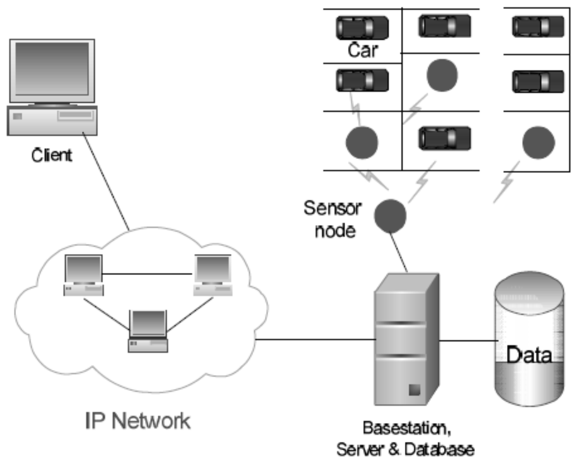

Figure 2.3: Smart parking architecture [24]

This project will argue only about on second level of this architecture, the data transmission between the parking space to the Metro-Access network. As for the SGrid, transmission technology will be presented in the next chapter that aggregates the design choices. The wireless technology options will be discussed in the subsection 2.2.2

From the perspective of the application design the investigation yielded many different approaches. Among these two generic groups can be identified based on their operational principle:

- Information Based
- Reservation Based

The first group is a collection of applications where the parking system is passive and simply informs the driver about the amount of free parking spots. Such implementations might be realized either as an isolated network where sensors data is shown on a screen outside the parking or it might as well be non-isolated by propagating their data to a database which users can access through internet.

The second group refers to applications where the user is more passive. As revealed by its name, the driver sends through some graphical interface a request for parking spot near his destination. A central server which has an updated database of the state of the parking spaces finds a free spot based on the drivers query and reserves it for some to let the driver reach the place.

Regarding the QoS requirement, SPark has no special needs in bandwidth or latency. The information updating frequency of the application is low of the order of one several minutes. The data packet is small also. In e first implementation of this application the deal is knowing in real-time the free parking spots of one given smart parking area.

Traffic Video monitoring

The Smart City concept is aiming for a city that is safer and self organizes its resources. These include the transportation system which has been proven of great importance for the development of any city. As more people choose to live in the city centres, managing such complex system as a road network becomes increasingly challenging. A citywide video monitoring infrastructure focused on critical locations will ensure a more efficient traffic management. Deploying cameras at intersections in order to control the traffic lights and the flow of cameras based on the provided picture is probably, the most evident application. In a SC, though, data from sensors can be reclaimed from a variety of applications through devices belonging in heterogeneous networks. Future Intelligent Transport Systems (ITS), for instance, can take advantage of the camera network to inform the drivers about collisions and reroute the flow of vehicles. The communications network to be designed should be capable of handling the network traffic that can be produced by such a system in a way that enables a seamless cooperation with the rest SC systems.

This application was chosen because it has special QoS requirements. According to [9] guaranteed bandwidth is an important factor to be taken in account. As the information may be important, the packet loss should not be more than 5 %. Regarding latency and jitter, video monitoring has no special requirements because of the application buffering. But, in the case of a real-time application these two requirements are essential for the proper functioning of the application.

2.1.3 Applications constraints

As discussed in the section above, the chosen applications have different demands regarding the service quality. The following table will resume the demands of each application, in order to highlights the important ones.

	Latency	Jitter	Network throughput	Reliability	Availability
Smart Grid	High	High	Medium	High	High
Smart Parking	Low	Low	Low	High	High
Video monitoring	Medium	Medium	High	High	High

Table 2.1: Comparison of the applications QoS requirements

SGrid and video monitoring have high demands in network throughput, while SParking has a lower demand. SGrid is less tolerant to latency and jitter than the parking and video monitoring application. But, all of them require a network with a high reliability and availability level.

2.2 State of the art

The scope of this section is to provide an overall view about different network architectures, technologies and topologies in order to design a SC network. It describes several hybrid optical-wireless architectures that may be implemented in a SC environment. The discussion about different technologies to provide access network will take place in a later section. Finally different topologies, suitable to a MAN network will be addressed.

2.2.1 Next Generation Access Networks

Access network is the term that describes that part of the network which provides connectivity between the end nodes and the core network. The end nodes can also be the network gateways of underlying sub-networks. The Next Generation Network (NGN) term refers to the strive towards the convergence of fixed and mobile communications, regardless the access technology used by the underlying networks [16]. Key factor to accomplish this goal is the encapsulation of traffic under the IP protocol. On other hand, the concept of IoT for Smart Cities is rather new and not much research has been conducted up until this day, on a network dedicated to accommodate its applications. The combination of the aforementioned facts led the research towards NGN hybrid optical-wireless solutions to acquire inspiration and knowledge applicable to the current project.

Thereafter, several hybrid optical-wireless network architectures are proposed, emphasising the advantages of each one.

Metro Access Rings Integrated Network (MARIN) architecture

MARIN is a hybrid optical–wireless access network designed for a metropolitan area network [26]. Its topology includes an optical backhaul ring where multiple tree networks are connected. The ends of those networks (the wireless gateways), form between them a wireless mesh network (WMN) as shown at 2.4

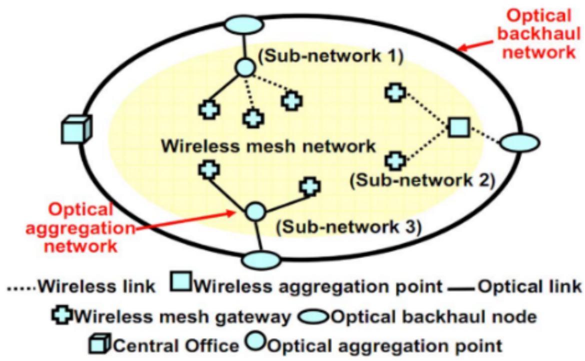

Figure 2.4: MARIN system architecture [26]

This architecture consists of several network elements [26]:

- Optical central hub connecting the optical ring to the Wide Area Network (WAN);
- Optical networks nodes, whose role is to route the traffic from the optical central hub to the optical aggregation nodes;
- Optical aggregation nodes that aggregate the traffic from the optical wireless gateways;
- Optical wireless gateways that represent the interface between the optical tree network and the wireless mesh network. They can handle both wireless and optical traffic. Their role is to route the wireless traffic to the optical network;
- Wireless mesh routers that can only handle wireless traffic;

MARIN is a convenient network architecture for the cities due to the scalable and high performance optical backbone capable of supporting the next generation, ubiquitous wireless network [26].

Grid Reconfigurable Optical and Wireless Network (GROWNet)

GROWnet is a broadband architecture designed for hybrid optical-wireless access network implemented in a city scenario. [27]. According to this architecture, optical cells are deployed throughout the city and forming what is called the optical grid. In each cell there is a wireless mesh network (see figure 2.5)

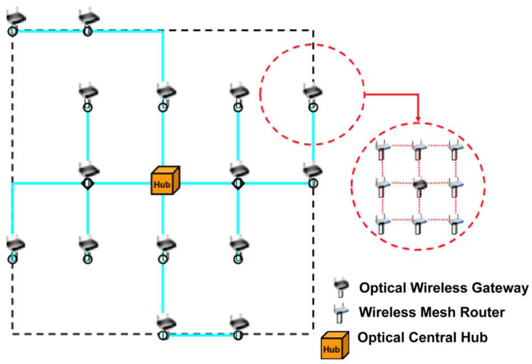

Figure 2.5: GROWNet architecture [17]

The main advantages of this architecture are the high - capacity provided, as it brings fiber deeper in the city, and the ubiquitous link due to omnipresence of the wireless mesh network [27]. Another asset of the GROWNet architecture is the so-called "Cell breathing". This technique consists of changing the cell range according to the traffic produced inside the cell, and therefore, the number of users by changing the transmitted power [17].

Fibre-Wireless access network (FiWi)

The main focus of the FiWi architecture is the peer to peer communication between wireless nodes. To achieve their objective of higher throughput, they interpose links of optically interconnected Optical Network Units (ONUs). Apart from the higher throughput thanks to the reliable optical path, it also reduces the interference of the channel due to the reduction of the wireless hops.

An architecture based on this concept is the one proposed in [19]. It differs from the rest by introducing the idea of direct communication in between the ONUs, as well as distributed dynamic bandwidth allocation method. The optical part of the network consists of a hybrid Wavelength Division Multiplexed/Time Division Multiplexed

Passive Optical Network (WDM/TDM PON) where the traffic of the ONUs doesn't need to go through the Optical Line Terminal (OLT).

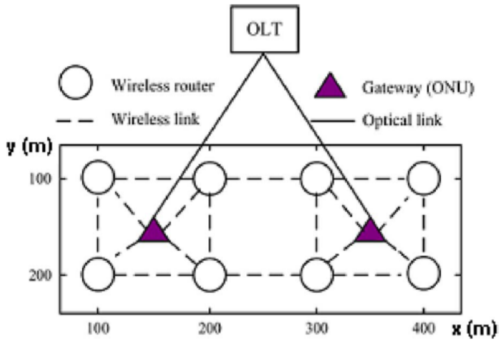

Figure 2.6: Small scale FiWi topology [19] [1]

FUTON

THe FUTON project is a hybrid-wireless architecture, used in wireless systems. This architecture uses simplified base stations called Radio Access Units (RAU) instead of the tradition Base Stations (BS) to cover an area connected trough fibre to the Central Units (CU). The RAUs are transparent multi-frequency transceivers, that receives and transmits radio signals from the users. From the RAU, the radio signals will be relayed to the CU using Radio over Fibre (RoF), where the joint processing of the radio signals takes place.

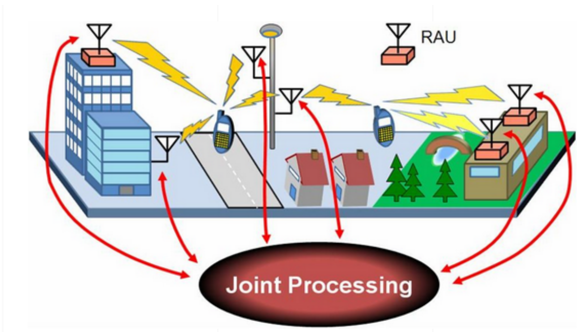

Figure 2.7: FUTON architecture [1]

This architecture will enable the high bit rates targeted in the broadband component of future wireless systems and will provide a framework for the integration of heterogeneous wireless system.

Wireless-Optical Broadband Access network (WOBAN)

WOBAN architecture consists of an optical backhaul (PON) and a wireless front-end [8]. At this architecture the PON segment starts from the opticaal terminal line (OTL)to the telecom CO and finishes at the optical netwok unit (ONU). The front-end network is composed of wireless routers forming a WMN between them. Among these routers, some of them serve as gateways and are connected to the ONU.

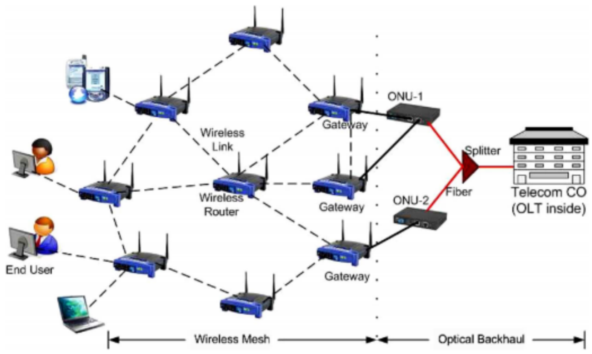

Figure 2.8: WOBAN architecture [8]

This architecture maximizes the bandwidth provided to the broadband networks and minimizes the cost of deployment due to the cost-effective wireless front-end [8].

The analysis of these hybrid network architectures, resulted in different proposals offering high bandwidths for the access network. Among them, the most appropriate to be implemented in a SC seems to be the MARIN architecture, as it offers a WDM with point-to-point connections to the access network. Obviously, as it was designed for a broadband network, further modifications are necessary in order to adapt it to the SC concept. The final decisions on the chosen architecture will be discussed further in the section 4.4.

2.2.2 Wireless technologies

In this section, the investigation of the wireless technologies suitable to provide access network when deploying fibre would not be a reasonable solution will be discussed. Among all the technologies studied, WiFi and LTE were found to be more convenient, they are thus presented more detailed in the following paragraphs.

Wireless communication is a non-wired communication, where two or more points can send and receive signals without using any electrical/optical line. Several technologies can be used to transport the information from one point to another like Zigbee, WiFi, WiMax, 2G, 3G, LTE, etc. Considering the demands of the application described in the subsection 2.1.2, two of these technologies WiFi and LTE, were chosen as possible candidates to be used in the Metro-Access network.

WiFi

WiFi based Access Points are proposed as part of many NGN architectures. WiFi is based on the IEEE 802.11 protocol stack which was initially designed to provide Wireless Local Area Network (WLAN) connectivity. Despite this fact, its broad dissemination led to additional research and technological advances of the protocol and the WiFi enabled devices subsequently. It consists of specifications on the physical and Media Access Control layers and was first released in 1997. Since then, WiFi radically evolved to keep up with the increased throughput new services demand (see figure 2.9).

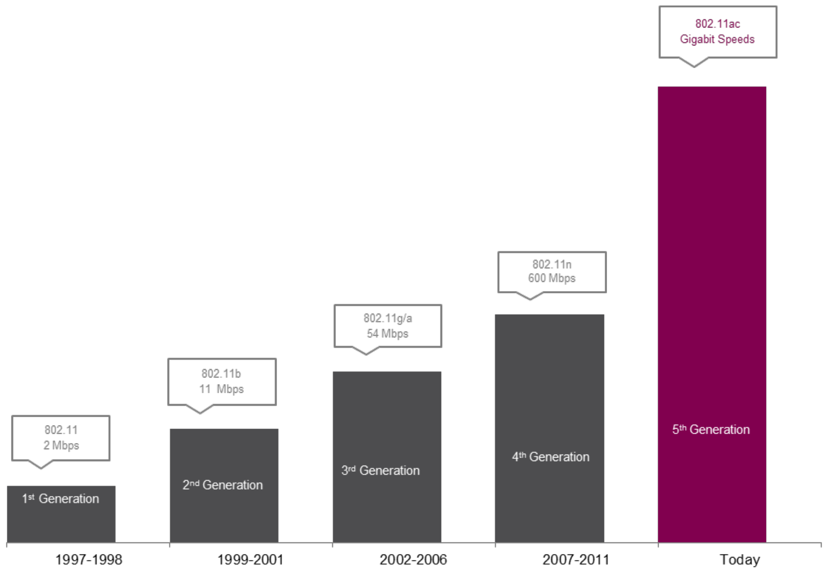

Figure 2.9: The evolution of 802.11

Multiple Input Multiple Output (MIMO) [23] techniques along with the use of multiple antennas, both at the receiver and the transmitter, had a great impact on the wireless communication systems in terms of data rates, range and link reliability. It takes advantage of one of the drawbacks of wireless communications, the multipath effect, to turn it to a benefit. When the link quality is good it has the ability of sending independent streams leading to theoretical datarates up to 600 Mbps (in 802.11n 4x4 MIMO), or even higher with the latest 802.11ac standard. When the signal quality is degraded due to multipath, MIMO techniques such as selection combining and Maximal Ratio Combining (MRC) are used to achieve better Signal to Noise Ration (SNR). The first just picks the signal with the best characteristics among the ones received from the multiple antennas, while the latter is summing the signals to achieve a better SNR, based on the fact that unlike the signal the noise is correlated. The diversity gains can be seen at the figure 2.10 where the cumulative distribution of SNR for one to three antennas is plotted.

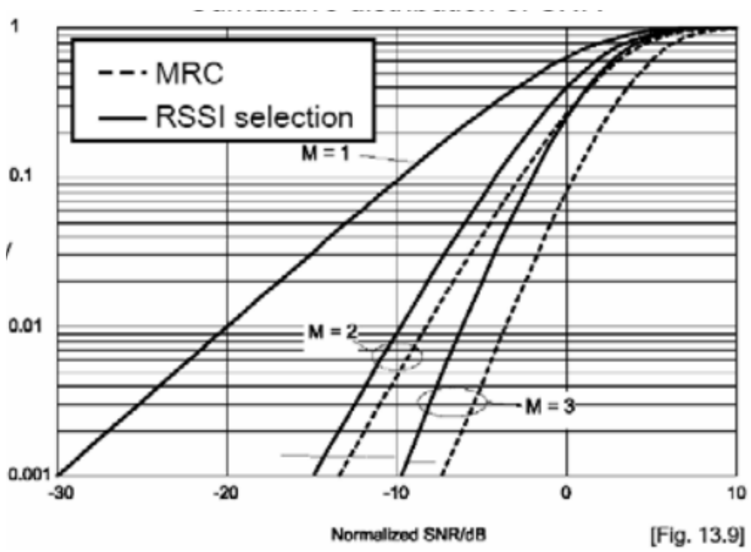

Figure 2.10: Cumulative distribution of SNR with 1,2 and 3 antennas [23]

LTE

LTE stands for Long-Term Evolution and is a new standard in mobile communication systems, developed by 3GPP (3rd Generation Partnership Project) [2]. It is designed to supports only packet-switched systems as it is based on an IP architecture. LTE protocols use TCP/IP to manage the packet-switching. This evolved technology provides many advantages compared to other existing wireless standards, such as higher throughput, low cost of transmission per bit, higher spectral efficiency and lower latency.

While the first standard of LTE date of 2008 with LTE Release 8, there have been many improvements that leed to the thinking that LTE offers a huge potential for the future.

The main characteristics of the LTE Releases: [6]

- 3GPP Release 8 (2008)
  LTE was introduced for the first time by the Release 8 at 2008, with a completely new radio interface and core network. It improved data performance compared with previous systems achieving up to 300 Mbps en downlink and 75 Mbps en uplink. Latency is down to 10ms and the possibility to use different bandwidths of 1.4, 3 ,5 , 10, 15 or 20MHz allows different deployment scenarios.

LTE uses OFDMA (orthogonal frequency domain multiple access) in downlink and SC-FDMA (single-carrier frequency domain multiple access) in uplink. It also uses the MIMO technique for higher bandwidth and reliability.

- 3GPP Release 9 (2009)
  Release 9 ameliorates the elements of Realise 8, and brings new developments to the network architecture and new service features. The most important improvements were the self organising network (SON) features such as optimisation of the random access channel. This release introduced also the multimedia broadcast and multicast service (eMBMS) as well as the efficient delivery of the same multimedia content to multiple destinations.

- 3GPP Release 10 (2011)
  Release 10 offers higher throughputs up to 3 Gb/s in downlink and 1.5 Gb/s in uplink and higher bandwidths up to 100 MHz. This release introduced the relay nodes to support Heterogeneous Networks ("HetNets") containing different cell sizes. The order of MIMO antenna is configurable up to 8*8 in downlink and 4*4 in uplink.

- 3GPP Release 11 (2013)
  Release 11 introduces new frequency bands, advanced receivers and coordinated multipoint transmission and reception to enable simultaneous communication with multiple cells.

- 3GPP Release 12 (2014)
  The Release 12 is supposed not only to support the rapid increase of the mobile data usage, but also the support of other different application while ensuring a high quality of service for the end users. It offers internetworking between LTE and WiFi or HSPDA, and improves the support of HetNets.

Currently, only the Release 8 and 9 are being commercially deployed. As a result, the parameters of these releases will be used in the rest of this project. LTE cell size varies up to 30 km, depending on the geographical scenario. A considerable signal degradation takes place after 10 km.

In conclusion, LTE compared to WiFi offers a better coverage as the radius of LTE cells are bigger than in the case of WiFi. WiFi has a limited radius of coverage as it was designed for local networks. Concerning the latency, LTE seems to have a lower latency than WiFi as it is shown in the picture 2.11.

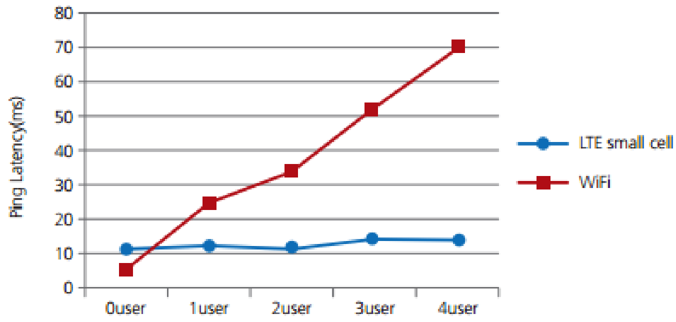

Figure 2.11: Latency comparison between LTE and WiFi

2.2.3 Optical fibre technology

Optical fibre is a light, flexible fibre made from glass (silica) or plastic used in telecommunication used to carry light signals with a higher bandwidth that any other other wired technologies. Due to the low attenuation, signals are transmitted over long distances [30].

Optical fibre can be multi-mode or single-mode according the the number of modes The multi-mode fibre are characterized by a large core diameter (50 to 62 micorns). Due to this fact, in multi-mode fibre there is a risk of dispersion that limits the distance of deployment of this type of fibre

The single-mode fibre has a smaller diameter than the multi-mode (5 to 10 microns). The use of WDM technology (Wavelengh Devision Multipexing), multiple wavelengths are sent simultaneously, achieving this high speeds of transmission of the order of terabits/s. The optical fibres already deployed use up to 32 wavelengths, offering bandwidths of 320 Gbps as each wavelength can carry up to 10 Gbps of information. Experimental research show that the number of channels in a single-mode fibre can be even bigger up to 72 channels or even more, thus supporting high bandwidths.

Advantages of using optical fibre

- High data rates, of the order of terabits/s under laboratory conditions
- Used in long distance due to the low attenuation
- No external electromagnetic field, providing though security against sniffing the network
- Low bit error rate of the order of 10^{-10}

Drawbacks of using optical fibre

- High cost of deployment
- High purity of the glass in the fibre is necessary in order to minimize the losses

2.2.4 MAN topologies

Network topology refers to the way the network devices are connected between them. Physical topology describes the physical placement of the network elements, while the logical topology points out the way the information flows in the network. In this section the MAN physical technology studied during this project will be discussed. The most common technologies for such network are ring, double-ring and mesh topologies [22].

Ring topology

Ring technology is a regular symmetric 2-degree topology, where the traffic between the nodes will flow in a circular way from a node to another. This topology is easily deployed and in case of cable faults, the troubleshooting is easy. But, the ring topology doesn't meet the scalability requirement. In case of adding new nodes or links, the structural properties of the topology may change.

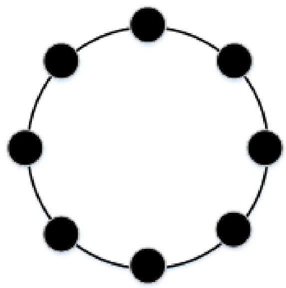

Figure 2.12: Ring topology

Double-ring topology

Double-ring topology is a regular 3-degree topology. It consists of two rings connecting exactly the same number of nodes. The redundancy is provided by links between each pair of nodes connecting thus, the inner and outer ring. Each ring is independent of the other, unless a failure happens in the primary ring. This topology is often used in MAN networks as it offers high level of reliability and redundancy. But, as in the case of the ring topology, the scalability requirement is not totally satisfied.

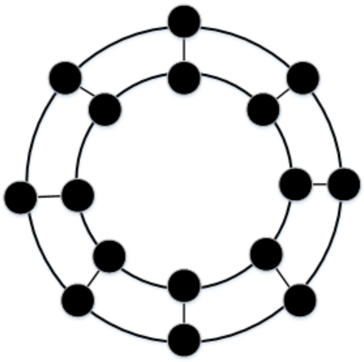

Figure 2.13: Double-ring topology

Planar or mesh topology

Planar or mesh topologies are not necessary regular of symmetric. Different topologies are considered as mesh topologies, like grid, honeycomb etc. In this topology, the nodes have different degrees. For example, in the grid topology, the nodes can be degree 2, 3 or 4 depending on their position in the grid.

Mesh topologies offer high level of redundancy of the network. In general, they are more more difficult to be implemented than ring or double-ring topology because of the high cost of deployment.

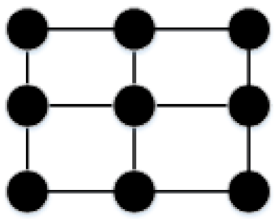

Figure 2.14: Grid topology

Comparison of the topology

The topologies presented above were compared between them according to several criteria as the difficulty of deployment and troubleshooting under failure conditions. Moreover, scalability, redundancy are important factors to be considered in order to offer the desired connectivity for the SC network. Finally, financial cost is another parameter to be considered in order to have an overall view of each topology, not only based in the networks requirements.

The analyse of each topology gave the results shown in the following table where 1 stands for low and 3 for high:

	Deployment difficulty	Troubleshooting difficulty	Scalability	Redundancy	Availability	Financial cost
Ring	1	1	1	1	1	1
Double-ring	2	2	2	3	2	2
Mesh	3	2	3	3	3	3

Table 2.2: Comparison of network topologies

To sum up, ring topology is easier to be deployed and less expensive than double-ring or mesh topology. But, it offers a low level of redundancy and availability. Mesh topology is the best candidate for a network willing to have a high level of redundancy, availability and scalability, but its drawbacks are the complexity of deployment and its cost. Finally, the double-ring topology stands between the ring and mesh topology, offering a higher degree of redundancy than the ring topoogy, and has a lower cost in deployment than the mesh topologies.

Chapter 3

Case study

3.1 Aalborg municipality

For the implementation of this project, the municipality of Aalborg was chosen, as GIS data was available from the University of Aalborg.

Aalborg municipality is situated in the region of Nordjylland at the north of Denmark. Aalborg city, the centre of the municipality, is the fourth biggest city in Denmark, behind Copenhagen, Aarhus and Odsen. The Aalborg municipality has a population of 205 809 habitants (2014) [11].

The density of the population varies from one area to another. Typically, Aalborg city can be characterized as un urban area because of a high density of inhabitants, while the whole municipality can be generally considered as an suburban and rural area.

The municipality has a specific layout as it situated on both sides of the Limfjord. This geographic position may introduce some challenges for the project in terms of network planning as the obstacle of the fjord has to be considered.

3.2 GIS data

Geographical Information System (GIS) is a database containing useful information for a network deployment, especially for the optical lines. This information consists of a collection of roads, houses and population. Every house, called NT (network terminal) in the GIS data, is represented through 2 coordinates x and y.

The GIS information available to the project included data about Aalborg municipality, the number of houses and their addresses as well as geographical information about the road network.

The Nts table contains mainly information about the address of the houses and their geographical position. The most useful fields are the following ones:

- Kommuner: The ID of the municipality (851 for Aalborg)
- Kommunenavn: The name of the municipality
- Vejkode: The unique street number where every NT is located
- Vejnavn: The name of the street where NTs are situated
- Husnr_Bogs: The number of each NT
- Adresse: The address of each NT, containing the name of the street and number of the NT
- Postnr: The postcode for each NT
- X_koordinat: The x-coordinate of each NT
- Y_koordinat: The y-coordinate of each NT

Concerning the road network, it is described as segments interconnected to each other. Each segment is defined by two points, denoted as sp1 and sp2, standing for segment point 1 and 2. The segment points table contains the following information:

- Sp1: The ID of the firs segment point
- Sp2: The ID of the second segment point
- L: The length of each segment
- Id: The unique ID of each segment, which is the result of the concatenation of the sp1 and sp2
- Spx1: The x-coordinate of the first point of each segment
- Spy1: The y-coordinate of the first point of each segment
- Spx2: The x-coordinate of the second point of each segment
- Spy2: The y-coordinate of the second point of each segment
- Vejnavn: The name of the street
- Komnr: The municipality number

Chapter 4

Design

The following chapter analyses the most significant design aspects of the overall system. It follows a bottom up approach, starting by defining each of the three SC applications and how their nodes are deployed in the field to conclude to a future proof Metro-Access network designed to provide them connectivity. This chapter embodies the logical continuation of the investigation presented in the Pre-analysis chapter and contributes to a stable background for the network planning in the next chapter Network Planning.

4.1 Smart Grid System

4.1.1 Application design

An investigation of the current power grid needs in relation to the services a SGgrid ICT infrastructure can offer, has yielded a number of proposals of applications mainly focused around billing and more importantly a clever power production management and distribution. Most of these applications are categorized as Machine to Machine (M2M) technologies as they have they enable actuators to directly take decisions based on data produced by sensors over the network, without the mediation of the human factor.

The aforementioned applications in the section 2.1 constitute only a small subset of those proposed for the future SGrid. In favour of simplicity, the problem is reduced to one application equivalent to DLC with main objective to balance the load of the power grid from the side of the consumer. This may be achieved by disseminating information of the state and consumption of power hungry appliances and at the same time enabling M2M control services on appliances with flexibility on the availability of power.

This reduced application whose outline is described above, yields a bidirectional flow of information. The most challenging in terms of traffic is the uplink since it requires to update promptly the state of all the devices so that the SGrid is aware of the whole picture at every moment. At the downlink, minimizing the delay is more important to assure that the appliances will comply to the current need of the power grid to prevent power shortages at the consumption peaks.

Figure 4.1: SGrid application design

In a more realistic implementation of such application there are methods that can be applied to scale down the traffic of the uplink. This is done due to limitations either to the available capacity of the communication channel or to the available energy of battery-powered transceivers. A common method accomplish that is by performing in-network data aggregation techniques such as data fusion. In short data fusion is combining (e.g. averaging) data from multiple sensors in one as depicted in the figure 4.2.

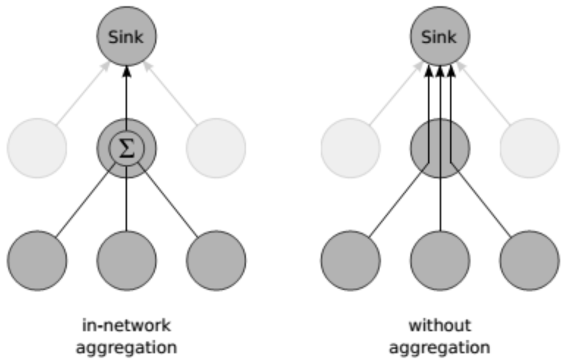

Figure 4.2: Relaying with and without in-network data aggregation, where the Σ symbol corresponds to a data fusion method

Data fusion, constitutes a viable solution in many cases, but at the same time compromises the granularity of the data which can be of great importance in applications responsible for critical fields like the power grid.

4.1.2 SGrid Node distribution

Nowadays the concept of smart appliances is mostly in a research stage. Houses are not equipped yet with SGrid enabled devices, but this likely to change in the near future in favour of a more rational power production-consumption model. Of course, home appliances are designed to last more than ten years, so one should expect a radical increase in the SG devices. Moreover, as aforementioned, it is only the energy-intensive devices that justify the need for such functionalities.

Following the above reasoning path an average of four SGrid appliances per house was considered a rational choice for the following twenty years. These appliances may be a washing machine, a clothes dryer, a hot water heater and an Electric Vehicle charger. This number is likely to be increased, but the choice was based on the fact that this average is zero and the frequency these appliances are renewed is low.

$$\begin{aligned} Total\, SGrid\, nodes &= Average\, nodesper\, house * Amount\, of\, NTs \\ &= 4 * 82681 \\ &= 330724 \quad SGrid\ nodes \end{aligned} \tag{4.1}$$

4.1.3 Network Traffic

The traffic produced by each of the SGrid devices is a result of the size of the data to be transmitted and the frequency the data need to be disseminated. Again there are different opinions and proposals on the values these factors should have, it is obvious, though, that more data can only be good since it assures no information is disregarded in order to save system resources. For the sake of simplicity the SG devices are assumed to be homogeneous, meaning that they produce the same amount of packets at equally sized time intervals. Below are stated the specific values used in the implementation.

- Packet Size: 150 B
- Update Frequency: Once every 60s

$$\begin{aligned} Minimum\, Throuput &= Packet\, Size / Update\, Frquency \\ &= 150 * 8bits/60sec \\ &= 20 \quad bps\, per\, SGrid\, node \end{aligned} \tag{4.2}$$

4.1.4 Architecture

The architecture of the SGrid used for the project is based on the proposal of Yu *et al.* [31]. According to this scheme, the network is strictly hierarchical and organized in sub-networks named after the area they operate, namely Home Area Network (HAN) and Neighbourhood Area Network(NAN). In practice, this means that smart nodes in a house belong to a HAN, where one of them operates as a gateway and is called Home Area Gateway (HGW). The HGWs of a specified area are then responsible of relaying the data to a Neighbourhood Area Gateway (NGW) and this to an Access

Gateway (AGW), which provides access to the power grid backbone communication network. The figure 4.3 depicts the relation of the devices involved in the SGrid architecture.

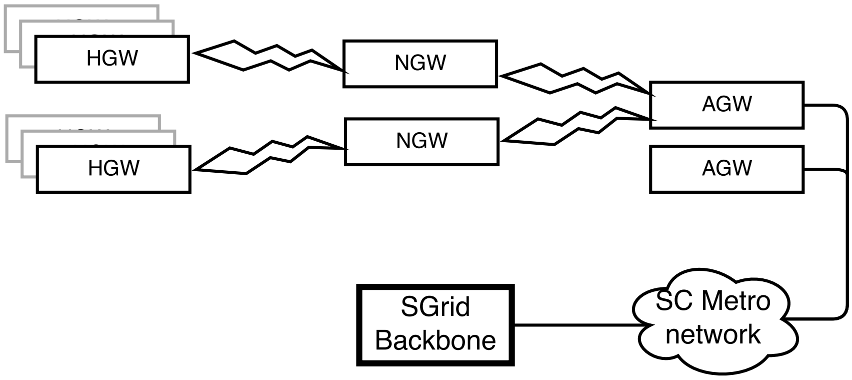

Figure 4.3: Components of the SGrid architecture

The decision of a wireless link to connect the NGWs to the AGW was made on the basis of two facts. Firstly the big amount of NGWs spread throughout the municipality, secondly the low throughput requirements of the devices (compared to modern network standards) would not justify the deployment of so much wire (or fibre).

4.1.5 Implementation

The NANs are implemented by splitting the area in neighbourhoods. This is realized by creating a grid over the map, with every cell sized 200m x 200m. From these cells only those within the terrain of the municipality that have at least one NT in their area. The centre of the cell is then found to be used as the point where the NGW is placed.

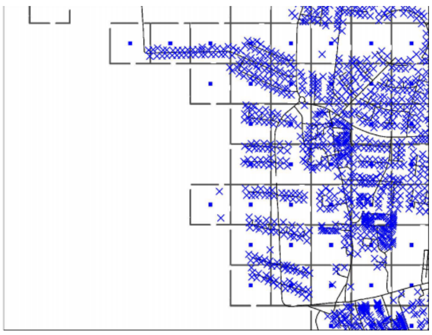

Figure 4.4: The region split in a 200m x 200m grid. The NGWs are assumed to be in the centre of each cell and are responsible for the HGW nodes in their vicinity.

4.2 Smart Parking design

4.2.1 Application design

Being an application that can highly influence the daily life in a city, Smart Parking (SPark), has caught the attention of both academia and the industry. The outcome of their interest can be seen not only inside lab test-beds but also deployed and operating in cities like Santander in Spain with ambitions to turn into Smart Cities [25]. There are different implementations and even more proposals on how it should operate.

The application design considered in this project belongs to the second group of reservation based SPark systems as it is more user friendly and more convenient for the future SC. The process flow is as follows:

- A gateway updates the current state of the parking to a central server
- The driver sends a request containing personalised information of his needs to the server
- The server asks the gateway before reserving the spot to assure it still is free

It is apparent from the description of the application that a bidirectional communication link is necessary for this system. In contrast to the SGrid, the downlink is expected to be more demanding. This is due to the worst case scenario where a big amount of people may request parking spots in a specific area at the same time (e.g. when going to see a football match).

4.2.2 SPark Node distribution

The parking system for a SC should try to keep the cars away from side road parking spots. The reasoning for this is related to leaving space for short term stopping (e.g. 5 minutes to get the kid from the school), provide better accessibility to disabled people and lastly even for aesthetic reasons.

These led to the decision of choosing specific parking areas instead of assuming that every road can provide parking spots. The chosen values are outlined below:

- An number of 20 parking lots spread around the municipality
- 250 spots in every lot, meaning 250 Spark nodes per lot

The research on the statistics of Aalborg municipality showed that there are 48.501 families with at least one car and that more than 77% of the all transportation in Denmark is done by car. The provision outlined above provides 5000 parking spots which is more than 10% of the families with cars.

4.2.3 SPark Network Traffic

The traffic intensity of IoT nodes in general is a mostly a result of the vast amount of nodes that started to be deployed in 2009. More than 50 billion "things" are expected to be connected worldwide by 2020 according to Cisco forecasts[13]. The data these devices hold and propagate is usually small, but the challenge for the ICT infrastructure occurs as their amount grows and the traffic accumulates.

The number of nodes of the SPark system is 5000 in total, but the load of the will be distributed among a chosen number of gateways. Moreover, the packet size among different research papers fluctuates around 100 Bytes. Taking into consideration the aforementioned personalised data (accessibility, vehicle size, etc.) that should fit the data packet, the packet size and update frequency chosen are stated below:

- Packet Size: 200 Bytes
- Update frequency: 1/120 seconds

$$\begin{aligned} Minimum\,Throuput &= Packet\,Size/Update\,Frquency \\ &= 200 * 8bits/120sec \\ &= 13,34 \quad bps\,per\,SGrid\,node \end{aligned} \tag{4.3}$$

4.2.4 Architecture

The architecture design of the SPark system is rather simplistic compared to the other two applications and is also revealed previously in this chapter. The SPark nodes in a parking lot, which are nothing more than sensors with a communication interface, form a hierarchical network where all of them are at the same level apart from a more sophisticated node that acts as the gateway for the whole network in the parking lot. This gateway is responsible for relaying the data to the AGW, which is part of the SC access network.

4.2.5 Implementation

A research on available parking lots and solving such a facility location problem is out of the scope of this project. The only GIS data reclaimed was the map of Aalborg region in order acquire coordinates within the municipality boundaries. The entirety of the nodes in each parking lot is represented by one point which corresponds to the position of the SPark gateway. Each of these (20) points are manually chosen and spread around the municipality 4.5.

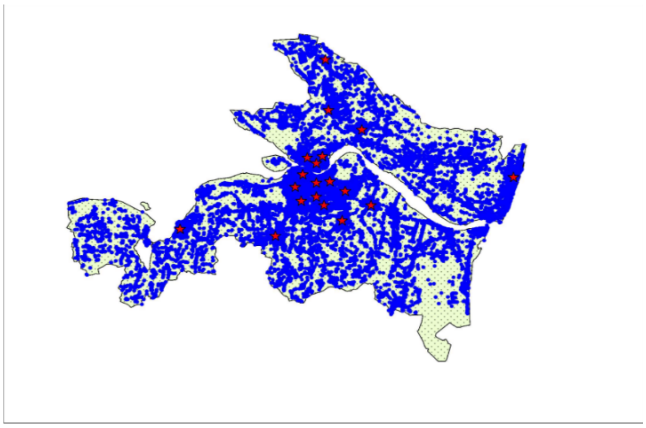

Figure 4.5: Manually placed parking locations at the areas with the highest population density

4.3 Traffic Video Monitoring design

4.3.1 Application design

Traffic Video Monitoring (TVM) in conjunction with Intelligent Transportation Systems (ITS) are expected to transform the landscape of transportation. Such applications mainly aim the improvement of safety and traffic flow of the road networks. While ITS is designed in principal for disseminating alarm and warning signals, TVM, on the other hand, consists of a network of cameras to provide High Definition (HD) video to traffic engineers, the police and other institutions responsible for the road network.

A number of cameras are deployed at the dangerous road positions of the SC and they continuously upload HD video to assure timely response of police, hospital and traffic engineers who aim to avoid congestions.
The cameras can also be controlled remotely to achieve better image and angle. Such controls may include pan, zoom, rotate, etc.

4.3.2 Camera distribution

Statistics on roads with high probability of accidents and congestion for the municipality were not available, therefore, the TVM node placement was based on the assumption that intersections where more than three road segments meet are dangerous. Moreover, due to the fact that at least two roads meet it is more likely to have traffic lights operating to coordinate the vehicle flow and avoid traffic jams.

The output of the algorithms we run on the available GIS data yielded a total of 1098 cameras throughout the region. Of course, this includes pedestrian streets or roads with low traffic intensity but this simplification does not affect the generality of the problem.

4.3.3 Camera Network traffic

Accepting the assumption that "a picture is worth a thousand words", 30 pictures per second (30 fps) that one camera records produces a lot of traffic to the network. Nowadays, traffic cameras have already been operating for years and combined with the fact that obsolete communication networks achieve much lower data rates than the modern ones resulted in low quality, sometimes black and white video.

Today's camera sensors are able to capture images of size 7680 x 4320 pixels with up to 120 fps. Such devices are intended for cinematic production. For the TVM network 1080p ($1,920$ x $1,080$) cameras at 30 fps, also known as Full HD) are considered more realistic and applicable to the aforementioned applications. The video is compressed using the H.264 video codec compression ratio for medium motion video (rank 2 according to Adobe®[3]). The traffic produced by each of the HD cameras is computed as follows:

$$\begin{aligned} BitRate &= PixelWidth * PixelHight * fps * rank * 0.07 \\ &= 1920 * 1080 * 30 * 2 * 0.07 \\ &= 8.7\, Mbps \end{aligned} \tag{4.4}$$

4.3.4 Camera Network architecture

The TVM camera network has to provide both high bandwidth and protection from link failures. The first is due to the magnitude of traffic produced by each camera with low latency requirements for real time video streaming, the later because of the criticality of the application for the safety of the road infrastructure. On this basis, the following decisions on the architecture emerged:

- The cameras are connected on a fibre network
- The cameras are grouped forming ring networks
- Two camera nodes on each ring act as GWs to provide protection (see figure 4.6)

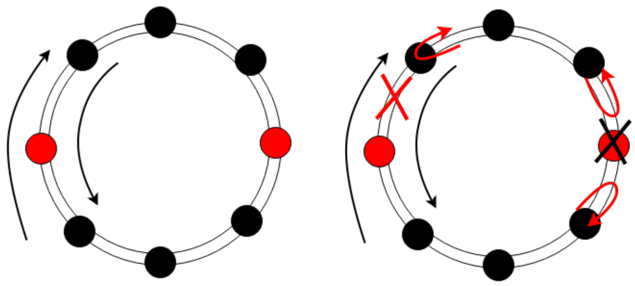

Figure 4.6: Path restoration in case of node or fibre failure

4.3.5 Implementation

The implementation of the camera placement consists of three stages:

- Find the intersections to place the TVM nodes
- Create groups of nodes based on their distance in between them
- Choose the nodes that will be GWs

In order to find the intersections the programming language Python with the NetworkX framework was used in order to create a graph using the GIS data. The next step was to find all the degree-4 and over nodes in the graph, which represent junctions of more than three road segments.

The 1098 TVM nodes are then grouped in 20 groups using the K-means unsupervised learning clustering algorithm.

The last stage is to choose the nodes that will act as GWs. This is done for each group by finding two pairs of TVM and AGW nodes with the minimum Euclidean distance. The two pairs are independent (neither a TVM, nor an AGW can be in both pairs) to reduce the possibility that the fibre will follow the same path during the fibre planning. This will result in a longer path for the second pair but provides additional protection, since it's less likely to happen that digging on both paths will cut both the fibres at the same time.

4.4 Metro-Access design

Metro-Access is the network that comprises the access network for the SC applications and the MAN. In previous sections 4.1, 4.2 and 4.3 the architecture and the implantation of the SC application was described. In this section the design of the Metro-Access network will be discussed.

4.4.1 Access network design

As presented in the section 2.1.3 the applications considered in this project have different constraints concerning the quality of service requirements. As a consequence, the access network has to be designed in such way to satisfy all of these demands.

Wireless link

SGrid and SPark have no special requirements in network throughput, but they demand a high coverage throughout the city. Moreover, SGrid has is highly delay intolerant, meaning that a technology that offers low latency should be preferred. Wireless technologies seems to be the best candidate providing a deep penetration in the city with a low cost.

After investigating different wireless technologies, LTE is chosen to be implemented in order to provide wireless connectivity to the aforementioned SC applications. While the throughput of LTE is lower than WiFi, it has a better performance with respect to latency, which as mentioned above is an important factor for these applications. Moreover, the wireless link is there to accommodate mainly M2M applications where the throughput demands are low since they mostly exchange signal messages. Finally, WiFi is designed for local networks (LAN), whereas LTE can provide access to larger areas, which suits more to the dimension of a city. Based on the specifications of the future releases, as outlined in chapter 2, LTE appears to be a promising technology, therefore implementing it in a Smart City network architecture seems to be the best choice at this stage of the project.

TVM and other throughput aggressive applications

The SC design has to consider applications with high demands in throughput and TVM is one of them. The main technology with capacity enough to accommodate such requirements is the fibre which will be the choice for such applications. Specifically for this scenario the TVM network the camera gateways will be connected to the AGWs using WDM point-to-point (PtP) connection over a single mode fibre. This choice is based on the consideration that the demands of this application in terms of bandwidths may increase rapidly if more cameras are deployed. In that case this link will not be a bottleneck since a 32 channel DWDM with 10Gbps per channel can carry 32*10Gbps = 320Gbps of traffic.

Metro to AGW link

The AGWs are distributed throughout the municipality of Aalborg and are destined to serve all the underlying SC networks. This means that it is necessary to have a connection that is capable to carry all the traffic it for the nodes it is going to be responsible. The only networking method that can assure to provide a satisfying communication channel is the optical fibre. Again a 32 channel DWDM PtP was chosen to assure the required high datarates.

4.4.2 Metro network design

The design of the metro network consists of several steps. Firstly, a topology meeting the requirements of the future network should be defined. Afterwards, the number of its nodes and finally additional roles they are going to be assigned for some of them.

Choice of the MAN topology

The metro network in the case of Smart Cities, must provide a high degree of redundancy, connectivity and availability. The comparison of different topologies that took place in chapter 2, resulted in the choice of a double-ring topology to be implemented in the SC network architecture. This topology meets the requirements of the SC metro network, offering redundancy and availability at the same time with a lower cost and difficulty of deployment than the others.

Number of MAN nodes

The choice of the number of MAN nodes can be based on different factors like the maximum traffic they can relay or special demands according to the topology as in the case of a chordal ring topology. There the number of nodes cannot be less than five. The lack of available data about traffic estimations combined with the fact that there was no robust argument to support a maximum traffic per node assumption, lead to a another way of solving this issue. Considering the constraint from the double-ring topology: The number of the nodes must be an even number, with six being the minimum.

MAN network architecture

The overall architecture of how the MAN network architecture should look is presented in the following picture:

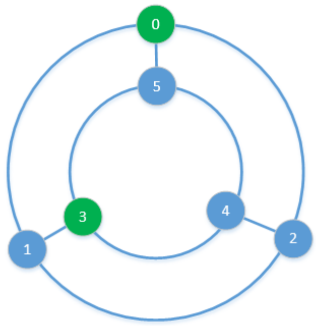

Figure 4.7: MAN network architecture

The nodes coloured in green represent the "intelligent" nodes of the SC. Their role is to process the information received from the AGW. The position on the inner and outer ring provides redundancy in terms of links and in terms of positions as well, as they are placed in two separate physical sites.

Concerning the WAN gateways, their placement is not a goal of this project. It is presumed that the "intelligent" nodes will be assuming the gateway role for the WAN as well.

Metro network traffic

The Metro-Access network should be designed in such way to accommodate all the applications of the future SC. Knowing that the number of these applications can increase rapidly, it can be easily assumed that the traffic they could produce may be huge.

Estimating the traffic of SC turned out to be a difficult task. At the moment, there is no final definition of all the SC applications. However, it is generally agreed that their evolution will be very fast and new applications will emerge. Thus, giving an estimation has a high risk of leading to an error. Nevertheless, being aware of this fact it is essential to propose a future-proof MAN architecture, able to incorporate all the traffic of the SC.

The traffic produced by the city can be either internal or external traffic. It is assumed that the internal traffic represents the most of the traffic according to the SC concept of self-management. External is the traffic relayed outside the city to the WAN. This project considers that 70% of the SC traffic is internal one and 30% is external traffic. The external traffic will be relayed directly to the WAN if the MAN node is at the same time the WAN gateway. In the other case, the traffic is going to be distributed in an equal way to the neighbouring nodes, relaying it towards the WAN gateway following the shortest path in terms of hops. The analysis of both internal and external traffic will be discussed in the next chapter 5.

4.4.3 Metro-Access and application architecture summary

This section presents the overall Metro-Access architecture of the SC, gathering all the choices made in the previous sections about applications architecture and access network and metro network architecture.

The Metro-Access network is responsible for accommodating the traffic of all the SC applications and relaying part of it to the Wide Area Network (WAN). It must provide high bandwidth as the number of the applications can rapidly increase and scalability to accommodate new ones. Moreover, redundancy and multi-technology support are key requirements to be considered.

Starting from a hybrid optical network, namely the MARIN architecture described in the section 2.2.1, as a basis, the group built a metro-access architecture suitable for the SC concept. As aforementioned, WiFi technology proposed by MARIN was neglected in favour of LTE, as well as the in-access rings proposed where PtP links were chosen.

The figure 4.8 describes the Metro-Access architecture. It consists of:

- Optical gateway connecting the MAN with the WAN network. To prevent failure, two of such gateways should be deployed. In case that the principal gateway is dysfunctional, the secondary will assure the routing of the traffic to the WAN.
- Smart City MAN nodes (SCMN) responsible for aggregating the traffic of multiple Access gateways (AGW) and transporting part of it to the WAN. These nodes are connected between them following a double-ring topology as shown in 2.2.4
- Access gateways aggregating the traffic form the SC applications gateways. They provide wireless link using LTE for SGrid and SPark, while the camera gateways are directly connected to them by optical fibre.

- Neighbourhood gateways (NGW) aggregating all the traffic of the SGrid. Their role is to route the traffic from each house to the AGW. The link between NGW and AGW is a wireless link using LTE.
- Smart parking gateways (PGW) collecting the traffic of the parking areas and sending it to the AGW through a wireless link using LTE as well.
- Camera gateways (CGW), responsible for aggregating the traffic inside the TVM rings and relaying it to the AGW using optic fibre.

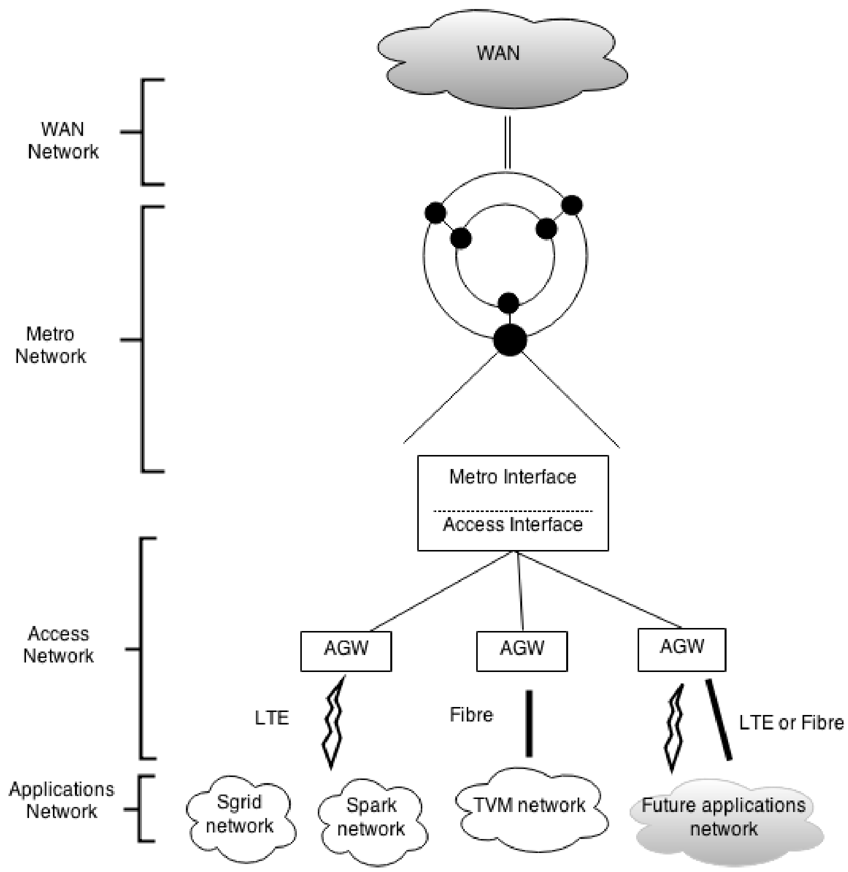

Figure 4.8: Network architecture of a Smart City

Chapter 5

Network Planning

This chapter describes the process followed to plan the Smart City Metro-Access network. The decisions made in the Design chapter include both wireless and wired solutions for the access part of the network, which means that both radio and fibre planning have to be performed in order to decide where to placement of the LTE base stations and which paths the fibres should follow in order to connect all the AGW to the MAN network and the MAN nodes between them. There are different approaches for the network planning, the one followed during this project was to use procedures as automated as possible, using a set of different algorithms to search for optimised results.

5.1 Radio Planning

The radio planning can be a fairly complicated process due to amount of factors involved in combination to antagonistic objectives. More specifically, one should consider covering as many clients as possible, while using the least amount of Base Stations (BS) and minimizing the interference. In this project the AGWs correspond to the BS, while the NGWs and the SPark GWs correspond to the terminals of an LTE network. Below is the process flow followed to solve the problem:

- Find Candidate sites
- Find the coverage of an AGW for every site
- Solve the optimisation problem for better coverage with the least AGWs and interference

5.1.1 AGW candidate sites

During the radio planning process, one should inspect the area for available sites to place the BS. At the same the engineer should also note the qualitative characteristics for each of those. Main characteristics that impact the radio propagation channel are the height of the site, the building density, other constructions and vegetation that cause deep fades of the signal.

Such data was not available to the group. This issue was encountered by assuming that there is an available site every kilometre. The entirety of the region was divided in 1 Km x 1 Km square cells with the site assumed to be in the centre. This procedure yielded 1145 candidate spots for the AGWs which highlights how difficult it can be to find the optimal subset that fulfils all the objectives.

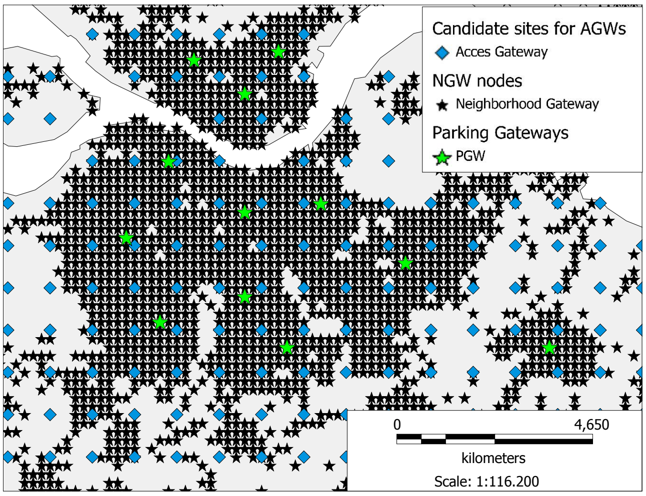

Figure 5.1: Candidate sites distributed every kilometre

5.1.2 AGW coverage

The radio propagation channel is governed by the phenomena electromagnetic waves are affected, such as reflection, scattering and diffraction. The propagation models are empirical models which are trying to approximate the power loss of the transmitted signal at the location of the receiver's antenna. They can be functions of frequency, distance, antenna's heights and other characteristics of the area as stated above.

Wireless World Initiative New Radio (WINNER) is a consortium of universities and companies that developed such a propagation model. Specifically the WINNER II is appropriate for the LTE frequency band and provides Line Of Sight (LOS) and No Line Of Sight (NLOS) variations of the model for 18 different scenarios. The path loss for each NGW/CGW - AGW pair was calculated in order to check whether it can exist a viable link between them that can satisfy the terminal's minimum communication requirements. WINNER II proposes the following equation to calculate the path loss [18]:

$$PL = Alog_{10}(d[m]) + B + Clog_{10}(\frac{f_c[GHz]}{5}) + X \tag{5.1}$$

$$PL_{free} = 20log_{10}(d) + 46.4 + 20log_{10}(\frac{f_c[GHz]}{5}) \tag{5.2}$$

where:

A is a fitting parameter that includes the path loss exponent

B is the intercept

C is the dependence of the path loss on the frequency

X describes the attenuation for the specific scenario

d is the distance in metres between transmitter and receiver

f_c is the carrier frequency in GHz

By using a scenario-specific flavour of the equations 5.1 and 5.2 and by following the process flow depicted in figure 5.2 it is feasible to approximate the channel capacity for every terminal - AGW pair.

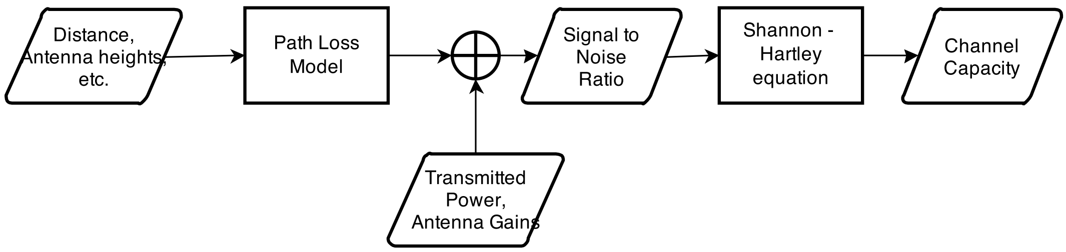

Figure 5.2: Process flow to estimate the feasibility of wireless link

Applying the WINNER II path loss model

As stated above, the WINNER II distinguishes between a number of different specific scenarios to provide better estimations. Below are the facts and assumptions that guided the selection among the predefined scenarios.

- The terminals (NGW/CGW) are placed on the rooftops
- The AGW antennas are on the rooftops as well
- There is no mobility of the terminals
- The environment of the sites can be urban, suburban or rural

	Urban	Suburban	Rural
AGW sites	42	104	999

Table 5.1: Number of AGW per geographical area

This practically results in three different scenarios with LOS, no mobility and environment dependant. The correspondent WINNER II are called *B1* for the urban case, *C1* for the suburban case and *D1* for the rural case. The path loss in each case can be calculated using the equations below:

- Urban (B1):

$$PL = 40log_{10}(d) + 9.45 - 17.3log_{10}(h_{BS}) - 17.3log_{10}(h_{MS}) + 2.7log_{10}(\frac{f_c}{5}) \quad (5.3)$$

- Suburban (C1)):

$$PL = 40log_{10}(d) + 11.65 - 16.2log_{10}(h_{BS}) - 16.2log_{10}(h_{MS}) + 3.8log_{10}(\frac{f_c}{5}) \quad (5.4)$$

- Rural (B1):

$$PL = 40log_{10}(d) + 10.5 - 18.5log_{10}(h_{BS}) - 18.5log_{10}(h_{MS}) + 1.5log_{10}(\frac{f_c}{5}) \quad (5.5)$$

where:

h_{BS} is the AGW antenna height (assumed to be 15 metres)

h_{MS} is the terminal antenna height (assumed to be 7 metres)

The GIS data were utilised in order to determine the environment. This was achieved by counting the houses (NTs) in a 1 Km by 1 Km area around each AGW. The outcome of this was fed to a K-means clustering algorithm to group the AGWs in three clusters.

Link capacity

The path loss itself is not useful here, but it is necessary to compute the datarate the channel can achieve. The Shannon - Hartley theorem is using the Signal to Noise Ratio (SNR) to estimate the theoretical maximum channel datarate. The figure 5.3 depicts the channel behaviour in the rural environment and the maximum datarates that may be achieved as a function of the distance between receiver and transmitter.

$$C = B * log_2(1 + SNR) \quad (5.6)$$

where:

C is the channel capacity

B is the bandwidth used

SNR is the Signal to Noise Ratio

The SNR is computed using the equation 5.7 :

$$SNR = \frac{P_r}{N} \tag{5.7}$$

where:

P_r is the received power which can obtained through the link budget by accounting the major path loss and path gain contributions.

$$P_r = P_t + G_r - PL \tag{5.8}$$

with P_t being the transmitted power (Effective Isotropic Radiated Power - EIRP) in dBm, G_r the receiver antenna gain in dBi and PL is the path loss in dB.

N is the thermal noise

$$N = -174 + 10log_{10}(B) \tag{5.9}$$

with B being the bandwidth.

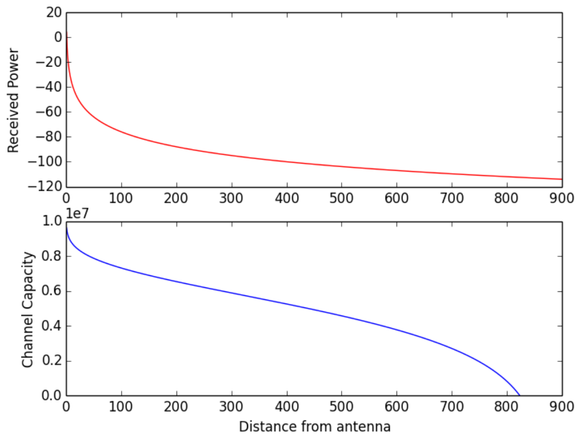

Figure 5.3: Channel capacity (in blue)and received power (in red)in an urban area

5.1.3 Formulate the problem

At this point a large state space is created containing coverage sets for every candidate AGW site. A subset of those has to be found such that will achieve the maximum coverage possible with the least amount of AGWs. This can be directly mapped to the set covering optimization problem which was proved to be NP-complete. The ILP formulation of the problem to find the minimum set can be written as follows:

$$\text{Minimize :} \quad N = \sum\nolimits_{s \in S} x_s$$

$$\text{Subject to:} \quad \sum\nolimits_{s:e \in s} x_s >= 1, \ \forall\, e \in U$$

$$x_s \in \{0, 1\}\,, \ \forall\, s \in S$$

where

N is the amount AGWs

S are the coverage sets

U is the set of terminals to cover

Obviously the objectives of the radio planning are contradictory. This means there are trade offs between maximizing the coverage and minimizing the AGWs and the interference. A classic multi-objective optimization method is the weighted sum, where each of the different objectives can be combined into one by assigning weights to each of them based on what is considered to be more important.
Meaning that the multi-objective optimization problem 5.10 will be formulated as 5.11:

$$\min_{x \in C} F(x) = \begin{cases} f_1(x) \\ f_2(x) \\ \vdots \\ f_n(x) \end{cases} \tag{5.10}$$

Weighted sum:

$$\min_{x \in C} \sum_{i=1}^{n} w_i f_i(x) = \begin{bmatrix} w_1(x) & w_2(x) & \dots & w_n(x) \end{bmatrix} \begin{bmatrix} f_1(x) \\ f_2(x) \\ \vdots \\ f_n(x) \end{bmatrix} \tag{5.11}$$

with C is the set of constraints.

Choosing the exact values for the weights would mean taking a decision on the extent of the importance of one objective over the other. Instead of making such assumption the problem can be reformulated in a multi-objective formulation which is more appropriate conflicting objectives. The result of a multi-objective optimisation algorithm is a set of Pareto optimal solutions called Pareto front. A Pareto optimal solution is the one that best fulfils some of the objectives and is impossible to find any better without worsening the result of other objective functions. The radio planning problem from 5.11 in a multi-objective (MO) formulation:

$$\min_{s \in C} F(s) = \begin{bmatrix} f_{cov}(s) \\ f_{agw}(s) \\ f_{int}(s) \end{bmatrix} \tag{5.12}$$

where:

s is the set of AGWs (set of coverage sets)

f_{cov} is a fitness function of the coverage maximization objective

f_{agw} is a fitness function of the AGW number minimization objective

f_{int} is a fitness function of interference minimization objective

C are all the available sets

Evolutionary algorithms and more specifically Genetic Algorithms are widely used for finding Pareto optimal solutions.

5.1.4 Genetic Algorithm

Search and Optimization is the process of finding best solutions for a number of objectives. When the objective is only one it's called single objective optimization. In most of the real life problems, though, one decision(solution) affects multiple factors of interest. Evolutionary Algorithms (EA) can find multiple optimal solutions with the population approach with respect to different objectives.

Genetic Algorithms (GA) are evolutionary optimization methods inspired by nature and the way the generations evolve. They incorporate mechanisms of selection, mating and mutating to evolve an initial population to *stronger* ones.It starts with an initial population and reproduces it using crossover (mate) and mutation operators. Then it selects the individuals that best fulfil the objectives. The figure 5.4 outlines the working principle of a GA.

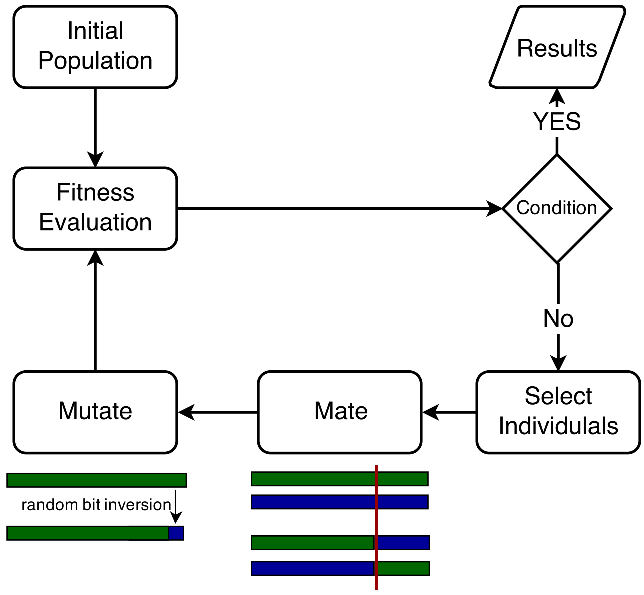

Figure 5.4: Genetic Algorithm process flow

The NSGA II selection

The selection process is among the most important in a genetic algorithm and highly influence the results. While it seems apparent that choosing always the best individuals will yield better generations, on the contrary -like in nature- mixture is helping the evolution. In single objective optimization the roulette wheel operator is the broadly used to achieve this. It works by simply selecting random individuals with a probability proportionate to their fitness.

Multi-objective Optimization Evolutionary Algorithms are capable of producing multiple Pareto-optimal solutions for an optimization problem. The Non-dominated Sorting Genetic Algorithm II (NSGA II) proposed by *Kalyanmoy Deb, et al.* [10] has the ability to do so. Moreover, thanks to the crowding distance operator for the selection process, to maintain the diversity of the population. In short, the NSGA II orders lexicographically the solutions based on their fitness and if there is a tie between two of them, then the crowding distance operator is applied to choose the one which is as far as possible from the others. Equation 5.1.4 and figure 5.5 portray the lexicographical ordering and the crowding distance respectively.

$$\begin{bmatrix} f_{cov}(s_1) \\ f_{agw}(s_1) \\ f_{int}(s_1) \end{bmatrix} < \begin{bmatrix} f_{cov}(s_2) \\ f_{agw}(s_2) \\ f_{int}(s_2) \end{bmatrix}$$
$$if \tag{5.13}$$
$$f_{cov}(s_1) < f_{cov}(s_2)$$
$$or\ f_{cov}(s_1) = f_{cov}(s_2)\ and\ f_{agw}(s_1 < f_{agw}(s_2)$$
$$or\ f_{cov}(s_1) = f_{cov}(s_2)\ and\ f_{agw}(s_1 = f_{agw}(s_2)\ and\ f_{int}(s_2) < f_{int}(s_2)$$

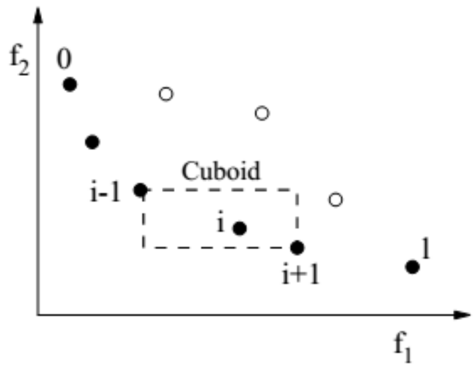

Figure 5.5: Crowding distance: choose the solution with the maximum perimeter/free space around it [10]

5.1.5 Encode the problem into a GA

The radio planning problem had to be encoded in such a way as to be usable by a computer program. Decisions on the encoding can be proved critical for the computational complexity and in the end the time the algorithms need to run to produce results. For the coding demands Python 3.3 was used along with two frameworks. The first is called NetworkX and was mainly used for its data structures which are convenient for representing graphs. The latter is the Distributed Evolutionary Algorithms in Python (DEAP) framework which was found to be suitable for the implementation of a GA for the multi-objective optimization problem described in equation 5.12.

The problem was split in two main tasks. To create the coverage sets in a graph structure and to represent them in a form it can be fed to the DEAP functions.

Coverage sets

The coverage sets were implemented as a bipartite graph in NetworkX. The one side of the graph is a collection of vertices that serve as the candidate sites for AGWs, whereas the other side is a collection of vertices that correspond to the NGWs and the PGWs of the Smart Grid and the SPark respectively. The existence or non-existence of edges connecting two nodes from the two sides is governed by the WINNER II path loss model. Apart for the channel model, the average throughput of the terminals was also considered, it did not have a noticeable impact on the coverage sets though. This is explained by the fact that the high bitrates the LTE offers can easily accommodate the traffic produced by the SGrid and the SPark systems.

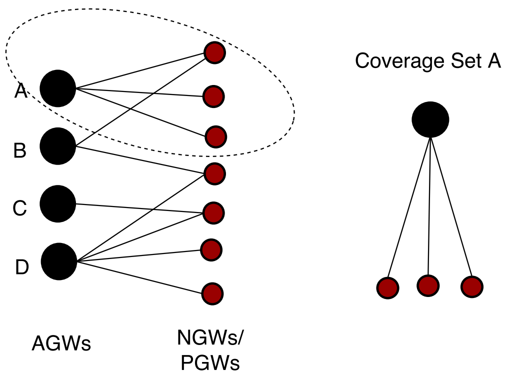

Figure 5.6: The coverage sets as a bipartite graph.

GA chromosome representation

As mentioned earlier, the problem has to be encoded in a convenient way for the GA functions to be effective. This implies that each solution (set of AGWs) has to be encoded into a chromosome/individual, and consequently each candidate AGW is a gene. The genes can be zeros and ones to select or not an AGW position.

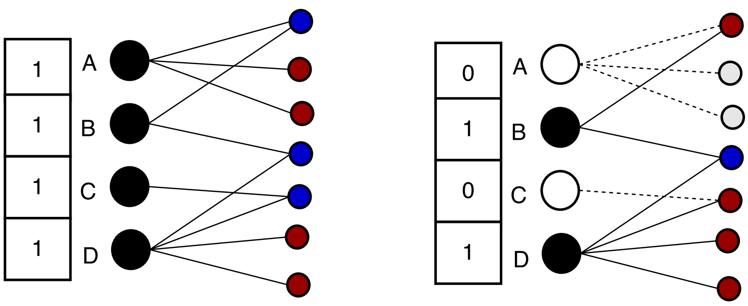

Figure 5.7: Two different chromosomes

Figure 5.7 depicts two different chromosomes that could occur during the evolution.

The red nodes are covered by one AGW, the blue nodes are in the range of more than one AGW causing interference and the grey ones are out of range of any selected AGW. The chromosome on the left provides full coverage but at the expense of many AGWs and interference. On the contrary, the right one provides lower coverage, but uses less AGWs and causes less interference to the terminal nodes.

5.1.6 Results

At this part of the chapter the produced results of the above methodology are going to be presented and discussed. Before proceeding on the final results, though, some adjustments had to be performed to confront computational complexity and sub optimal radio planning solutions.

Adjustments

The first modification is related the computation time needed when manipulating a very big graph. The size of the graph is an outcome of the big amount of candidate AGWs sites combined with the big ranges. More specifically, the method of placing one AGW site every kilometre yielded 999 potential rural sites with range around 10 kilometres. Considering the long range of the rural AGWs, reducing their amount appeared sensible. This was implemented by disregarding sites closer to each other of less than 3 km. The table *5.1* changes to *5.2* with 823 less rural sites. This is a radical reduction, but it is sufficient for the Aalborg region which is 1152 km^2 in total, while each of the rural AGWs can cover up to 314 km^2.

	Urban	Suburban	Rural	Total
AGW sites	42	104	176	322

Table 5.2: New distribution of AGWs per geographical area

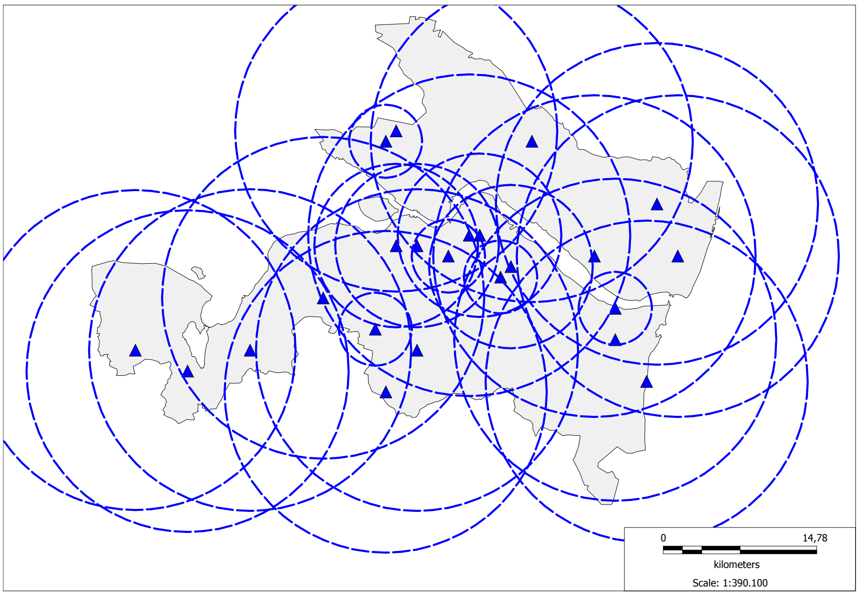

Figure 5.8: One resulting radio planning output using the first algorithm for the interference fitness.

After 200 generations, which took two hours to complete on 2.5 GHz core, the result gave a minimum of 20 AGWs for 100% coverage. It is apparent from the figure 5.8 that the fitness function to reduce the interference was not effective enough. This is due to its design that counts the amount of NTs under interference and disregards the how big is the overlapping area. In figure 5.9 there are two examples where the fitness function would give the same result. In practice, the second should have a higher penalty due to the fact that the interference will be much more severe.

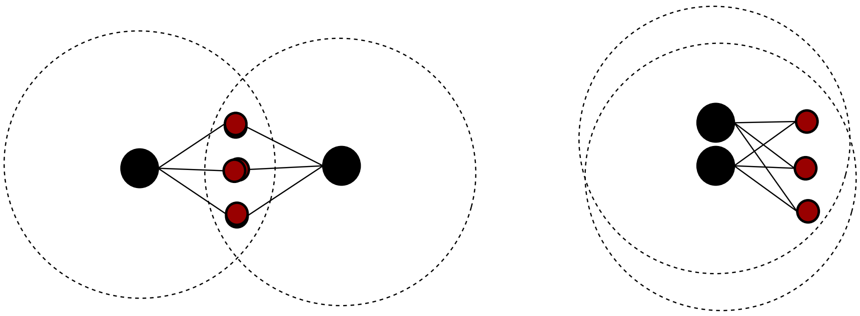

Figure 5.9: Two different examples of interfering cell

Interference fitness function redesign

The new design of the fitness function is using the distance between the AGWs with respect to their range to assign penalties. The penalty of a cell containing another is greater than when the AGWs are outside each others cells but their cells simply intersect. This would result in better fitness of the left example in figure 5.9 than the one on the right. Moreover, the GA is expected to choose more urban and suburban AGWs than in the previous results with this approach, since small urban cells are easier fit in the map without containing each other.

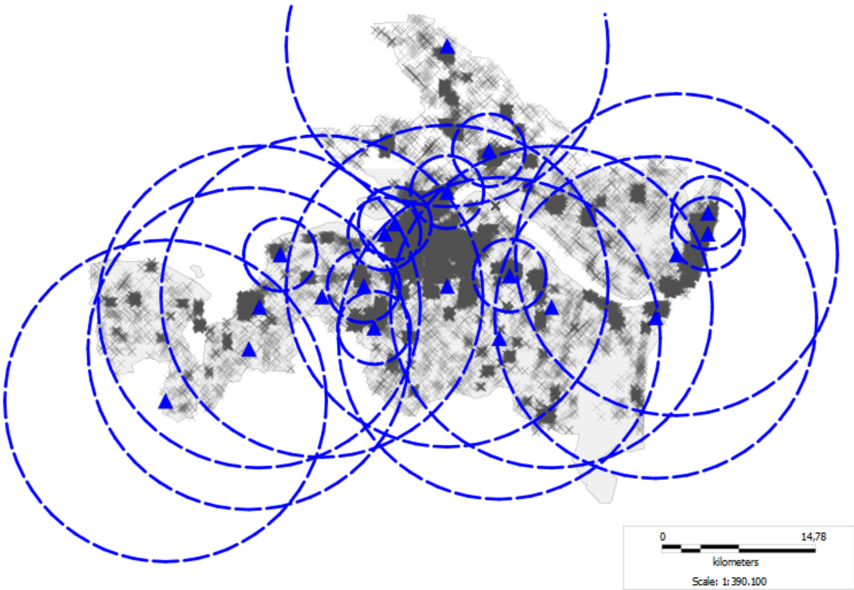

Figure 5.10: Another result with the new interference fitness function and mutation, crossover probabilities

The results the GA produced after 1000 generations are presented in figure 5.10. As expected, more small cells are selected. More specifically, 20 AGW sites were chosen, out of which 10 AGWs in rural environment and 10 in urban. The fact that no AGW was selected in a suburban environment is assumed to be due to their medium coverage. Meaning that when the interference is big, it is more intuitive to select the smallest ranges in the next generation.

It is stated previously in this chapter that NSGA II will provide not one solution, but a whole Pareto front which contains the non dominated individuals that occurred during the evolution of the population. Out of 223000 individuals that were produced during the evolution, the Pareto optimal solutions dominated all the rest. It is obvious that only one of them can be chosen to be implemented, but since there is a portrayal of the metrics that the result affects, it is much easier to do so. Figure 5.11 depicts how the set of optimal solutions with respect to different objectives is formed.

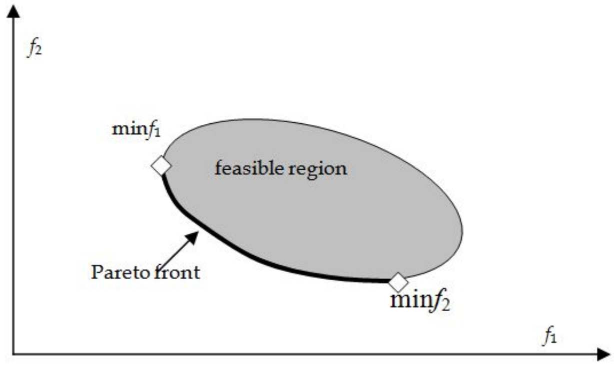

Figure 5.11: A two objective Pareto front

5.1.7 Final results for radio planning

In order to provide better results both for minimizing the AGWs and the interference (the coverage already had good results) the algorithm was set to run for 5000 generations. Usually one will notice that the GA seems to converge much earlier than the last generation. The convergence in MO GA can be observed through the stability of average fitness of the population. Despite, this convergence, a solution can occur in the population such that dominates previous ones.

The GA generated 60 possible solutions that dominated all the rest throughout the 5000 generations. Some of those with lower coverage in favour of the AGW minimization. The one chosen for the radio planning is the one that provides over 95% coverage by using the least AGWs and as low interference as possible. The selected results compared to the averages of the rest best results as well as the final population are outlined on the following table 5.3.

The average ranges as a result of the WINNER II channel model and the channel capacity are summarized in the table below:

	Average Coverage	Average #AGWs	Average Interference
Total best solutions	85.5%	17.5	2845
Final population	89.6%	17.6	2845
Chosen best solution	96.7%	19	2900

Table 5.3: Genetic algorithms results

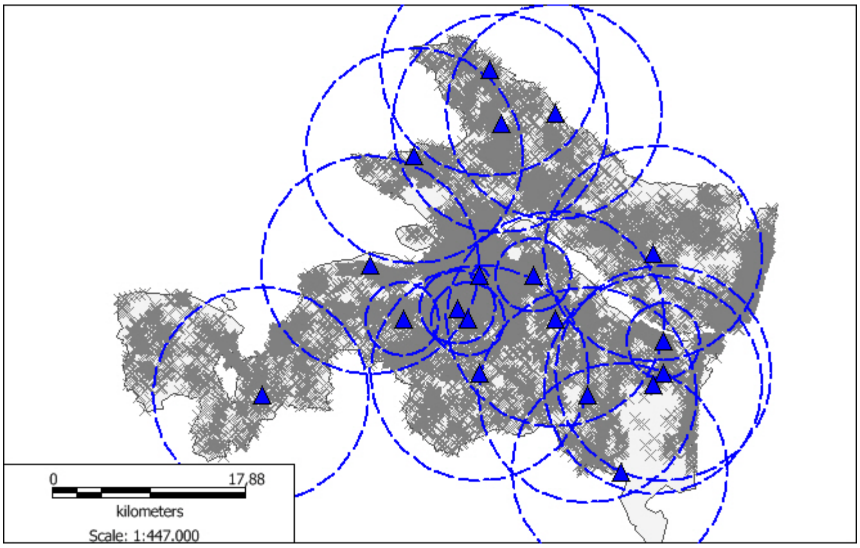

Figure 5.12: 5000 generations, 96.7 % coverage

	Urban	Suburban	Rural
Range (km)	0.8	3.5	10

Table 5.4: LTE range in different environments

5.2 SC Metro node placement

In this section the placement of the MAN nodes is being addressed. Finding an appropriate number of nodes and choosing their placement throughout the city are its main objectives.

5.2.1 Number of MAN nodes

Finding the number of the MAN node can be a complex task as several parameters have to be considered:

- The topology: As the double-ring topology was chosen, the number of nodes must be a pair number.
- Traffic distribution: The more nodes are deployed the less traffic they will have to accommodate.
- Economical and feasibility cost : The more nodes are deployed the more the project will cost and the complexity of its realization is bigger.

The MAN nodes will relay the traffic from the AGW to the WAN. In the section above the final result for the number of AGW is 19. It is obvious that the number of the MAN nodes will be less than the number of AGW, but at least 6 due to the use of the double-ring topology.

K-means algorithm was used to automatically find appropriate sites for the placement of the MAN nodes. It grouped the AGW into 6 clusters and the centroids it provided were used as the sites where the MAN nodes should be placed.
It is assumed that 6 nodes will completely the demands of the SC. The average number of AGW per node is 4.

5.2.2 Results of MAN placement

The picture below shows the placement of the MAN nodes (colored in red) throughout the Aalborg municipality.

Figure 5.13: MAN nodes placement

The placement of these nodes is based on mathematical calculations, that do not take into consideration real life obstacles that will make this sites inappropriate for this purpose. For example, the output of k-means places nodes in the middle of the fields, where usually even access to electricity can not be taken for granted.

5.3 Traffic analysis

In this section the internal and external traffic of the MAN nodes will be discussed in details. The traffic matrix will be addressed in order to compute the link capacity between each node. An estimation of future trends for the traffic will be discussed as well.

5.3.1 Traffic dimensioning

The traffic matrix represents the amount of traffic that flows from one node denoted as source to the other node denoted as destination over an interval of time. Traffic matrices are used in traffic engineering in order to design a network, estimate the required capacity of its links and predict the behaviour of the networks in case of a failure [14]. In this project, the traffic matrix is used for calculating the minimum requirement in link capacity between each pair of nodes.

Internal traffic matrix

For computing the internal traffic matrix the following information is necessary:

- Number of NTs, SPark nodes and cameras assigned to each MAN node in order to calculate the total traffic in Gbps the node is responsible for. Only 70% of this traffic will count for internal traffic as described in the section
- Percentage of NTs in from each node
- Internal traffic matrix from each node to the others

Using a Voronoi diagram, the city is divided in 6 parts, according the the number of MAN nodes. The total number of NTs, SPark nodes and cameras inside each region was calculated from Mapinfo. The total internal traffic of the municipality is the sum of the traffic of the 3 applications as calculated in the table 5.5

$$T_{internal} = 0.7 * (T_{SGrid} + T_{SPark} + T_{TVM}) \tag{5.14}$$

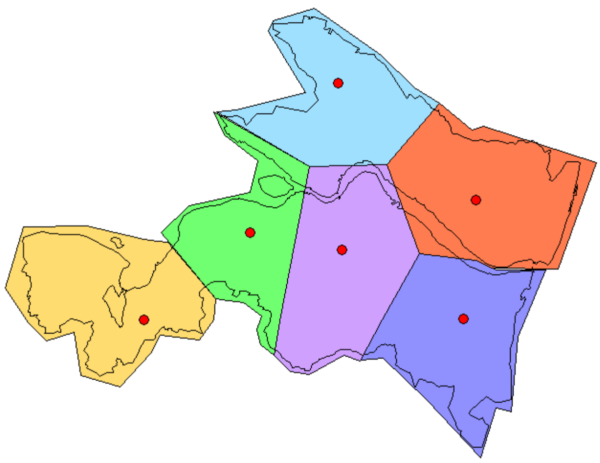

Figure 5.14: Voronoi diagram (MAN nodes colored in red

MAN_node	Number_NTs	Number_PGW	Number_Cameras	Total internal traffic (Gbps)	Percentage (%)
0	41844	12	576	5,85	50,57
1	5144	0	50	0,59	6,2
2	7715	3	139	1,28	9,33
3	4460	1	61	0,62	5,39
4	11153	1	137	1,46	13,49
5	12397	2	135	1,52	14,99
Total	82713	19	1098	11,32	

Table 5.5: Internal traffic calculated for each Voronoi cell

The choice to be interested in the amount of houses each Voronoi cell contains, is justified with the assumption that the internal traffic of one node is going to be distributed to the rest of the nodes according to the percentage of their population. This corresponds to the Gravity Model [14] used in calculating the traffic between two nodes:

$$T_{1\to 2} = T_1 * Pop_2/Pop\_t \tag{5.15}$$

where:

$T_{1\to 2}$ is the traffic over the link connecting node 1 to 2

T_1 is the traffic of the node 1

Pop_2 is the population in the node 2

Pop_t is the total population of the region

Applying this equation, the all-to-all internal traffic matrix is obtained:

MAN_node	0	1	2	3	4	5	Total traffic (Gbps)
0	2,96	0,36	0,55	0,32	0,79	0,88	5,85
1	0,30	0,04	0,06	0,03	0,08	0,09	0,59
2	0,65	0,08	0,12	0,07	0,17	0,19	1,28
3	0,31	0,04	0,06	0,03	0,08	0,09	0,62
4	0,74	0,09	0,14	0,08	0,20	0,22	1,46
5	0,77	0,09	0,14	0,08	0,20	0,23	1,52

Table 5.6: All-to-all internal traffic matrix

According to the topology, it is assumed that the internal traffic will flow from the source node to the destination one following the shortest path in terms of hops. The table 5.7 shows the number of hops between each node according to the topology shown at figure 4.7.

MAN_node	0	1	2	3	4	5
0						
1	1					
2	1	1				
3	2	1	2			
4	2	2	1	1		
5	1	2	2	1	1	

Table 5.7: Number of hops between each node

The accumulated internal traffic between each link is represented in the following table:

MAN_node	0	1	2	3	4	5
0						
1	1,29					
2	0,99	0,42				
3		0,40				
4			0,34	0,28		
5	0,77		0,08	0,20		

Table 5.8: Internal traffic matrix

External traffic matrix

The external traffic represents only 30% of the total traffic produced in the SC. This traffic as assumed in the section is supposed to go directly outside the MAN if the node is where the WAN gateway is placed, or to be equally distributed to the neighbour nodes relaying it to the gateway in following the shortest path in terms of hops. Following this assumption the external traffic matrix is computed. For this calculation, it is assumed that the links have to provide the minimum capacity, including the case when one link fails. This assumption explains why the external traffic of the node 1 is not divided between the links to node 0 and 2. For example, in case of failure of the link 0 to 1, the other link must provide the capacity to relay the total external traffic of node 1, in this case 0,25 Gbps.

MAN_node	0	1	2	3	4	5
0	2,51					
1	0,25		0,25			
2	0,55					
3				0,27		
4				0,63		
5	0,65		0,65			

Table 5.9: External traffic matrix

Link requirements

In this sub-section the minimum link-requirements are obtained by accumulating the internal and external traffic matrices. The following results were obtained:

MAN_node	0	1	2	3	4	5
0	2,51					
1	1,54					
2	1,54	0,42				
3		0,40		0,27		
4			0,34	0,91		
5	1,42			0,73	0,20	

Table 5.10: Total traffic matrix

The figure below visualises the distribution of the traffic between each pair of nodes. The traffic going directly outside from nodes 0 and 3 is not displayed in the picture.

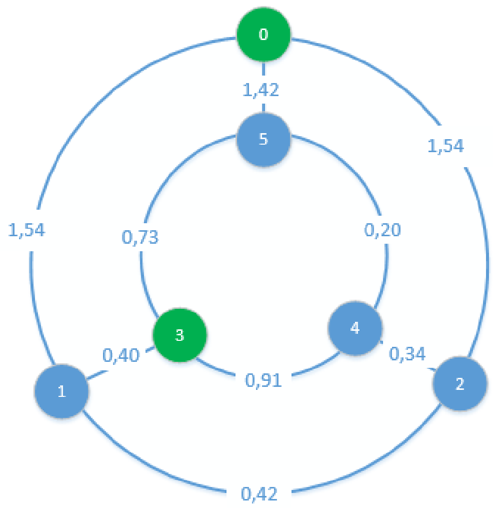

Figure 5.15: Traffic diagram

The total traffic including internal and external traffic of the 3 applications considered in this project is calculated from table 5.5 and is estimated at 16,18 Gbps. This number is really low, but it has to be considered the fact that this is an initial prediction about only 3 applications in the SC. Moreover, M2M applications as part of the SC concept are just now starting to be deployed.

Link fibre calculation

The fibre chosen to be used in the metro network to interconnect the nodes is the single-mode fibre, which offers high capacity. For computing the number of fibres the assumption that the traffic that one fibre can carry is 320 Gbps. Knowing the small amount of the traffic took in the consideration during this project, one fibre per link will be adequate to transport the traffic of each link.

Traffic future predictions

Estimating the traffic of the SC is a difficult task as explained in the section 4.4.2. The concept of SC is still being developed and there are no real application implemented yet. Companies like Cisco or IBM, who are already working in the IoT direction, predict billion of devices connected in 2020. Cisco, for example, estimates this number up to 50 billion of devices [13]. Even if companies try to predict the future evolution of the IoT concept in general, their predictions change form company to company. Hence, no reliable data was able to be found.

At this stage of the project, the only future traffic estimation is the estimation on the that it doubles each two years. Using this assumption, the traffic of the 3 application considered in this project will be doubling each two years year. The table below estimates the traffic for 2020 and 2030.

	2014	2020	2030
Traffic (Gbps)	16,18	242,7	4125,9

Table 5.11: Estimation about the traffic evolution

Applying this estimation to each one of the links, the below amounts of data are obtained:

MAN_node	0	1	2	3	4	5
0	639,63					
1	392,05					
2	391,71	107,20				
3		102,98		67,93		
4			86,90	231,72		
5	361,37			186,62	52,18	

Table 5.12: Estimation of link capacity requirement for 2030

Link fibre calculation

Applying the assumption that the traffic one fibre can carry 320 Gbps of information, the number of fibres needed to transport the information of the 3 applications in 2030 is shown below.

MAN_node	0	1	2	3	4	5
0	2					
1	2					
2	2	1				
3		1		1		
4			1	1		
5	2			1	1	

Table 5.13: Estimation of link capacity requirement in 2030

This calculation is made on the fibre technology that is deployed at this stage of the project. Research towards fibre technologies may result in advances in technologies providing higher bandwidths than the one considered, impacting thus results in a considerable way.

5.4 Fibre Planning

The aim of fibre planning is to find the optimal paths for the cables in order to minimize the trenching and the amount of fibre needed. These two metrics directly influence the cost of a network. Different algorithms designed to find Minimum Spanning Trees (MST) and Shortest Paths (SP) are widely applied to achieve this goal.

This sub-chapter discusses the roadmap followed for the fibre planning procedure. More specifically, at this point all the nodes forming the network are placed on the map and paths for the optical fibre deployment have to be found. The problem is divided in small different tasks to finally form the overall network. Following, the outline of these tasks is give in order to provide an overview of their sequence towards the final goal.

- Connect the AGWs to the graph: At this point they are just positioned on the map, they have to be part of the network graph to apply algorithms on them
- Connect the SC metro nodes to the graph: The same procedure as above
- Normalize the graph: The graph derived from the GIS data contains redundant information. This is removed in favour of the planning algorithm's efficiency
- Group the cameras to form rings: Create groups and assign each camera to one of them in order to find which cameras should be interconnected
- Camera ring network fibre planning: Find the paths for the ring topology
- Camera access network planning: Find paths for the fibre connecting CGWs to AGWs
- AGW access fibre planning: Find paths for AGW to the metro nodes.

- Metro network fibre planning: Find paths to interconnect the SC metro nodes

5.4.1 Preparing the graph

The two major fibre planning approaches involve the use of the MST and SP sets of algorithms. These algorithms are part of graph theory and consequently they operate on graphs. At this point though, most of the network components are not connected to the graph, so the first task is to create edges to add them.
The next thing that should be done, as long as, every network element is part of the graph, is to remove information that is not useful for the succeeding tasks. This refers to the amount of segment points that define a road that will be handled in way to radically reduce them, while keeping the data necessary for the fibre planning.

Connect the AGWs to the graph

There are 19 AGWs with specific coordinates placed on the map. The method adopted to connect to the graph was to find the closest segment point from the segment database of Aalborg municipality the containing the streets and add an edge connecting the two points. A length is assigned to each edge, which will later serve as weights for the MST and SP algorithms. The length assigned is not the Euclidean distance itself, but an approximation of what the real distance could be considering the fact that the trenching cannot always follow straight lines. The equation giving the distance:

$$Euclidean\ distance * \sqrt{2}$$

Connect the SC metro nodes to the graph

As the AGWs, the SC metro nodes are just points on the map at this stage. Moreover, due to the method followed to produce them (k-means) they could even be placed at the sea or the Limfjord. This is because the k-means returns the centre of the group as the location of the node. For this reason, the position of the results obtained have to be verified to be feasibly (they are situated on the land). Then, the same methodology as for the AGWs was followed for their connection the graph

Normalize the graph

The GIS data is designed to serve different kinds of applications that need precision correlated to the curves of the streets. To achieve this realistic representation there is a high density of road segments. In practice, this means that there is a big amount of intermediate road segment points in between the ones significant for the fibre planning. Using the fibre planning algorithms on such complex graphs can be proven to be highly time consuming.

It is common practice in such scenarios to normalize the graph to reduce this computational complexity. This is accomplished by connecting that have a common degree-2 vertex. In other words the goal is remove all the degree-2 nodes without losing information about neither the connectivity of the graph nor the length of the streets. The figure 5.16 describes the procedure of normalization along with the resulting graph.

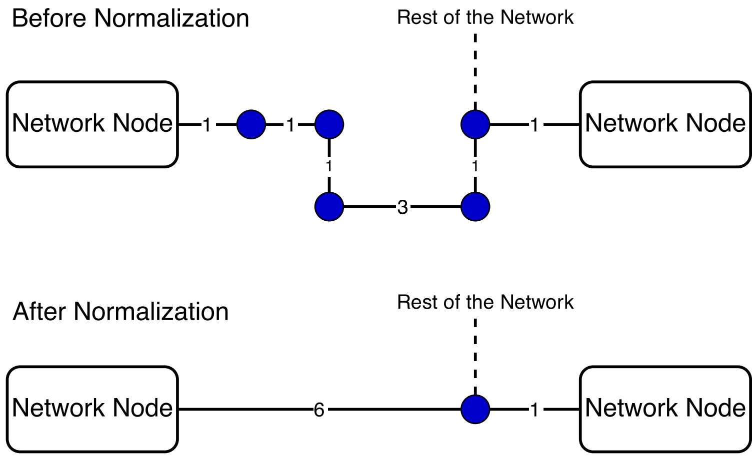

Figure 5.16: Graph before and after normalization

5.4.2 Camera ring network fibre planning

The cameras for the TVM are divided in groups and organized in ring topologies to provide reliability in case of link or node errors. It is obvious that these groups should consist of the nodes which are closer together, so initially a clustering was performed on their positions. The k means algorithm was used to create 19 groups (equal to the amount of AGWs).

This oversimplified procedure gave rise to several problems proving its inefficiency if directly applied as described above. Firstly and most importantly, it has no knowledge of the actual environment, it only uses the distances. This resulted in groups spread across the Limfjord. Using such an output would need the use of the assumption that there are pipes available for this use close to the rings.

Secondly, k-means creates an amount of clusters disregarding the size of them, meaning that one cluster may contain 50 nodes and another one 150. This compromises to some extent the initial objective of the grouping the cameras which is to balance the traffic of the access network.

The last problem is correlated to the initialization of k-means. When there is no reasonable initial proposal for the centres of the clusters, it randomly assigns random positions from the input. This can usually lead to poor clustering and different results after each run.

The first flaw was confronted by splitting Aalborg municipality in two georaphical areas using the Limfjord as border between them. This immediately solved the issue and no groups where spread across the fjord as shown in figure 5.17.

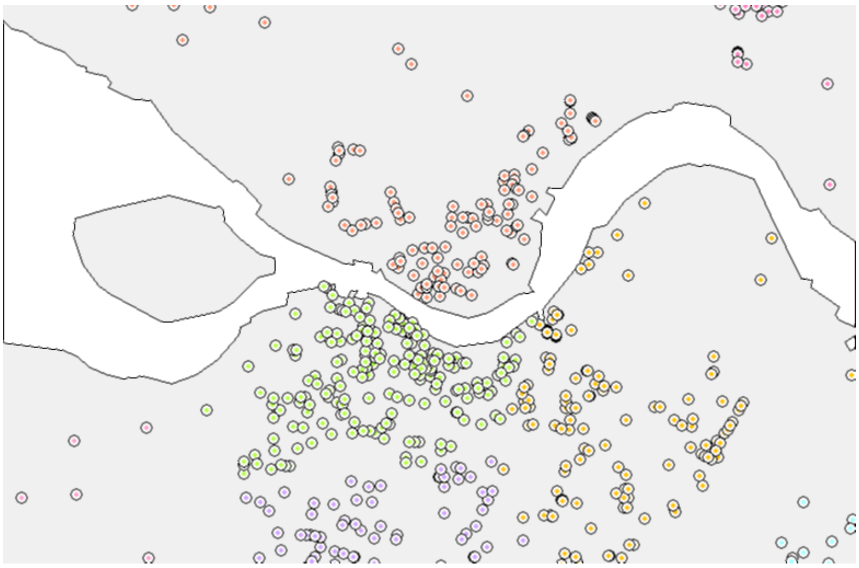

Figure 5.17: Groups of cameras are not spread across the river banks

Concerning the second flaw, associated to the deviation of the clusters size, it was decided to delimit from it since clustering is an np-hard problem itself and at the same time a major balancing is achieved since the traffic of the cameras will be shared among the AGWs.

In order to overcome the last obstacle described in the previous paragraph, an obvious choice would be to just initialize the seed of the program. This way the same points would be chosen in every run as cluster centroids, but would not solve the problem of converging to local minimum (leading to poor clustering). Considering this, the solution was found into a centroid initialization algorithm for k-means named k-means++ [4] which assures that a solution close to the k-means optimal will be found.

Line planning

As long as the groups are created, they are ready for the fibre planning process. As mentioned in the design chapter the cameras are organized in a single ring physical topology. This means that each of them is physically interconnected to two others through fibre. The task at this point is to find the best paths in order to minimize the trenching and cabling costs.

The main algorithms for the line planning used here are the Minimum Spanning Tree (MST) and the Shortest Path (SP) spanning tree. The MST, is a sub-graph of a given weighted graph that includes all the vertices, but only selects the edges that minimize the sum of their weights. When the segments and segment points of GIS data are assigned on a graph, with their respective lengths added as weights on the edges, then the MST practically finds the minimum amount of trenching that has to be done for the fibre planning. In other words, in the special case where one cable has to be deployed interconnecting all the network elements, the MST would provide the solution that minimizes both the trenching and the cable length.

The SP tree, on the other hand, is a spanning tree with all those edges that minimize the cost from the root of the tree to any other vertex. This approach is used in fibre planning to minimize the amount fibre, but it will not guaranty minimum trenching.

The approach followed for this part of the line planning was to apply a pairwise search for shortest paths between sequentially placed camera nodes. This solution provides a ring-like result which reduces significantly the amount of common paths for the cables. While this increases the trenching cost, the resulting network will have better protection against fibre cuts in a Counter-Rotating Ring 4.6. This is due to the diminished possibility of cutting two pairs of fibres on different paths at the same time.

Avoiding to compromise the protection and survivability, that can be offered to ring based networks, so as to protect parts of the network from being isolated comes at a price. This being the assumption that, either there are already tubes deployed and available for the fibres, or digging new trenches is not an issue in order to provide a high quality network to the city.

An example ring showing the output of the algorithm as plotted by MapInfo is shown in figure 5.18. It can be seen that the biggest part of the route the fibre follows is not shared, which was the desired outcome as stated above.

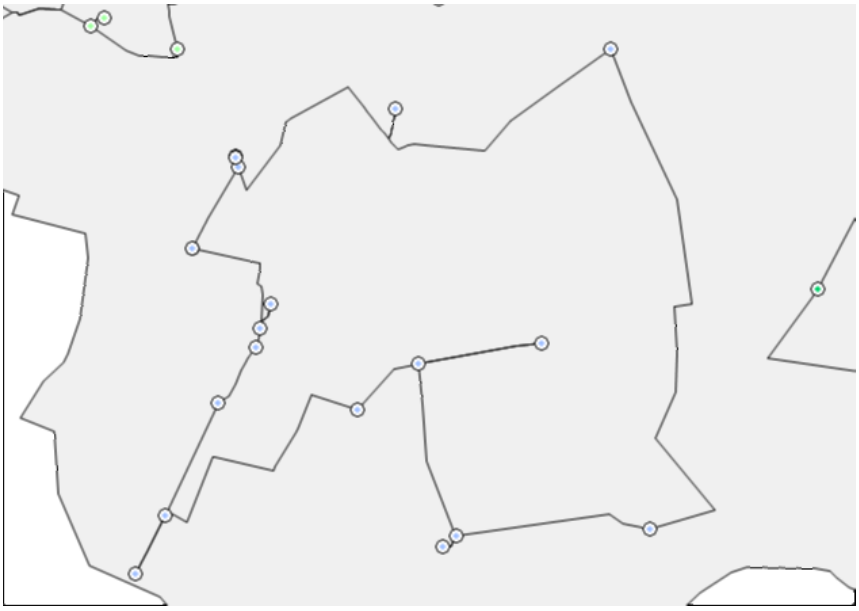

Figure 5.18: A resulting ring camera network

Below table 5.14 shows analytically the amount of fibre needed per ring as well as the total of 953 km for all the cameras. With a minimum of 23 and a maximum of 97 kilometres a remark for the results is that it does fluctuate to a great extent, something which was expected based on the fact that the clusters are not equally sized, and at the same time some of them are placed in rural areas where the distances are considerable, whereas others are placed in the centre where the camera density is higher and the distances in-between them shorter.

In order to provide protection to the ring, a double fibre is assumed on each link as shown in chapter 4. This means that the total amount of fibre stated in table 5.14 should multiplied by two to find the fibre length for such implementation.

Cluster	0	1	2	3	4	5	6	7	8	9
Fibre (m)	55259	46478	91189	61451	76298	73831	35357	102964	27195	31488
Trenching(m)	55082	46361	90780	61025	69568	69374	33758	97071	26865	31488

Cluster	10	11	12	13	14	15	16	17	18	Total
Fibre (m)	44259	42367	40210	35862	34366	70892	25563	35484	23256	953.7 Km
trenching(m)	38757	41578	40030	34173	34366	67241	25057	35484	22786	920.1 km

Table 5.14: Fibre and trenching calculation per camera ring

5.4.3 Camera access network fibre planning

The camera rings are spread throughout the Aalborg municipality. The decision made in the 4 chapter was to assign the task of providing connectivity to the rings, to the AGWs, as they are already there and dispersed on the area. Moreover, the design of the SC metro-access network sees the AGWs as the part of the network where all the sub-networks are supposed to connect to.

Another decision which is part of the design is to assign two camera nodes as CGW on each ring, which will be their gateways to AGW. Having two CGWs on each ring increases the cost in favour of providing protection to the ring.

The objective derived from the above was find two paths interconnecting each two of the camera nodes from each ring to an AGW. In order to provide a sensible solution the problem was attacked by splitting in two smaller tasks. For every ring created in the previous section the following steps were performed:

1. Find two independent AGW-CGW pairs as close as possible
2. Find a path interconnecting them

For the first task the distance was calculated based their Euclidean distance. When the pair with the minimum distance was found, another pair was found such that it would not consist of any of the nodes of the previous pair. The second step uses the Dijkstra SP to find the shortest route between them. While this overall approach provides protection in case of node failure it cannot assure protection in the event of fibre cut. This is due to the fact the algorithm does not try to find two totally independent paths, but the shortest ones. This effect is reduced by performing the route search on the entire graph instead of a reduced MST. An example of the resulting fibre planning is depicted in figure 5.19 bellow. The yellow circles belong to the same circle. Two of them are the CGWs and are connected to two different AGWs (blue triangles).

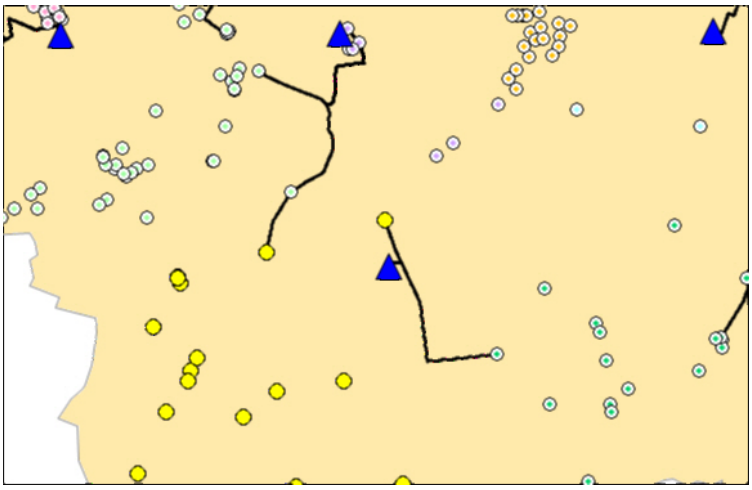

Figure 5.19: The pair of paths connecting the CGWs to the AGWs.

5.4.4 AGW access fibre planning

Continuing with the bottom-up approach of the fibre planning, the subsequent phase the path finding between the AGWs and the SC metro network.

The task of line planning presupposes that each of the AGWs is assigned to an SC metro node (SCMN). This is practically done through the process described in 5.2, where the sites for the metro nodes are determined. These sites are the centroids produced by k-means with the AGW positions as an input. At the same time, the AGWs are clustered around the these centres. This means that the distance between the AGWs and the centroids (SCMNs) is the minimum for this given set of centroids, it is, therefore, sensible to use the same clustering to assign the SCMN to AGW physical link connections. The following table shows the amount of AGWs each of the SCMNs is connected to.

SCMN	0	1	2	3	4	5	Total
Number of AGWs	6	5	4	1	1	2	19

Table 5.15: Amount of AGW per metro node

Since the SCMN-AGW physical connection relation is clarified and determined all the necessary information needed for the path finding is ready and available. The paths were found for each SCMN-AGW pair using the Dijkstra's shortest path algorithm on the GIS normalized graph. The outcome of this procedure is depicted in figure 5.20

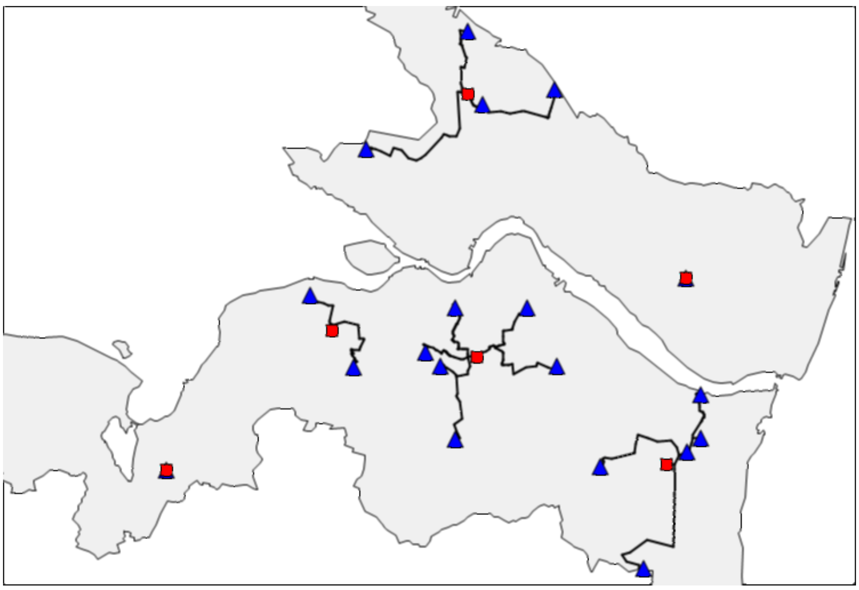

Figure 5.20: The paths for the AGW to SCMN physical connection

It can be seen in the figure 5.20 that in the two cases where the SCMNs are assigned only one AGW (North-Eastern and South-Western SCMNs), they overlap each other on the map, meaning that they are position on the same spot. This is convenient since only one site is to be found to place the equipment and no additional trenching will be necessary for the fibre interconnecting them.

Moreover, due to sharing some paths, trenching length is going to be slightly less than the the fibre length. This, under the assumption that one single mode WDM fibre is to be place for each physical connection. Table 5.16 summarizes the fibre and trenching length resulted during the process.

Fibre	111.8 km
Trenching	96.5 km

Table 5.16: Trenching and fiber length for AGW-SCMN connections

5.4.5 Metro network fibre planning

During the previous section 5.2 a discussion on the topology and the amount of SCMNs, as well as their placement took place. The results of it, was a double ring topology to interconnect six SCMNs positioned as shown in figures 5.21 and 5.22 respectively.

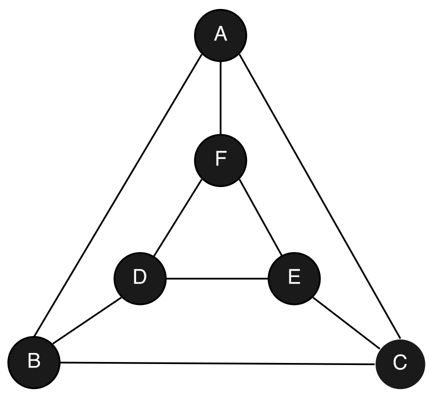

Figure 5.21: Double ring topology to be implemented for the metropolitan part of the network

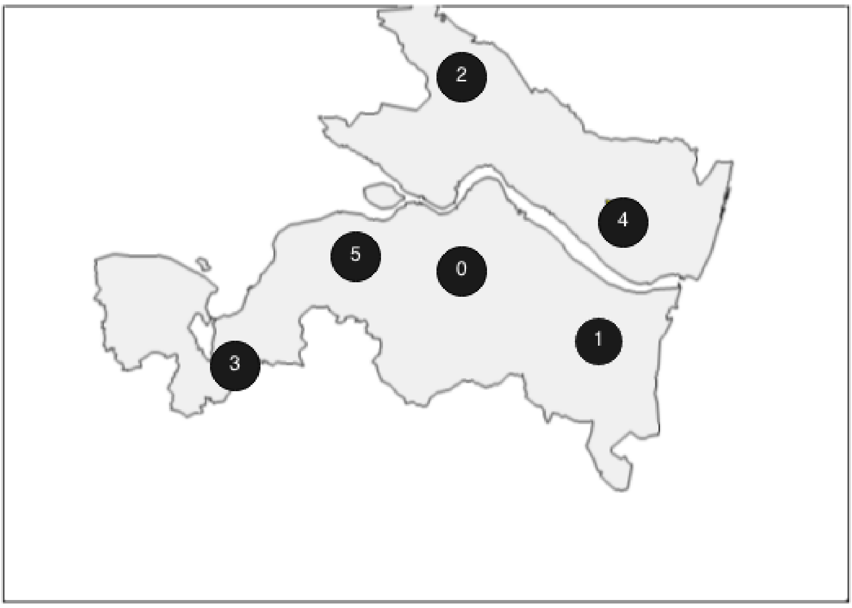

Figure 5.22: The position of the SCMN nodes

Given the double ring topology from 5.21 and the SCMNs positioned according to 5.22 a problem arises in relation to which SCMN node should be mapped to which graph node on the double ring. The topology graph provides an adjacency matrix that governs the physical interconnection between each node. According to this, since it is a cubic regular graph every node is interconnected to three others and its adjacency matrix (based on the 5.21 looks like the one in the following table 5.17. The total amount of links is constant and equal to $(3 * N)/2 = (3 * 6)/2 = 9$.

C_{ij}	A	B	C	D	E	F
A	0	1	1	0	0	1
B	1	0	1	1	0	0
C	1	1	0	0	1	0
D	0	1	0	0	1	1
E	0	0	1	1	0	1
F	1	0	0	1	1	0

Table 5.17: Adjacency matrix

Choosing a mapping from the graph to the real node placement can be expressed as a search and optimization problem since each solution can impact different aspects of the planning and the network quality. An example of the objectives for the optimization is the path length minimization. Here, though, the manually chosen scheme shown in figure 5.23 is used.

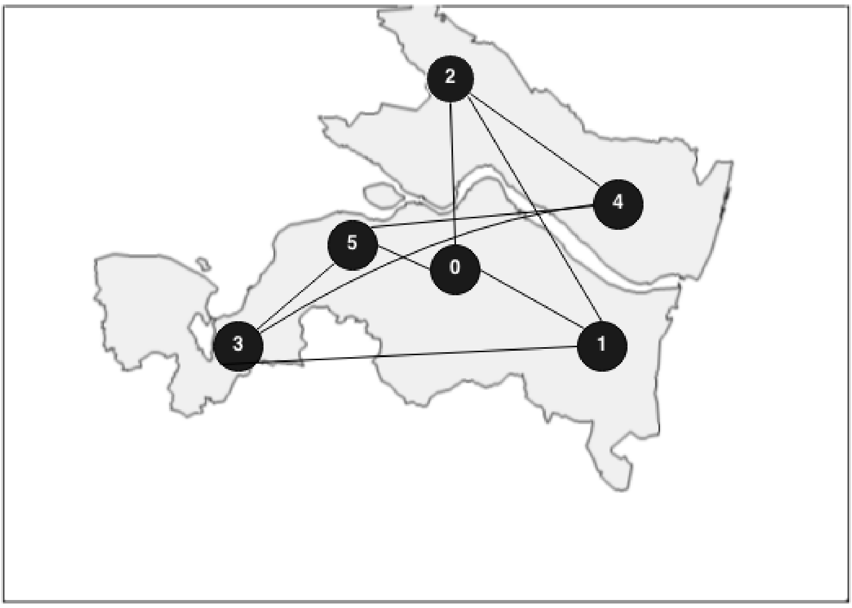

Figure 5.23: The double ring topology on the map

The shaping of the landscape splits the Aalborg region in two parts following the Limjord line. Subsequently the graph generated from the street segment GIS data consists of two unconnected sub-graphs. On the other hand, based on figure 5.23 there are paths to be found based such that connect nodes from both sides of the Limfjord. To overcome this, it was assumed that ducts are available for this use in two different locations. The one placed beside the bridge *Limfjordsbroen* and the latter at *Tunnelvej*.

After applying Dijkstra's shortest path algorithm on every pair, it resulted on the paths depicted in 5.24. One can notice that the trenching could be optimized since two paths to the south-western SCMN are almost parallel. For that reason, an attempt was made to ameliorate the result by finding paths on an MST. The MST was created using Kruskal's algorithm. The results from both algorithms are summarized in table **??**. The term *fibre path length* refers to the total amount of fibre if one cable per link was sufficient. If for example two fibres are needed on each link, then this length has to be doubled to calculate the total. The *total fibre* term refers to the amount of fibre that should be deployed by taking into consideration the results of the traffic forecasting and dimensioning performed earlier in this chapter.

A final remark on the results is that the MST solution provided over 21% shorter trenching path as initially expected. The fibre needed though in such implementation, increases the total amount of fibre by almost 15% making it an inferior choice for the implementation of the network planning from this point of view. Considering that trenching costs per meter are usually much greater than this of the fibre, the implementation that minimizes the trenching is the most sensible choice.

	Dijkstra's SP	Kruskal's MST
Fibre path length	264.6 km	301.7 km
Total Fibre	319.7 km	367.4 km
Trenching	164.8 km	128.9 km

Table 5.18: Final fibre and trenching results using Dijkstra's SP and MST algorithms

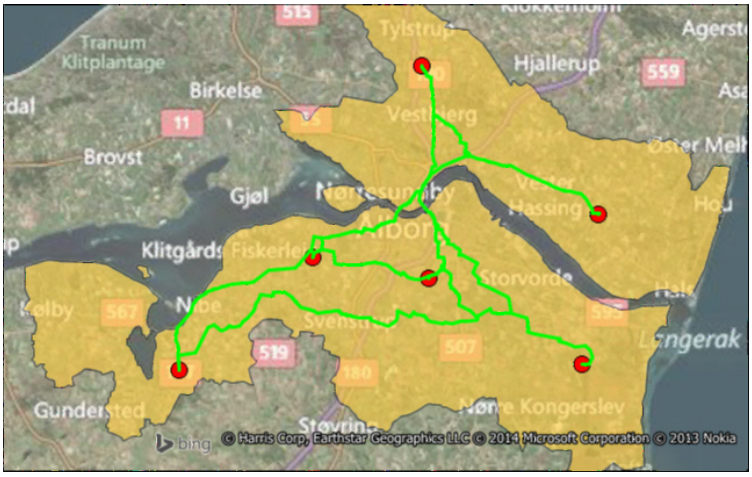

Figure 5.24: Map with the trenching paths for the SCMN ring using Dijkstra's SP. The two assumed ducts crossing the Limfjord can be observed

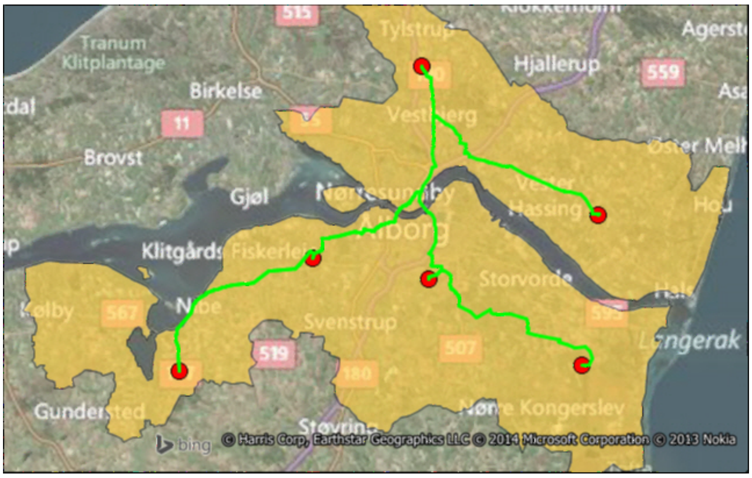

Figure 5.25: Map with the trenching paths for the SCMN ring using Kruskal's MST. It can be seen that the trenching paths are shorter than in figure 5.24

Chapter 6

Conclusion

As humanity gets more deep into the digital era and a constantly increasing amount of *intelligent* things are becoming inseparable to our daily routine, academia and industry research are envisioning a future of seamless communication between people and things. Following this concept, Smart City, from the ICT point of view, constitutes the implementation of this idea in a city wide environment.

Applications responsible for the smooth functioning of an entire city should not be depending on an ICT infrastructure that could compromise its reliability. For this reason, a dedicated infrastructure to the Smart City network should be deployed, which rises the following question:

How to plan and design a Metro-Access network that satisfies the applications of the future Smart City?

The lack of research on such networks was the main motivation to design and plan a metropolitan wide network that will comply with applications of the future Smart City. To reach this goal, an investigation took place on the applications that could be deployed in the near future, as well as existing metropolitan and access network technologies and topologies. Moreover, well known algorithms were used to automate as much as possible the network planning process.

The roadmap followed is outlined by the chapter titles, which describe how the project was partitioned to achieve the objectives of the problem. A per chapter synopsis of the approach followed by the group concludes this report.

After rough description of the overall objective and the effort to specify as clearly as possible the problem in the first chapter, a pre-analysis is performed to further delimit it and investigate applicable technologies. Three different applications having diverse QOS requirements were chosen and examined, namely Smart Parking, Traffic

Video Monitoring and Smart Grid.

Then, the research continued on looking for appropriate hybrid optical-wireless network architectures which can provide access to both wired and wireless terminals. These technologies define the specific technology used for the wireless link. Despie this fact, the group looked into other existing wireless technologies in order to chose the one that better fits the Smart City concept and its applications.

The last point presented in the pre-analysis chapter are well known topologies suitable for Metropolitan Area Networks. Ring, double-ring, and mesh topologies are examined with respect to their advantages and disadvantages in order to have an overview and make a choice among them in the Design 4 chapter.

Chapter 3 is a case study of the scenario and the GIS data available to the group. It discusses on the specificity of Aalborg municipality and briefly describes the structure of the GIS tables used in the latter parts of the project.

The Design chapter 4 comprises the three different application designs with their respective architecture and implementation. This last part was attained by exploiting the aforementioned GIS data in order to provide realistic results. Moreover, this is the chapter where the final decisions were taken on the Metro-Access network design and the technology for the wireless links. A WDM double-ring was selected for the metro part of the network and a WDM Point-to-Point links between the SCMNs (metro) and the AGWs (access). LTE was found to be the most appropriate for the wireless links due to the combination of big range, high throughput and low latency, which is of high importance on delay intolerant applications.

The last chapter that introduces additional content to the reader is the the network planning chapter 5. It begins by providing an insight on the radio propagation channel, describing the methodology of the radio planning. There, the radio planning problem was encoded into a genetic algorithm so as to provide good answers to the questions concerning the amount of LTE base stations that should be deployed and where they should be placed.
The next task performed was to find sensible sites for the metropolitan nodes according to the access nodes placement and the agreed topology as well as estimate the traffic on each link. This estimation is critical later to the dimensioning of the metro network.

The last action documented in the network planning thesis report is the fibre planning procedure. Mainly shortest path algorithms where used as an attempt to minimize the trenching and the fibre to be deployed. This strategy was followed in every part of the network where the design proposes fibre links, namely the TVM camera rings, the TVM CGWs to AGW links, the AGWs to the SCMNs and finally the SCMNs ring paths.

Apart for Dijkstra's shortest path algorithm for the path finding, Kruskal's Minimum Spanning Tree algorithm was also utilized to minimize the trenching, to the detriment of the fibre minimization. This approach, though, only slightly improved the trenching results, while it almost double the necessary fibre for interconnecting the SCMNs using a double ring.

The content of this report presented the investigation performed, as well as a detailed methodology to design and plan a Metro-Access network for the future Smart City, which answers the initial question of the problem statement.

6.1 Future Work

This project tried to address different aspects of the design and planning of a Smart City network. The work that was carried out, provides an initial insight on how this network should be planned and designed. However, in order to achieve a better overview of the problem, further elaboration is necessary.

The following paragraphs introduce future works that can be carried out to improve the overall outcome of this project, according to the directions below:

- Fibre planning
- Traffic dimensioning and forecasting
- Network performance calculation
- Radio planning

For the fibre planning, two main tasks would complement this thesis. The first is related to the interconnection decision where the link assignment given the double ring topology was performed manually. Another approach as stated in the corresponding chapter would be to develop an optimization algorithm with fibre or trenching minimization as objectives.
The later task would be to improve the network planning algorithms by exploiting environment specific details and constraints. This could as well encompass planning choices, such as providing disjoint paths or avoiding streets where trenching can cause problems to the traffic.

In relation with traffic dimensioning, more realistic results may be obtained through analysing more Smart City's applications. Traffic forecasting is an essential parameter to be considered as well in order to design a future-proof network. During this project, a considerable amount of predictions were found which were deemed to be unreliable since they were highly contradictory. Such information is crucial to produce robust estimations on the traffic. Moreover, the task of dimensioning can be more complex than in this project, where only six nodes were part of the traffic matrix. In the project the dimensioning was performed manually, in a complex scenario, though, with many nodes the need for a automated tool may arise.

In relation to the choice of MAN topology, SQoS should also to be considered as an important factor when designing a network. Then, network performance metrics, like availability, average hop distance have to be computed and compared to other topologies.

Before realizing such a big project as the city wide hybrid network, it would be sensible to evaluate the behaviour in a simulation environment. There, design deficiencies can be identified and solved with low cost. A simulation library with such capabilities is the OMNeT++ simulator which has numerous protocols and technologies available for use.

To conclude, another task that would complement this project is related to the radio planning. In an attempt to simplify the radio planning task, the theoretical maximum capacity of the channel was considered. Despite achieving high channel efficiency it will not reach the Shannon's maximum. It defines instead modulation schemes that govern the datarate, which depend on the quality of the channel. Including this information to the radio planning algorithm it would lead to more secure results.

List of abbreviations

3GPP: 3rd Generation Partnership Project
AGW: Access Gateway
AMR: Automatic Meter Reading
BS: Base Station
CU: Central Unit
FiWi: Fibre-Wireless access network
GA: Genetic Algorithms
GIS: Geographical System Information
GROWNet: Grid Reconfigurable Optical and Wireless Network
HetNets: Heterogeneous Networks
HGW: Home Gateway
ICT: Information and Communication Technology
IoS: Internet of Services
IoT: Internet of Things
LAN: Local Area Network
LTE: Long Term Evolution
M2M: Machine to Machine
MAN: Metro Area Network
MARIN: Metro Access Rings Integrated Network
MIMO: Multiple Input Multiple Output
MST: Minimum Spanning Tree
NGN: Next Generation Network
NGW: Neighbourhood Gateway
NT: Network Terminal
OFDMA: Orthogonal Frequancy Domain Multiple Access
PON: Passive Optical Network
RAU: Radio Access Unit
RoF: Radio over Fibre
SC: Smart City
SC-FDMA: Singlle-Carrier Frequancy Domain Multiple Access
SCMN: Smart City Metropolitan Node
SGrid: Smart Grid application
SON: Self Organizing Network

SP: Shortest Path
SPark: Smart Parking application
3GPP:SQoS: Structural Quality of Service
TVM: Traffic Video Monitoring
WAN: Wide Area Network
WDM: Wavelength Division Multiplexer
WOBAN: Wireless-Optical Broadband Access Network
WSN: Wireless Sensors Network

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