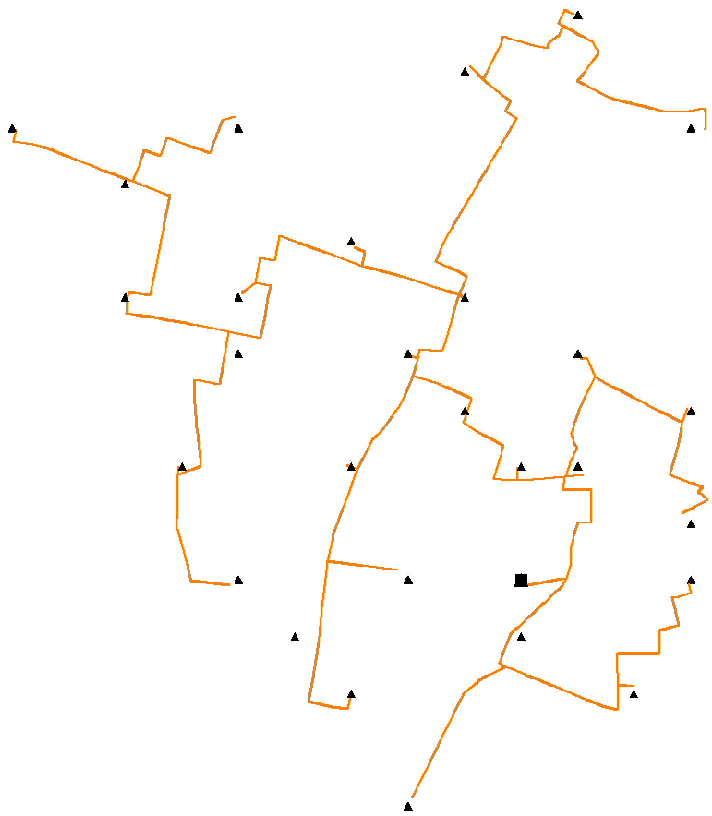
AALBORG UNIVERSITY

2009

Planning of RoF Heterogeneous Wireless Networks



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June 2009

Faculties of Engineering, Science and Medicine

Aalborg University

Master of Science in Engineering – Network Planning and Management

Theme:

Network Planning and Management

Subject:

Network Planning and Management

Title:

Planning of RoF Heterogeneous Wireless Networks
10th Semester – Master Thesis

Period:

1st of February – 3rd of June 2009

Group:

1000

Members:

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Copies:

Five Copies

Pages:

173

Abstract

The number of users in wireless WANs are increasing like never before, at the same time as the bandwidth demands by users increase. The structure of the third generation Wireless WANs makes it expensive for Wireless ISPs to meet these demands. The FUTON architecture is an RoF heterogeneous wireless network architecture under development, that will be cheaper to deploy and operate.

The goal of this thesis is to plan an implementation of this architecture. The planning should be done as automatic as possible, covering radio planning, fiber planning and network dimensioning.

An introduction to the FUTON architecture and the technologies is given, before the approach to the problem is described. After this the planning of the different architecture is done part by part. When the physical parts of the network are planned, the bandwidth demands for the users are estimated, and the networks dimensioned accordingly.

The outcome of the project is a planning process that uses GIS-data to automate planning for the entire architecture. During the project a collection of scripts that can easily be modified for planning a FUTON architecture anywhere has been made. The scripts are made using functions for the different tasks, in order to make them easy to extend and modify.

Preface

This thesis is written by a group of 3 students on the final semester of the specialization of Network Planning and Management. The thesis was prepared at the Department of Electronic Systems, Faculties of Engineering, Science and Medicine at Aalborg University, in the period from 1st of February 2009 to 3rd of June 2009. The project group has hereby based their thesis on the project proposal of "Planning of RoF Heterogeneous Wireless Network". This thesis is intended to be viewed by the supervisor, the examiner and those who may have an interest in the subject.

This thesis is written in Microsoft Word 2007. The figures and graphs are made with Microsoft Visio 2007, Microsoft Excel 2007, Paint.NET, MapInfo and from external sources. The calculations and programs were made using Python and MapBasic languages. For more information on the tools used in this project, see appendix 8.

Thesis structure

The thesis is structured in ten main chapters:

- **Chapter one: Introduction:** The first chapter is an introduction containing the motivation behind the thesis and how the project was formulated and defined.
- **Chapter two: Futon Architecture:** The FUTON architecture and the technologies involved are reviewed in this chapter.
- **Chapter three: Pre-Planning:** The approach to solving the problem is explained, and scenarios for planning are defined, together with the assumptions made for the project.
- **Chapter four: Radio Planning:** The radio planning is done in this chapter. This involves creating link budgets, using propagation models and automating cell planning.
- **Chapter five: CU-Placement:** This chapter describes the process of planning the locations of the Central Units (CUs) that handles radio signal processing.
- **Chapter six: Fiber Planning:** This chapter involves two planning processes. The fiber network connecting the multifrequency Remote Access Units (RAUs) to CUs is planned here, as well as the fiber network for interconnecting CUs.
- **Chapter seven: Traffic Estimation and Capacity Dimensioning:** The seventh chapter describes the current and future trends in wireless technologies and its applications. When these trends are known, they are used to dimension the planned wireless and wired networks.
- **Chapter eight: Conclusion**: Chapter eight concludes on the findings and planning methods of this thesis.
- **Chapter nine**: **References**: The ninth chapter holds the references used throughout the thesis.

- **Chapter ten: Appendixes:** The final chapter includes appendices with more detailed information about some of the procedures used in the project.

Reading Instructions

- References and literature are referred to with square brackets as [1] and can be located in chapter 9 of the thesis.
- Abbreviations will be fully written the first time they are introduced e.g. Green Grass (GG).
- A Compact-Disk (CD) will be enclosed in the rear of the thesis. The CD will contain source- and data files for Python, MapBasic and a soft copy of this thesis. The full results of the project can also be found on this CD.
- The algorithms used in this thesis and how they were implemented will be introduced where they are first used. If they are used multiple times a reference to the first time they were used will be given.

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Nomenclature

The symbols in the illustrations and charts used in this project are explained here.

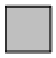
Symbol	Meaning
■	CU (MapInfo)
▲	RAU (MapInfo)
—	Segment/Fiber-optic cable (MapInfo)
	Wireless Cell (MapInfo)
	CU (Visio)
	RAU (Visio)
	Segment (Visio)
	Segment Point (Visio)

Table of Contents

1 Introduction

In recent years, the use of wireless broadband services has increased significantly. It is a challenge for the WISP to keep up with the increasing demand for bandwidth and “always on” mobility by the market. The fast evolution of wireless technologies and market demands makes it difficult and expensive for operators to keep up with the market challenges, as it requires careful planning and new expensive Base-Stations (BS). The vision of the 4^{th} generation of mobile network (4G) is to achieve speeds of 1 Gbit/s for pedestrian mobility and 100 Mbit/s for full mobility. The FUTON project was founded to make the 4^{th} generation of mobile networks cheaper to deploy and operate.

The FUTON project envisions a hybrid fiber-radio architecture, where expensive BSs are replaced by multi-frequency RAU’s. The wireless signals from the RAU are forwarded via Radio over Fiber (RoF) to a CU. The CU will do a joint processing of the radio signals and Internet Protocol (IP) packets correctly. This can make use of distributed Multiple Input Multiple Output (MIMO) algorithms to improve throughput and cancel interference. Depending on the area of coverage several CUs may be interconnected. This architecture can also make use of legacy systems such as 3G and WiMAX.

Since the architecture is vastly different from the ones that are deployed today, it requires a different planning process. This project aims to find an effective way of planning and deploying this architecture, by doing a hypothetical planning for implementing the FUTON architecture in the Danish municipality of Aalborg. The planning should be as automated as possible, to ease the work of the planner, and cut down the time-consumption of the planning process.

This process involves planning the location of CUs and RAUs, wireless cell planning, and planning the fiber placement. It also involves estimating the traffic and dimensioning the network.

1.1Visions of 4G Systems

4G or “fourth generation mobile service” is a loose term, with no official definition. In Europe, it is however common to reference the IMT-advanced standard as a guideline for what a 4G system should be like. This specification calls for bandwidth of 100 Mbit/s for high mobility users, and 1 Gbit/s for pedestrian users. [12]

In general, it can be said that a 4G network is a convergence of the WAN, MAN and LAN, using technologies that enables a user to be online anywhere, at any time. It is an all IP network that enables handover between heterogeneous networks, and provides similar Quality of Service (QoS) as wired connections. There is also a lot of focus on making it more secure than the current wireless networks.

There are numerous proposals for 4G technologies being researched around the globe. FUTON aims to create 4G architecture by making it ready for the technologies it is likely to use and making it transparent so multiple wireless technologies can use the same infrastructure and make advantages of joint processing.

1.2 Motivation

The FUTON project addresses the challenges of a 4G network by making it feasible to implement a hybrid radio fiber infrastructure which connects RAUs to CUs where a joint processing can be performed. The FUTON architecture is vastly different than what is normally implemented by Wireless Internet Service Providers (WISPs) today, which means that the normal planning procedures may not be applicable.

It is therefore interesting to see if it possible to make a planning method that incorporates the FUTON architecture and its technologies. The planning methodology should be as automated as possible and base on Geographical Information System-data (GIS). This will ease the job of the network planner, and reduce the time needed for the planning process.

The scope of the project is defined below in the primary Project Objectives.

1.2.1 Project Objectives

The task of planning a network can be very challenging, as it can be done almost infinitely detailed. Due to the limited time period of this project, it is necessary to do a high level approach to cover the most interesting areas.

The project objectives can be summarized in these points:

- Radio planning
- CU location planning
- Fiber planning
- Traffic estimation and dimensioning

The next chapter will give a review of the FUTON architecture, and the technologies involved, before describing the approach to the problem in chapter 3.

2 The FUTON Architecture

Before starting the planning process it is necessary to take detailed look at the features of the FUTON architecture and the technologies to be used by it. Additional information about the FUTON project can be found at [70].

2.1 Why a New Architecture is Needed

Increasing demand on wireless networks has created a need for a brand new network architecture. The reasons for starting the FUTON project are threefold:

1. The users require higher bitrates and mobility. During the last years, there has been a rapid increase in mobile broadband, and the demand continues to grow. People get used to the advantages and mobility such services offer, and new applications are introduced [42].

2. The total network capacity needs are increasing as well, with the bandwidth demand per user increasing. At the same time the total number of users for the system also increases.

3. As more wireless technologies are implemented, and the quest towards higher bit rates and better QoS continues, the result is increasingly complex wireless systems. As new technologies become available, it is necessary to place more sophisticated BSs. This can be a major part of the total network cost.

2.2 The FUTON Components

The proposed FUTON architecture can be seen above. The geographical area to be served will be covered by simplified base stations Called RAUs. The RAUs are transparent multi-frequency transceivers, that receives/transmits radio signals from the users. From the RAU, the radio signals will simply be forwarded to the CU using RoF. At the CU there will be joint processing of the radio-signals. The new infrastructure will allow for use of heterogeneous networks, which means that 3G, WiMAX, WLAN and a proposed Distributed Broadband Wireless Service (DBWS) which is explained in section 2.4.3 can all be located at the same RAU-location.

The FUTON project consists of three physical components:

1 - The Mobile Terminals:

Mobile Terminals (MTs) refer to hand held devices such as mobile phones, smart phones, laptops. It is in general any device that supports one or more of the known wireless technologies i.e. they are wireless devices running 3G,WiMAX,WLAN and/or DBWS.

2 - The Hybrid Optical-Radio Structure:

The hybrid optical-radio structure consists of the RAUs connected to the CU through optical links on an optical fiber.

RAUs are the FUTON projects solution to increasingly more complex and expensive BSs. The BSs are simplified to transparent wireless transceivers with optical-electronic converters that sends/transmits wireless signals to and from the CU. The RAUs will be connected to the CUs via fiber, using a tree or other topology, as seen in Figure 1.

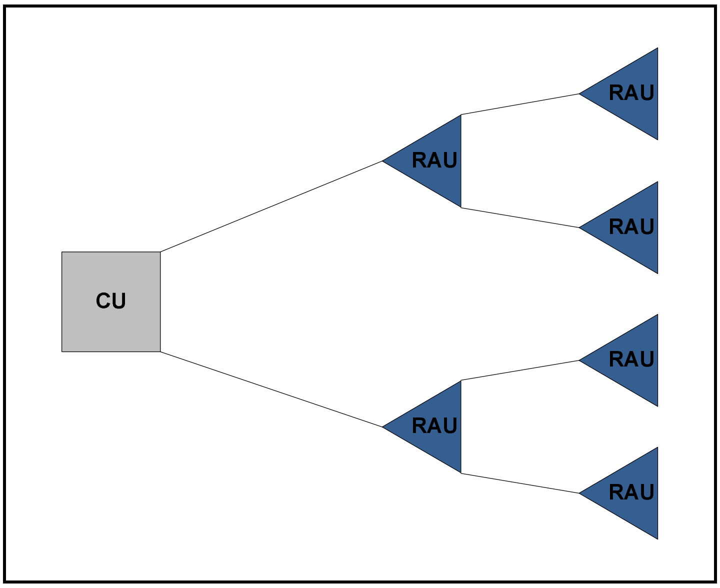


Figure 1: CU to RAU tree topology.

This structure allows for lower installation costs than today's wireless systems so the Capital Expenditures (CAPEX) will be lower. Since there is no expensive processing electronics in the BSs there is also a lower Operational Expense (OPEX) of this system.

The FUTON project will also lead to better deployment flexibility since the reconfiguration is done algorithmically as well as easier upgradeability since only the CU needs to be updated.

3 - The Central Units:

The CU has the task of processing the radio signals to and from the RAUs. The FUTON project will develop all the necessary middleware including resource management and cross-layer algorithms to make this possible.

Several fibers can be attached to each CU. Each CU consists of one or more Joint Processing Unit (JPU). Each JPU is responsible for the process of radio signals and the routing of IP packages to and from a limited number of RAUs.

Additionally, several CUs can be interconnected, to create even bigger serving areas.

A CU and its attached RAUs will provide a geographical area of wireless coverage. This area will be called service area. Depending on the size of the system implemented, several CU's may be connected, as shown in Figure **2**. The CUs are also able to cooperate for instance with soft handover and MIMO.

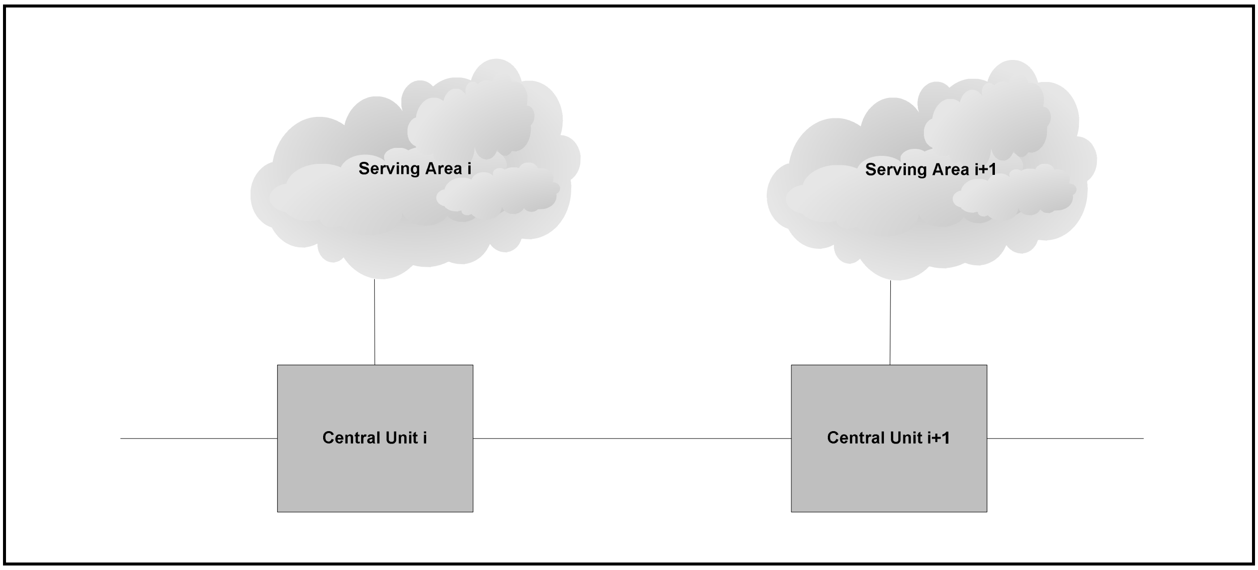


Figure 2: Interconnection of CUs.

2.3 Benefits

This architecture is expected to have an impact on the economic costs of a network, and may also create new business models. The company owning this infrastructure could lease out the bandwidth for several service providers wanting to deliver "always on-access", leading to a competitive market and lower prices for the user.

It also allows for usage of MIMO transmissions to achieve the high transmission rates envisioned for 4G. MIMO is a technique using several antennas for transmitting and receiving data on a wireless device, and will be explained in section 2.4.3.2. MIMO algorithms and technologies are popular research areas at the time of writing, due to its promising features like improvement of bitrates. The technology is expected to be a part of several of the upcoming 4G systems. The way this is envisioned for the FUTON project can be seen in Figure 3.

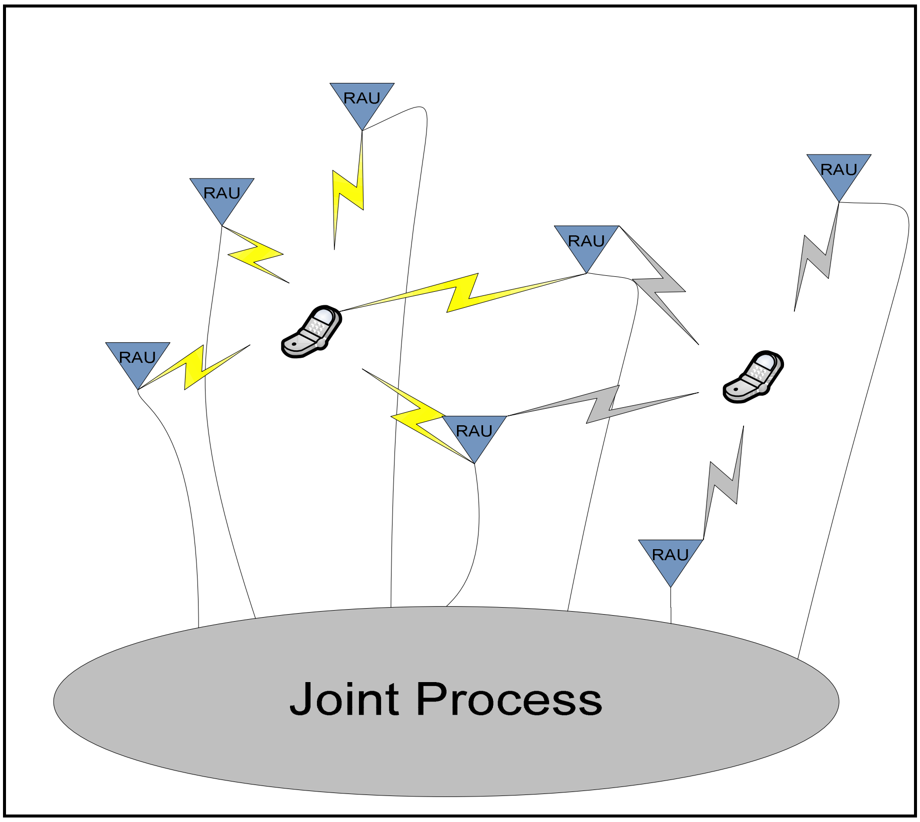


Figure 3: Joint processing and MIMO.

In Figure 3, the RAUs can be seen as physically distributed antennas at one BS. The transparent architecture makes it possible for a mobile device using one or more legacy systems (e.g. 3G, WiMAX etc) or the proposed DBWS to exploit the benefits of MIMO. The CU will detect which algorithms to use for processing.

The distributed MIMO techniques can be used to obtain a high diversity gain, serve multiple MTs via multiuser MIMO or minimize interference between MTs. section 2.4.3.2 goes into more details about MIMO. The CU must choose what options to use and allocate resources in space, time and frequency. This allocation will adaptively consider changes in the state of the wireless channel, to maximize the system capacity.

2.4FUTON Technologies

Last section introduced the basic concepts of the FUTON architecture. This section will introduce the technologies in use by the FUTON architecture, which will be utilized in the planning for this project. For explanations of terms and definitions, see appendix 4.

2.4.1 WiMAX

WiMAX is the common name for technologies under the IEEE 802.16 umbrella. IEEE 802 defines international Standards for Local Area Networks (LAN) and Metropolitan Area Networks (MAN), the most famous being Ethernet (IEEE 802.3). IEEE 802 projects are aimed at the Physical layer transmission (PHY) and Medium Access Control (MAC) [1], the above layers are left for other international organizations.

There are already several standards in the 802.16 family e.g. 802.16d and 802.16e, but the goals for development are:

- Quick deployment
- Provides coverage in areas where it is difficult for wired infrastructure to reach
- Reasonable installation costs to support high access rate

For this project, only the 802.16e-2005, also known as Mobile WiMAX is considered. When the term "WiMAX" is used throughout the thesis, it in fact refers to the 802.16e-2005 standard.

2.4.1.1 Mobile WiMAX

Mobile WiMAX is intended to increase the market for broadband wireless access solutions by taking advantage of the inherent mobility of wireless media. It aims to fill the gap between high data rate access technologies as Digital Subscribers Line(xDSL), Cable and other wired technologies and high mobility cellular systems such as 3G [2]. It supports fixed and mobile services for both businesses and regular home users.

The most important features of WiMAX 802.16e can be seen in Table 1

IEEE 802.16e-2005 uses frequency ranges from 2GHz to 6GHz for mobile applications. The peak down link rate (DL) is 46Mbps with 3:1 DL-to-UL ratio TDD (see appendix 4) or 32Mbps if the ratio is 1:1.The peak uplink rate is 7Mbps in 10MHz channel using a 3:1 DL-to-UL ratio or 4Mbps if using 1:1 ratio [3].

	WiMAX 802.16e
Subscribers	Fixed/Portable/Mobile
Channel conditions	LOS, Near-LOS, Non-LOS
Spectrum	3400-3500 Mhz
Access method	OFDM
Duplex method	FDD/TDD
Sub-carrier modulation	QPSK. 16QAM
Channel bandwidth	10 MHz
Data rate (peak)	46 Mbit/s downling 7 Mbit/s uplink
Cell range	< 1000 meters in urban area < 2500 meters in suburban area

Table 1: WiMAX features [3].

2.4.2 UMTS

Before 3G the most commonly used mobile communication technology was (and still is) Global System for Mobile communication (GSM). GSM is referred to as the second generation of mobile devices or 2G. The reason for that is that it uses digital signaling and speech channels rather than analogue as the first generation, 1G, did (standards like NMT). General Packet Radio Service (GPRS) is a later version of the 2G standard and backwards compatible to GSM. Enhanced Data Rates for GSM Evolution (EDGE) is then the next version of the standard and also backwards compatible to GSM.

Universal Mobile Telecommunication System (UMTS) is an umbrella term for 3rd generation of telecommunication technology, 3G. The specification provide for Frequency Division Duplex (FDD) and Time Division Duplex (TDD). UMTS includes the original scheme for Wideband Code Division Multiple Access (WCDMA) which is the most widely used today [4]. WCDMA is a spread spectrum modulation technique. It shares one channel with high bandwidth among many simultaneous users, see appendix 4.

The UMTS uses a core network that is derived from the old GSM which ensures a backward compatibility between WCDMA and GSM. Since the deployment of GSM is very wide spread this enables voice communication in areas where UMTS has not been deployed yet and therefore helps the deployment of UMTS since users aren't connectionless even though they are not within range of a UMTS cell. This GSM backward compatibility has been one of the reasons for the success of 3G.

High Speed Packet Access (HSPA) is an extension to UMTS that allows for better performance. When the term “3G” is used throughout the thesis, it in fact refers to UMTS with HSPA.

2.4.2.1 HSPA

With the introduction of HSPA the transfer rate increases as well as the round trip times for IP packets goes below 100 ms. In release 5 from 3GPP the downstream data transfer, High Speed Downlink Packet Access (HSDPA), has been increased up to 14 Mbit/s peak rate at best conditions using Single Input Single Output (SISO). In release 6 the upstream data transfer, High Speed Uplink Packet Access (HSUPA) is 5.7 Mbit/s using SISO while HSDPA stays at 14 Mbit/s [4] HSDPA was commercially deployed in 2005 while HSUPA was commercially deployed in 2007. Release 7 is expected to be commercially released in 2009 but that will bring HSPA up to 28 Mbit/s peak in the downlink and up to 11 Mbit/s peak in the uplink using HSPA+. [4]. Release 8 takes HSPA+ up to 42 Mbit/s down using 2x2 MIMO and also introduces LTE that goes up to 160 Mbit/s down and 50 Mbit/s up [4]. For this thesis releases 5 and 6 will be used because it plans for a wireless network that is in operation in 2009.

UMTS has been allocated the spectrums 1920 – 1980 MHz and 2010 – 2170 MHz to use in Europe. WCDMA has a paired uplink and downlink and uses 5 MHz channel spacing [4].

The most important features of UMTS can be seen in Table 2.

	HSPA
Subscribers	Fixed/Portable/Mobile
Channel conditions	LOS, Near-LOS, Non-LOS
Spectrum	1920 – 1980 MHz, 2110 – 2170 MHz
Access method	WCDMA
Duplex method	FDD/TDD
Sub-carrier modulation	QPSK. 16QAM
Channel bandwidth	5 MHz
Data rate (peak)	14 Mbit/s for downlink 5.7 Mbit/s for uplink
Cell range	< 1000 meters in urban area < 3000 meters in suburban area

Table 2: HSPA features [4][5].

2.4.3 DBWS

The FUTON project envisions a DBWS that is able to make use of the benefits of the FUTON architecture. The goal of FUTON is not to invent a new wireless technology, but to create PHY and MAC layer protocols that enable a future DBWS.

The functionality of the DBWS is that it enables the use of several RAUs in a centralized manner that can be seen as a distributed MIMO system. DBWS is thought to use a wireless technology that follows the IMT-advanced specification, which will likely use frequencies from 3 to 5 Ghz. The IMT-advanced specification is what is often referred to as 4G. The choice of the technology for the DBWS is not yet done, but LTE-advanced and 802.16m are stated as the most likely choice by FUTON. When the term "DBWS" is used throughout the thesis, it is assumed that the DBWS uses the LTE-Advanced as the wireless technology.

2.4.3.1 LTE and LTE-Advanced

LTE-Advanced is an evolution of the LTE standard, and has a goal of fulfilling the goals of the IMT-Advanced specification [6]. There are still limited resources available on the details of this exact technology. A starting point is however to look at how LTE works, and mention the methods of improvement believed to lead to the LTE-Advanced specification.

LTE is an evolution of the UMTS standard, and uses scaleable bandwidths from 1.25 to 20 Mhz to provide channel capacities of up to 160 Mbit/s downlink and 50 Mbit/s uplink [4]. It uses Orthogonal Frequency Division Multiplexing (OFDM) as the access method for the downlink and Single-Carrier Frequency Division Multiple Access (SC- FDMA) for the uplink. The modulation schemes for the downlink are Quadrature Phase Shift Keying (QPSK), 16 Quadrate Amplitude Modulation (16QAM) and 64 Quadrate Amplitude Modulation (64QAM). The uplink can use Binary Phase Shift Keying (BPSK), QPSK, 8 Phase Shift Keying (8PSK) and 16QAM. More information on modulation schemes and access methods can be found in appendix 4. LTE supports both FDD and TDD. LTE provides the best performance with mobility under 15 Km/h but aims to have high performance between 15 – 120 Km/h. For speeds ranging from 120 Km/h - 350 Km/h cell mobility will still be maintained. Cells coverage under 5 Km will have full throughput, spectrum efficiency and mobility and cells from 5 Km - 30 Km will have some degradation. [7] [4]. MIMO helps increasing the bandwidth as well as the number of users that can be supported by each cell.

LTE-Advanced will take many of these concepts further by implementing better MIMO schemes, increased spectral bandwidth (scalable from 1 to 100 MHz)and higher frequencies (from 3 to 5 GHz) to facilitate higher throughput. The need for higher throughput will however result smaller cell sizes. Since no concise technical data was available at the time of writing, the group has used the assumptions made by FUTON to plan the DBWS. These assumptions can be seen in Table 3.

	LTE-Advanced
Subscribers	Fixed/Portable/Mobile
Channel Conditions	LOS, near-LOS, non-LOS
Spectrum	450-470 MHz, 698-960 MHz, 1710-2025 MHz, 2110-2200 MHz, 2300-2400 MHz, 2500-2690 MHz, and 3400-3600 MHz
Access method	OFDMA (128 – 2048 FFT sizes)
Duplex method	FDD/TDD (currently both options kept open for further research)
Subcarrier modulation scheme	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM
Channel bandwidth	1-100 MHz, scalable
Data rate (peak)	1 Gbit/s for pedestrian mobility 100 Mbit/s for full mobility
Cell range	~300 meters

Table 3: LTE-Advanced features.

2.4.3.2 MIMO

MIMO is a term for techniques using multiple antennas for transmitting and receiving data on a wireless device. There are many MIMO schemes out there, which enable different performance gains. Common for all of them is that they are all balancing between the array gain, spatial multiplexing, and diversity gain.

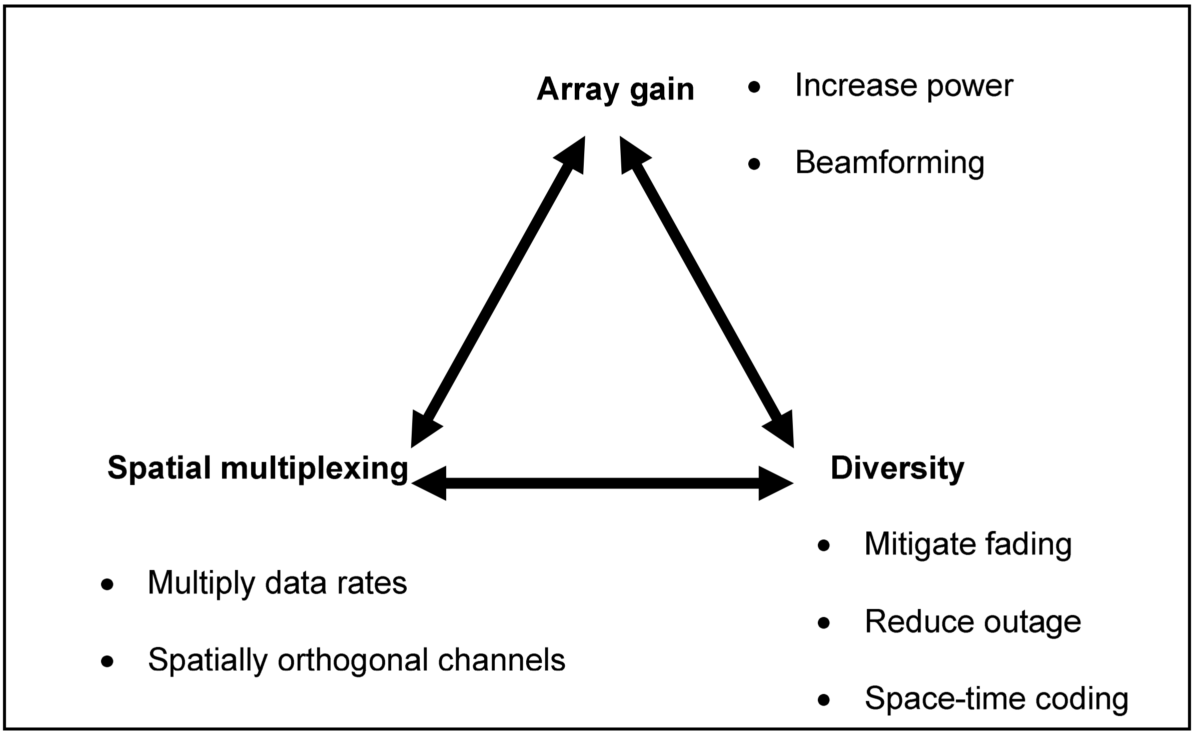


Figure 4: The triangle of MIMO tradeoffs [8].

Focusing on the diversity gain gives better link quality, spatial multiplexing gives higher throughput, and array gain gives larger coverage areas.

- Array gain is a result of the effect of combining several antennas at the sender, receiver or both. It requires channel knowledge on the sender, receiver or both.

- Diversity gain is achieved by sending multiple replicas of the signal, to combat multipath fading. The signal can be replicated either in time, frequency or space-domain. The latter, which is called spatial diversity is the diversity gain used in this project, as each RAU is seen as an antenna for the MT. The point of this is that the MT receives two (or more) independent signals, and the probability that all signals are in a deep fade are small.

- Spatial multiplexing gain comes from splitting up the bit-stream and sending it from several antennas. The receiver receives the split bit-streams, and combines them into the original stream. This way, the total achieved capacity is linearly increasing with the number of antenna-pairs.

2.4.4 Fiber Optics

Fiber technology has been used in the backbones of telecommunications networks since the late 1970s. Today the fiber optic technology is slowly taking over the role of the copper wire technology in the telecommunication world.

Until recent years the copper wire has been the main last mile access technology. Copper wires are however limited when it comes to bandwidth and interferences. Fiber optics is a more effective means of communication signal transmission. Fiber is not affected by electromagnetic interferences and has much higher bandwidth potential than copper cables. Fiber optics technology is the most common way today to connect medium to large enterprises to the telecommunications networks and also to connect the last mile of cable TV telephony and broadband networks to their backbones. Due to its large deployment on the market now a day, high potential bandwidth, lowering prices and its efficiency, fiber has proven to be the most promising technology in the near future for the telecommunications world [9].

2.4.4.1 Radio over Fiber

One of the main ideas behind the FUTON project is to make the BSs into a simplified RAU and connecting these RAUs to a CU. To be able to use simplified RAUs it requires the use of RoF.

RoF is the process of modulating light by a radio signal and transmitting it over an optical fiber link. The features of fiber-optic transfer like low loss and disturbance ensures that the processing of radio signals can be done a long distance from the radio antenna. The fiber-infrastructure is therefore only used to forward the radio signal, to a central location that can process the signals. The FUTON architecture takes advantage of this, by using RAUs as distributed antennas of a central BS (the CU).

Use of RoF has been considered since the early 90’s, although because the cost of the lasers needed was so high, general deployment did not happen. Today commercially available RoF equipment for cellular and WLAN systems already exists [10][11]. The equipment offers frequency band between 350 and 2500 MHz at optical wavelengths 1310 and 1550 nm over distances ranging from 100m up to 20 Km [12].

2.5Summary

This chapter of the thesis introduced the idea for the FUTON project. The architecture of the FUTON project was also introduced and the different technologies used in this architecture have been discussed briefly. The next chapter of the thesis will discuss the different traffic estimations for the technologies used in the FUTON architecture.

3 Pre-planning

Now that the FUTON architecture is explained, it is necessary to find a way of approaching the problem. The planning of the entire network will have many steps, which all needs to be explained. This chapter will present these steps, the assumptions and scenarios made for the project.

3.1Approach to the Problem

There are five tasks that are most important in order to have a suitable network plan for the FUTON architecture:

- Radio planning
- CU placement
- Fiber planning of RAU to CU network
- Fiber planning of CU to CU network
- Traffic estimation and capacity dimensioning

These steps cover the scope of this project, and the methods, results and conclusions for each step will be presented in separate chapters and sections.

The radio planning is found in chapter 4. The radio planning consists of providing coverage to MTs in an area. Since this project has the aim of including 3G, WiMAX and the DBWS as wireless technologies, all three networks need to be planned. The main results of the radio planning will be the positions of RAUs, and the number of MTs per RAU.

When the RAUs are placed, they need to be connected to a CU that can process the radio signals. Each RAU can only be connected to one CU. The task consists of finding optimal locations for the CUs to minimize the trenches needed in fiber planning, and creating as even as possible number of RAUs per CU to ensure an evenly loaded CU to CU network. The details of this planning are presented in chapter 5.

When the CUs locations are ready, it is necessary to plan the physical connection from each RAU to the CUs. This involves using road information, to find the optimal paths to lay the fiber. The CUs will also need to be interconnected. This planning process uses many of the same methods as the planning of CU to RAU network. These two fiber planning tasks will therefore be found in chapter 6.

Lastly, it is necessary to do estimation of the traffic in the networks, in order to dimension the both the wired and wireless networks correctly. This involves sectorizing the cells in the wireless networks, and assigning wavelengths in the fiber-network. This process can be found in chapter 7.

3.1.1 Assumptions

Planning of any kind of network can be a very large and complex task. It is therefore necessary to make some assumptions to simplify the process. Assumptions will be mentioned throughout the thesis where they are made, and the general assumptions of the project will be presented in this chapter.

Figure 5 shows different layers in network planning, as defined by the Swedish ICT commission [13]. The planning in this project is mainly restricted to ducting and cable levels with the exception of the logical topology in the fiber network it is a result of WDM and is transmission level planning.

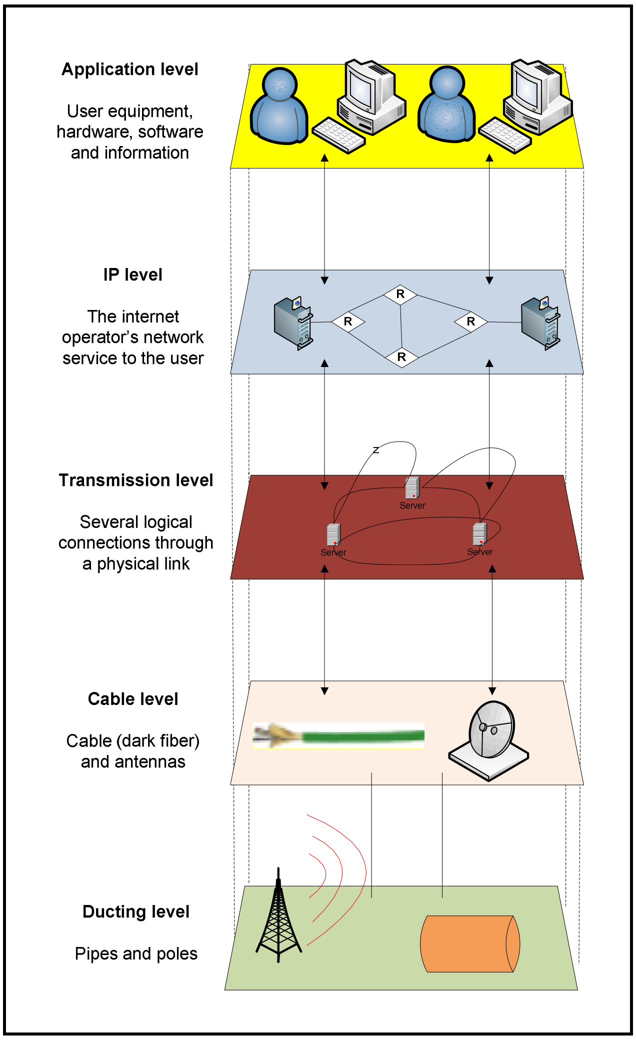


Figure 5: The layers of network planning [13].

It is assumed that the planning done in this project is for an organization that wants to deploy the FUTON architecture and lease it out to interested ISPs. The architecture can include any 3G or WiMAX BSs the ISPs already have active.

The FUTON project is scheduled to be finished in 2013. The networks planned in this thesis are therefore assumed to be used in 2013. For that reason the networks need to be ready for the estimated number of MTs and traffic in 2013. As a ground for comparison, estimations of current traffic (2009) will also be done.

This project intends to do wireless radio planning for three different wireless technologies. The three technologies where introduced in section 2.4 and are WiMAX, 3G and DBWS. Both WiMAX and 3G are expected to be technologies deployed by different WISPs in 2009. In 2013 DBWS will be deployed by an organization that that allows the two WISPs to use the same infrastructure and deploys all three wireless technologies together using FUTON infrastructure.

3.2 Scenarios

Now that the approach has been presented, and the general assumptions have been given, the next step is to create some scenarios that will be used as a basis for the planning. The scenarios are geographical scenario, wireless scenarios and optical infrastructure scenarios.

3.2.1 Geographical Scenario

It was necessary to choose a geographical area that could hypothetically be suitable for implementing the FUTON architecture. The Danish municipality of Aalborg was chosen, since GIS-data of the area was available to the group. For more information on GIS, see appendix 8.

Aalborg is located on both sides of Limfjorden in the county of North Jutland. It is Denmark's fourth largest city, with 192 000 inhabitants in the whole municipality and 122 000 in the city area [14]. The landscape is typically Danish, with an urban town centre surrounded by flat farmland and a few hills. The geographical size of the municipality is 1 143, 99 square km [15].

Statistics show that 11 785 people commute out of Aalborg every work day, and 21 215 commute into Aalborg. This means that during the work-hours on weekdays, there are 201 430 people in the municipality [14].

The map in Figure 6 is made using some of the available GIS data used in this project, and shows the municipality borders and road system in Aalborg.

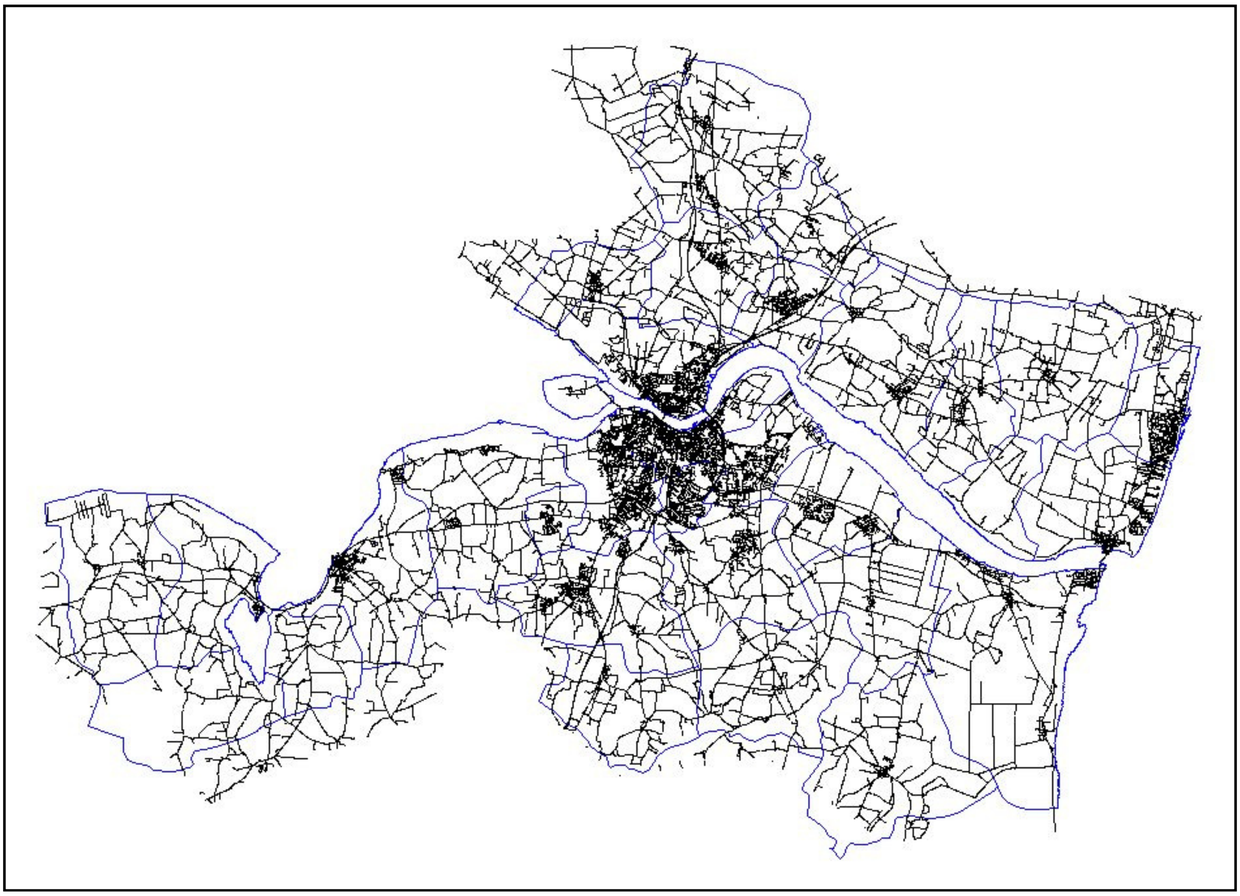


Figure 6: Segment data for Aalborg

Based on the size and population of the municipality, it is possible to find the average population density, which is 168 people per square km. The GIS-data available for this project contains no direct measure of where people live. It is however natural that Network Terminations (NTs) can be used as a measure of where people live (or work). The database used in this project shows that there are 71818 NTs in Aalborg. This gives an average of 2.67 persons per NT during evenings, and 2.80 persons per NT during work-hours. Figure 7 shows the distribution of NT density in Aalborg, in a grid with 250*250 meter squares. It can be seen that the densest area is in and close to the city center of Aalborg.

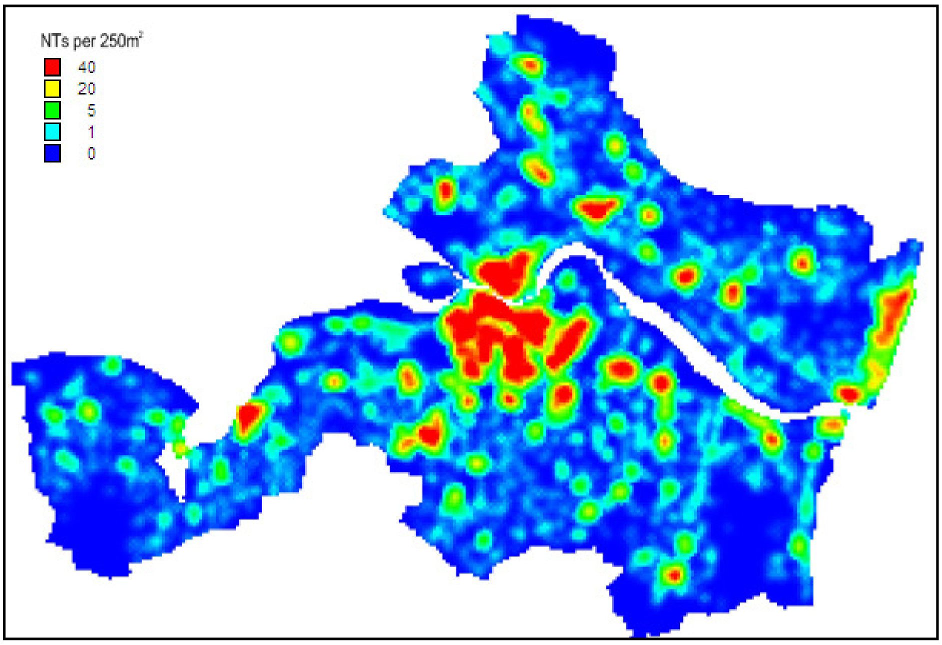


Figure 7: NT density in Aalborg

Information about geographical height is not available in the GIS-data used for this project neither regarding area height nor building heights, and will therefore not be included in the coverage calculations. This is a simplification of how it might be done in a real implementation, but due to the flat nature of Aalborg municipality, it is considered to be of little importance.

3.2.2 Radio Coverage Scenarios

This chapter will explain the scenarios and assumptions made when planning the radio coverage. It is not decided how many wireless technologies the FUTON architecture will support, but it is assumed that it is at least 3G, WiMAX, WiFi and one of the future technologies that will follow the IMT-Advanced specification. For simplicity it was chosen that radio coverage planning for this project should only involve 3G, and WiMAX and use LTE-Advanced as the enabling technology for the DBWS.

3G and WiMAX were chosen because they are already widespread as WAN-technologies, and will also likely be so in the close future. LTE-Advanced was chosen because it is believed to gain popularity, based on the success of previous 3GPP-technologies, and its promising features like high throughput, low upgrade costs and backwards compatibility [16].

When planning the coverage, it is necessary to put constraints on how many of the users should be covered. This is done because it might not be economically feasible to provide coverage to 100% of the users. Since 4G networks should provide an “always-on” experience for the user, the calculations will need to take into account the loss experienced when the signal propagates through walls, to indoor users.

It is also necessary to make some assumptions on the penetration of each technology for the capacity dimensioning done in chapter 7. This chapter also needs assumed market shares for the WISPs, in order to dimension the network correctly.

The next section summarizes the radio planning assumptions and settings used throughout the thesis.

3.2.2.1 3G Scenario

3G coverage will be planned using UMTS with HSPA technologies. Table 4 list the assumptions for the 3G scenario.

Parameter	Constraint/assumption
Technology	UMTS (HSDPA,HSUPA)
Frequency	2010 Mhz
Coverage	>97%
Technology Penetration	30% in 2009 50% in 2013
WISP Market Share	30% in 2009 40% in 2013

Table 4: 3G assumptions.

3.2.2.2 WiMAX Scenario

WiMAX coverage will be provided using the 802.16e 2005 technology. Table 5 lists the assumptions and constraints for the planning process.

Parameter	Constraint/assumption
Technology	Mobile WiMAX (802.16e 2005)
Frequency	3500 Mhz
Coverage	>97%
Technology Penetration	0.2% in 2009 35% in 2013
WISP Market Share	100% in 2009 40% in 2013

Table 5: WiMAX assumptions.

3.2.2.3 DBWS Scenario

The DBWS system will be provided using LTE-Advanced. Table 6 lists the assumptions and constraints of the DBWS.

Parameter	Constraint/assumption
Technology	LTE-Advanced
Frequency	3500 Mhz
Coverage	>97% of Urban area
Technology Penetration	5%
WISP Market Share	100% in 2013

Table 6: DBWS assumptions.

DBWS will be implementing MIMO. Since the information on how DBWS will implement MIMO is limited, assumptions are made here in order for it to be implemented in the project.

MIMO is considered using a simplified method. A device that is capable of using all three technologies at once is not considered in this thesis.

The different MIMO schemes must balance the gains mentioned in section 2.4.3.2 to achieve the desired level of service. The details of how this is done are outside of this projects scope. For simplicity, it is assumed that the DBWS and the FUTON architecture will utilize two schemes found in WiMAX-technologies; MIMO matrix A and MIMO matrix B. Matrix A and Matrix B work in the following way:

- Matrix A: Coverage gain
- Matrix B: Capacity increase

For more information on the schemes, see [17]

According to [71] it is possible to achieve at least a 45% increase in range using the Matrix A scheme. It is assumed that this is possible also for the DBWS, and the extended range is calculated to 300*1.45 = 435 meters. Since no information about link budgets are available at the time of writing the 300 and 435 meter cell ranges are used in the planning of the DBWS.

The FUTON project will make an intelligent system that chooses the best MIMO schemes for the users. Since the details of such a system are not available at the time of writing, assumptions on the selected MIMO schemes for different kinds of users are made here. If a MT is only within a single 300 meter radius, a Regular service is achieved. This is the same service the RAU offers the MT without distributed MIMO. If a MT is within a 300 meter radius, and one or more other 300 or 435 meter radius, a Matrix B service will be achieved. If the MT is within two or more 435 meter radius, a Matrix A service will be achieved. These assumptions are summarized in Table 7.

MT location	Service
Single 300 meter	Regular
Single 300 meter + other (300 or 435 meter)	Matrix B
Two or more 435 meter	Matrix A

Table 7: MT location and achieved service.

In Figure 8, it can be seen what type of service the MTs will achieve.

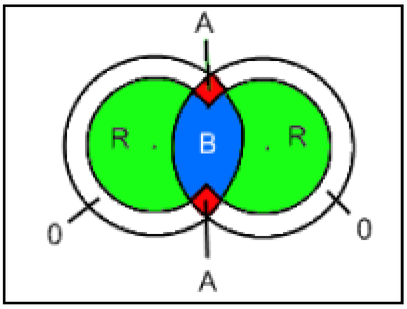


Figure 8: Assumed received service: R = Regular, A = Matrix A, B = Matrix B, 0 = none.

3.2.3 Optical Infrastructure Scenarios

The setup of the optical infrastructure between the CU and the RAUs can be done in different ways. The FUTON project lists many alternatives, the most interesting for this project are explained in this chapter. The optical infrastructure of the network interconnecting the CUs will not be covered here, but in Chapter 6.

In FUTON each RAU is a simple antenna unit but all radio signal processing are done by a CU as mentioned in chapter 2. Each CU includes several JPUs. Each JPU processes the signals from a group of RAUs. It is assumed that each JPU has the optical interfaces necessary to communicate radio signals to and from the RAUs it is connected to. Passive infrastructure is preferable to active infrastructure for the fiber-network, because it reduces cost for both OPEX and CAPEX.

There are many possible options when deciding on how to implement these connections, which all have different implications on the total network cost. These options will be reviewed in the following section.

3.2.3.1 Proposed Architectures

FUTON proposes five candidate architectures. These architectures must be able to support at least DBWS that requires an entire wavelength with 4 sub-carriers in each direction for each RAU. Support for legacy systems are also taken into consideration as will be seen in section 3.2.3.2. In this thesis all the architectures taken into consideration will depend on using the CWDM. It is considered more likely that the CWDM architecture will be implemented because of the high cost involved when implementing DWDM. Broadcast will also not be considered here because the power splitters and optical splitters needed are considered too expensive [75]. The candidate architectures are shown in Table 8.

Options	Description
Option A	CWDM mux/demux with two ports for each RAU
Option B	CWDM mux/demux with downstream wavelengths shared by multiple RAUs
Option C	CWDM mux/demux with upstream and downstream in a single CWDM channel

Table 8: Candidate fiber architecutres.

Option A: CWDM mux/demux with two ports for each RAU

In this architecture each RAU is served by one unique wavelength for uplink (UL) and another unique wavelength for downlink (DL). A single mux/demux is placed close to the area where the RAUs connected to corresponding JPUs are located. A CWDM grid has 16 wavelengths and therefore this architecture can support up to 8 RAUs. The higher attenuation region (1271 nm, 1291nm, 1311nm, 1331nm, 1351nm, 1371nm, 1431nm and 1451nm) is specified for the DL transmission. The reason for choosing these regions for the DL is that the attenuations is higher than in the other regions and the DL is considered as less critical since it will be carrying less traffic than the uplink. The lower attenuation region (1471nm, 1491nm, 1511nm, 1531nm, 1551nm, 1571nm, 1591nm and 1611nm) is then specified for the UL transmission (see fiber attenuation in appendix 3) [12]. Figure 9 shows option A graphically.

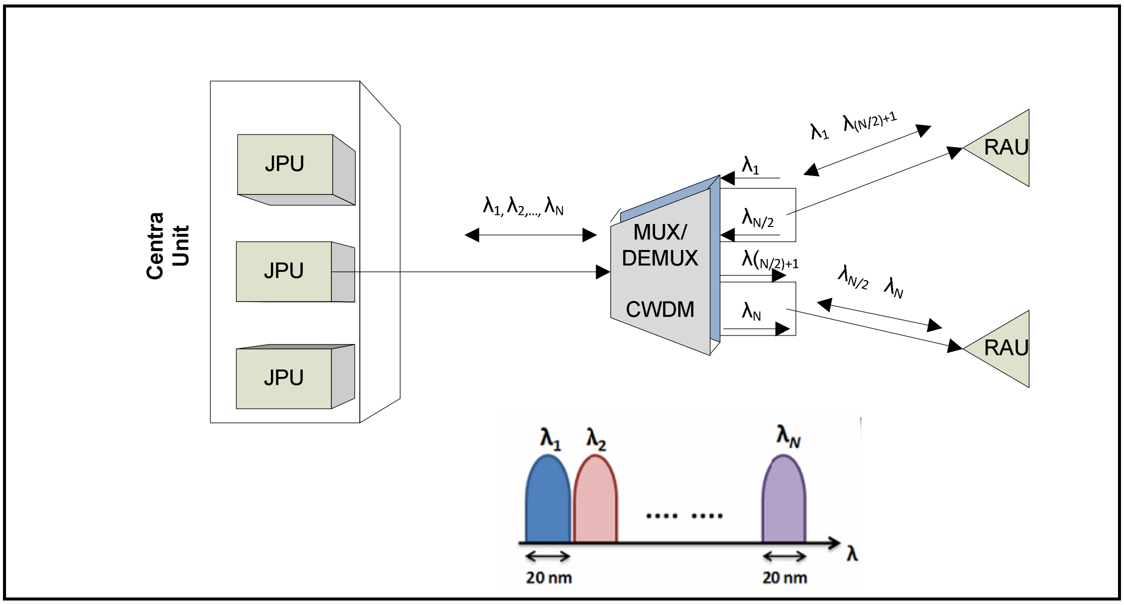


Figure 9: Logical overview of CWDM mux/demux with two ports for each RAU.

From the JPU to the CWDM mux/demux a single fiber cable is needed. But in the distribution section (from the mux/demux to the RAUs) there are two possible implementations. One is connecting each of the RAUs to the mux/demux with individual cable. It requires an additional coupler in order to connect both the UL and DL into a single fiber for each RAU. The second is using two fibers connecting each RAU to the mux/demux that will increase the range of the signal.

Option B: CWDM mux/demux with downstream wavelengths shared by multiple RAUs
This architecture is derived from option A. Each RAU gets an individual UL wavelength but one or more wavelengths are shared in the DL. To accomplish this, the DL uses Sub-Carrier Multiplexing (SCM). This increases the possible available RAUs supported by a JPU. The number of RAUs supported depends on the number of available ports in the mux/demux and the number of sub-channels that a single wavelength can support. Assuming that one wavelength will be sufficient as an uplink for all the RAUs in a JPUs group then up to 15 RAUs can be supported [12]. This setup can be seen in Figure 10.

From the JPU to the CWDM mux/demux a single fiber cable is needed. In the distribution section an individual fiber connects the CWDM mux/demux to each of the RAUs. It is also possible to deploy two fibers to each RAU and thereby increase the range.

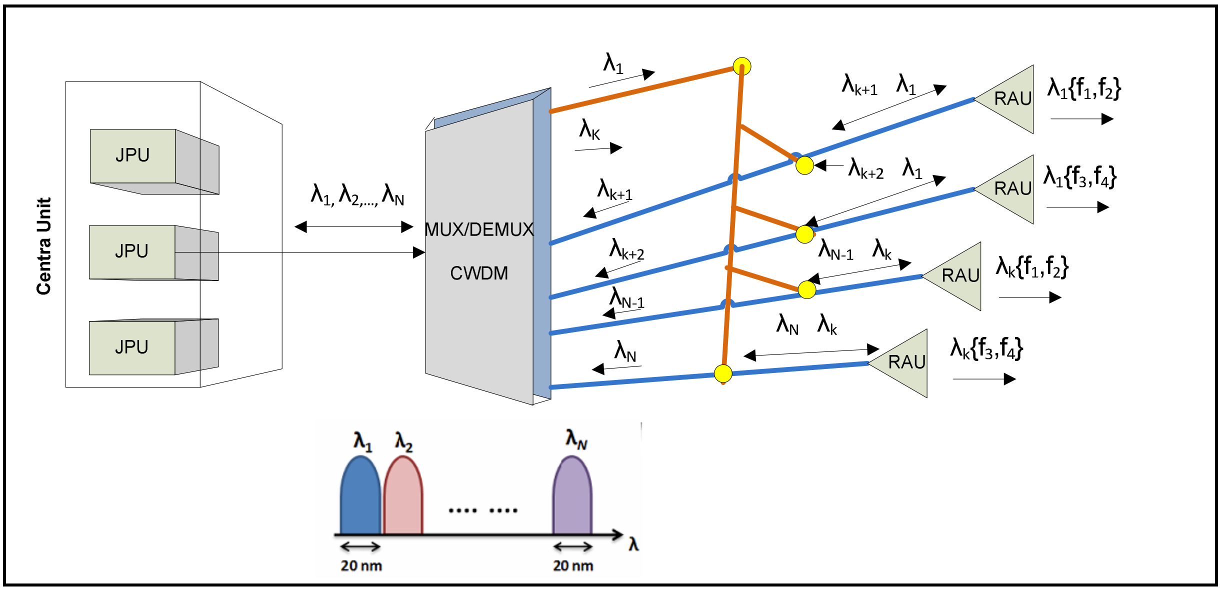


Figure 10: Logical overview of CWDM mux/demux with downstream wavelengths shared by multiple RAUs.

Option C: CWDM mux/demux with both directions inside the same CWDM channel
This architecture is aimed to support as many RAU per JPU as possible using the CWDM technology. This is achieved by transmitting both the UL and DL wavelengths within the 20nm bandwidth of each mux/demux port. Using this method the maximum number of ports of the mux/demux (16 ports) can be used to connect to corresponding number of RAUs [12]. This can be seen in Figure 11.

From the JPU to the CWDM mux/demux only one fiber cable is needed. One fiber cable is then needed to connect to each of the RAUs.

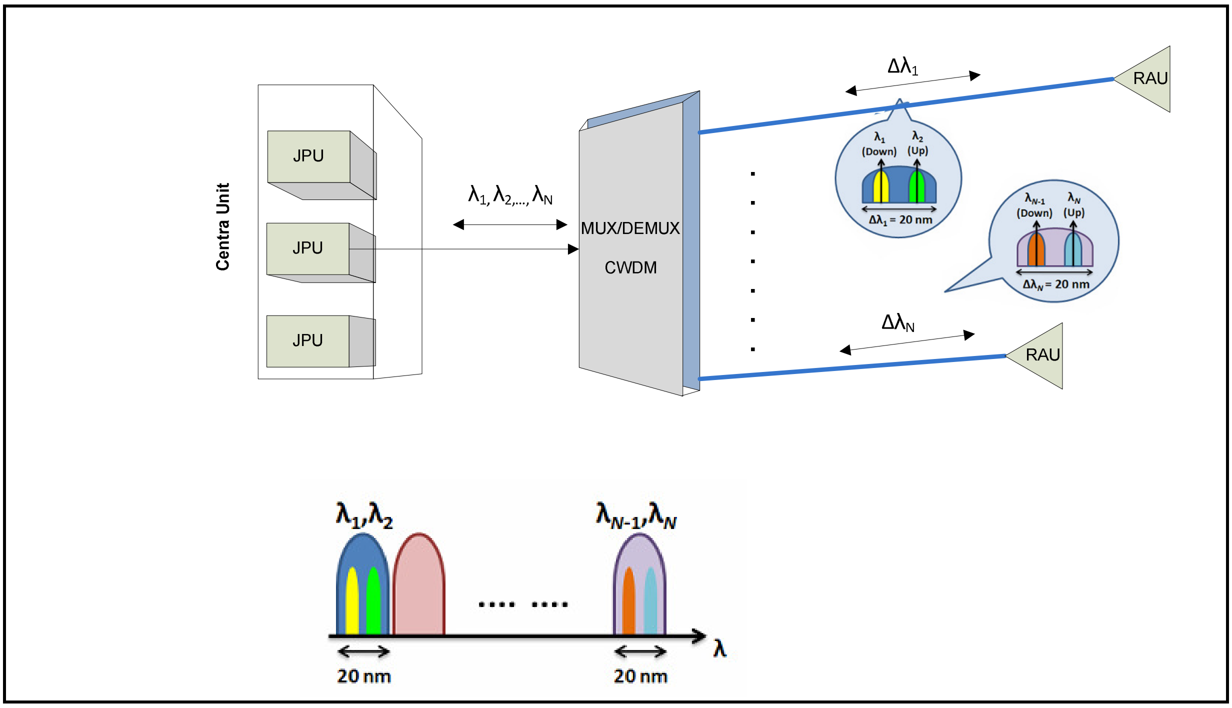


Figure 11: Logical overview of CWDM mux/demux with both directions inside the same CWDM channel.

3.2.3.2 Support of Legacy Systems

In order to make WISP want to adapt and implement FUTON systems, it is critical to make it coexist with legacy systems, as the WISP want to keep maintaining their current services. The FUTON project therefore aims to make the infrastructure support legacy systems together with the DBWS.

It is likely that only a few of the RAUs will need to support the legacy systems, as there will be more RAUs needed for the DBWS than the legacy systems, due to the expected small size of the DBWS cells (around 300) meters. Another aspect is that the legacy systems has lower throughput than the DBWS system, so assigning a separate optical wavelength up and down for the legacy systems could mean a large waste of resources.

Instead, three possible options are suggested: Space Division Multiplexing (SDM), WDM and WDM/SCM.

- **SDM**

  This solution ensures that all RAUs can support legacy systems, and works by duplicating the entire fiber plant. One fiber is for the DBWS, and the other is for the legacy systems. The downside of this is that it will increase the cost of the system, and will waste resources.

- **WDM**

  One possibility is using pure CWDM, assigning channel for legacy for each RAU that needs it. Using this method, if L RAUs needs to support legacy systems, scenario A will support up to 8-L RAUs, scenario B will support up to 15-L RAUs and Scenario C will support up to 16-L RAUs.

- **WDM/SCM**

  Another possibility is to allocate one UL and one DL CWDM channel for the legacy systems, and then use SCM to multiplex them together. In this case, if one or more of the RAUs of a JPU supports legacy systems, scenario A will support up to 7 RAUs, scenario B will support up to 14 RAUs and scenario C will support up to 15 RAUs.

For this project, it will be assumed that the WDM/SCM can be used for legacy support.

3.2.3.3 Comparing Proposed Architectures

Table 9 shows a comparison of the different alternatives of connecting RAUs to the CUs.

	Option A		Option B		Option C
	Single fiber	Double fiber	Single fiber	Double fiber	Single fiber
Maximum number of RAUs per JPU	At most ≤ 8		At most ≤ 15 (requires 60 sub channels in a single wavelength for the downlink)		At most ≤ 16
Splitting points	CWDM mux/demux with at most 2*8 channels and at most 8 couplers	CWDM mux/demux with at most 2*8 channels	CWDM mux/demux with at most 2*8 channels, (max nr of DL) power splitters and (max nr of RAU) couplers	CWDM mux/demux with at most 2*8 channels and (max nr of DL) power splitters	CWDM mux/demux with at most 2*8 channels
Fiber layout	All single fiber	Double amount of fiber in the distribution	All single fiber	Double amount of fiber in the distribution	All single fiber
DL trans-mitting equipment	(Max nr of RAU) CWDM lasers (low cost)		(Max nr of DL) CWDM lasers (low cost)		(Max nr of RAU) higher cost lasers with wavelength dirift control
UL trans-mitting equipment	(Max nr of RAU) CWDM lasers (low cost)		(Max nr of RAU) CWDM lasers (low cost)		(Max nr of RAU) CWDM lasers (low cost)
DL receiving equipment	(Max nr of RAU) wideband optical filters	Non required	(Max nr of RAU) wideband optical filters and (Max nr of RAU)*(nr of subchannels)	(Max nr of RAU)*(nr of subchannels) electrical filters	(Max nr of RAU) optical filters

			electrical filters		
UL receiving equipment	(Max nr of RAU) wideband optical filters in the JPU (low cost)		(Max nr of RAU) wideband optical filters in the JPU (low cost)		(Max nr of RAU) wideband optical filters in the JPU (higher cost)
Optical amplifi-cation	Difficult (and expensive), one amplifier needed per wavelength		(Nr of DL) optical amplifiers at the JPU		Difficult (and expensive), one amplifier needed per wavelength
DL power budget	2.5 km	12.5km	5km	15km	7.5km
	14dB	10dB	13dB	9dB	12dB
UL power budget	5km	25km	5km	25km	7.5km
	12dB	8dB	12dB	8dB	12dB

Table 9: Comparison of composed architectures [75].

In the power budget in Table 9 the distance is calculated according to 11dB link budget optical loss and the loss (in db) in accordance 10 km network reach. It also shows how high the loss will go if the reach is 10 km [75].

The choice of a deployment options mostly revolves around finding a solution that is cheap but at the same time has sufficient range for the situation. The area of Aalborg makes the decision for the right method hard because the area consists of rural, suburban and urban areas. In the Urban area access to electricity is easier than in the rural areas, this makes it easier to deploy amplifiers for the chosen solution if they are needed. The amplifiers themselves however may be so expensive that another method needs to be used. To reduce cost it is good to make the solution as passive as possible, since the passive equipment is cheap and doesn't require as high maintenance as active equipment. An example could be the single fiber solution in option A which might be the best choice for dense areas with short distances and many RAUs, but unsuitable for rural areas where the distances are long.

For simplicity, the "double fiber option B" is selected as the fiber optic scenario in this project, since it allows for the longest distance to the RAUs, and amplification is economically feasible.

3.3Summary

This chapter of the thesis presented the pre-planning stage by showing the approaches that were followed to solve the problem. It also introduced the geographical scenario, optical infrastructure scenarios and radio coverage scenarios. Next chapter introduces the approach to Radio planning used for this project.

4 Radio Planning

This chapter will introduce the radio planning approach that was followed to create wireless networks. The radio planning consists of placing wireless BSs for 3G, WiMAX and LTE in the Aalborg area.

To be able to plan this, the number of potential users and their location in the municipality will have to be estimated. When this is done the potential positions of RAUs that will be used to provide the service has to be found. It is then necessary to set up link budgets for the technologies to find the maximum allowable path loss in each network. This information can be used in a propagation model, to find the range for the RAUs. When all this information is in place, the planning of radio coverage to the users in the municipality can commence. It is desired to make an automated method that provides a solution that covers a limited set of users at the lowest possible cost. For information on implementations done for this project, see appendix 1.

For this project, cell planning will be performed for 3G, WiMAX and the proposed DBWS in the municipality of Aalborg. No attention will be paid to frequency reuse planning, since it is a small geographical area, and the FUTON system handles frequency reuse algorithmically.

4.1 Distribution of Potential Users

As a starting point for radio planning it was necessary to find how the population in Aalborg is distributed. The population contains potential customers to which the assumed WISPs want to provide a service. The GIS-data available to the group contains NTs of homes and businesses in the Aalborg municipality. This information cannot be directly used for a wireless scenario, as wireless users are mobile. An approximation was made using information presented in chapter 3 that showed there are approximately 2.8 people per NT during the work hours (worst case). A new distribution of users was created from the distribution of NTs. The new distribution was picked from the normal distribution with a mean of 2.8, and a standard deviation of 1. The new users were then placed uniformly within 10*10 meters of the original NT. Although it is more likely that the users will not be evenly distributed during work hours, since most of the inhabitants would be at work, it is considered enough approximation with the limited data available.

Using this method, 201 707 users were generated from the 78818 NTs. This number is only 0.14% higher than the statistical estimation done in chapter 3 of 201 430 people, and was therefore found to be a reasonable estimation of the user distribution in Aalborg. The new distribution of users in the Aalborg area can be seen in Figure 12.

Figure 12: Distribution of potential users in Aalborg municipality.

4.2 Distribution of potential RAUs

When the positions of the potential users are known, it is necessary to find locations for potential RAUs that can provide the services. As mentioned in section 3.1.1 it is assumed that the planning is done for an organization that wants to provide the FUTON architecture to any WISP in the area. Since no information about the existing 3G and WiMAX networks in the Aalborg area was available, these networks have to be planned, to have a starting point for implementing the FUTON architecture. Because of this, it is assumed that two WISPs are already providing wireless internet access in the municipality, and want to make use of the FUTON architecture.

Since they are two independent ISPs, their networks and coverage areas might not be the same. If for example it was a 3G operator that wanted to provide WiMAX as well, the operator would most likely use their current 3G BSs as a starting point when trying to find good locations for the WiMAX BS, in order to save money. When planning 3G and WiMAX in this project it means that the cost of a BS is not affected whether or not a wireless BS already exists at the location. For simplicity, the backhaul for 3G and WiMAX networks are not considered in this project, as they will be connected using the FUTON architecture in the fiber planning process.

When planning the DBWS however, the BSs with 3G and WiMAX will be given a lower cost, since there already is a wireless BS at the location, which just needs to be switched with an RAU that supports legacy. In fact, even if there is no need for a DBWS site in the area of the 3G or WiMAX BS, it would still have to be replaced with a RAU for it to be compatible with the FUTON infrastructure.

When planning a wireless network, it is necessary to find the best locations for the antennas, in order to provide the best coverage. This is normally found by inspecting the subject area for high buildings and hilltops in order to find good locations for antenna placement. It is also necessary to find out which of the good locations are available for lease. Practical considerations like power supply, backhaul possibilities and local zoning laws also need to be considered. When all the suitable sites are identified, it is necessary to choose the fewest ones needed to provide the desired coverage.

Since no information about possible BS locations is available to the group, a grid of hypothetically available locations were made. Every 1000 meter within the municipality was marked as a possible location, as can be seen in Figure 13. The reason that some of the locations is outside the municipality boundaries is that some of the NTs (and therefore also users) are located outside the boundaries, and therefore still needs to be covered.

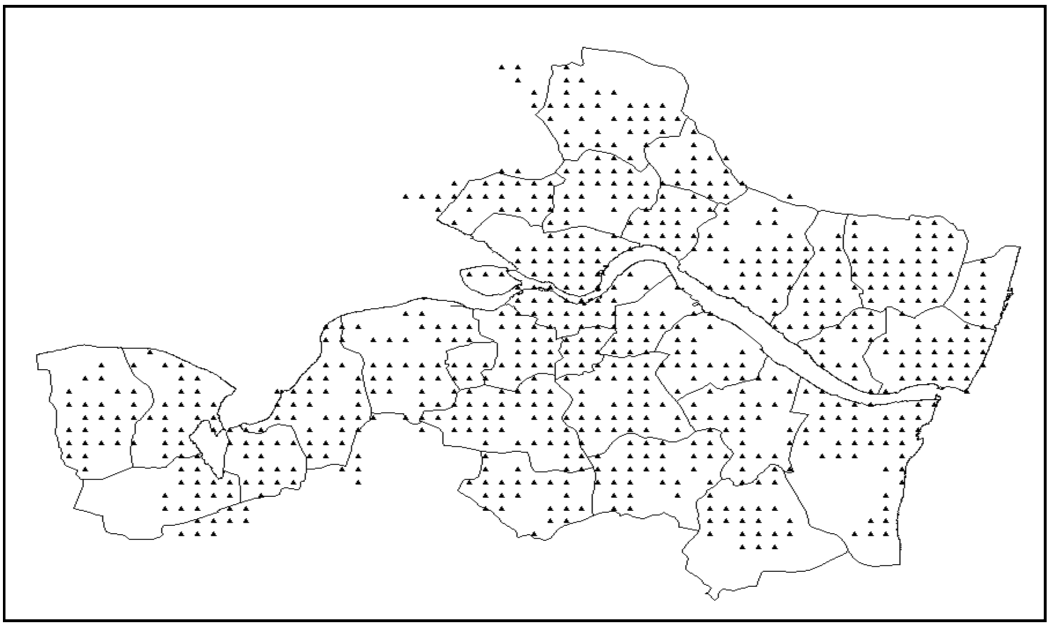


Figure 13: Possible 3G and WiMAX locations in the municipality of Aalborg.

When finding possible RAU and BS locations for the wireless technologies in the urban areas, it was necessary to make a more fine-grained grid, due to the short ranges in urban areas. An area of downtown Aalborg was selected, and the fine-grained grid was placed on top of the existing grid in this area. The distance between possible RAU locations in the resulting grid was 200 meters. The grid of downtown Aalborg can be seen in Figure 14.

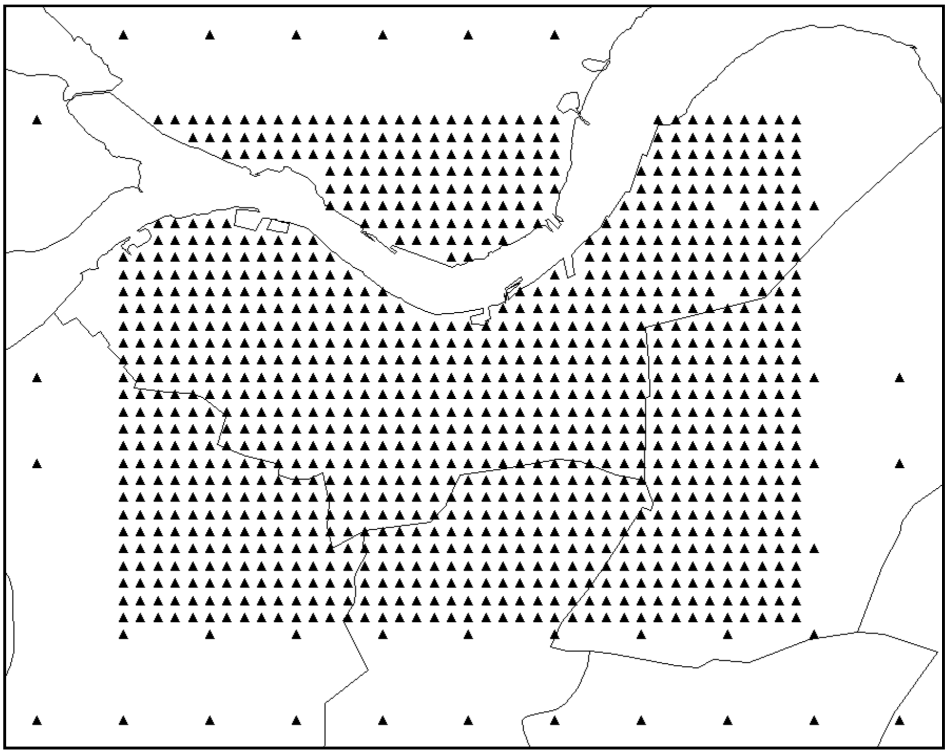


Figure 14: Possible RAU locations in the urban area of Aalborg.

When the positions of possible RAU-locations was made, it becomes necessary to find the range each RAU has, to find out how many MTs are within this range. The range of the RAU is decided by the radio link budget that decides the maximum allowed path loss, and the propagation model which estimates how the radio signal propagates through space.

4.3Link Budget

The radio link budget estimates the maximum allowable path loss by taking into consideration all possible gains and losses experienced by the signal in propagation from transmitter to receiver.

The link itself is defined by three parts: transmitter, receiver and transmission media. From this a simple form of a link equation can then be written as the sum of all gains minus the sum of all losses, as seen in Equation 1. In this formula, Tx is transmitter, and Rx is receiver.

$$Signal\ path\ loss = Tx\ power + Tx\ antenna\ gain + Rx\ antenna\ gain - all\ losses$$

Equation 1: Signal path loss.

There are countless gains and losses that can be included in this equation, depending on how detailed and accurate it is needed to be. For this project, only the largest contributors to the link budget will be considered, since information about smaller contributors were hard to find for students, but often given by the suppliers of network equipment or can be found by performing measurements. The gains and losses accounted for in this project will be presented in this section.

Effective Isotopic Radiated Power

Effective Isotopic Radiated Power (EIRP) is the theoretical power emitted by an antenna to produce the peak power density observed in the direction of maximum antenna gain. EIRP takes into account losses such cable and connector losses for more accurate link budget calculation. Using EIRP and the antenna gain it is possible to calculate the real power emitted and field strength values. EIRP can be seen in Figure 15 and is calculated with Equation 2.

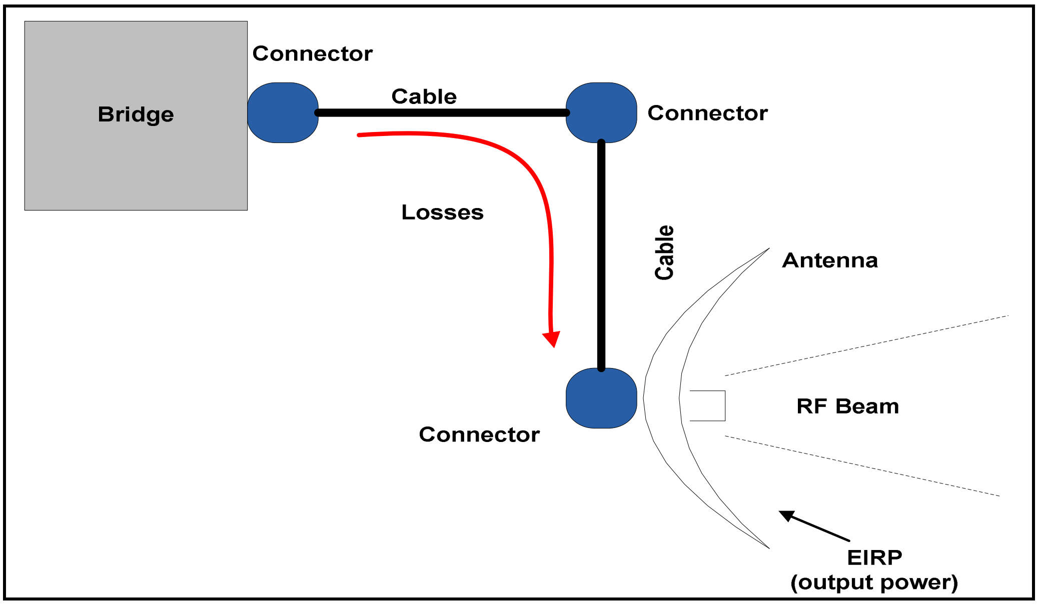


Figure 15: EIRP [3].

$$EIRP = Tx\ power\ [dBm] - Cable\ losses\ [dB] + Antenna\ gain\ [dBi]$$

Equation 2: EIRP [3].

Receiver Sensitivity

Receiver sensitivity indicates how weak a RF signal can be and still be successfully received by the receiver. The lower the power level that the receiver can successfully process, the better the receive sensitivity [18].

Receiver sensitivity is affected by noise and is therefore defined by noise parameters such as Thermal noise and desired Signal to Noise Ratio (SNR). Receiver sensitivity can be calculated using Equation 3.

$$Receiver\ Sensitivity = Thermal\ noise + Receiver\ SNR$$

Equation 3: Receiver sensitivity

The thermal noise is electronic noise that is dependent on the channel noise and is calculated using Equation 4.

$$Thermal\,noise = -174 + NF$$

Equation 4: Thermal noise.

Where -174 is the noise factor and NF is the noise figure.

The Noise Figure is the noise factor i.e. it is ratio of SNR at input to ratio of SNR at output and is calculated in Equation 5.

$$NF = 10log_{10}(\Delta f)$$

Equation 5: Noise figure.

Where (Δf) is the channel bandwidth measured in hertz.

The receiver SNR parameter is the ratio between the signal power and the noise that weakens the signal. The desired SNR is different from one wireless technology to another and is dependent on the modulation scheme being used. The desired SNR values for technologies are shown in table 28 in section 7.4.1.1. For more on modulation schemes see appendix 4 [19].

Margins

Margins are added to the link budget to account for factors that affect the signal during propagation. The most common types of margins are fading margin, interference margin and Building Penetration Losses (BPL).

The fading margin (FM) is the amount by which the system gain and sensitivity may be reduced without causing the system performance to fall below a specified threshold value. This is normally done to account for drop in desired QoS. In this project 7.5 dB was used as FM.

The interference margin (IM) is interference due to the Co-Channel Interference (CCI). CCI occurs due to frequency reuse where MTs at the cell edge or the sector boundaries may suffer degradation in connection quality [21].

Radio signals suffer a 5 – 15 dB signal loss when propagating through walls. This is called Building Penetration Losses. It is therefore necessary to account for these in the planning process. This means that for example that even though a BS has a reach of 5 km, it may still provide coverage for users outside this area, if they are located outdoors. An illustration of this can be seen in Figure 16. For this project, a building penetration loss of 10 dB was assumed [3].

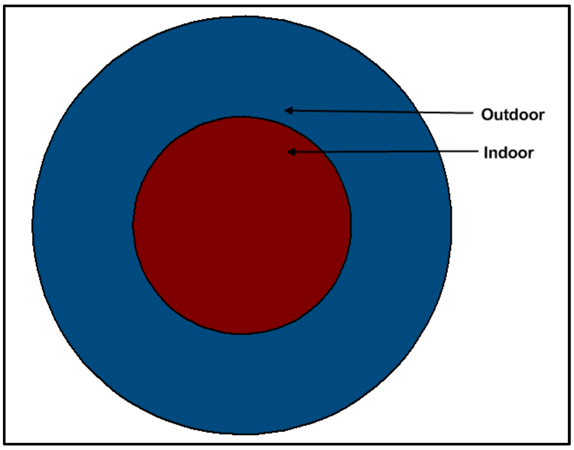


Figure 16: Indoor vs outdoor coverage.

Link Budget Calculation

When all the major contributors to the link budget is explained, Equation 1 can be expanded to Equation 6 for downlink and Equation 7 for uplink.

$$MAPL_{down} = EIRP + MT's\ antenna\ gain + DG - MT's\ sensitivity - FM - IM - BPL$$

Equation 6: Downlink maximum allowable path loss.

$$MAPL_{up} = EIRP + RAU\ antenna\ gain + DG - RAU\ sensitivity - FM - IM - BPL$$

Equation 7: Uplink maximum allowable path loss.

In Equation 6 and Equation 7, DG is Diversity Gain, FM is Fading Margin, IM is Interference Margin, BPL is Building Penetration Loss and $MAPL$ is the Maximum Allowable Path Loss in the downlink and uplink respectively. Using these equations, it is possible to calculate the link budgets for 3G and WiMAX. Link budget information for LTE-Advanced which will be used for the DBWS could not be found, so a range of 300 meters is assumed [12].

4.3.1 Link Budget Results

This chapter presents the link budget calculation results for both WiMAX 802.16e and HSPA. Table 10 shows the link budget without SNR.

	WiMAXup	WiMAXdown	HSDPA	HSUPA
EIRP	22	57.3	61	24
Rx sensitivity	-111.1	-97.39	-101.2	-117.9
Rx antenna gain	15	-1	0	17
Diveristy Gain	3	3	0	0
Shadow fade margin	7.5	7.5	7.5	7.5
Interference margin	3	2	5.2	3
Building penetration loss	10	10	10	10
Link budget	***130.6***	***137.19***	***139.5***	***138.4***

Table 10: Link budget in dB without SNR [22] [4].

Different modulations require different SNRs. To find out what kind of modulation a MT can expect, it is necessary to include the SNR of these modulations in the link budget calculations. Table 28 shows the SNR that was used for each modulation. This gives a link budget with a MAPL-value for each modulation as can be seen in Table 11.

Modulation	WiMAXdown	WiMAXup	HSDPA	HSUPA
QPSK 1/8		133.1		
QPSK 1/2	134.29	127.7	134.9	133.8
QPSK 3/4	130.89	124.3	132.46	131.36
16QAM 1/2	128.59	122	130.27	129.17
16QAM 3/4	124.49	117.9	126.8	125.7
64QAM 1/2	123.39	116.8		
64QAM 3/4	119.19	112.6		

Table 11: Link budget in dB for different modulations.

When the link budgets are available, the range of the RAUs can be found by using a propagation model.

4.4Propagation Model

Propagation models are used to estimate the median path loss in radio channels. There are many propagation models that can estimate the propagation of a radio signal more or less accurate. They may differ in frequency range which they are valid for, and what information it uses as input.

The choice of propagation model for this project was the COST-213 Hata model. It was chosen because it was proven to be expandable to frequencies between 2000 - 3500, and gives the best fit for 3.5 GHz compared to other statistical propagation models [23].

It is important to realize that these models are only an indication of the propagation, as it does not consider features like terrain, height and houses and other obstructions that may reduce the signal strength. If more detailed information about these factors is available to the planner, it is favorable to choose a more advanced model that can include this in the modeling, to get more accurate results.

4.4.1 The COST-231 Hata Model

Several models for radio propagation have been made from extensive measurements in European cities by COST 231. One of them is the COST 231 Hata model. The original Hata model is only valid for frequencies between 150 and 1000 Mhz, but has been extended by COST 231 to 1500 to 2000 Mhz later [24]. Later research has shown it to be useable at frequencies up to 3500 MHz [23]. The validity of the model is constrained to flat terrain. The basic equation for predicting path loss in dB using COST-231 Hata model is shown in Equation 8.

$$PL = 46.3 + 33.9\, log10(f) - 13.82\, log10(hb) – ahm + \big(44.9 - 6.55\, log10(hb)\big) log10\, d + cm + cf$$

Equation 8: Path loss equation.

Where, f is the frequency in MHz, d is the distance between RAU and MT antennas in km. The parameter hb is the RAU antenna height above ground level in meters, and is set to 30 meters in the calculations used in this project. The parameter cm is defined as 0 dB for suburban or open environments and 3 dB for urban environments. The parameter ahm is a correction for the MTs antenna height and is defined for urban environments by Equation 9.

$$ahm = 3.20(log10(11.75hr))2 - 4.97$$

Equation 9: ahm for urban areas.

For suburban or rural environments Equation 10 is used.

$$ahm = (1.1\ log10\ f - 0.7)hr - (1.56\ log10\ f - 0.8)$$

Equation 10: ahm for suburban and rural areas.

Where, hr is the MT's antenna height above ground level. A value of 1.5 meters was used for hr in this project.

Even though it is stated by COST 231 that the model is valid between 1 and 20 km, it will be used to calculate propagation in cells smaller than 1 km during this project. It might be necessary to use a separate model for these cells in a real implementation, to get more accurate results.

Regardless of the model chosen, the correctness should be checked using measurements from similar networks, so that correction factors could be implemented. Since no measurements were available to the group, correction factors for application of the model to suburban and rural areas were taken from [25]. The Rural correction factor (cf) can be found in Equation 11.

$$cf\ =\ -4.78 * log10(f) * log10(f) + 18.33 * log10(f) - 40.94$$

Equation 11: Rural correction factor.

For suburban environments, cf is defined in Equation 12 [25].

$$cf\ =\ -2(log10(f/28.0))(log10(f/28.0)) - 5.4$$

Equation 12: Suburban correction factor.

For urban environments, cf is 0

4.4.2 Cell Ranges

Using the MAPL values from the link budget, and the formulas of the propagation model, the ranges of the cells for each technology can be found. The exception is DBWS, where no link budget-information was available, and a 300 meter range has been assumed. It is important to note that the range found for each technology is for indoor coverage using the lowest modulation of each technology.

The ranges differ for the up and downlink. The reason for this difference in the up and downlink range is that the EIRP is much higher for the downlink than the uplink because of the gains the BS has compared to the antenna gains in the MTs. Table 12 shows the ranges of all the wireless technologies as a result of the link budgets and the propagation model.

	WiMAX down	WiMAX up	HSDPA	HSUPA	DBWS
Urban	0,383	0,355	0,682	0,635	0,3
Sub-urban	1,179	1,091	1,852	1,724	-
Rural	4,911	4,543	6,957	6,475	-

Table 12: Cell ranges in km for each technology according to environment.

When the ranges of the cells are known for all technologies, the next step is to find a method that will automatically generate network plans with locations of BSs.

4.5 Radio Coverage Algorithms

Now the locations of MTs are known as well as the possible locations of RAUs. The ranges of the RAUs have also been calculated. Therefore some way of deciding where to place the RAUs can now be implemented. This chapter describes the methods and assumptions for achieving this.

The reach of each BS is determined by the link budget. It is assumed that the base station is capable of providing adequate service to users within this geographical area. This assumption makes it possible to formulate the cell planning as a "set covering problem" [26]. The objective is to calculate how many of the potential BSs are needed for all MTs to have the required signal strength (i.e. "be covered").

The set covering problem can be formulated mathematically as done in Equation 13 and Equation 14.

$$Minimize\ Z = \sum_{j \in J} x_j$$

Equation 13: Objective function.

$$subject\ to: \\ \sum_{j \in N_i} x_j \geq 1\ \forall\ i \in I, \forall\ j \in J$$

Equation 14: Constraints.

Where

Z number of BSs

J set of potential BS sites (indexed by j)

I set of MTs (indexed by i)

$$x_j = \begin{cases} 1\ if\ BS\ at\ j \\ 0\ otherwise \end{cases}$$

N_i set of BSs j within range of MT i

This definition minimizes the base stations required to cover all MTs. In wireless networks, it is often too expensive to provide coverage for everyone, and it is therefore possible to change the constraint in Equation 14 from "to be valid for all i" to "a fixed percentage of i". This way, the total coverage is not 100% of the nodes, but larger than an agreed upon coverage limit, as seen in Equation 15. In this Equation 15 is the percentage of MTs covered.

$$p \geq coverage\ limit$$

Equation 15: Coverage limit.

Since the problem is NP-hard, it was decided to solve it using heuristic algorithms [78]. This way it is possible to implement this planning method to areas with many MTs and potential BS locations. There are several heuristic methods that can solve the set covering problem. This project will implement a greedy approach, and a genetic algorithm.

4.5.1 Greedy Algorithm

Greedy algorithms are the simplest forms of heuristic algorithms. They work by selecting the optimal local choice at each stage. The benefits of greedy algorithms are that they are simple to implement, and provides a solution fast. The downside is that due to the greedy nature it may get stuck in local optima, thus providing a sub-optimal solution.

The greedy algorithm was implemented in this project for solving the set-cover problem [27]. It starts by selecting the BS that provides the best coverage at the lowest cost (users/cost). It then removes the MTs covered by this BS from the list of MTs that needs to be covered. When the coverage is larger than the coverage constraint, the algorithm terminates. The flow of the algorithm is illustrated in Figure 17. The correction process will be explained in section 4.6.

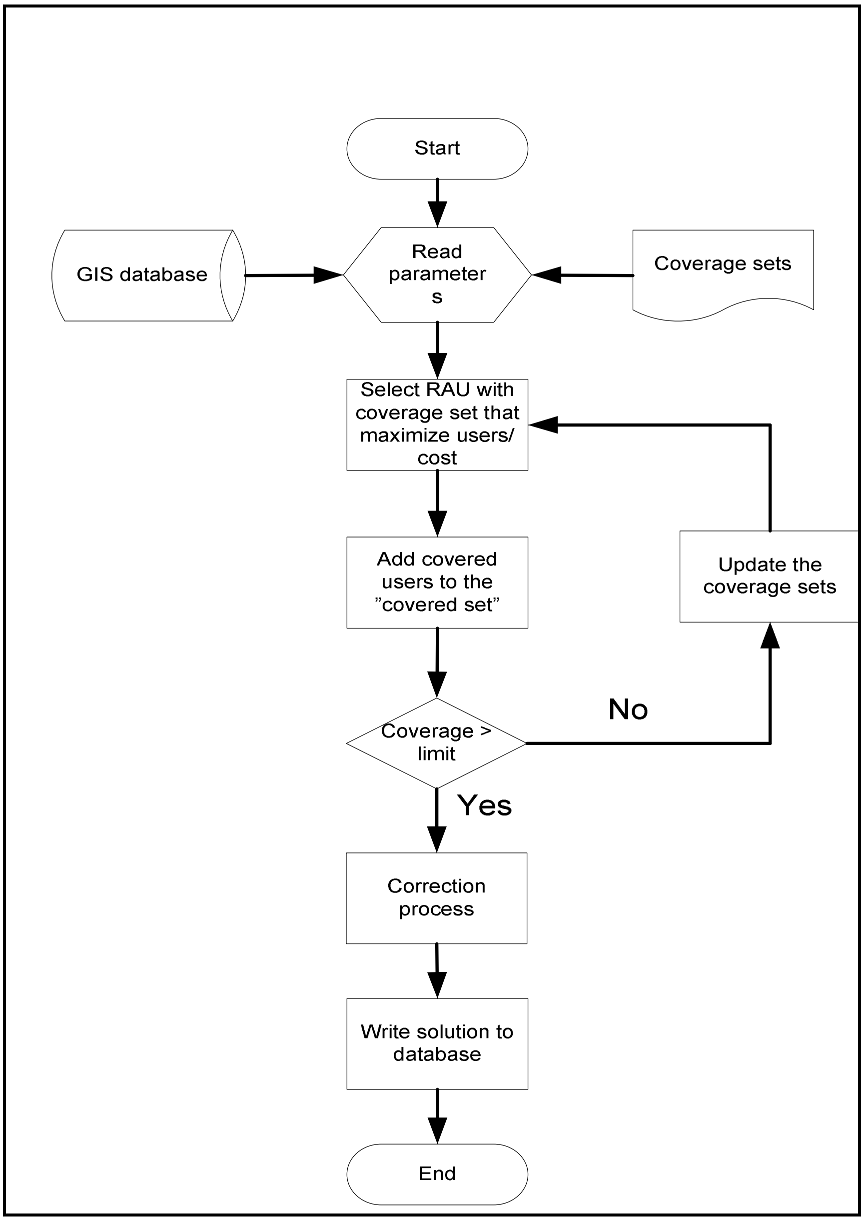


Figure 17: The greedy algorithm for solving the set-cover problem.

To find what MTs are covered by an RAU, coverage sets was made for all RAUs. The coverage sets simply contains the identification numbers of the MTs in range.

When planning radio networks, small cells are preferred. To achieve this, the cost function has to prioritize small cells. The urban BS covers 32% of the area of a suburban BS, and 10.5% of the area of a rural BS. If the cost of an urban BS is set to 10, it means that in order to prioritize smaller BSs, the suburban must cost more than 3.125 times as much, and the rural more than 9.5 times as much. Because of this, the costs are set to 10 for an urban, 32 for a suburban and 96 for a rural BS. These costs can be changed to the planners liking, depending on what cell size is wanted.

4.5.2 Genetic Algorithm

Since the greedy algorithms in many cases create sub-optimal solutions, it was decided to implement another algorithm that could improve the results. The choice fell on the Genetic Algorithm (GA). The GA mimics natural selection and survival of the fittest, by encoding the problem in a chromosome. In GAs a chromosome is a trial solution to the encoded problem, which can be evolved over time by the algorithm.

When the problem is encoded, a pool of initial solutions is made randomly. This solution pool is called population, and the GA works by evolving this pool by improving the solutions it contains. The solution alternatives are rated by a fitness function. The rating is used by a selection mechanism that decides what solutions in the pool should be used as a basis for the next generation of solutions. There are several selection methods possible, but normally the solutions with the best fitness have a higher possibility of making it to the next generation. When the parents are selected, they generate "children" using genetic operations such as mutation and crossover on the parents. The children go into the next generation of solutions. This way, the algorithm produces better and better results. For more details on the different parts of the genetic algorithm and how it works, see appendix 7.

The advantages of the genetic algorithm are that it scans large parts of the solution space, and through evolution produce better and better solutions. The mutation operator should introduce randomness into the solution space, to avoid getting stuck in local optima. The disadvantages are that the solution is only as good as the computation time given. Unfortunately large solution spaces may take too long to search, and it might therefore be necessary to settle for a sub-optimal solution. It might also be the case that solutions closer to the global optimum are eliminated from the population, because the local optimum looks better. In these cases the algorithm may produce sub-optimal results.

The genetic algorithm is implemented here to solve the set cover problem described in the beginning of section 0. The problem is encoded in a chromosome, using binary encoding with one bit for each possible RAU location. This gives a chromosome with 1's representing active RAUs, and 0's representing non-active RAUs. The population contains 10 solutions, and the fitness score for each solution is calculated in the fitness function. The fitness for a solution is calculated as the sum of the cost for all active RAUs in the solution. The cost for each RAU is the same as used in the greedy algorithm. If the coverage of a solution is lower than the coverage limit, it is given the highest possible cost, since it is not a valid solution. Elitism is used whenever a new generation is made, so as not to move away from the best looking solution. Apart from elitism, roulette selection is used as the selection technique, while mutation and crossover is the reproduction operators. The reproduction operator is chosen by a comparing a uniformly random variable to a pre-set limit. This limit can be experimented with for performance. Figure 18 shows the flow of the implementation of the genetic algorithm for this project.

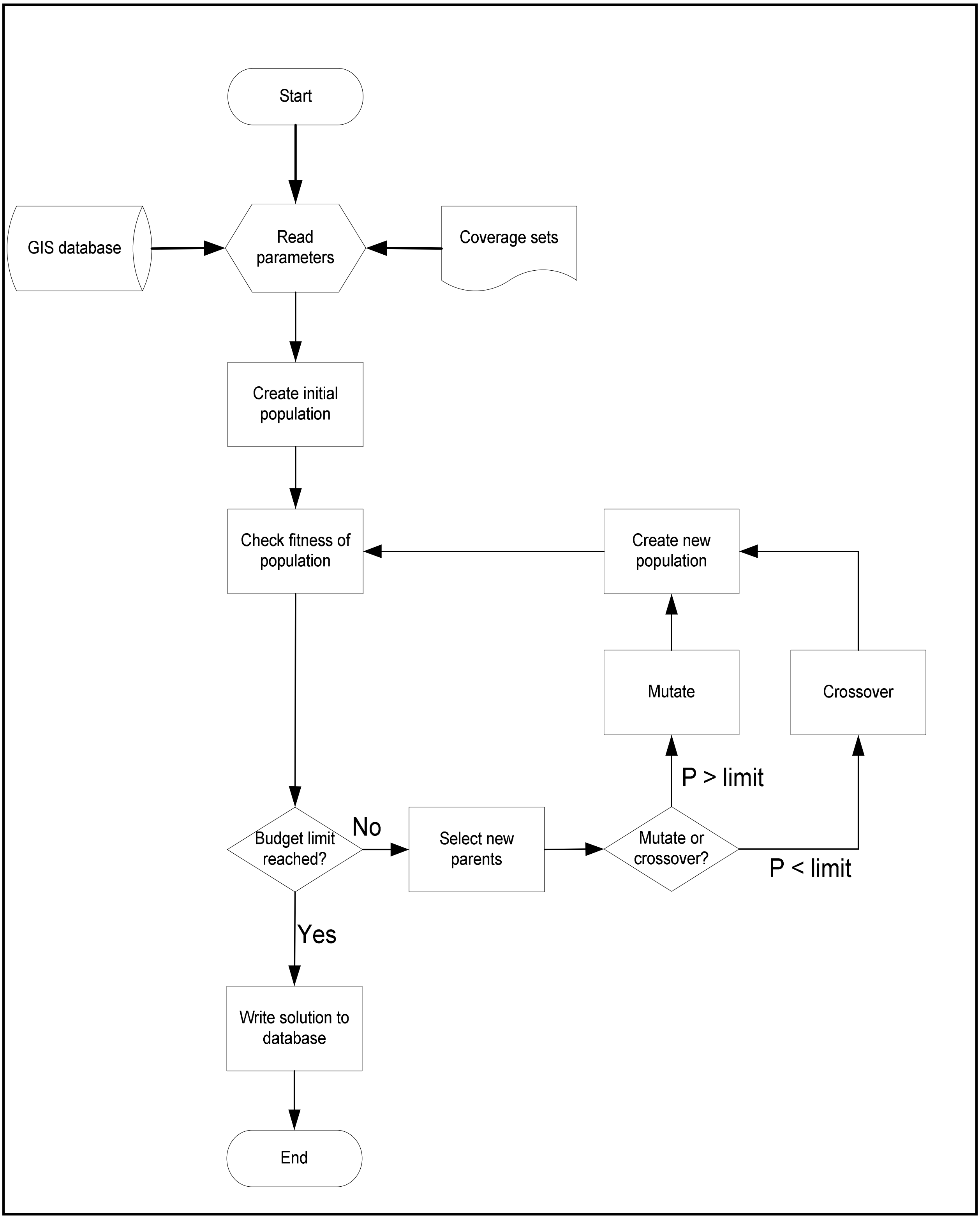


Figure 18: Genetic algorithm for solving the set-cover problem.

4.6 Implementation and First Results

When running the GA-program it quickly became clear that the GA runs to slow to be useable on its own. Execution time is more than 2 days for 200 000 generations on GA, compared to a running time of 1 minute on the greedy algorithm on a 2Ghz core. Even after this long running time, the GA does not produce better results than the greedy algorithm. The long computation time on the genetic algorithm is due to a computationally expensive fitness function. The slow convergence can be explained by the large state space. The table of possible RAU-locations contains more than 1700 locations. This performance could be enhanced by experimenting with genetic parameters like mutation probability, choosing another selection scheme, adjusting the fitness function or including other search methods in the GA [29].

The greedy algorithm proved to be fast, and provided results with lower costs than the genetic algorithm could provide in much longer time. However, by taking a closer look at the results of the greedy algorithm it became apparent that further optimization is still possible. Figure 19 shows how an area is covered by three RAUs, when it clearly could be covered by a single RAU.

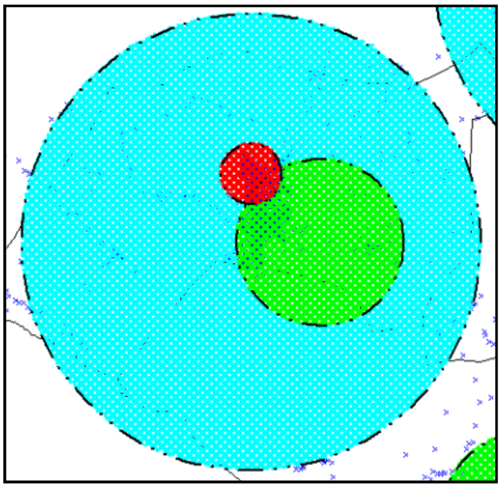


Figure 19: Sub-optimal solutions of greedy algorithm.

A solution to minimize these two problems was to first run the greedy algorithm to provide a fast sub-optimal solution. After this, a correction process is run on the solution, to remove the multiple covered areas. Then the GA is run for 20 000 generations on the solution, to see if it can improve it further.

Another problem that becomes obvious in Figure 19 is the fact that in some areas the assignment of environment to the RAUs might not be correct. This leads to an “urban” area being covered by signals from a “rural” RAU. In real life however, the signals would not reach into the urban area due to increased path loss in these environments. In lack of more detailed propagation models and GIS-data, this was however considered an acceptable approximation, since this flaw does not affect the correctness of the method itself, and can be made more accurate with a proper propagation model.

When the program was working, the only thing left to do before finding final radio coverage results is to decide on a percentage of users to cover.

4.6.1 Choosing Coverage Area

Normally, an ISP will decide on how many percent of the users or area to cover. Figure 20 shows the 3G internet coverage in Denmark by post-numbers. From this picture it can be seen that the coverage varies a lot. The trend is that the most populated areas have the best coverage. The picture shows accumulated coverage from four 3G operators.

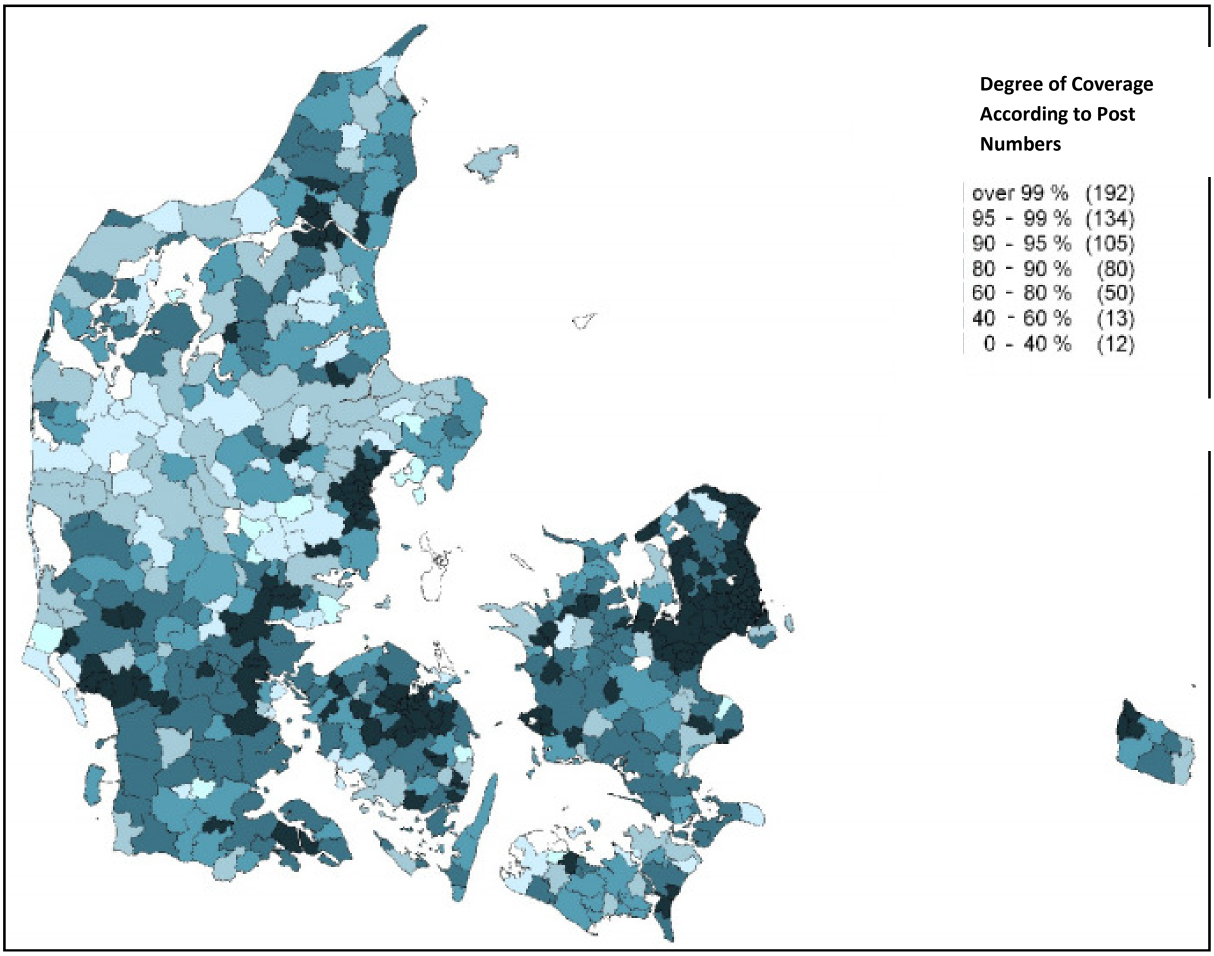


Figure 20: Wireless internet coverage in Denmark by postnumbers [29].

To find a reasonable coverage area, some trials to see the impact of coverage were made. Three alternatives was tried out, covering 95, 97 and 99% coverage of the MTs. Figure 21 shows how this affected the number of RAUs needed to provide this coverage, using the WiMAX technology.

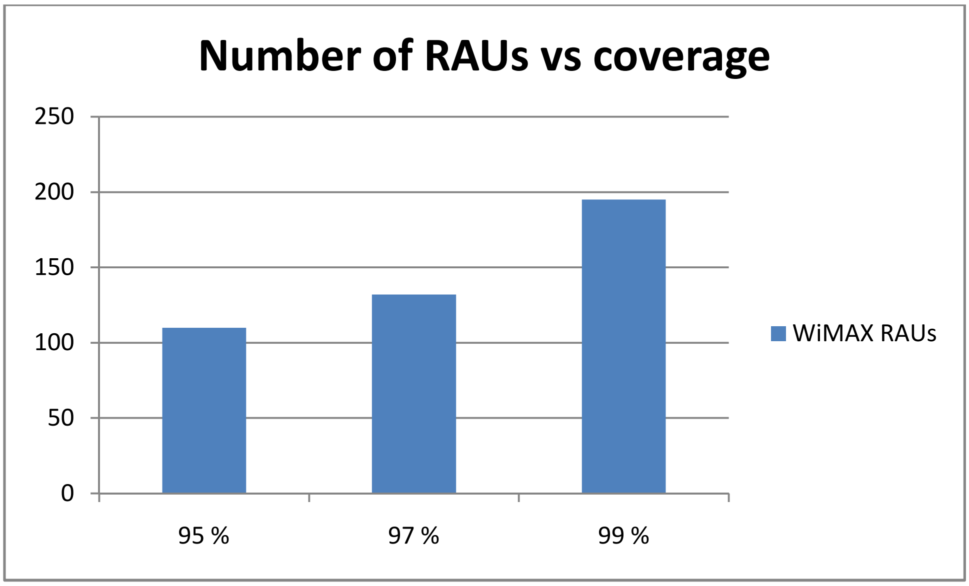


Figure 21: Needed RAUs for 95, 97 and 99% indoor coverage.

Coverage maps showing how this affected the geographical area of coverage was also made for the three technologies, and can be found in appendix 9 on the attached CD. It was decided to assume that the WISPs all wanted to provide indoor coverage to 97% of the MTs in Aalborg municipality.

It becomes clear from these maps that are shown in appendix 9 that even though 97% of the MTs are covered, it does not mean that 97% of the area is covered. It is however important to remember that the coverage planned is indoor coverage. The outdoor coverage is much larger, since the signal does not have to propagate through walls. This is important, because 4G networks are supposed to provide mobility for the users, which means that it becomes vital to provide full coverage for the area.

4.7 Final Radio Planning Results

Now the coverage has been decided, the possible RAU-locations have been found and the range of each site has been found. It is now possible to calculate what RAUs need to be active to cover the decided number of MTs. The assumptions and setup of the solutions can be summarized in these bullet-points:

- Coverage of 97% of the MTs for each network
- Solved by greedy and 20 000 generations of GA
- RAU range for each technology and environment found by Cost 231 Hata model
- Each RAU successfully covers all MTs within its range

4.7.1 3G Results

The 3G indoor coverage can be seen in Figure 22. It can be seen that even though over 97% of MTs are covered the geographical coverage is not 97% of the area. The most densely populated areas are covered while many of the rural areas don't get indoor coverage. The solution from the greedy algorithm required 43 RAUs, but the GA reduced it to 40 RAUs in 7 hours (20 000 generations) on a 2Ghz core. This is a reduction of 7%.

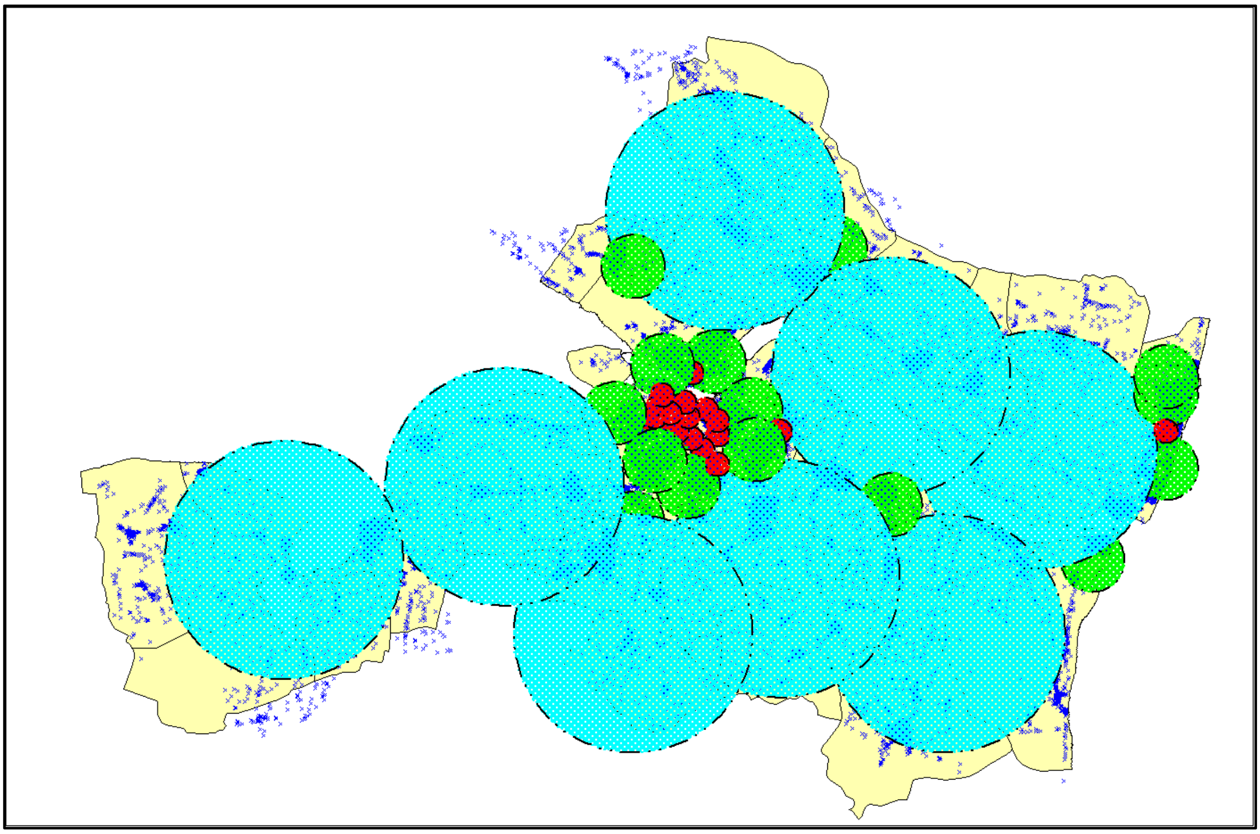


Figure 22: Coverage map for 97% indoor coverage for 3G. Blue circles = rural BS, green circle = suburban BS, red circle = urban BS.

The outdoor coverage can be seen in Figure 23. This shows that the whole area is covered for outdoors where wireless mobility is most likely to be needed.

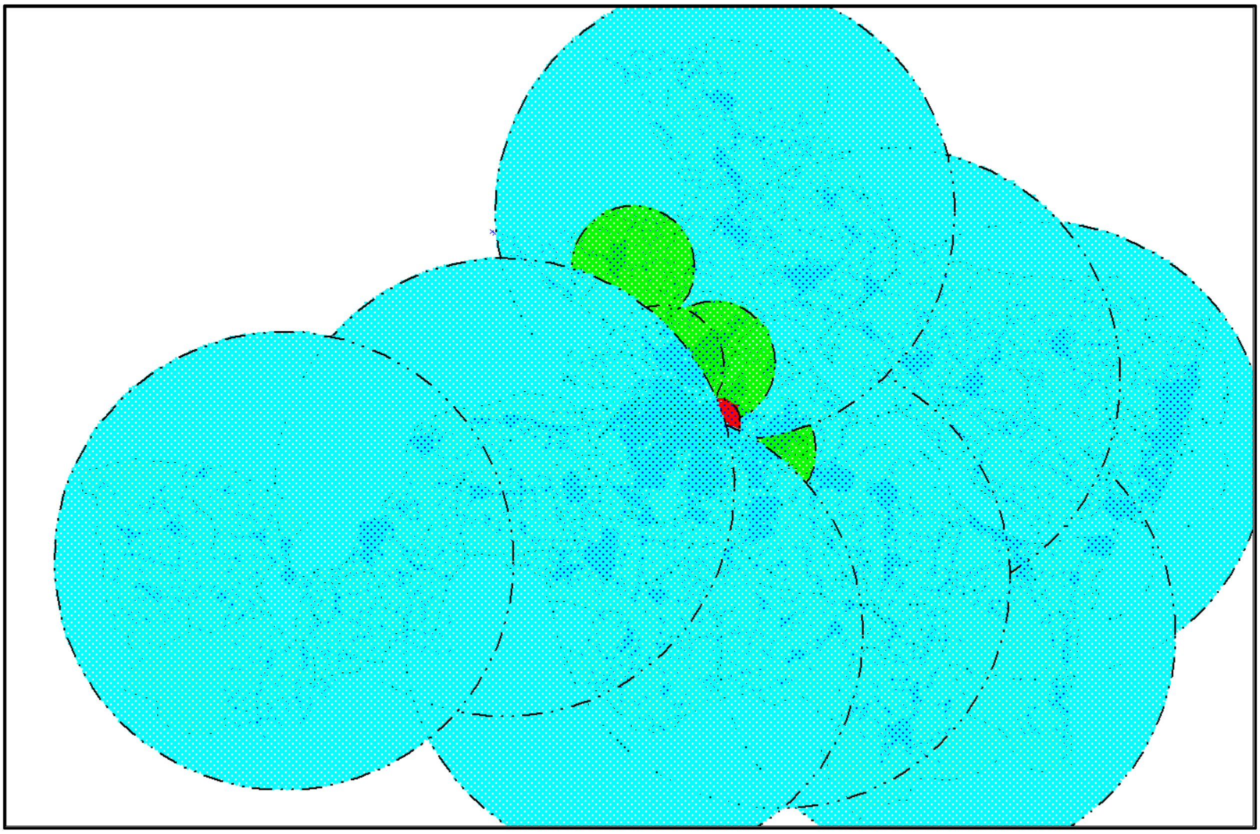


Figure 23: Coverage map for 100% outdoor coverage for 3G. Blue circles = rural BS, green circle = suburban BS, red circle = urban BS.

4.7.2 WiMAX Results

Mobile WiMAX has shorter range than 3G and the solution therefore requires more RAUs to provide coverage to the same amount of MTs. The coverage of indoor WiMAX can be seen in Figure 24. The solution requires 132 RAUs to cover 97% of the MTs. The GA could not improve these results in 20 000 generations.

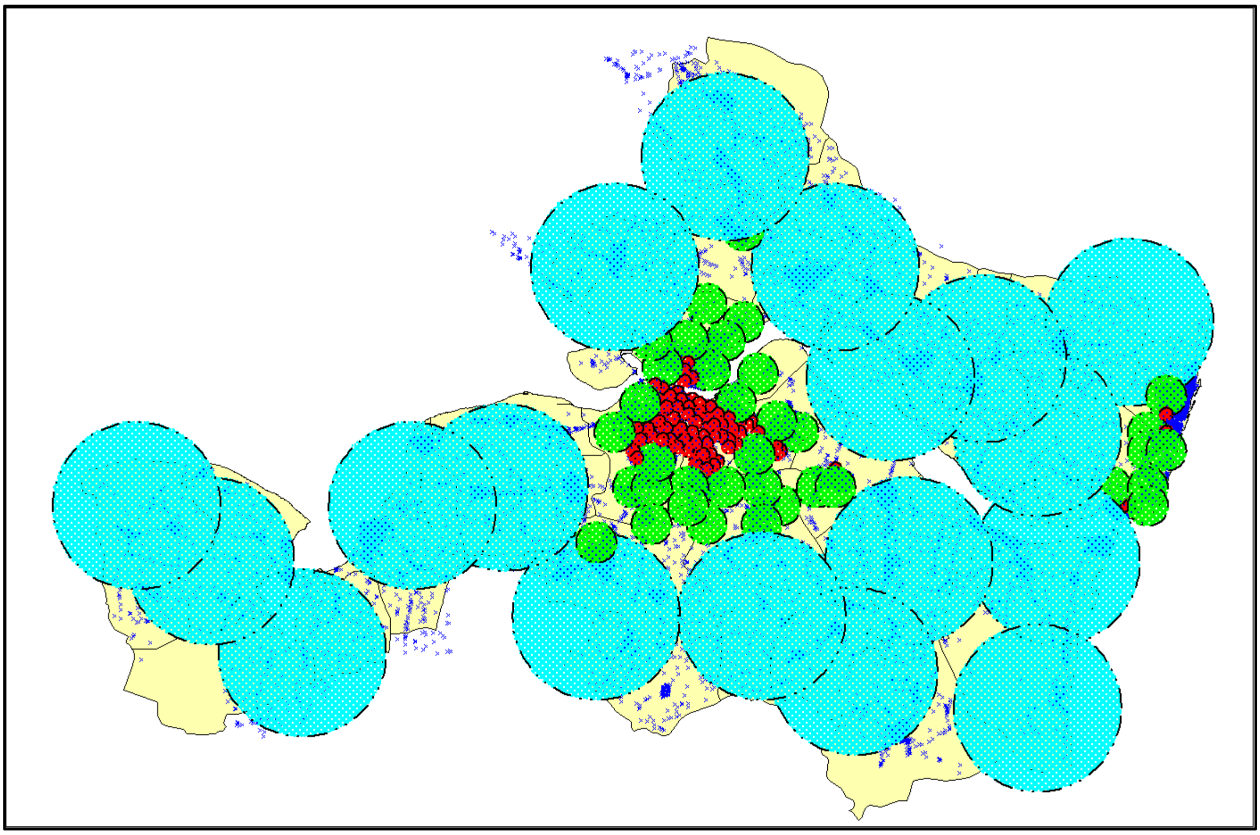


Figure 24: Coverage map for 97% indoor coverage for WiMAX. Blue circles = rural BS, green circle = suburban BS, red circle = urban BS

It can also be seen vieiwing the coverage plots found appendix 9 that the outdoor coverage for WiMAX covers the whole area.

4.7.3 DBWS Results

The planning algorithms try to reuse sites where other wireless technologies have already been deployed to save costs when the DBWS is planned. The indoor coverage of DBWS can be seen in Figure 25. The range of the cells is only 300 meters, which means that a high amount of RAUs is required. The solution requires 162 RAUs. Of these, 69 RAUs are only used for the DBWS, and 3 RAUs have all three technologies in use. The rest has either 3G or WiMAX and the DBWS. The GA could not improve this result in 20 000 generations.

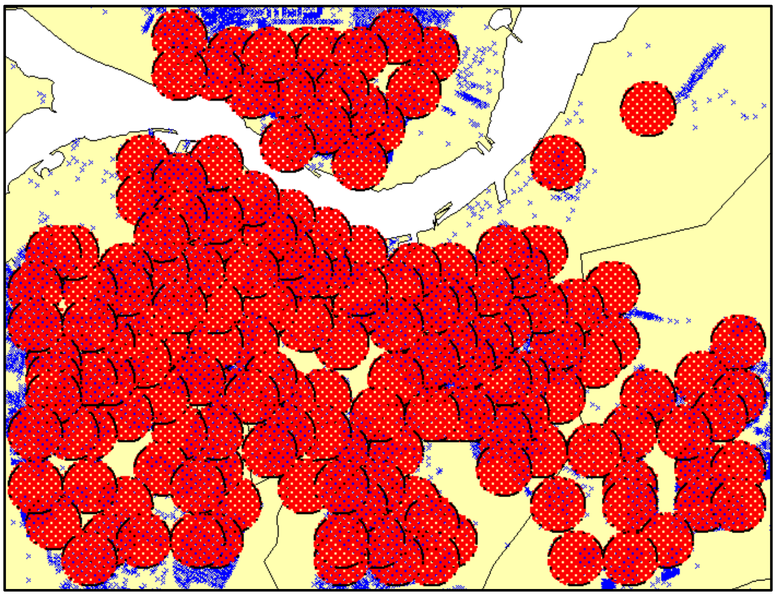


Figure 25: DBWS coverage in the downtown area of Aalborg.

Using the MIMO schemes mentioned in section 2.4.3.2, this leads to 1.5% of the users receiving matrix A service, 89.5% matrix B service, 6.1% gets regular service and 2.9% gets no DBWS service.

In fiber-planning, the three wireless networks planned in this chapter will be connected in a common architecture. The BSs of 3G, WiMAX and the DBWS will then be replaced by the transparent multi-frequency RAUs. The total number of RAUs needed in the Aalborg municipality is 233. This means that 40% of the locations are used by two or more technologies. The locations of the RAUs can be seen in Figure 26. It can be seen that the RAUs with two or more technologies are mostly located in the urban area of Aalborg.

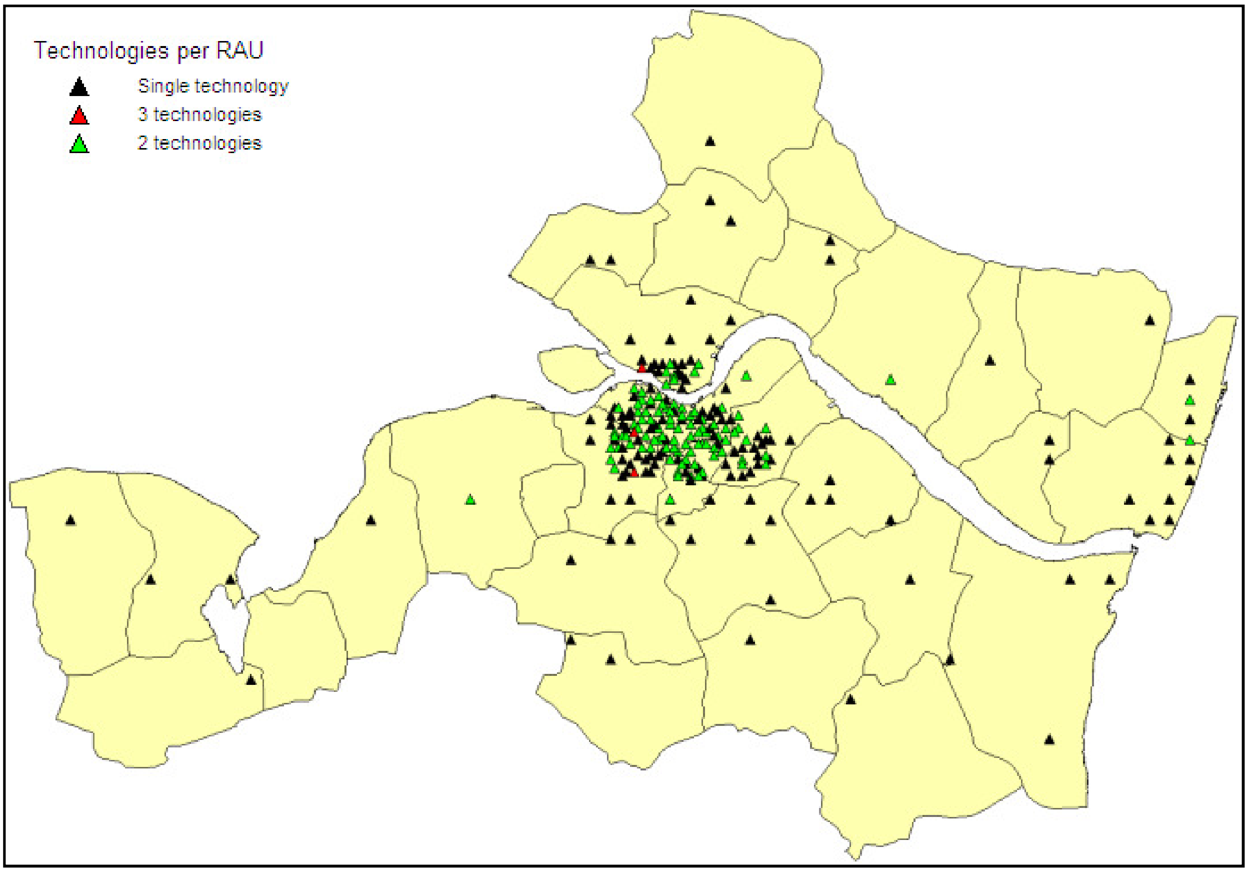


Figure 26: RAU locations and technologies per RAU.

4.8Discussion of Chapter 4 Results

It is possible to find the range of wireless BS by calculating the link budget and using it with a propagation model. The ranges and locations of potential RAUs can be used to create coverage sets for all RAUs.

By formulating the radio coverage planning as a set-cover problem, it is possible to automatically generate results and plans for the entire area, using heuristic methods to find the RAU-locations. The GA can in some cases improve the results created by the greedy algorithm, and would therefore be needed in situations where cost is critical. The implementation of the GA on its own uses too long time to be of any practical use.

Coverage plans for 3G, WiMAX and DBWS was made automatically using these methods. Each covers 97% of the area, but due to the short range of WiMAX it requires many RAUs compared to 3G. The DBWS planning reuses the locations of 3G and WiMAX firsts, and then adds the additional RAUs needed to provide 97% coverage of the downtown area. 89.5% of the users of this network would receive improved bandwidth due to the assumed MIMO schemes. The total number of RAUs that will need to be connected in the FUTON architecture is 233, which is 40% less than if the three networks were deployed separately. The 233 locations will be equipped with a multi-frequency RAU, that will further reduce the cost. The radio signal processing will be done in the CUs. The locations of the CUs will be planned in Chapter 5: CU-placement.

Even though the indoor coverage is 97% of the MTs, and even less of the area, the resulting outdoor coverage is 100% of the area. This means that the networks are able to provide mobility for outdoor users. The planning method does however not incorporate the outdoor coverage, but it is a result of the outdoor coverage being better due to the fact that the signal does not have to penetrate buildings. A method that ensures that 100% coverage of the outdoor area is considered one of the interesting subjects for further work.

This method of planning is able to quickly automate a sub-optimal solution with the greedy algorithm, which can be optimized using GA or other optimization algorithms. It can also be used as a basis of manually planned solutions. Due to the inaccuracy of the propagation model used in this project the coverage area of each BS might be unrealistic. The results of the automated planning would therefore be more realistic if using more detailed propagation models to get more accurate information about the coverage area of each RAU.

4.9Summary

This chapter has explained the steps taken in this project to plan radio coverage to the Aalborg municipality using 3G, WiMAX and the DBWS. The distributions of potential users and RAUs were made, and used together with the link budget and propagation model, to make coverage sets for each RAU. These coverage sets were used with the GA and greedy algorithms to automatically plan solutions for the three networks. The three networks and their RAUs will be used further in the thesis, to plan the fiber-optic infrastructure and the location of the CUs.

5 CU-placement

When radio coverage planning is done, it is necessary to find out where in the municipality the CUs should be located. The FUTON project does not specify how many RAUs can be connected to each CU, and it is assumed that each CU can be fitted with as many JPU's as needed to handle the amount of RAUs. It is however important to spread the CU-locations out geographically, so as to have redundancy in case of a failure. It is also desired to have the number of RAUs distributed evenly amongst the CUs, to achieve a more even traffic load.

Like with RAU placement, it is likely that in a real implementation the operator would have some locations that are suitable and available for this use. The considerations when choosing locations for the CUs are similar to the considerations made when placing main nodes and distribution nodes in regular IP networks. Factors like backbone-connectivity, accessibility, power supply, physical firewalls and security are important. Because of this, the operators might consider using common locations as their main and distribution nodes for the CUs. Since the locations of these nodes are unknown for the three wireless networks planned in this project, it is assumed that each RAU-location can be thought of as a possible CU location.

It is possible to solve this problem in a similar manner as the radio planning, by looking at it as a set-cover problem. In this case it is necessary to find out how many of the RAU-locations needs to have a CU in place, in order to provide a CU-connection for all RAUs. The distance of a CU is limited by the max distance of the fiber-connection between the CUs and RAUs, which is a result of what fiber optic scenario from section 3.2.3 is chosen. It can therefore be said that each CU "covers" the RAU's within this distance. To account for the fact that fibers are laid in trenches, the common rule of thumb of getting from Euclidian distance to wired distance is applied [30]. This rule can be seen in Equation 16.

$$Wired\ distance = \frac{Euclidian\ distance}{\sqrt{2}}$$

Equation 16: Wired distance [30].

In the urban area of Aalborg however, there are many RAUs within range of one CU, which is undesirable when planning networks, as an evenly distributed network is wanted. For this reason an upper limit of the 50 closest RAUs was set in the coverage sets.

A solution is made in a similar manner as with the radio coverage, by first running a greedy algorithm that assigns a CU at the RAU that has the most RAUs within the wired distance. This is run until all RAUs are within range of a CU. It does this until all RAUs are covered. It then runs a GA on the result from the greedy algorithm. The GA shifts the CUs around amongst the RAUs to minimize the variance of the number of RAUs covered by each CU. This is done so that the number of RAUs per CU will be as evenly distributed as possible. This is desirable to achieve an even traffic load in the network, so as to minimize the chances of congestion. For more details on how this works, the commented source code can be found in appendix 10 on the attached CD.

After the CUs have been placed, each RAU is then assigned to the closest CU using a path-finding algorithm to find best path from CU to RAU using the segment information in the GIS-database.

5.1 Path-finding and the A* Algorithm

To make the path-finding as fast as possible, it was necessary to reduce the complexity of the available GIS-data by removing redundant information. The GIS database contains information on segments (small pieces of road), and segment points, which are the points where the segments interconnect. The segment database contains many segment points that have a degree of 2. All these segment points are there to make the GIS-data geographically correct, but for the purpose of network planning, it is redundant information. These points can therefore be removed without loss of information. The SPs with degree 2 is removed, and the new segment has a length equal to the sum of the replaced segments. This procedure is illustrated in Figure 27, and described in more detail in appendix 6.

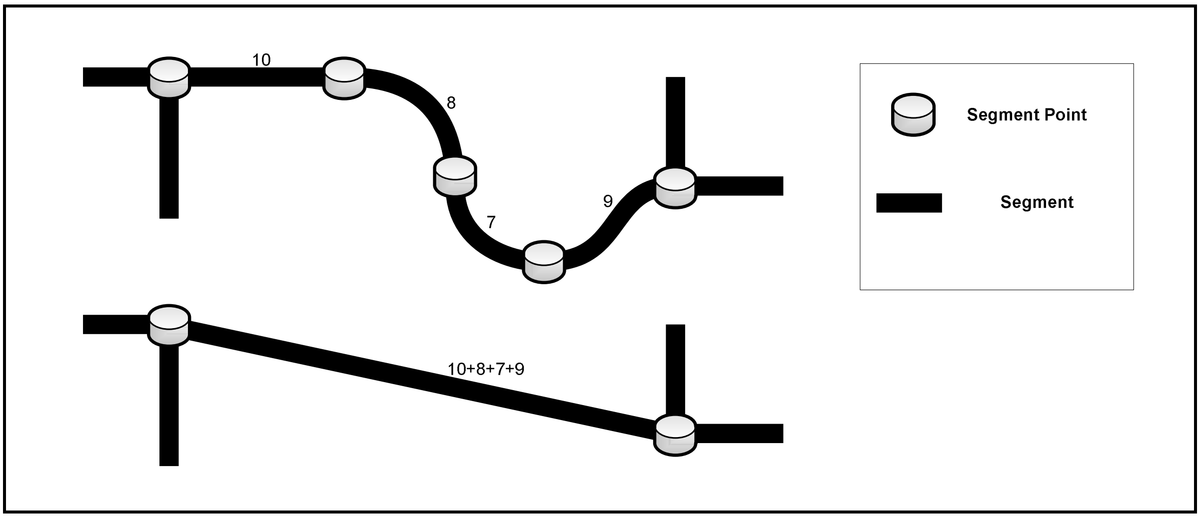


Figure 27: Segment table reduction.

The Dijkstras shortest path algorithm was originally implemented as the path-finding algorithm. Even though the segment-database was reduced, the calculation time for a path was very time-consuming. In order to improve the performance, only the features needed to perform path-finding was imported from the database and read to memory, the segment information was then accessed from there. This improved performance, by reducing the search time for a specific segment approximately 10 times. The overall performance was still too time-consuming, having in mind the short time-frame of the project.

For this reason it was necessary to look for a faster algorithm. The choice fell on the A* search algorithm, which like Dijkstra gives optimal results, but promises to be faster, since it is a guided search [32]. The condition for A* to give an optimal result is that the heuristic cost function never over estimates the actual cost of reaching the target. Both algorithms were implemented, and the difference in speed is quite large, since Dijkstras searches all possible paths until the target is found in one of them. A* on the other hand limits its search space by using the estimated cost to a goal vertex, which guides the search in the right direction and therefore solves it faster. To illustrate the difference, some tests were made by comparing the computation time of both algorithms on a 1.6 Ghz core, with 2GB of RAM available. Three tests were made, in order to eliminate random behavior. The results of these tests can be seen in Table 13.

Test	Path-length [m]	Hops	Mean A* [s]	Std-dev A* [s]	Mean Dijkstra [s]	Std-dev Dijkstra [s]
1	3066	2	0.08	0.00	0.18	0.01
2	3100	18	2.0	0.05	18.1	0.3
3	42177	132	62.5	1.0	710.9	3.7
4	44690	188	308.8	3.2	687.0	5.9

Table 13: Example results of path-finding algorithms.

It can be seen from Table 13 that the computation time for both algorithms is very much dependent on number of hops. The A* is consistently faster than Dijkstras, and the longest performance improvements are seen in similar situations as test 3, where the heuristic cost function is a good estimate of the actual path. In situations where the path goes through the city center as in test 4, the difference is lower since the A* also will have to search many possible paths in the dense city centre. Given that they both produce the same (optimal) result, the A* is a clear choice for use as a path-finding algorithm.

The A* search uses two cost functions in order to find the shortest path: cost of getting to current location, and estimated cost of getting from current location to the goal. In this project, the cost of getting to the location is the length of the segments travelled, and the estimated cost to goal is the Euclidian distance.

For information on both the Dijkstra and A* algorithm, see appendix 2. Information on the implementation done in this project can be seen in the source code in appendix 10 on the attached CD.

5.2 Results

The solution made with the automatic placement requires 11 CUs. Even though the GA tries to equalize the variance in the number of RAUs covered by a CU, it has a standard-deviation of 30. The positions of the CUs and its assigned RAUs can be seen in Figure 28.

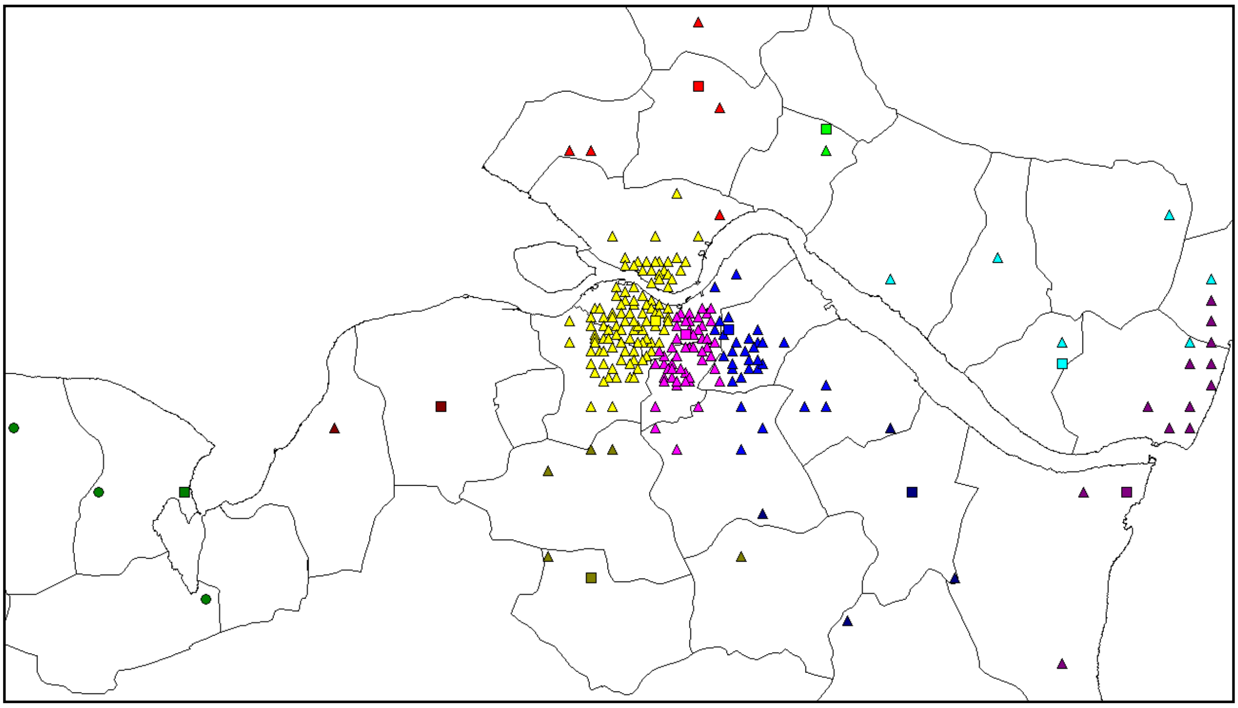


Figure 28: Automatic CU placement.

It was apparent that the solution had flaws, like assigning RAUs on both sides of the Limfjord in the Hals-area to the same CU. This would probably not have been done in a regular implementation, as laying cables in the water is more expensive than laying them along roads. On the other hand, it is likely that there already are ducts with cables in this area, and that the fiber only needs to be blown through. This will make it cheaper. It also seemed that the RAUs could be distributed better amongst the CUs. It was therefore decided to make a manual placement of the CUs, and see which of the solutions provided the best results for the upcoming fiber planning, and eventually the traffic dimensioning.

The manually made solution also requires 11 CUs, to make the two solutions comparable. When placing the CUs, the focus was on making the RAUs more evenly distributed amongst the CUs. The results for this solution have a standard-deviation reduced to 14.5.

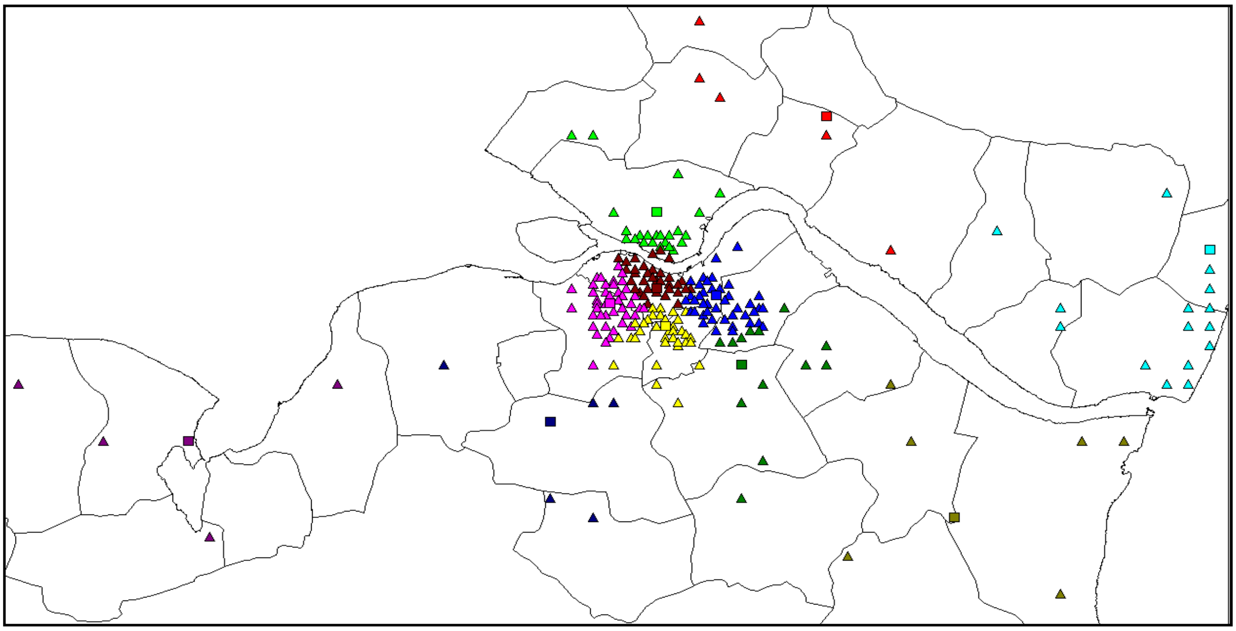


Figure 29: Manual CU placement.

It can be seen that three RAUs are still assigned to the “wrong” CU down town Aalborg. In this area there is a bridge however, which makes it cheaper than laying the fibers in the water. In a real implementation however, accurate costs of using regular roads, bridges, tunnels and water could be investigated, and used in the path-finding algorithm. This way, the path-finding algorithm would try to find other solutions, if crossing the fjord is expensive. This was however left for future work in this project.

When the CUs are placed, it is necessary to perform the fiber planning, which deals with where to place the fiber connecting the RAUs to the CUs, and the CUs to each other.

5.3 Discussion of Chapter 5 Results

The automatic CU placement was done using a combination of Greedy and GA for the set-cover problem. The RAU positions were used as potential CU locations, and “cover” the RAUs within a distance of the RAU. This distance is defined as the fiber length in section 3.2.3 divided by the square root of 2. The RAUs are assigned to its closest CU using a path-finding algorithm. Originally the Dijkstra-algorithm was implemented for this, but the A* proved to have a major advantage in speed, in some cases more than 11 times faster. Since they both provide optimal results, the A* should be the clear choice.

The automatically planned solution still has room for improvement since it was found that the standard deviation of RAUs per CU seems to be high. A manual solution is therefore planned using the same number of CUs that were placed in the automatic solution in order to compare the two solutions in the upcoming fiber planning and capacity dimensioning.

To avoid RAUs being assigned to a CU on the other side of the Limfjord, the real cost of laying fiber across the fjord could be used in the path-finding algorithm.

Due to the sub-optimal solutions of the automatic CU placement program, it seems that the way CU placement is implemented in this project has a lot of room for improvement. This is therefore one of the subjects that are interesting for further work.

For more on implementation see appendix 1.

5.4 Summary

This chapter showed the steps taken in the planning of CU-placement. Using a modified version of the GA from chapter 4, the CUs were automatically placed. The result however did not seem optimal, so a manual solution was also made. The manual solution can then be compared to the automatic solution in the fiber planning chapter. The A* algorithm was introduced as the path-finding algorithm.

When the CUs are placed, it is possible to start planning the fiber networks from CU to CU and CU to RAU.

6 Fiber Planning

When the Cell Planning is done and the CUs are placed, the RAUs need to be connected to the CUs. Also, the CUs need to be interconnected. This chapter of the thesis will discuss the steps taken to plan the layout of the fiber-network, together with the necessary assumptions.

The objective of the fiber planning stage is to minimize the fiber and trenches lengths needed to connect RAUs with the CUs as well as interconnecting the CUs because the costs for fiber and digging to lay trenches are considered to be expensive [32]. It is assumed that there is no available infrastructure for the deployment in the region. This means that the planning assumes that no fibers or trenches are available for use in this project. In a real implementation it might decrease the cost of the total project if parts of the original infrastructure were available for reuse. This could be included in the path-finding algorithm, by assigning a lower cost to the segments with already utilized infrastructure. In this project however, this is left for future work.

When finding the distance between RAUs, the path-finding algorithm is used. It utilizes the segment information of the GIS-database to determine the optimal path. There is however usually no segment points at the exact same location as the RAUs and CUs. In these cases the Euclidian distance from the RAU or CU to the closest segment point is used, and added to the length found by the path-finding algorithm. On the visual plots of the paths, only the parts of the path traversing the segments can be seen.

6.1 Connecting RAUs to the CUs

When the CU-placement was done, each RAU was assigned to one of the CUs. This chapter will describe the planning of these connections.

For the fiber-planning scenarios, the fiber length is restricted to a defined number of kilometers, based on the fiber optic scenario chosen in section 3.2.3. While it is important to keep this information in mind when planning solutions, it is not an absolute value. It is possible to add optical amplifiers along the path to extend the range at an added cost. A more detailed survey comparing the costs of optical amplifiers versus providing separate trenches, fibers and more CUs must be done in order to set clear boundaries on this. For this project however, the range is only used as a guideline for determining the number of CUs necessary.

A factor that further reduces the practical length of an optical signal is optical splitters [75]. Since the Tree-topology is being used, it is necessary to use splitters. These splitters affect the optical link budget, shortening the range. A survey investigating the costs of splitting (and amplifying where needed) versus providing separate fiber cables could be made, but is left for future work.

The FUTON project specifies the tree topology as a likely topology for this part of the network. The planning is therefore focused on using trees to connect each RAU to its assigned CU. Even though the RAUs are connected to the CU physically in a tree-topology, the logical connection will be point to point, due to the WDM as seen in Figure 30.

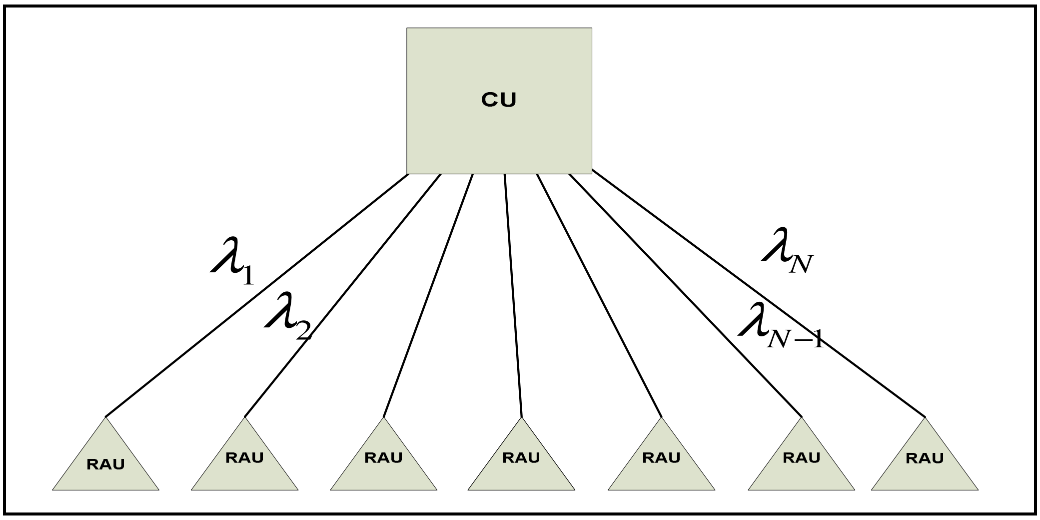


Figure 30: Logical topology.

In order to minimize the total amount of trenches needed, it was decided to create Minimum Spanning Trees (MSTs) for each CU and its assigned RAUs, using an implementation of Prim's MST-algorithm.

6.1.1 Prim's Minimum Spanning Tree Algorithm

An MST is a sub graph containing a spanning tree whose sum of weights is a minimum. Prims algorithm builds a tree from the root vertex, selecting the closest vertex in every step and adding it to the tree [33]. This procedure can be seen in Figure 31, where the red segment is added to the tree in every step, until all RAUs are in the tree. To find the closest RAU in every step, the A*algorithm introduced in Section 5.1 is used.

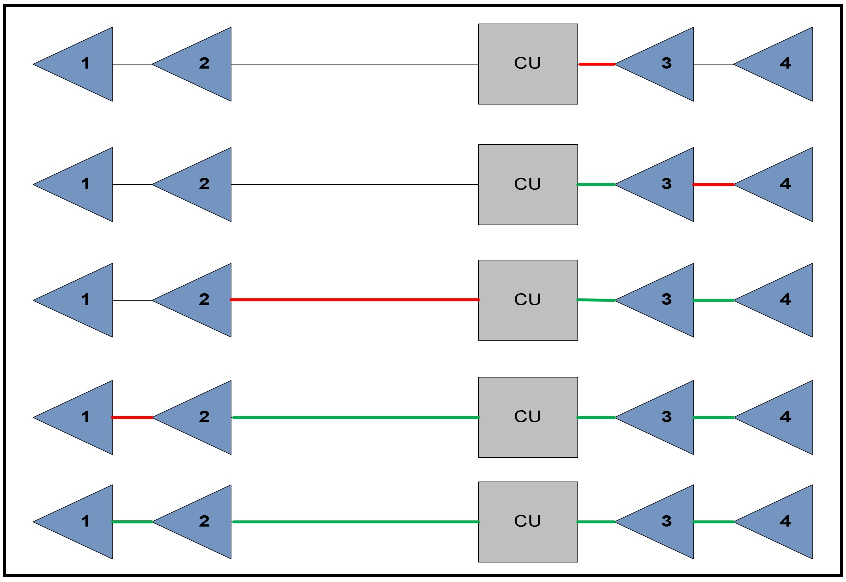


Figure 31: The MST algorithm.

When building the MSTs, some decisions needs to be made regarding the planning rules. Figure 32 shows some of the dilemmas that can occur when creating the MSTs. In this figure an MST is being built from the CU to the blue RAUs, which are within the CUs "range". The maximum range in this example is 15. RAUs 1, 2 and 3 are added according to the MST algorithm, but when RAU 4 is being added, there are three choices:

A. It will be added to the existing branch and exceed maximum range
B. It will get its own branch
C. It will be added to the tree of the other CU

The least length of trenches would be achieved by option C, since RAU 5 is the closest to RAU 4. This option will however never be considered, since the RAU is already assigned to CU A. An interesting topic for future work could therefore be to look at how the RAUs are assigned, or implement a correction algorithm, that fixes problems where they occur.

Option B is what would happen if a strict maximum range on the fiber length is used. In this case it would be impossible or too expensive to amplify the optical signal after RAU 3, so RAU 4 would have to get its own trench directly from the CU.

Option A is what is implemented in the programs for this project. RAU 4 will be added to the existing tree, even though the total distance from the CU exceeds the range of the fiber optical scenario from section 3.2.3. It is assumed that the optical signal can be amplified, to enable communication from RAU 4 to the CU.

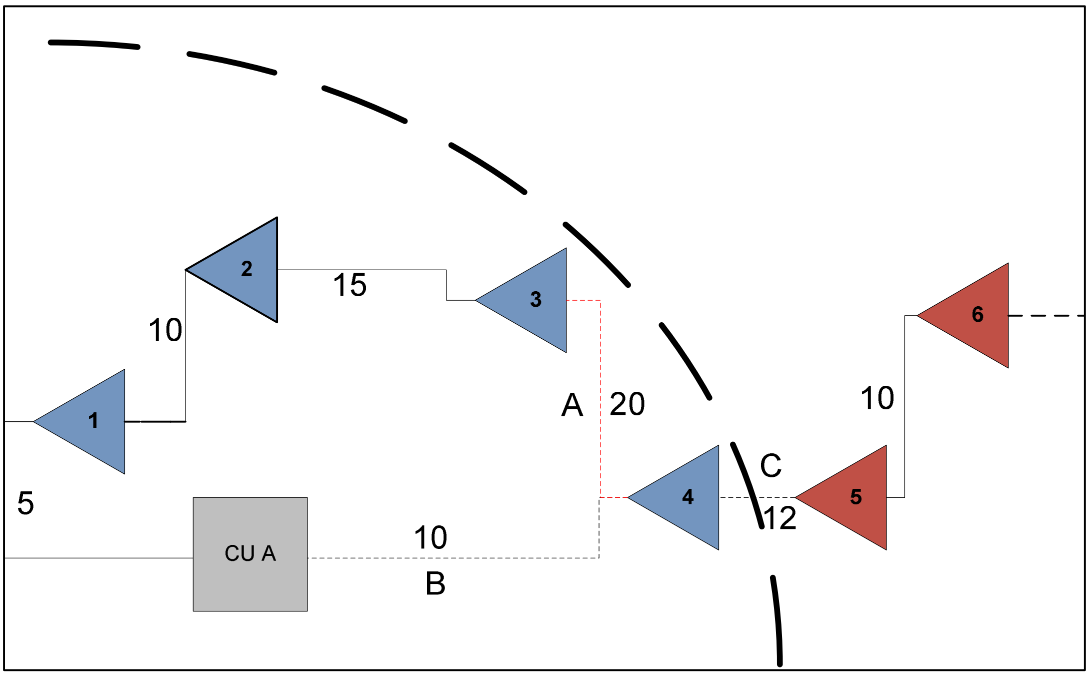


Figure 32: Issues when creating MSTs.

6.1.2 Calculating Amount of Fibers Needed

When a tree is made, it is necessary to calculate how many fibers are needed in each trench, so that every RAU has a channel assigned on the fiber. It is needed to optimize this assignment of fibers, so that the total amount of fiber-length is minimized. The number of RAUs supported by a fiber is depending on the fiber-scenario being deployed, as explained in chapter 3.2.3. In order to find the shortest needed fiber length, a small GA (see appendix 7) was implemented. The GA works by shifting the assignment of RAUs around, in order to find what solution gives the shortest needed fiber length.

To illustrate this, the example in Figure 33 shows how the GA tries different combinations of fiber assignment. In Solution 1, RAU 1 and 4 are assigned to fiber B, and RAU 2 and 3 to fiber A. In Solution 2, RAU 1 and 3 are assigned to fiber B and RAU 2 and 4 are assigned to fiber A. From this it can be seen that Solution 2 requires the least total fiber length, since it only requires one fiber in each branch, while Solution 1 requires 2 fibers to RAU 1 and 2. When the GA is finished, the program gathers statistics about the length of fibers, length of trenches and number of splitters needed. Splitters are needed where one fiber is located in two or more of the children. An example can be seen in Figure 33, where a splitter would be needed at the CU in Solution 1, and no splitters would be needed in Solution 2.

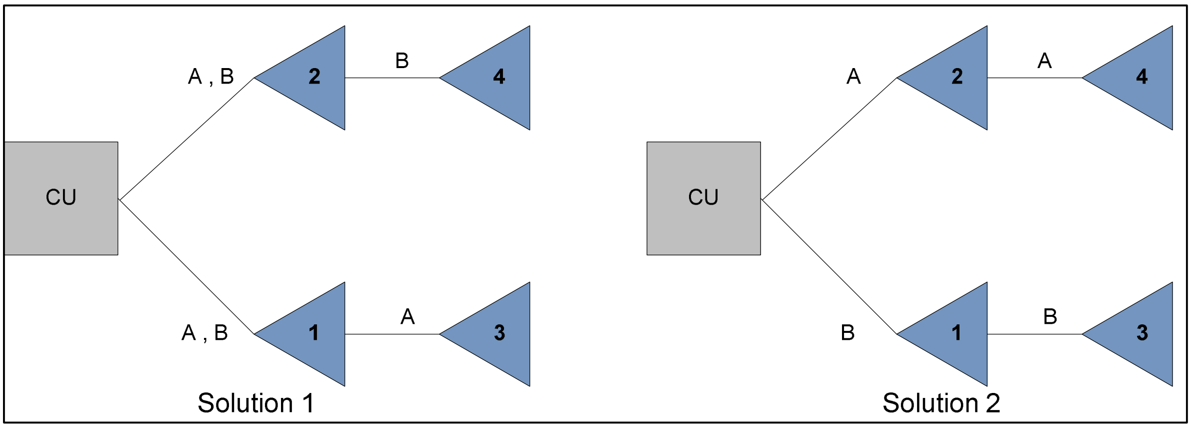


Figure 33: Two possible solutions for fiber assignment in the MST.

The splitting and amplification is stated as “difficult and expensive” in some of the fiber-optic scenarios listed by FUTON, the solutions made by the previously mentioned GA might therefore not be suitable, as the solutions made utilize splitters where necessary. Another option would be to not consider splitters, i.e. use separate fibers where a tree splits. This was implemented to see how much difference it makes in fiber-length, so that it is possible to weigh up the two alternatives. It is possible to calculate if the option without splitters will be cheaper according to Equation 17 and Equation 18.

$$price\ of\ solution\ with\ no\ splitters < \ price\ of\ solution\ with\ splitters$$

Equation 17: splitter equation 1.

$$added\ meters\ of\ fiber * price\ pr\ meter\ of\ fiber < \ number\ of\ splitters * cost\ of\ splitters$$

Equation 18: splitter equation 2.

There are also other factors that influence the difference in cost for the solutions, for example how many JPUs are needed for each solution. The cost of the solution with splitters will increase, if amplification is needed due to the splitting.

6.1.3 Implementation

The flow of the program for connecting RAUs to CUs can be seen in Figure 34. It starts by reading the databases containing segment information and RAU locations into memory. It then loops through the RAUs, to find the ones that also have a CU-location. If a CU-location is found, it starts a loop that creates an MST by adding the closest of the RAUs assigned to the current CU-location. When all assigned RAUs are added to the tree, it calculates the number of fibers and splitters needed by the tree. When there are no more RAU-locations to investigate, the program writes the segments of the MSTs, statistical information about the fiber length, trench-length and splitters needed by the solution to a database.

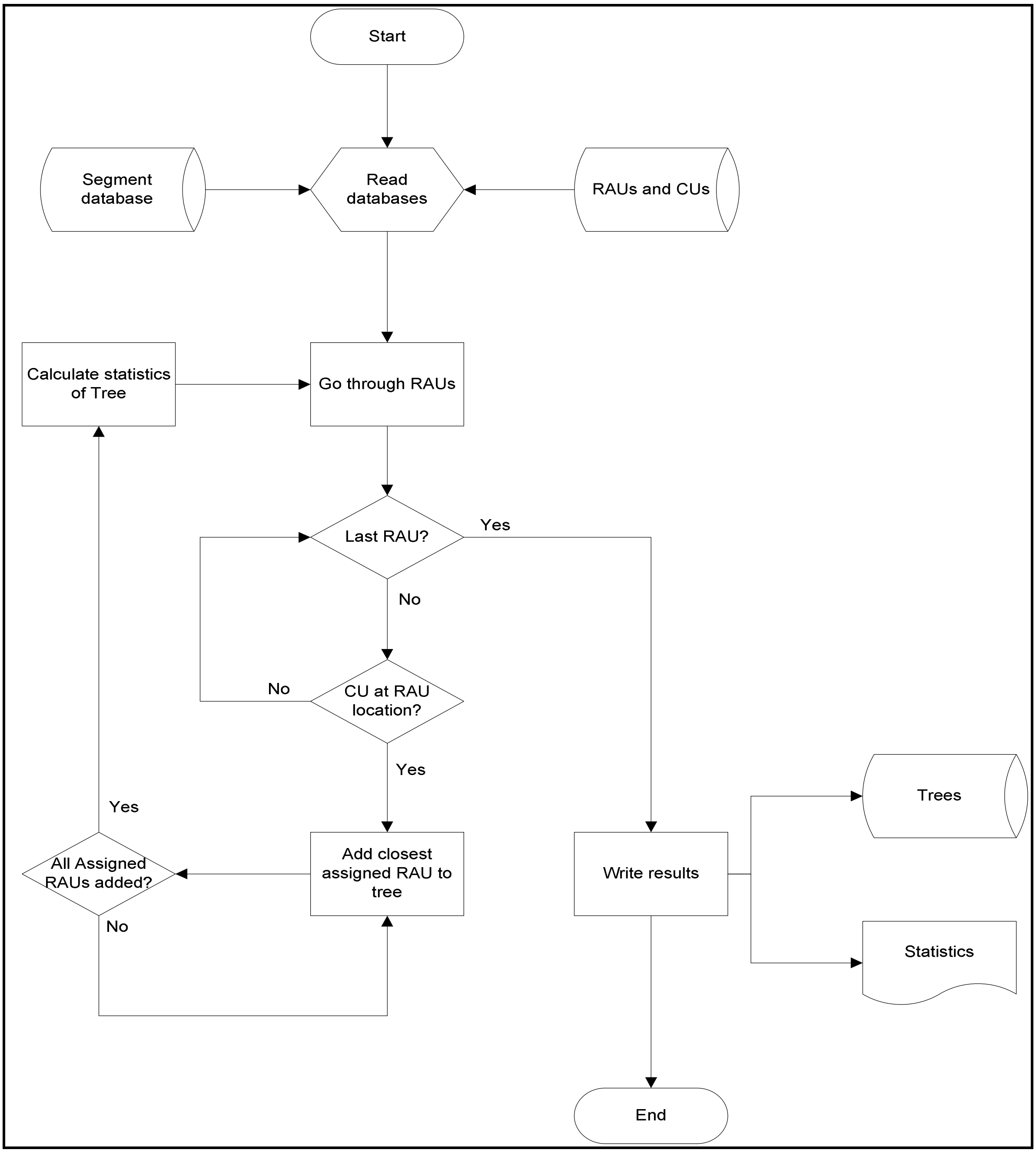


Figure 34: Flow of the program planning CU-RAU trees.

6.1.4 Results

This chapter will review some of the results of the planning of the CU-RAU connections. Before looking at the results, the settings and assumptions made are listed in the following bullet-points:

- No available infrastructure
- Optical signals can be amplified where necessary
- Optical signals can be split where necessary (for the solution with splitters)
- Fiber scenario B (double fiber) with a “range” of 15 km for each CU.
- CUs placed both automatically and manually.

The full results can be found as pictures and databases on the attached CD, as appendix 9. 4 solutions have been made:

- Automatically placed CUs with splitters
- Automatically placed CUs without splitters
- Manually placed CUs with splitters
- Manually placed CUs without splitters

Visually, the solutions with and without splitters look the same, as they use the same trenches. The difference of these solutions lies in the number of fibers and fiber-length used. This can be seen in Table 14. The table shows the total number of fibers, splitters and length of trenches and fibers needed for each solution.

	Fibers	Splitters	Trench length [m]	Fiber length [m]
Automatic with splitters	26	39	309165	401687*2
Automatic without splitters	79	0	309165	592707*2
Manual with splitters	24	45	319024	364275*2
Manual without splitters	83	0	319024	510095*2

Table 14: Differences between automatic and manual CU placements.

It can be seen that removing the splitters increases the fiber length by 47.5% for the automatically placed CUs and 40% for the manually placed CUs. In addition to this the number of fibers increased with 204% and 246% for the automatically and manually placed CUs respectively. The manual solutions use less fiber than the automatic ones, but require slightly longer trenches.

Using Equation 17 and Equation 18 it is possible to calculate which option would be the cheapest for both the manual and automatic solution. The results are that the “Automatic without splitters” is the cheapest if the cost of a splitter is more than 4898 times the cost of a fiber-pair meter.

The calculations are done in a similar manner for the manual solutions, and shows that the Manual without splitters is the cheapest if the cost of a splitter is more than 3240 times the cost of a fiber-pair meter.

Figure 35 shows parts of the trees for two of the CUs. It can be seen that the program successfully creates an MST for a CU and its assigned RAUs. It can also be seen how the predefined assignments of CUs leads to longer than optimal trench-length, as described in figure 30.

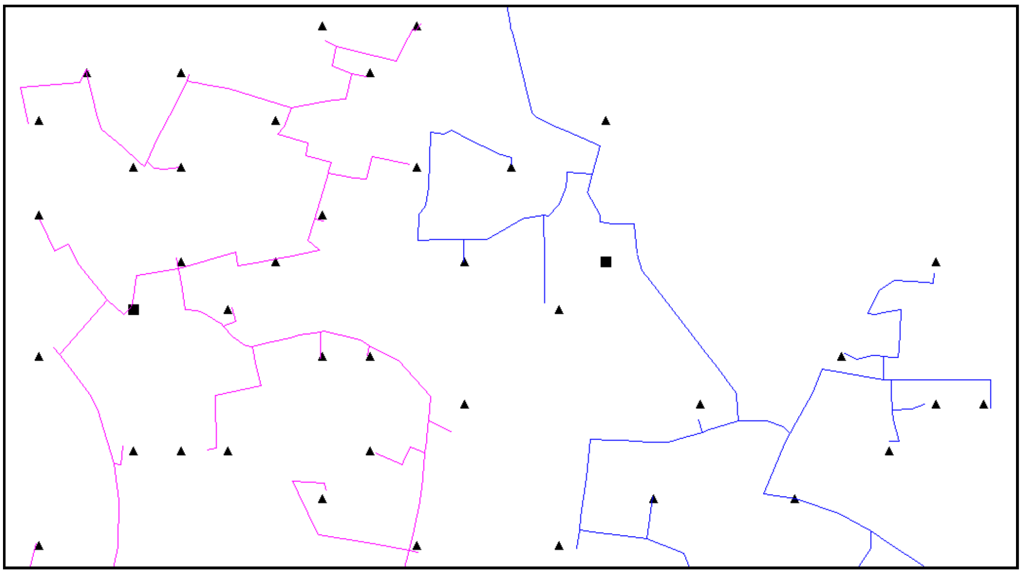


Figure 35: Part of the MSTs from the CUs to the RAUs.

Figure 36 shows a limitation of only using the segment information to plan the paths for the fibers. If the alternate route is over a farmland or a similar territory it might be much cheaper to choose this rather than follow the segments. Identifying cases like these can reduce the cost of the deployment.

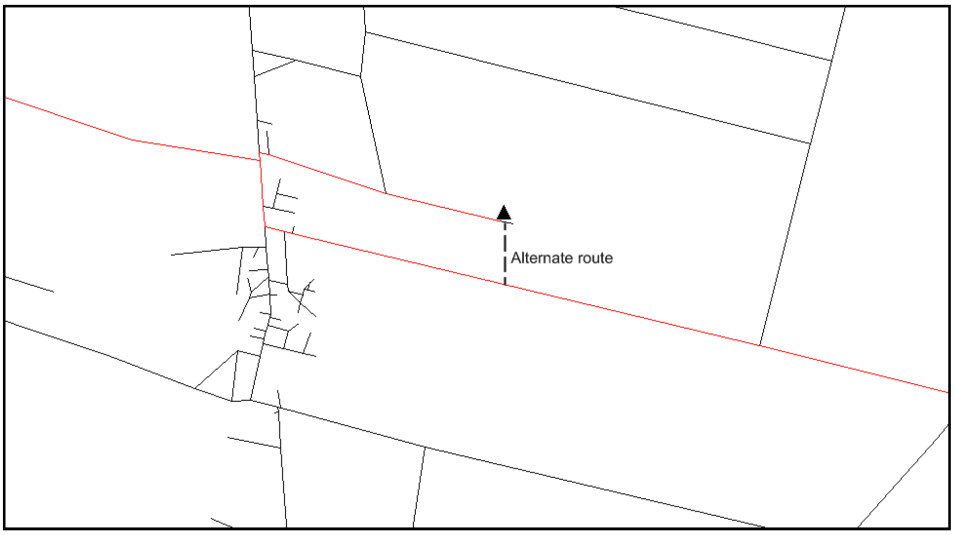


Figure 36:Automated planning mistake.

The program that builds the MSTs takes from 3 to 10 hours to run on a 2 Ghz core with 2 GB RAM. The reason for the big variation is that if a CU has n RAUs, the RAU must find n-1! paths using the A* algorithm. The trees for the manually placed CUs was therefore much faster to calculate than for the automatically placed CUs, since it has more evenly distributed RAUs.

Now that the trees connecting the RAUs to the CUs have been planned, the CUs need to be interconnected.

6.2 Connecting CUs

FUTON has no guidelines for what topology should be used to interconnect the CUs. Depending on the size of the total network, and the applications and services being provided by it, a topology providing the necessary Structural Quality of Service (SQoS) should be used. SQoS looks at the network performance parameters from a structural point of view, by looking at features of the topology such as number of hops, connectivity, diameter and routing schemes. Previous research has shown that topologies like N2R and double ring provides better SQoS than rings [79].

Despite this, ring structures and interconnected rings are still heavily utilized and are the most common structures in ISP backbone and distribution networks due to their simplicity and cost-effective nature [34]. The CUs will therefore be interconnected using a physical ring structure, with a logical fully connected mesh. The logical mesh is made possible by using WDM, and assigning one or more optical channel to each node-pair. For more information on the wavelength assignment in the CU-CU ring, see chapter 7. To have redundancy in case of failures, it is vital that two or more CUs in the ring have a backbone-connection. To calculate the fiber length needed, the protection method used will be a dedicated 1:1 ring protection. This means that there is an unused protection fiber, which can be utilized in case of failure. The needed fiber length will therefore be twice as long as the trenches. For this project it will be assumed that this structure will be able to provide satisfactory redundancy and availability.

The challenge in interconnecting the CUs lies in finding the ring using the least fiber. This is a famous problem in the field of graph theory, and is known as the Travelling Salesman-Problem (TSP) [33]. There are many methods for solving this. Since GAs are fast to implement, and has already been used in several of the programs in the project, it was decided to use GAs here as well.

In order to use a GA for the TSP, it is necessary to encode the problem. It is natural to use permutation encoding in this case, where genes represent CUs and the chromosome represent the order of which they are visited (the tour). An example can be seen in Figure 37. If the start CU is 1, the chromosome would look like [1,5,3,2,4]. It could also look like [1,4,2,3,5], since it represents the same tour.

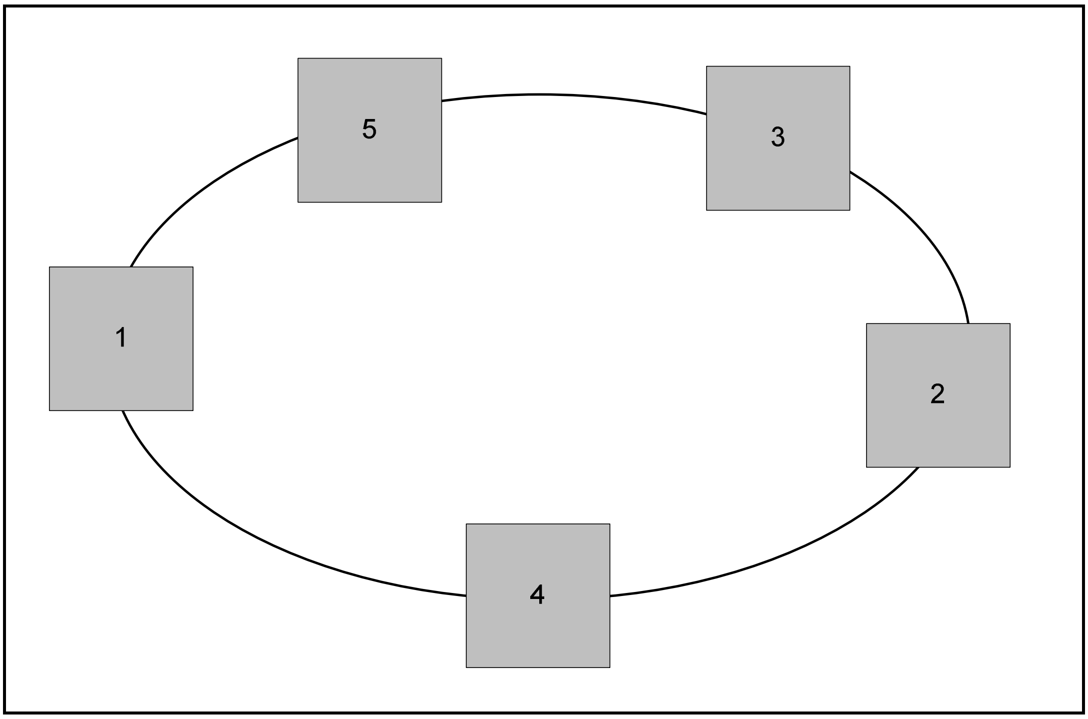


Figure 37: CUs interconnected in a ring structure.

The GA evolves to better results by mutating the chromosomes by switching the position of two CUs. If the chromosome was [1,5,3,2,4], and position 0 and 2 was switched, the new tour would be [3,5,1,2,4]. The GA then evaluates the chromosomes, using the fiber length as the criteria. Since the state-space is small in this problem, mutation is the only regeneration operator necessary to achieve the results. It is also possible to utilize crossover in permutation GAs, but it requires some adjustments to the way they are implemented in regular GAs, since each allele only can occur once [35]. The selection method used is Roulette Wheel selection as in the radio planning GA from Section 4.5.2, together with elitism to ensure that the best looking result is not lost.

This planning also requires finding paths using the segment network. For the GA to be able to quickly evaluate the results, the length of the paths between all CUs are found before the GA starts, so the GA only need to fetch the length of the path, and not calculate it. This means that if there are n CUs, the time-consuming task of finding n-1! paths are found in the beginning. After this the GA can find the result in a matter of seconds. When the GA is finished, the paths are found once more, to write them to a database for visualization. Figure 38 shows the flow of the program interconnecting the CUs. For more detailed information, the reader is referred to the commented source code on the CD.

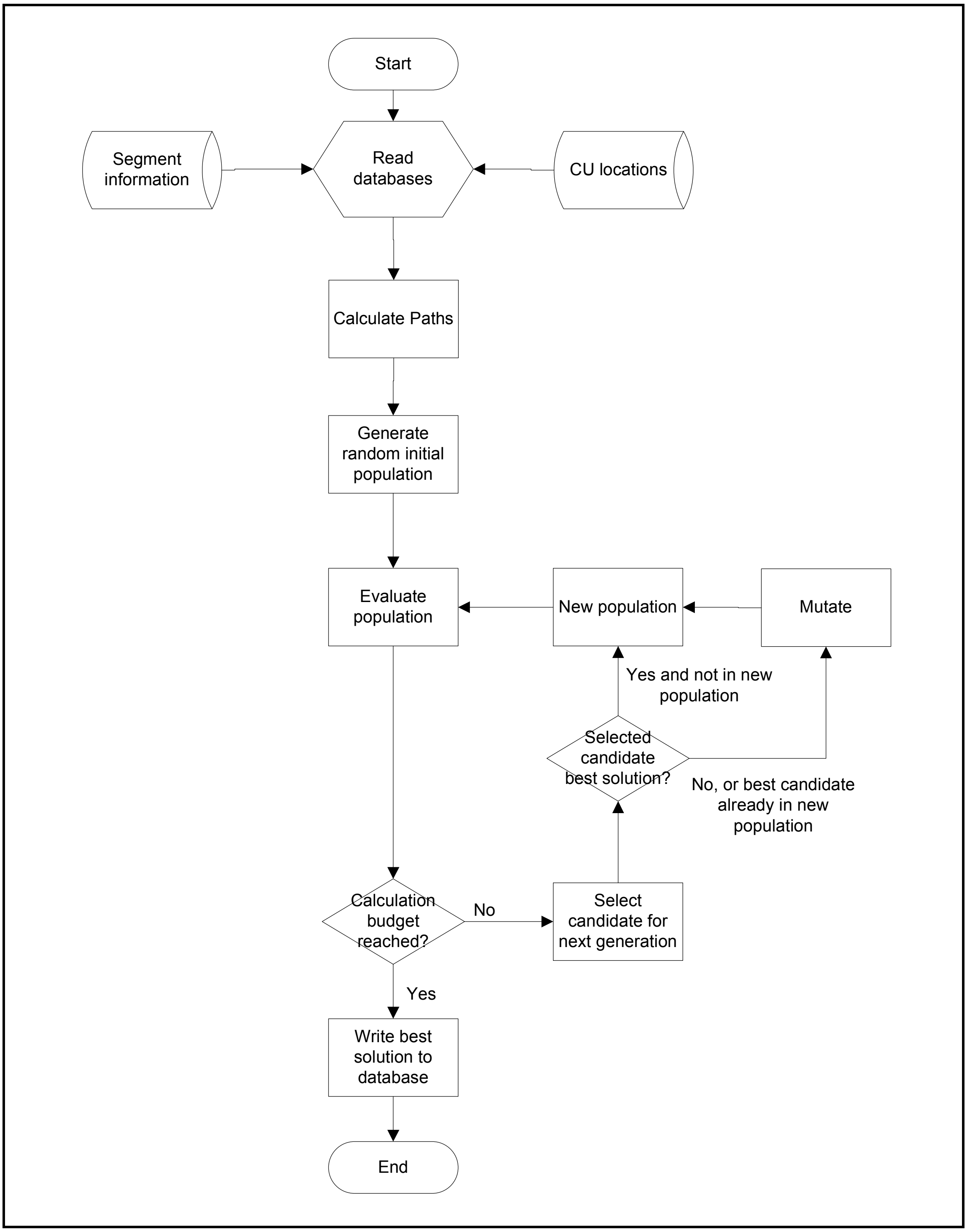


Figure 38: Flow of the program planning the CU-CU ring.

6.2.1 Results

The length of the trenches in the CU-ring is an important measure since it has a large influence on the cost. In chapter 5 on CU placement it was decided to place the CUs manually in addition to the automatic placement. These two solutions are compared in this chapter, to see how they differ.

Table 15 shows that both solutions use around 145 km of trenches. The manual placement is slightly shorter, using 0.9 % less trenches than the automatic placement. The fiber length is twice as long as the trench length, due to the extra protection fiber. These numbers assume that there are enough wavelengths on the fiber to facilitate all the CUs. This capacity dimensioning will be addressed in chapter 7.

	Fiber length [m]	Trench length [m]
Automatic	296976	147988
Manual	290492	145246

Table 15: Fiber and trench lengths for both solutions.

The ring interconnecting the automatically placed CUs can be seen in Figure 39.

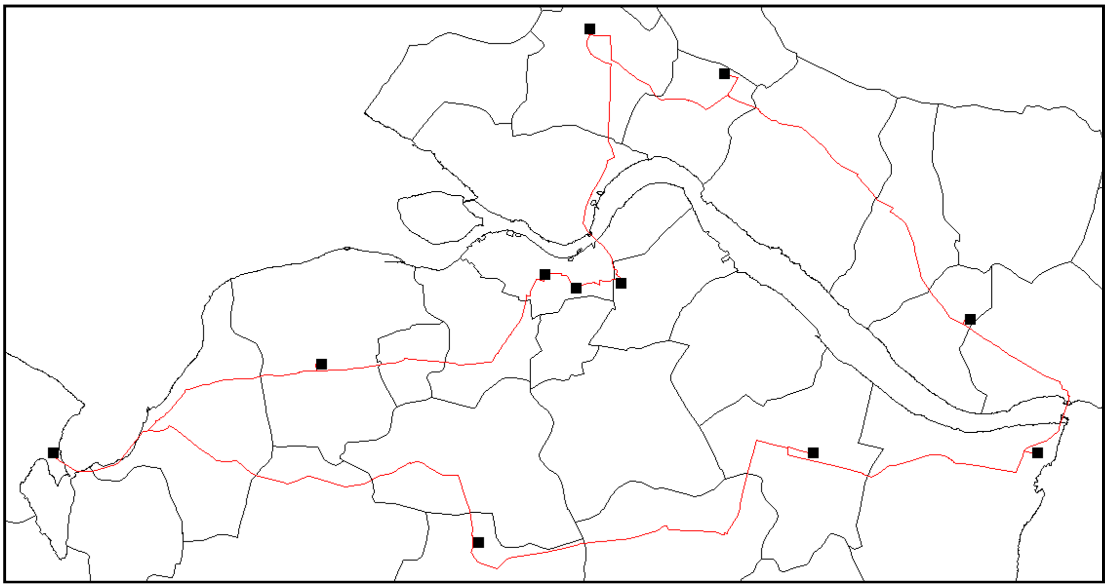


Figure 39: CU-ring of automatically placed CUs.

The ring interconnecting the manually placed CUs can be seen in Figure 40.

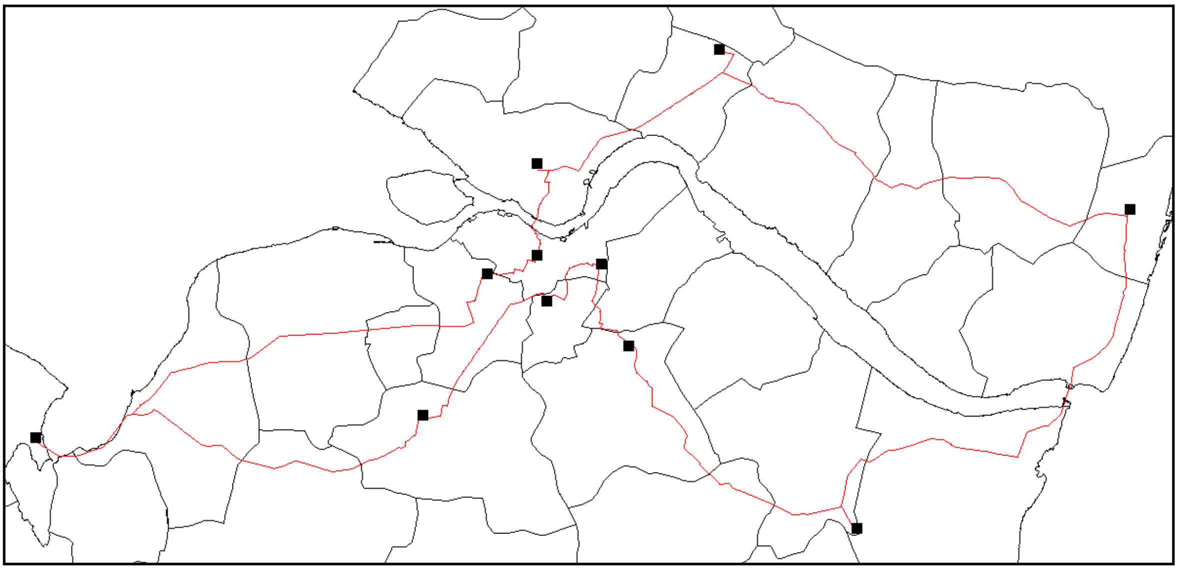


Figure 40:CU-ring of manually placed CUs.

It can be seen that in fact the program is able to create a ring that minimizes the fiber length. The difference in length of trenches needed by the two solutions are not noticeable. In the areas where the same road is used in two directions, trenches on both sides of the road should be used, for higher availability.

It is worth noticing that this implementation does not consider reusing trenches used for CU-RAU planning, or other infrastructure. This would however be easy to implement if wanted, by giving trenches that are already utilized by other infrastructure a lower cost in the path-finding algorithm. It is however important to keep in mind that reusing trenches will increase the probability of digging accidents, reducing the total availability of the network.

6.3 Discussion of Chapter 6 Results

The RAUs was connected to the CUs using the tree topology. In order to minimize the digging needed, the MST-algorithm was used. One MST was made for each CU. A solution was made both with and without splitters. If no splitters are used it adds significantly to the length of fiber, and number of fibers, but might still be a cheaper solution, depending on the price of the splitters and if amplification is needed as a result of the splitting. The trees of the manually placed CUs require more trenches than the trees of the automatically placed CUs, but less fiber. The cheapest solution is therefore dependent on the relationship between the cost of trenches and fiber.

The CU-RAU planning could be improved by implementing a method that eliminates the cases where RAUs are assigned to the wrong tree (and CU). It also shows that laying paths along the segments might not always be the best solution, since it does not consider shortcuts over farmland.

The CUs were interconnected using a fiber-ring. A permutation GA was implemented and quickly found the solution needing the least trenches. The manually and automatically placed CUs do not differ noticably in trench-length.

For more on implementation see appendix 1.

6.4 Summary

This chapter showed the steps taken to plan the fiber networks interconnecting the CUs and connecting the RAUs to the CUs. This was the final chapter with physical planning of the FUTON architecture. Two important tasks still remain: estimating the traffic of the users, and dimensioning the wired and wireless networks accordingly.

7 Traffic Estimation and Capacity Dimensioning

This chapter describes the current and future trends in wireless technologies, before this information is used to dimension the wireless and wired networks planned in this thesis. In order to plan and dimension a network it is necessary to have knowledge about the applications that will be used in the network. It is also important to know the number of users and their bandwidth consumption. Using this information, the wireless cells will be sectorized, and wavelengths in the fiber-network need to be calculated.

7.1 Current Wireless Traffic Usage

A few years ago, the wireless networks were mainly used for calls. Today, data traffic is taking over [43], both due to more advanced phones with easier internet access and USB-dongles providing wireless broadband. To correctly estimate the bandwidth in a wireless network, it is needed to understand the applications and bandwidth demands of the different devices. Because of this, the users have been divided into three different groups, according to their devices: phones, smartphones and wireless dongle.

There is a fundamental difference of use in phones, smart phone devices and laptop devices. The difference is in the application being most commonly used in each of the different types of devices. According to [36] it can be estimated that one smart phone device can generate as much traffic as 30 cell phones. It is also estimated that one cellular connected laptop can generate as much as 450 cell phones worth of traffic. This can be seen when it is considered that today there is relatively small number of cellular connected laptops but the P2P traffic in wireless networks still counts for up to 20% of the traffic [36].

As seen in [29] Denmark is ahead of OECD in the adoption of broadband and that in the beginning of 2008 the penetration of wireless broadband users is 1%. In [37] it can be seen that the wireless broadband subscribers in Norway has doubled from the beginning of 2008 to the beginning of 2009. It is assumed here that the same development applies for Denmark. This means that 2% of the population in the Aalborg area has broadband wireless resulting in 4034 wireless broadband users in the area.

Wireless broadband today is mainly dominated by 3G and WiMAX [29]. WiMAX is at its early stages of deployment in the area and no information about the current number of subscribers can be found. Therefore the number of current WiMAX users is considered to be 10% of the wireless broadband users. It is assumed that 3G account for the rest, i.e. 90% of the wireless broadband users.

Today users are offered high capacities using their wireless broadband. The capacity is so high that wireless broadband now competes with wired technologies such as ADSL and cable. A user with his computer connected to a HSDPA enabled device can today reach up to 10.4 Mbit/s [38]. WiMAX can reach 14.26 Mbit/s [39]. 3G and WiMAX technologies can therefore be used as regular wired broadband connections and the traffic they carry, among regular call traffic, can be considered having the same characteristics as the traffic in wired broadband networks.

In Table 16 the trends in application usage of mobile phones can be seen. 3G phones evolution is moving more towards being smart phones and iPhones. This trend along with higher capacities of the mobile networks drives the usage of higher bandwidth demanding applications for phone users.

Activity	iphone	Smartphone	Market
Any news or info via browser	84.8 %	58.2 %	13.1 %
Accessed web search	58.6 %	37.0 %	6.1 %
Watched mobile TV and/or video	30.9 %	14.2 %	4.6 %
Watched on-demand video or TV programming	20.9 %	7.0%	1.4 %
Accessed social Networking Site or Blog	49.7 %	19.4 %	4.2 %
Listened to music on Mobile phone	74.1 %	27.9 %	6.7 %

Table 16: Application usage in 2008 in the U.S [40].

7.2 Future Trends

To be able to estimate the bandwidth requirements of future networks, it is necessary to anticipate how the market, devices and technologies evolve.

Cellular penetration had reached 111.8 percent in Denmark according to [41]. In the near future the accumulated penetration of 3G, WiMAX and LTE-Advanced can be expected to close up on to this penetration, as GSM-devices is being replaced by more advanced devices. It can also be expected that trends in wired broadband will emerge even more into the wireless traffic as devices get more mobile and the cost reduces. In addition to this, laptops already equipped with WAN-technologies are starting to hit the market, which will further increase the penetration.

The current trends of users moving to 3G, WiMAX and other 3rd generation technologies combined with increasing usage of more bandwidth demanding applications puts higher demand on available capacity both between the MT and BS and from the BS to the backbone network. The effects of this can be seen in [42] where it can be seen that in 10 months, up until July 2008, while a business was promoting HSPA dongles for computers it sold 500.000 units. The result was that the data traffic in their network increased by 700% when measured in March 2008 and compared to September 2007.

With the development of 3G handheld devices into the direction of more versatile smart phones and the increasing number of HSDPA dongles as well as the expected emerge of WiMAX and LTE-Advanced the traffic is expected to grow rapidly in the coming years. In [43] it is predicted that the total global traffic in mobile networks will increase by 2 petabytes every year until 2013 when it will have increased 66 times compared to 2008. It also predicts that in 2013 64% of the traffic in the mobile network will be video traffic. This can be seen in Figure 41.

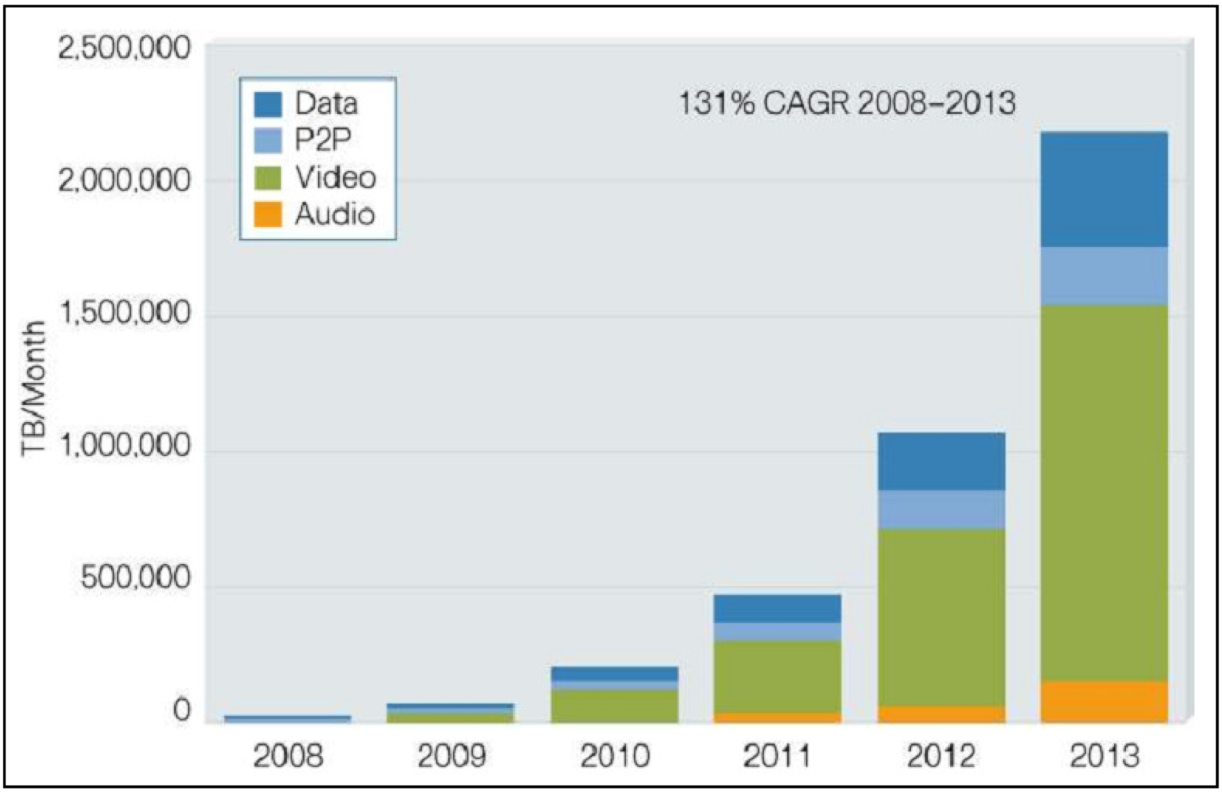


Figure 41: The growth of mobile data traffic and the distribution of apllications [43].

For a cellular network to be compatible with wired network it is not only enough to consider increase in bandwidth. Applications require more than just higher bandwidth. It is also necessary to consider reliability, link quality, delays and security which mean that the wireless technologies also must provide improvements in these areas.

7.3 Average Bandwidth Estimation

In order to find out how many users a wireless cell can support, it is important to know how much traffic the users generate.

7.3.1 Average Bandwidth Estimation for 2009

To calculate the average bandwidth needed by a user, it is necessary to look at how phones, smart phones and broadband wireless devices operate.

Phone Traffic

Currently it can be assumed that the most important function of wireless phone activity is still the ability to make a phone call. Therefore it can be interesting to estimate how much bandwidth is needed for the phone calls.

If it's assumed that the peak hour in mobile networks follows the same trends as in backbone internet traffic, the peak hour traffic can be estimated to be 77% higher during peak hours than the average traffic. This is found using average and max values for 30 day periods at three international internet exchanges [72][73][74].

According to [44] each user makes 6.2 phone calls per 24 hours, therefore λ can be set to 6.2 (calls per 24 hours) in Equation 19. It is assumed that each phone call lasts for 3 minutes on average. According to [45] each phone call counts for 6 – 12 Kbit/s and 12 kbit/s has been used for the calculations in this project. It is assumed that the uplink requires as much bandwidth as the downlink.

Having this information the Erlang equation, as seen in Equation 19, can be used to calculate the average expected bandwidth usage.

$$A = \lambda * \mathrm{H}$$

Equation 19: Erlang equation.

In Equation 19 A is the traffic in Erlangs, λ is the mean arrival rate of new calls and H is the average call holding time. To find the average bandwidth usage this requires, A is multiplied with the bandwidth needed for a phone call.

Table 17 shows the calculations for the Erlangs and the calculations for the average capacity needed for phone calls.

	Formula	Calculations	Result	Note
Erlangs	A = λ * H	6.2 / 86400 * 180	0.013 (Erlangs)	λ = Phone calls per day, seconds in 24 hours = 86400 sec, H = holding time = 3 minutes (180 seconds)
Phone call traffic	A * B * PH	0.013 * 12 * 1.77	0.276 (kbit/s)	A = Erlangs, B = Phone call bandwidth, PH = Peak hour factor

Table 17: Average Erlangs and bandwidth generated by a phone user.

As mentioned in Section 3.2.1 the total population in the Aalborg area during work hours is 201 430 people. In [41] it can be found that the penetration of cell phones is 111.8% which means that there are 225508 phones in Aalborg during busy hour. 3G phones accounted for 20% of these in 2007 according to [41]. For this project it is assumed that the penetration has grown to 30% in 2009 and the number of 3G phone users has reached 67652 located in the Aalborg area.

As several WISPs are competing for the 3G market it is necessary to assume each provider only gets a share of the total users. A market share for the WISP was therefore assumed to be 30%, bringing the number of 3G phone customers to 20295.

Smart Phone Traffic

Smart phone traffic is according to [43] 30 times the traffic of each phone call in 2013. Here it is assumed that in 2009 the smart phone traffic is 50% of this, meaning smart phone produces as much traffic as 15 cell phones. This assumption is made because it is likely that the applications today are less bandwidth-intensive than in 2013. In 2009 11% of all cell phones are smart phones according to [46]. The calculations for smart phones can be seen in Table 18. It is assumed that the uplink uses 75% less traffic as can be seen in Table 18. The reason for the lower uplink than downlink is that most of the high bandwidth consuming applications like web browsing, e-mail and streaming require much higher downstream than upstream

	Formula	Calculations	Result	Note
Smart phone traffic downlink	P * PT * S	15 * 0.276 * 0.11	0.455 (kbit/s)	P = Nr. of phones factor, PT = Phone call traffic, S = Share of smart phones
Smart phone traffic uplink	P * PT * S * U	15 * 0.276 * 0.11 * 0.25	0.114 (kbit/s)	P = Nr. of phones factor, PT = Phone call traffic, S = Share of smart phones, U = Uplink factor

Table 18: Average bandwidth generated by a smart phone user.

In 2009 WiMAX has not entered the phone and smart phone market and those calculations will therefore not be included in these calculations.

Wireless Broadband Traffic

The number of broadband wireless users is 4034 as found in section 7.1. WiMAX is new on the market and currently has low market penetration. It was assumed that the wireless broadband market is divided between WiMAX and 3G such that WiMAX has 10% market share and 3G has 90%. Currently number of providers competes for the 3G market and therefore it is assumed that the provider considered in this thesis has 30% market share. WiMAX is relatively new on the market and few providers compete for the market share. For this thesis it is assumed the provider is first on the market and currently has a market share of 100% Table 19 shows the penetration, market share and number of users of WiMAX and 3G.

	Total users	Technology penetration	Wireless broadband market share	Assumed WISP Market share	Number of users (incl. market share)
WiMAX	403	0.2%	10%	100%	403
3G	3631	1.8%	90%	30%	1089

Table 19: Market shares, number of users and penetration of wireless broadband technologies.

The average wireless traffic is calculated as seen in Equation 20

$$Avg\ Wireless\ broadband\ traffic = \frac{Avg.traffic * Nr.users * Peak\ hour\ factor}{Nr.wireless\ broadband\ users + Nr\ phone\ users}$$

Equation 20: Average wireless broadband traffic.

The average bandwidth that each wireless broadband user adds to the average bandwidth usage of all users at the site can be seen in Table 20. The uplink is assumed to have 25% of the uplink traffic for the same reason as with smart phones.

	Result (downlink)	Calculation	Result (uplink)	Calculation
WiMAX	44.25 (kbit/s)	$\frac{25 * 403 * 1.77}{403}$	11.07 (kbit/s)	$\frac{25 * 403 * 1.77 * 0.25}{403}$
3G	2.25 (kbit/s)	$\frac{25 * 1089 * 1.77}{1089 + 20295}$	0.56 (kbit/s)	$\frac{25 * 1089 * 1.77 * 0.25}{1089 + 20295}$

Table 20: Average bandwidth of a wireless broadband user.

Results for the Situation in 2009

The results for the uplink and downlink of both WiMAX and 3G are summed up in Table 21. The sum consists of phone and smart phone traffic for 3G and wireless broadband traffic for both WiMAX and 3G. The numbers for HSDPA and HSUPA is very low compared to the numbers for WiMAX, due to the large amount of phone users which have low bandwidth requirements.

	Average bandwidth per user in the network	Note
WiMAX (downlink)	*44.25 (kbit/s)*	*Only wireless broadband*
WiMAX (uplink)	*11.07 (kbit/s)*	*Only wireless broadband*
HSDPA	*2.98 (kbit/s)*	*2.25 + 0.455 + 0.276*
HSUPA	*0.95 (kbit/s)*	*0.56 + 0.114 + 0.276*

Table 21: Average bandwidth usage for 3G and WiMAX.

7.3.2 Average Bandwidth Estimation for 2013

In 2013 there will be dramatic change in the usage of wireless networks according to [43]. The traffic load increases 66 times compared to 2008 caused by broadband users moving from wired connections to wireless, increase in smart phone usage and more bandwidth demanding applications resulting in higher average amount of bandwidth each user requires. The 66 times increase in traffic from 2008 – 2013 gives the Compound Annual Growth Rate (CAGR) of 131%. CAGR describes the rate at which the annual growth goes [47] and is calculated as seen in Equation 21.

$$CAGR = \frac{Ending\ Value}{Beginning\ Value}^{\frac{1}{Nr\ of\ years}} - 1$$

Equation 21: CAGR calculation.

Cell Phone Traffic

It is assumed that the penetration of cell phone devices will not change particularly from 2009 to 2013, as it is more likely that old phones will be discarded for newer phones with either 3G, WiMAX or LTE-Advanced. The phone penetration for 2013 used in this project is therefore 111.8%. It is also assumed that the bandwidth requirement of a phone call will be the same in 2013 as it is in 2009, which was calculated to 0.275 kbit/s.

According to [49] the year to year increase in 3rd generation devices in Europe is 46.6%. Since it is assumed here that the penetration of phones will remain the same, this rapid increase will have to slow down. It is therefore assumed that the penetration of 3rd and 4th generation phone devices will be reach 90% in 2013, leaving only 10% of phones with GSM as the only technology. This means that 202958 of the phones are either 3G, WiMAX or LTE-Advanced phones. Table 22 shows how this is divided between the technologies.

3G has been on the phone market the longest and is assumed to have 50% penetration in the market because of its head start. In 2013 WiMAX has been on the market for some time and is considered well known. Therefore it is assumed to have 35% market penetration. DBWS is relatively new to the market and is assumed to have gained 5% market penetration in 2013.

It is assumed that the 3G and WiMAX WISPs both has a 40% share of their market, while the DBWS will be used by multiple WISP achieving a 100% market share. This can be seen in Table 22

.

	Technology penetration	Nr. of users	Market share	WISP users
WiMAX	35%	71035	40%	28414
3G	50%	101478	40%	40591
DBWS	5%	20295	100%	10147

Table 22: Market shares, numbers of users and penetration of phone market in 2013.

Smart Phone Traffic

According to [49] worldwide annual growth of smart phones is expected to be over 30%. Therefore it is assumed that the use of smart phones has tripled and reached 33% penetration of the phone market in 2013.

In [43] it is assumed that smart phones produce traffic equivalent of 30 regular phones in 2013. The calculations for smart phones can be seen in Table 23. It is assumed, for the same reason as in the 2009 situation, that the uplink uses 75% less traffic.

	Formula	Calculations	Result	Note
Smart phone traffic downlink	P * PT * S	30 * 0.276 * 0.33	2.73 (kbit/s)	P = Nr. of phones factor, PT = Phone call traffic, S = Share of smart phones
Smart phone traffic uplink	P * PT * S * U	30 * 0.276 * 0.33 * 0.25	0.68 (kbit/s)	P = Nr. of phones factor, PT = Phone call traffic, S = Share of smart phones, U = Uplink factor

Table 23: Average bandwidth of a smart phone user in 2013.

Wireless Broadband Traffic

With TV streaming and especially HDTV catching on according to [50] and [43] the average traffic generated by broadband wireless users can be expected to rise significantly. Table 24 shows the most common applications in backbone networks in 2008/9.

The impact of an application on a network is decided by two things; how much bandwidth it requires and how many are using it. In order to realize the load applications put on the network a weighting system is introduced. Each application gets a weight in accordance to how high bandwidth it is considered to need for its operations. Here 1 Mbit/s equals 1 in the weighting. The bandwidth needs of the applications are in accordance to Table 39. The result of the total load one application puts on a system is then derived from the weight it has and its population in the network. The results from all the applications are then summed together. The results of the calculations from 2009 and 2013 can then be compared. This way when high bandwidth demanding applications become more popular the total weighting increases and the impact it has on the average bandwidth needs can be identified.

An example of how the weighting is done can be for instance P2P. P2P has different needs for bandwidth but is assumed to use 3 Mbit/s. This gives P2P the weight of 3 and since the popularity of P2P application in 2009 is 52.8% (0.528) the weighting result with 1.58. Table 24 shows the results from the weighting.

Application	Popularity 2009	Weight	Result	Popularity 2013 (est.)	Weight	Result
P2P	52,80%	3	1,58	40,00%	3	1,2
Web	25,80%	1	0,26	20,00%	1	0,2
Streaming	7,20%	1	0,07	7,00%	1	0,07
VoIP	0,90%	1	0,01	2,00%	1	0,02
IM	0,20%	1	0,00	0,50%	1	0,005
SDTV			0,00	7,00%	2	0,14
HDTV			0,00	20,00%	9	1,8
Other	13,10%		0,00	3,50%		0
Total			**1,93**			**3,435**

Table 24: The popularity in 2009 and estimates of the popularity in 2013 [50] [43].

In Table 24 the assumptions made for the popularity of applications in 2013 are based on [50] and [43] where increase in TV traffic and HDTV is predicted at the same time as there is decrease in P2P. Comparing the weighted result for 2009 and 2013 it is found that there will be 78% increase in the average traffic in broadband networks. This increases the average wireless broadband bandwidth usage up to 78% going from 25 kbit/s up to 44.5 kbit/s.

It is expected that wireless broadband enabled equipment (laptops and other devices) will get more common in coming years and thereby with the comfort of having wireless broadband whenever needed drives higher penetration of wireless broadband.

If the trend seen in [51] continues the number of wireless broadband users doubles every year the number of users will have increased 16 times in 2013. This gives 64544 wireless broadband users.

3G and WiMAX have been on the wireless broadband market for few years and are assumed to be well known by customers. Therefore it is assumed here that WiMAX has 35% and 3G has 55% of the wireless broadband market. 3G has 15% higher share because it has been longer on the market.

DBWS will be new to the market in 2013 but due to its high potential bandwidth it is assumed to have 10% of the wireless broadband market. In 2013 the deployment has newly started and it is assumed in this theses that only one provider has launched the technology giving him 100% market share. WiMAX has been on the market longer so there are more providers competing for the market share, since this provider was the only provider in 2009 to offer WiMAX it is assumed here that the WISP has a high market share of 50%. The 3G WISP is assumed to have a powerful position in the market, holding a market share of 40% the total 3G market. These statistics can be seen in Table 25 as well as the penetration of each of the technology for overall users in the Aalborg area.

	Total users	Technology penetration	Wireless broadband market share	Assumed WISP market share	Number of users (market share incl.)
WiMAX	22590	11.2%	35%	50%	11295
3G	35500	17.6%	55%	40%	14199
DBWS	6454	3.2%	10%	100%	6454

Table 25: The market share, number of users and penetration of wireless broadband technologies.

The average bandwidth per wireless broadband user is calculated using Equation 20, and the results can be seen in Table 26. The uplink is assumed to have 25% of the downlink traffic.

	Result (downlink)	Result (uplink)
WiMAX	22.4 (kbit/s)	5.6 (kbit/s)
3G	20.4 (kbit/s)	5.1 (kbit/s)
DBWS	30.6 (kbit/s)	7.7 (kbit/s)

Table 26: Average bandwidth usage of a wireless broadband user in 2013.

Results for the Situation in 2013

The results for the uplink and downlink of DBWS, WiMAX and 3G are summed up in Table 27. The sum consists of phone and smart phone and wireless broadband traffic.

	Average bandwidth per user in the network
WiMAX (downlink)	25.4 (kbit/s)
WiMAX (uplink)	6.6 (kbit/s)
HSDPA	23.4 (kbit/s)
HSUPA	6.1 (kbit/s)
DBWS (downlink)	33.6 (kbit/s)
DBWS (uplink)	8.7 (kbit/s)

Table 27: The average bandwidth per user.

7.4 Wireless Capacity Dimensioning

The traffic will be estimated on a sector by sector basis. It is done such that the possible users are assigned to sites and distributed evenly within the site. If the users generate more traffic than the capacity of a cell, a new sector is added. For more information on sectorization, see Appendix 4. According to [52] it is common to consider up to 6 sectors per site. If cells need more than 6 sectors, the area should be covered by adding other BSs.

7.4.1.1 Average Sector Capacity

In order to find how many users a cell can facilitate, the average sector capacity must be found. This section describes the procedure for finding this.

The coverage area is found for each modulation technique according to its link budget (see link budget calculations in chapter 4). Each modulation technique has different SNR which affects the link budget. An example of how each modulation covers an area can be seen in Figure 42 [5].

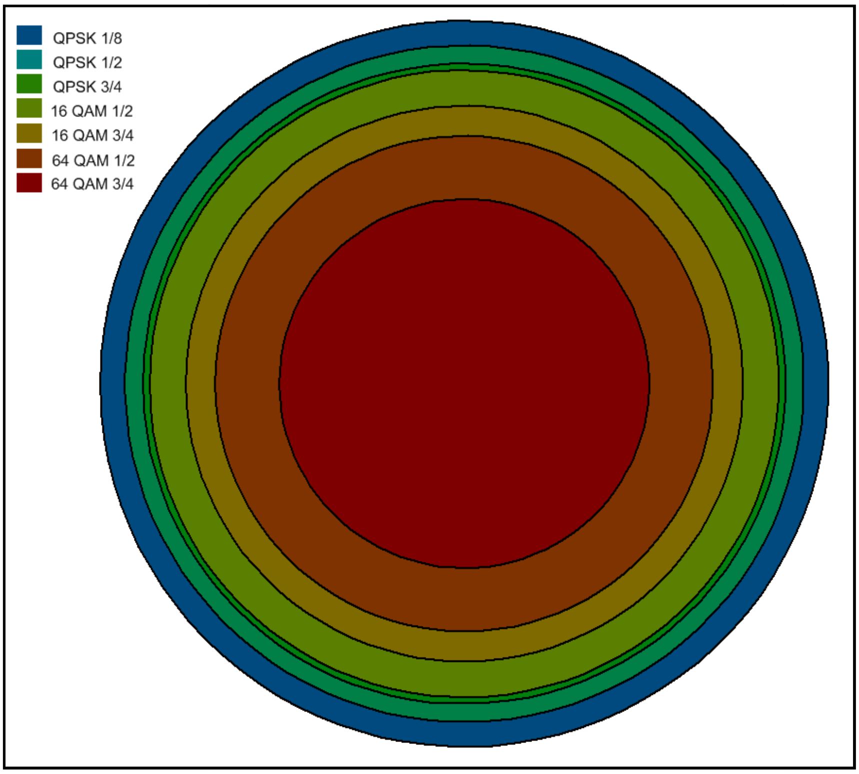


Figure 42: Area each modulation has for one sector in WiMAX Uplink.

In each wireless technology the limiting ranges of the up or downlink decides on the range of the cell. The highest modulation can only be used closest to the BS, where the user gets the best SNR. The further away the user is located, the SNR decrease and the adaptive modulation switches to a simpler modulation scheme. This is a simplification of how it would be in real life where the coverage area of each SNR would not look exactly like circles, due to obstructions in the path of the radio signals.

The area covered by its highest modulation available according to its link budget is multiplied with the bandwidth that modulation technique can provide. The area is presented as a percentage of the maximum cell range. This is done step by step for all the modulation schemes and summed together. This procedure can be seen in Equation 22. In this equation, B is Bandwidth of modulation scheme x, A is the part of the area covered by of modulation scheme x.

$$Average\ sector\ capacity = \sum B\,x * A\,x, \qquad x = QPSK\ ½, QPSK\ ¾, \ldots$$

Equation 22: Average sector capacity.

In Table 28 the SNR of each modulation can be seen. When the link budget is calculated the SNR for each modulation technique is withdrawn from the link budget (where the receiver Sensitivity does not include SNR in the link budget)

Modulation	WiMAXdown	WiMAXup	HSDPA	HSUPA
QPSK 1/8		-2.5		
QPSK 1/2	2.9	2.9	4.6	4.6
QPSK 3/4	6.3	6.3	7.04	7.04
16QAM 1/2	8.6	8.6	9.23	9.23
16QAM 3/4	12.7	12.7	12.7	12.7
64QAM 1/2	13.8	13.8		
64QAM 3/4	18	18		

Table 28: The SNR in dB for all modulations[39][5].

Using the link budget for every modulation the range of each modulation is found using the propagation model presented in chapter 4. These ranges are then used to find the percentage of area each modulation covers for each wireless technology. In both WiMAX and 3G the uplink has the shortest range. The full range of the downlink is therefore not anticipated. The area in percentages can be seen in Table 29.

Modulation	WiMAXdown	WiMAXup	HSDPA	HSUPA
QPSK 1/8	0	0,50802619	0	0
QPSK 1/2	0	0,17457647	0	0,274149668
QPSK 3/4	0,26051205	0,08265027	0,25008	0,180345961
16QAM 1/2	0,30654967	0,09857568	0,272824	0,198611197
16QAM 3/4	0,05793165	0,01806784	0,477096	0,346893174
64QAM 1/2	0,15803881	0,04947431	0	0
64QAM 3/4	0,21696782	0,06862924	0	0

Table 29: The percentage of a cell each modulation covers.

Each modulation is able to deliver certain bandwidth for each of the wireless technology. The bandwidth of each modulation scheme can be seen in Table 30.

Modulation	WiMAXdown	WiMAXup	HSDPA	HSUPA
QPSK 1/8	-	0,115	-	-
QPSK 1/2	3,17	1,68	1,8	0,96
QPSK 3/4	4,75	2,52	5,4	1,92
16QAM 1/2	6,34	3,36	7,2	3,84
16QAM 3/4	9,5	5,04	10,7	5,7
64QAM 1/2	9,5	5,04	-	-
64QAM 3/4	14,26	7,56	-	-

Table 30: The bandwidth each modulation can provide [38] [39].

By multiplying the results in Table 29 with the results in Table 30 the average sector capacity for each wireless technology can be found. The results from that multiplication can be seen in Table 31.

Modulation	WiMAXdown	WiMAXup	HSDPA	HSUPA
QPSK 1/8	0,00	0,06	0,00	0,00
QPSK 1/2	0,00	0,29	0,00	0,26
QPSK 3/4	1,24	0,21	1,35	0,35
16QAM 1/2	1,94	0,33	1,96	0,76
16QAM 3/4	0,55	0,09	5,10	1,98
64QAM 1/2	1,50	0,25	0,00	0,00
64QAM 3/4	3,09	0,52	0,00	0,00
	8,33	**1,75**	**8,42**	**3,35**

Table 31: The average sector capacity.

For the DBWS it is assumed that the average cell capacity is the 1Gbit/s which is set as a goal for the LTE-Advanced technology.

In this section the average sector capacity has been found, and in section 7.3 the average bandwidth usage was found. This information can be used to find the maximum number of users a sector can support.

7.5 Finding Maximum Users Per Sector

Using the average bandwidth requirements per user, and the average sector capacity, the Maximum Users Per Sector (MUPS) can be found. The MUPS shows how many users can be in a cell before it needs to be sectorized.

The MUPS can be derived from the average sector capacity and the average bandwidth requirements. This can be seen in Equation 23.

$$MUPS = \frac{Average\ sector\ capacity}{Average\ bandwidth\ requirement}$$

Equation 23: MUPS.

To account for peak hour traffic, all average bandwidths requirements has been multiplied with 1.77, as discussed in section 7.3.1.

7.5.1 MUPS for 2009

With the results for the 2009 average bandwidth requirements from section 7.3.1 and average sector capacities from section 7.4.1.1 the MUPS can be found for the wireless technologies.

The results of the MUPS calculations can be seen in Table 32

	MUPS
WiMAX (downlink)	193
WiMAX (uplink)	162
HSDPA	2886
HSUPA	3610

Table 32: MUPS for 2009.

The reason for the high MUPS in 3G is the high number of cell phone users in the system. When 3G is compared to WiMAX it can clearly be seen since WiMAX has only wireless broadband users and therefore lower MUPS.

The actual MUPS used is the minimum of uplink and downlink MUPS, since this is the limiting factor.

7.5.2 MUPS for 2013

With these results from the 2013 average bandwidth requirements from section 7.3.2 and average sector capacities from section 7.4.1.1 the MUPS can be found for the wireless technologies.

The results of the MUPS calculations can be seen in Table 33

	MUPS
WiMAX (downlink)	335
WiMAX (uplink)	271
HSDPA	367
HSUPA	559
DBWS (downlink)	31207
DBWS (uplink)	58850

Table 33: MUPS for 2013.

Here DBWS gets a very high MUPS. The reason for this is the high average capacity per sector, compared to 3G and WiMAX.

The actual MUPS used is the minimum of uplink and downlink MUPS, since this is the limiting factor.

In this section, the MUPS has been found. The next section shows how to find the number of sectors needed at each RAU-location.

7.5.3 Calculating Sectorization

If the number of users in a cell exceeds the MUPS, it means that the bandwidth requirements of the users are higher than the capacity of the cell, and the cell should therefore be sectorized.

Equation 24 shows how the number of users using the service in a cell is found.

$$Nr.of\ users\ using\ the\ service = N * P * MS$$

Equation 24: Number of users of a service.

N is the number of users in the cell being calculated. P is the penetration of the technology and MS is the market share of the technology.

To find the number of sectors at a site Equation 25 is used.

$$Sectors\ needed = ceil(\frac{Nr.of\ users\ using\ the\ service}{MUPS})$$

Equation 25: Number of sectors needed.

The calculations are performed as seen above for each of the wireless technologies.

Now that the required sectors of each RAU are found, and the number of users at each site is calculated, everything is ready to be calculated in the wireless section of the network. Since the traffic generated in the wireless networks needs to go through the fiber infrastructure, it is necessary to look at capacity dimensioning for the fiber-optic part of the network as well.

7.6 Fiber Capacity Dimensioning

All the traffic generated in the radio networks will be sent to the CU for joint processing. From the CU the traffic will either be routed out to a RAU belonging to the CU, sent to another CU or out through the backbone. The capacity in the CU-RAU part of the network is already dimensioned correctly, since each RAU has one CWDM channel on the fiber, and the legacy systems are multiplexed together in their own channel on the fiber. Because of this, it does not need further capacity dimensioning. The network that interconnects the CUs on the other hand, will need to be dimensioned according to the traffic.

When dimensioning networks, it is necessary to estimate how much is local traffic, internal traffic and external traffic. Local traffic is traffic going right back to the access network it came from, which in this case is the connected RAUs. Internal traffic is traffic going to the other CUs in the ring, and external traffic is the traffic going out of the backbone connection. Since Aalborg municipality is a small geographical area it is natural to assume that most of the traffic will go out, and come in through the backbone. It is therefore assumed that 95% of the traffic in each CU will be external traffic, while 5% is internal.

In this project it is assumed that if the CU has a backbone connection, all the external traffic from the CU will leave through the backbone connection. If it does not have a backbone connection, the external traffic will be evenly distributed amongst the backbone connected nodes. The internal traffic from a CU is divided amongst the other CUs according to how large percentage of the total users is located at the other CU. The local traffic is calculated as internal traffic to the same CU.

The traffic can be calculated in a traffic matrix, as seen in Table 34.

	CU 1	CU 2	CU 3	…	Internal traffic [Mbit]	% of total users
CU 1	0.32	0.62	0.41		3.2	10
CU 2	1.28	2.48	1.64		6.2	40
CU 3	0.64	1.24	0.82		4.1	20
…						

Table 34: Part of an example All-to-all traffic matrix.

As an example, the internal traffic between CU 1 and CU 2 is found by multiplying the total traffic of CU 2 with the percentage of users at CU 1, as seen in Equation 26.

$$CU\ 1 \rightarrow CU\ 2 = 6.2 * \frac{10}{100} = 0.62$$

Equation 26: Internal traffic between CUs.

The internal traffic in the other direction is found multiplying the total traffic of CU 1 with the percentage of users at CU 2, as seen in Equation 27.

$$CU\ 2 \rightarrow CU\ 1 = 3.2 * \frac{40}{100} = 1.28$$

Equation 27: The internal traffic in the other direction.

After this, the external traffic is added to and from the backbone connected CUs, assuming 25% is upload traffic, and 75% is download traffic.

The same wavelength can be used in both directions due to optical add drop multiplexers [55].which routes one specific wavelength from the fiber, and adds another signal with the same wavelength onto the fiber, as illustrated in Figure 43. In this figure, each color represents a wavelength. The other wavelengths pass through the multiplexer untouched.

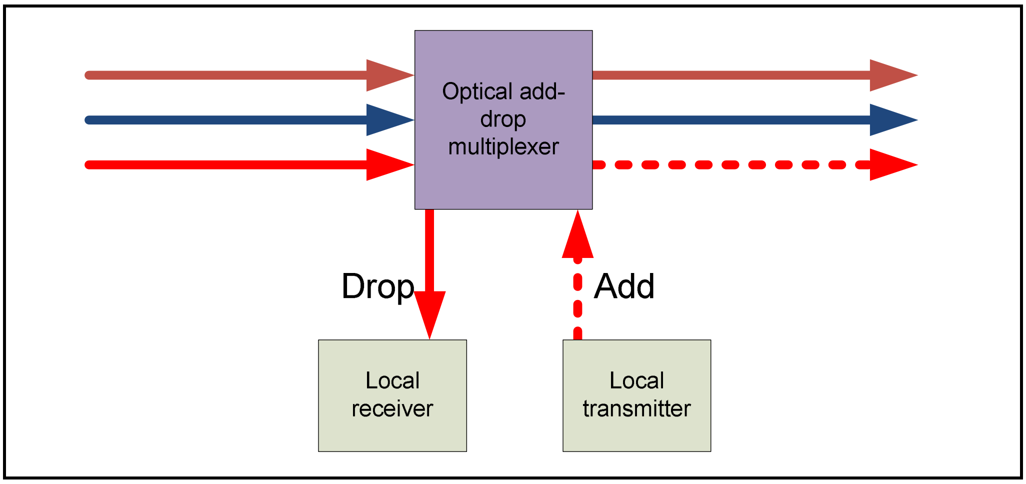


Figure 43: An optical add/drop multiplexer.

This means that every CU in the ring is connected to each other in a point to point manner using WDM. Equation 28 shows how the number of wavelengths is calculated and Figure 44 shows an overview of how it is set up.

$$wavelengths = \frac{n * (n-1)}{2}$$

Equation 28: Wavelengths equation.

In Equation 28 n stands for the number of CUs. It is assumed that each wavelength can carry 10 Gbit/s. This assumption is made because in 2009 1 Gbit/s is very common and 10 Gbit/s has been on the market for some time and is becoming cheaper. If the capacity needs for any of the wavelengths are higher than this, one or more extra wavelengths are required (adds 10 Gbit/s).

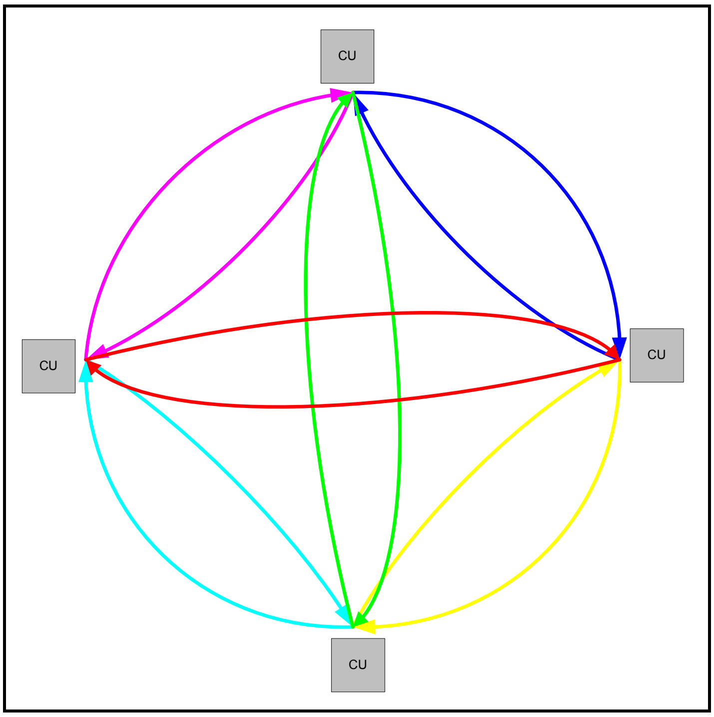


Figure 44: Logical connections in the CU-CU ring [54].

The number of wavelengths available in the ring depends on the DWDM-equipment in use. For this project equipment from [77] is assumed, which gives 72 available wavelengths. If more than 72 wavelengths are needed in the ring, a new fiber must be added, or a more advanced wavelength assignments scheme can be implemented [54].

It is assumed in the implementation used in this thesis that every fourth CU is a backbone connected CU, which equals to 3 CUs for both planned rings. That is done because the location of the backbone is unknown. For redundancy it is considered necessary to have 2 or more backbone connected CUs, in case one of the backbone-connections goes down.

7.7 Capacity Calculation Program

To perform the calculations presented in this chapter, a program was made. The source code of the program can be found on the attached CD as appendix 10. The flow of the program will be presented here.

Some tables need to be made and used by the program. First tables containing the RAUs and users in range for all the wireless technologies need to be made, that was already done in chapter 4. Then a table containing the area each modulation can cover for each of the wireless technologies is made. This table was made from an excel file and then used for the calculations. Finally a table containing the bandwidth each modulation can handle is used for the calculations. The tables used can be seen in Figure 45. The tables for the modulation bandwidth and modulation area are small and the values may be initialised in the code but for simplicity database tables were used instead.

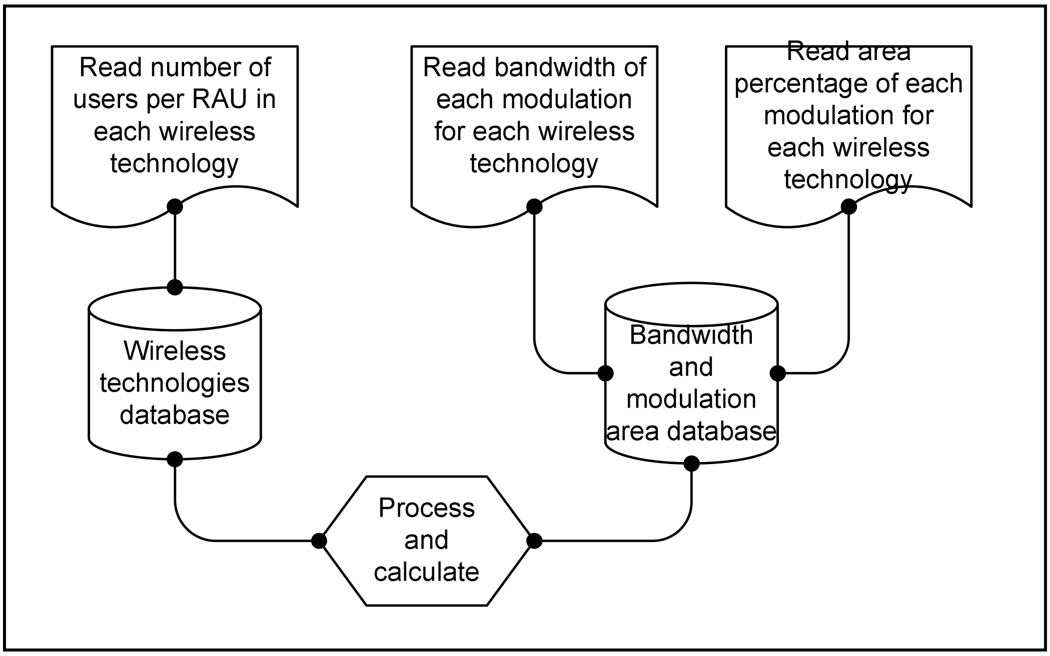


Figure 45: The table structure used when calculating the capacity.

Having these tables the modulation bandwidths multiplied with the respective area percentage that the modulation covers. The highest modulation (like 64 QAM ¾ in WiMAX) is multiplied with the percentage of area it can cover. Then the bandwidth of the next most powerful modulation is multiplied with the area it can cover minus the area of the highest modulation and so on.

The process can be seen in Figure 46.

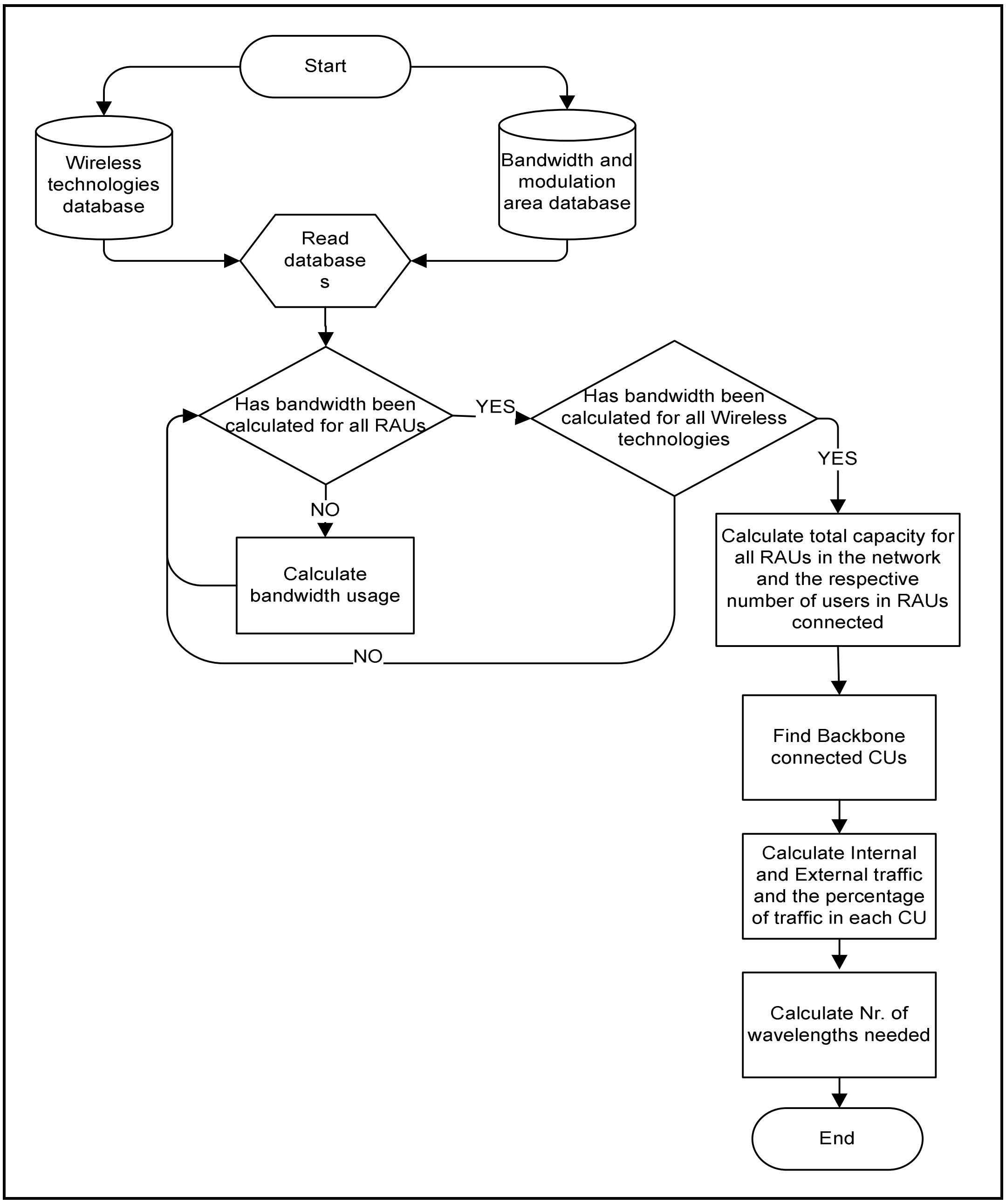


Figure 46: Full capacity calculation process.

The capacity needed for each cell is found and summed up for all the technologies at a RAU. The RAUs are connected to CUs as shown in chapter 6 and the capacity of these RAUs sum up in each CU they are connected to.

Since the location of backbones is not known for this thesis the backbone connected CUs are assumed such that every fourth CU is backbone connected.

Then an all-to-all traffic matrix is made using internal traffic, and the external traffic is added to this matrix to find the total traffic in the network. If the traffic between any node pair exceeds the capacity limit of a wavelength, a new wavelength is added for that node pair.

Finally the number of wavelengths is calculated. They are calculated using Equation 28. Each wavelength is assumed to be 10 Gbit/s. If the load surpasses 10 Gbit/s between a CU-pair, a new wavelength will be added.

7.8 Results

Here the overall results for the capacity and dimensioning of the network are presented. This includes both the wireless capacity results and the fiber capacity results.

7.8.1 Radio Capacity Results

This section reviews the results of the capacity planning for the networks. Results were found for both the 2009 and future situations.

7.8.1.1 Results for 2009

The results for each wireless technology can be seen in appendix 9 on the attached CD. There it can be seen that for 3G in the 2009 situation, that has fewest RAUs and most users, there is no RAU that needs sectorization. In fact the RAU that has the highest capacity in 3G has 4.88 Mbit/s and 1209 users in range. Since there is no need for sectorization the coverage looks the same as Figure 22 and Figure 23.

The results of WiMAX also show that no need for sectorization. The most trafficated RAU has 0.94 Mbit/s and 17 users. Since there is no need for sectorization the coverage looks the same as Figure 24.

7.8.1.2 Results for 2013

The results for each wireless technology RAU can be seen in appendix 9 on the attached CD. There it can be seen that for 3G in the 2013 situation, that has fewest RAUs and most users, most of the RAUs need sectorization and some need more than six sectors. This can be seen in Figure 47. The RAU that has the highest capacity needs 88.44 Mbit/s, and has 3093 users in range. This means it needs 9 sectors to facilitate all the traffic. In cases with this many sectors, it is necessary to plan more and smaller cells, or upgrade the BS to a technology that can facilitate higher throughput.

The most heavily loaded WiMAX cell has 42.54 Mbit/s and 1362 users. The sectorization can be seen in Figure 47.

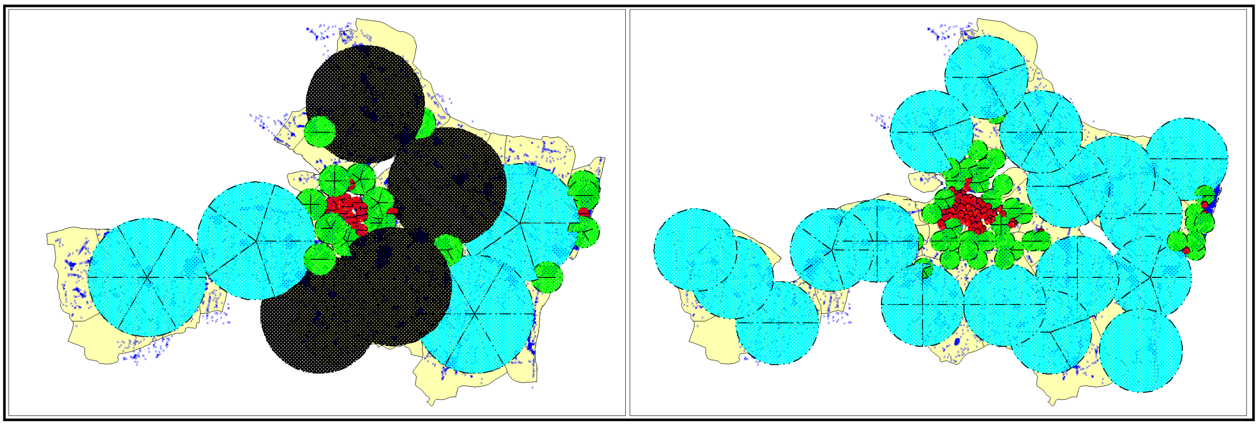


Figure 47: Sectorization for 3G (left) and WiMAX (right).

Figure 47 shows the need for sectorization of 3G to the left, and WiMAX on the right. The black circles indicate sites needing more than six sectors.

The DBWS has few users, since it becomes available in 2013. The most heavily loaded cell has 84 users, and a total traffic of 3.4 Mbit/s.

7.8.2 Fiber Capacity Results

Earlier in the coverage planning it has been found how many users each RAU has that is in use by a wireless technology. Using that as well as the average sector capacity and the MUPS can be calculated. When the capacity of each RAU has been found the capacity of a CU can be found by summing up the traffic for all the RAUs connected to it. Eventually the total traffic in the CU to CU network is found.

The load on each CU can differ highly. Some CUs have a high number of RAUs connected to them and/or are located in an urban area where high numbers of users are connected to each RAU. This results in the standard deviation becoming relatively high in the network. It is wanted to keep the network as evenly loaded as possible, in order to lower the probability of congestion.

Although there are no plans for deployment of a FUTON architecture before 2013, capacity dimensioning is done for the 2013 situation as if it was there, to compare the difference and growth of traffic.

7.8.2.1 Situation in 2009

For the situation in 2009 two CU placements are considered, automatic placement and manual placement. This is done to compare how the automatic placement performed compared to manual manipulation of the placements.

Automatically Placed CUs

There are 11 CUs placed in the automatic placement. The number of wavelengths needed to connect 11 CUs is 55, found using Equation 28 given that the needed capacity is lower than the wavelengths capacity. In Table 35 the traffic in the CUs can be seen. Since every fourth CU is backbone connected there will be three CUs connected to the backbone.

	Backbone connected	External traffic in Mbit/s	Internal traffic In Mbit/s	Users	Traffic percentage
CU 1	1	6,819	0,358	1574	0.0826
CU 2	0	1,397	0,073	164	0.0086
CU 3	0	8,921	0,469	1821	0.0955
CU 4	0	11,321	0,595	2372	0.1244
CU 5	1	22,780	1,198	4831	0.2535
CU 6	0	9,822	0,516	2378	0.1247
CU 7	0	3,590	0,188	661	0.0347
CU 8	0	3,725	0,196	897	0.0471
CU 9	1	8,874	0,467	2182	0.1145
CU 10	0	5,252	0,276	964	0.0505
CU 11	0	5,736	0,301	1209	0.0634

Table 35: Automatic CU placement results.

The average throughput in each CU is 8.443 Mbit/s and the standard deviation is 6.045 Mbit/s.

If the traffic between one or more CU-pair is larger than the capacity of a wavelength, a new wavelength must be assigned. This was not the case as can be seen in appendix 9. The average traffic between each CU-pair is 0.722 Mbit/s with a standard deviation of 1.2. This means that the CU-ring has an abundance of excess capacity.

Manually Placed CUs

In Table 36 the traffic in the CUs can be seen. Since every fourth CU is backbone connected there will be three CUs connected to the backbone.

	Backbone connected	External traffic in Mbit/s	Internal traffic in Mbit/s	Users	Percentage
CU 1	1	11,734	0,617	2686	0.1409
CU 2	0	9,182	0,483	2009	0.1054
CU 3	0	10,733	0,564	2410	0.1264
CU 4	0	6,119	0,322	1211	0.0635
CU 5	1	10,985	0,578	2405	0.1262
CU 6	0	8,550	0,450	1873	0.0983
CU 7	0	6,093	0,320	1241	0.0651
CU 8	0	5,060	0,266	980	0.0514
CU 9	1	8,313	0,437	1851	0.0971
CU 10	0	4,448	0,234	911	0.0478
CU 11	0	7,020	0,369	1474	0.0773

Table 36: Manual CU placement results.

The average throughput of each CU is 8.443 Mbit/s and the standard deviation is 2,661 Mbit/s. As can be seen the standard deviation decreases 2.26 times with manual placements of the CUs.

If the traffic between one or more CU-pair is larger than the capacity of a wavelength, a new wavelength must be assigned. This was not the case as can be seen in appendix 9. The average traffic between each CU-pair is 0.746 Mbit/s and the standard deviation is 1.00.

The standard deviation was lower for both estimated traffic in CUs and between CU-pairs for the solution with manually placed CUs. This indicates a more evenly loaded network.

7.8.2.2 Situation in 2013

For the situation in 2013 two CU placements are considered, automatic placement and manual placement. This is done to compare how the automatic placement performed compared to manual manipulation of the placements.

Automatically Placed CUs

The total number of RAUs needed for the FUTON network is 233. Thereof there are 11 who will be equipped as CUs. The number of wavelengths needed to connect 11 CUs is 55, found using Equation 28. In Table 37 the traffic in the CUs can be seen. Since every fourth CU is backbone connected there will be three CUs connected to the backbone.

	Backbone connected	External traffic in Mbit/s	Internal traffic In Mbit/s	Users	Traffic percentage
CU 1	1	156,109	8,216	5529	0.0675
CU 2	0	50,200	2,642	1714	0.0209
CU 3	0	259,640	13,665	8817	0.1077
CU 4	0	350,921	18,469	11727	0.1433
CU 5	1	688,727	36,248	23107	0.2824
CU 6	0	212,259	11,171	7562	0.0924
CU 7	0	101,411	5,337	3524	0.0430
CU 8	0	80,999	4,263	2884	0.0352
CU 9	1	187,888	9,888	6708	0.0819
CU 10	0	148,777	7,830	5169	0.0631
CU 11	0	144,549	7,607	5073	0.0620

Table 37: Automatic CU placement results.

The average throughput in each RAU is 227.9 Mbit/s and the standard deviation is 187.2

If the traffic between one or more CU-pair is larger than the capacity of a wavelength, a new wavelength must be assigned. This was not the case as can be seen in appendix 9. The average traffic between each CU-pair is 19.49 Mbit/s and a standard deviation of 33.64 Mbit/s.

Manually Placed CUs

In Table 38 the traffic in the CUs can be seen. Since every fourth CU is backbone connected there will be three CUs connected to the backbone.

	Backbone connected	External traffic in Mbit/s	Internal traffic In Mbit/s	Users	Traffic percentage
CU 1	1	271,263	14,277	9599	0.1173
CU 2	0	245,373	12,914	8434	0.1030
CU 3	0	305,370	16,072	10299	0.1258
CU 4	0	208,544	10,976	6876	0.0840
CU 5	1	300,850	15,834	10279	0.1256
CU 6	0	207,271	10,909	7301	0.0892
CU 7	0	205,165	10,798	6759	0.0826
CU 8	0	146,852	7,729	5018	0.0613
CU 9	1	198,208	10,432	6993	0.0854
CU 10	0	115,074	6,056	4029	0.0492
CU 11	0	177,513	9,342	6228	0.0761

Table 38: Manual CU placement results.

The average throughput in each RAU is 227.9 Mbit/s and the standard deviation is 63.3. As can be seen the standard deviation decreases 2.95 times with manual placements of the CUs.

If the traffic between one or more CU-pair is larger than the capacity of a wavelength, a new wavelength must be assigned. This was not the case as can be seen in appendix 9. The average traffic between each CU-pair is 20.34 Mbit/s with a standard deviation of 26.47 Mbit/s.

The standard deviation was lower for both estimated traffic in CUs and between CU-pairs for the solution with manually placed CUs. This indicates a more evenly loaded network.

Total Traffic Increase

The traffic in the network has increased 27 times from 2009 to 2013 which gives a CAGR (as seen in Equation 21) of 127%. In [37] a CAGR of 131% is expected, leading to the total traffic increasing 28.5 times in 4 years. These numbers show the same trend of rapidly growing wireless networks.

7.9 Discussion of Chapter 7 Results

The average bandwidth usage of each user was calculated for all technologies, both for the situation today, and the situation in 2013. The results for today shows that 3G users use less average bandwidth than WiMAX users, which is due to many 3G users only using the phones for calls, or light data-traffic, whilst WiMAX users have the same traffic amount as regular broadband users. By looking at what applications are assumed to be used in 2013, it was found that the average bandwidth usage will increase by 78%.

The number of users a sector can support was found by dividing the average capacity of a cell on the average bandwidth usage of the users. The results are that in 2009, 3G can support more users than WiMAX, due to the low average bandwidth usage of the 3G users. In 2013, the DBWS can support much more users in a sector than WiMAX or 3G, due to the high capacity of the LTE-Advanced technology.

The number of sectors can then easily be found by calculating the number of users within the cell, and dividing by the number of users a sector can support. In 2013, Figure 47 shows that 4 sites need more than six sectors for the 3G network. This means that these cells should be made into smaller cells needing more BSs. Another possibility is to upgrade the BS to a newer technology, such as HSPA+ (release 7) that takes the downlink up to maximum peak bandwidth of 28 Mbit/s and uplink to 11 Mbit/s.

The results of the sectorization are based on average busy hour traffic of the users. Even if this is a worst case-scenario the WISPs would in most cases dimension their network to handle more than this traffic, in case of sudden changes in usage, or growth in number of subscribers. Examples of sudden changes in usage could be the soccer stadium area during football-matches or Saturday nights down town, when the assumption of evenly distributed users does not hold. This could be implemented automatically in the planning algorithms, by adding more users to these special areas than the regular areas, or by manually adding more sectors or sites to these areas.

The fiber network is assumed to be a DWDM ring with the 11 CUs. The results show that there is much available capacity even in 2013, where only 0.2% of the capacity of each wavelength is used on average. This number will increase if fewer CUs are backbone connected, as more external traffic must traverse the ring. It will also increase if FTTH traffic is included in the FUTON architecture.

The total traffic in the network is expected to increase by 127% every year for the next four years. This is close to what is estimated in the global wireless networks in [37]. After four years, the total traffic will then have increased 27 times.

Although 0.2 % of the capacity of a fiber seems small, the average traffic on a wavelength will exceed 1 Gbit/s in 4.78 years after 2013, and 10 Gbit/s in 7.6 years after 2013, if the traffic increases in the same pattern. This shows the importance of deploying a network that is able to handle the future conditions of network traffic.

One wavelength is assigned to each CU-pair, which means that the number of wavelengths quickly increases if the number of CUs is high. Other methods that minimize the number of wavelengths may be used, but was not implemented in this project.

The standard deviation of traffic load on the CUs and the traffic between CU pairs are higher for the automatically placed CUs than for the manually placed CUs. This shows that the automatic method of placing CUs does not provide optimal solutions with regards to even network load.

For more on implementation see appendix 1.

7.10 Summary

This chapter investigated the current and future trends in wireless networks. Average bandwidth requirements for users was estimated and used to find the maximum users a sector can support. This information was used to sectorize the three networks planned in chapter 4. The needed number of wavelengths in the fiber-network was calculated, and predictions for the future were made.

The next chapter will conclude on the findings of this thesis.

8 Conclusion

The purpose of the project was to plan an implementation of the FUTON architecture, and develop a method of planning this kind of infrastructure. It was a goal to make as much of the planning as possible automated to ease the work of the network planner. The Danish municipality of Aalborg was selected as the geographical scenario for the project, and the planning was assumed to be done in 2013, when the FUTON project is finished.

The tasks defined in section 1.2.1 have all been done:

- **Radio Coverage**

  Radio coverage for 3G, WiMAX and DBWS was planned using greedy and genetic algorithms. The RAUs were placed so they provide coverage to the most number of users at the lowest cost.

  Results were made for the 3G, WiMAX and DBWS network using 97% indoor coverage of MTs as a limit. Since mobility plays a big role in 4G networks, the outdoor coverage must be as large as possible, to enable an always-on service for the user. The solutions generate 100% outdoor coverage.

  Due to the inaccuracy of the propagation model used in this project the coverage area of each BS is unrealistic. The results of the automated planning would therefore be more realistic if using more detailed propagation models to get more accurate information about the coverage area of each RAU.

- **CU Placement**

  The CUs are placed using a genetic algorithm much like the one used in radio planning, with the objective of "covering" the RAUs by having a CU within range. The results show that it is able to provide coverage of all RAUs, but it does not place the CUs in positions where they even out the number of connected RAUs. A manual solution was therefore created in addition to the automatic, to see how they compared in fiber planning and traffic dimensioning. Due to the sub-optimal solution from the automatic CU-placement in this project, this area is suggested as an interesting area for further work.

- **Fiber Planning**

  Fiber planning consists of planning the location of the fibers and trenches in the ring interconnecting CUs, and the trees connecting the RAUs to the CUs. In fiber planning, it was necessary to use a path-finding algorithm where A* proved to be much faster at finding optimal paths than the Dijkstra-algorithm. To minimize digging, the trees connecting RAUs to CUs were made with MSTs. When the trees are done, the number of splitters, fibers and fiber-length and trench-length needed is calculated and optimized using a GA.

The results show that if splitters are removed in the CU to RAU trees, the total fiber length increase by 47.5% for the automatically placed CUs and 40% for the manually placed CUs. The number of fibers increases with 204% and 246% for the automatically and manually placed CUs respectively.

The interconnection of CUs was planned using a ring-topology, due to its widespread deployment, simplicity and low cost. The paths between the CUs were found using A*, and a GA finds the ring using the minimum amount of trenches. The results show that the two placements of CUs that has been done, does not differ in the length of the trenches.

- **Traffic Estimation and Capacity Dimensioning**

  The number of sectors can then easily be found by calculating the number of users within the cell, and dividing by the number of users a sector can support. In 2013, 4 sites need more than six sectors for the 3G network. The WiMAX and DBWS network both have less than 6 sectors at the BSs. The results of the sectorization are based on average busy hour traffic of the users. Even if this is a worst case-scenario the WISPs would in most cases dimension their network to handle more than this traffic, in case of sudden changes in usage, or growth in number of subscribers. This could be implemented automatically in the planning algorithms, by adding more users to these special areas than the regular areas, or by manually adding more sectors or sites to these areas.

  The CAGR for the network was calculated to 127%. From 2009 to 2013, the total traffic will then have increased 27 times. The CU ring is assumed to be a DWDM ring with 11 CUs. The results show that there is much available capacity even in 2013, where only 0.2% of the capacity of each wavelength is used on average. Although 0.2 % of the capacity of a fiber seems small, the average traffic on a wavelength will exceed 1 Gbit/s in 4.78 years after 2013, and 10 Gbit/s in 7.6 years after 2013, if the traffic increases in the same pattern. This shows the importance of deploying a future proof network.

  The standard deviation of traffic load on the CUs and the traffic between CU pairs are higher for the automatically placed CUs than for the manually placed CUs. This shows that the automatic method of placing CUs from chapter 5 does not provide optimal solutions with regards to even network load.

All the tasks defined in the project objectives have been done. A method for planning an implementation of the FUTON architecture has been created, and tried out for Aalborg municipality. The planning process uses GIS-data to automate planning for the entire architecture. During the project a collection of scripts that can easily be modified for planning a FUTON architecture anywhere has been made. The scripts are made using functions for the different tasks, in order to make them easy to extend and modify. All planning scripts are made using Python, and some MapBasic has been used to visualize the results in MapInfo.

8.1 Future Work

This project is a high level planning of the FUTON architecture, in order to cover as many areas as possible of network planning in the time available. Therefore there are many possibilities for future work that was discovered during the course of this project.

- **Radio Planning**

  It proved hard to find a propagation model for usage with this project, because most available models are only valid for frequencies below 2000 Mhz. A challenge is therefore to find another propagation model or accurate correction factors so that the coverage sets are made as realistic as possible. The quality of the automated radio planning solutions is dependent on the accuracy of these coverage sets.

  To make coverage sets even more accurate, it could be a good idea to get a more detailed GIS-database, containing information on houses, floors, terrain etc. and use this information together with a propagation model.

  Network planning using MIMO is an area with very limited research available. Considering the major advantages MIMO technology offers, it is necessary to have tools that can be used to plan a network that takes full advantage of this. The planning method could be dynamic, by allowing the planner to set what kind of MIMO-scheme(s) and performance is wanted by the network.

- **CU Placement**

  The automatic CU placement used in this project led to unnecessary uneven traffic loads in the network, compared to the manually placed CUs. In smaller projects this CU planning could be done manually, but it is desired to keep this procedure automated as well. Unfortunately there was not enough time to look more into facility location problems, and finding a better solution for this procedure is therefore left for future work. The method should automatically configure the number of CUs, so it fits the fiber scenarios for CU to RAU planning, and small deviations in the number of RAUs per CU is wanted to create more even network load.

  The RAUs are assigned to its closest CU during the CU placement, and this information is used to build MSTs in the fiber planning. This sometimes leads to sub-optimal solutions, as the RAUs may be closer to a tree from another CU. This leads to more trenches than necessary being used in the CU to RAU network. A method for correcting this flaw afterwards, or another way of implementing this planning that eliminates the problem could be an interesting topic for further research.

- **Fiber Planning**

  The maximum fiber length from the fiber optic scenarios in section 3.2.3 is only used as guideline when placing CUs, and not as a constraint when building MSTs. This was chosen because it is possible to amplify the signal to achieve longer ranges. Comparisons of the implications on CAPEX and OPEX of amplification vs separate trenches could be made, to choose which method is cheapest. With this information it is also possible to make a dynamic method that utilizes link budget information and cost information when planning the MSTs.

  For this project, the tree-topology was used between the CUs and RAUs, as it is listed by the FUTON project as a likely topology. The tree-topology has weaknesses, like poor reliability and no redundancy, and might therefore not be the best suitable choice for all networks. It is therefore interesting to compare plans using different topologies, and their implications on costs, reliability and survivability of the network.

- **Economical Aspects**

  The economical aspects of network planning is very important. In this project, it is however only mentioned briefly. The success of a technology or architecture is dependent on being economically feasible, for it to be implemented to as wide extent as possible. A study on the economical impacts of the FUTON architecture and topologies could be studied.

- **Planning Tool**

  It would be interesting to create an expandable and easily configurable planning tool for planning this kind of architecture based on the scripts in this project. A GUI frontend could be made to enable fast configuration of the planning mechanisms. The splitting of tasks into functions means that if someone made an implementation of the SUI propagation model, the planner can simply choose whether to use the COST 231 Hata model or the SUI model as the propagation model in radio planning.

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10 Appendices

10.1 Appendix 1: Implementation

This appendix will explain how the planning process was implemented in this project. In order to solve the planning tasks, it was decided to use Python programming. Python is a powerful object-oriented programming language with easy syntax that enables rapid software development. For more information on Python and how to run the programs made during the project, see appendix 10.

The planning process involves many elements and areas, e.g. fiber-planning, radio planning, capacity dimensioning and database-modifications. Since there are many tasks, and some that are CPU-intensive and time consuming, separate programs for each task has been made. In order to provide the reader with an overview of how to generate results using the programs in this project, a small walkthrough is provided here. For more detailed information, please refer to the commented source code on the attached CD.

Figure 48 shows a flowchart of the planning process. Every box in the diagram represents a program that performs the described tasks. Each program has its own folder in the source-code folder on the appendix-cd.

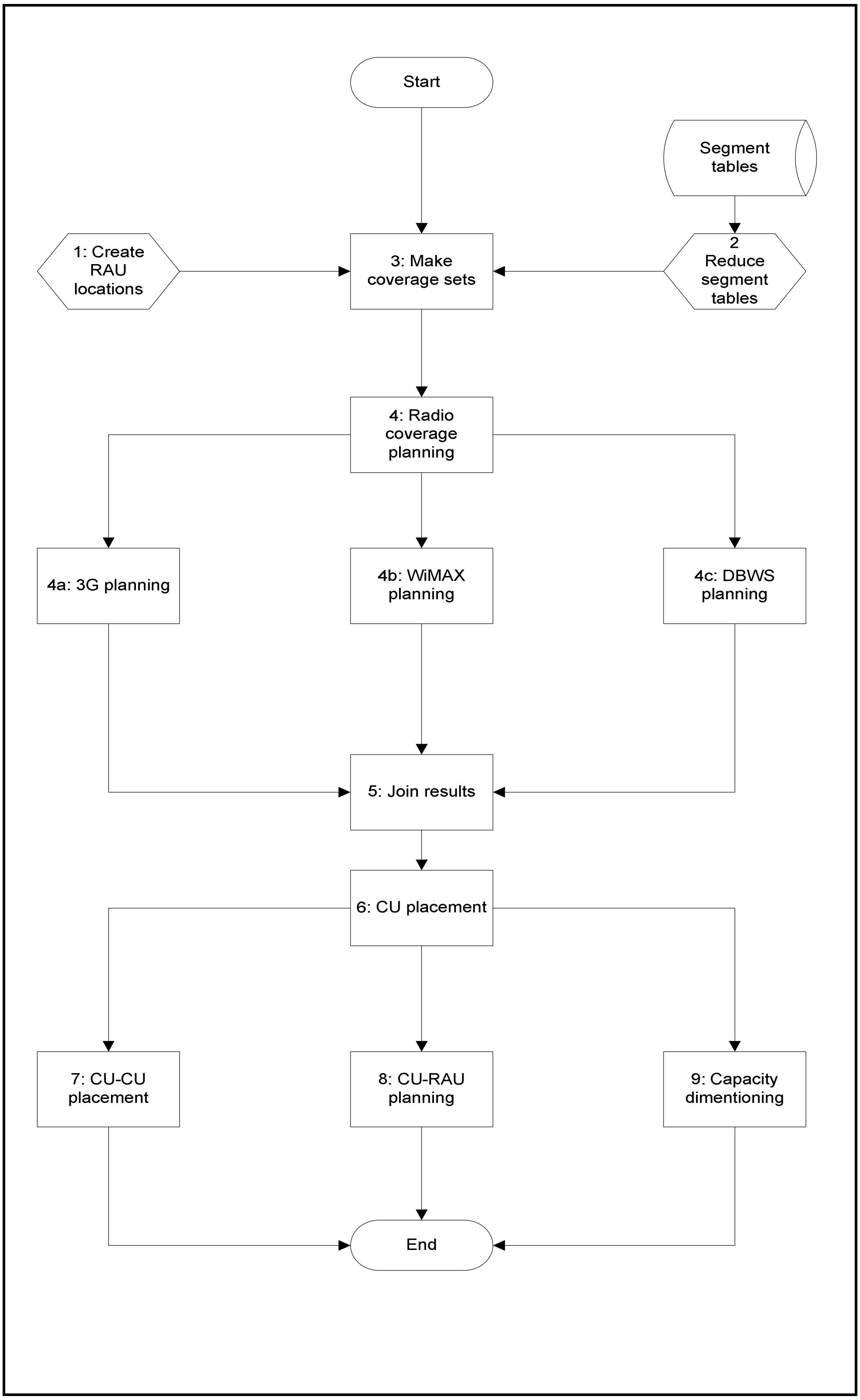

Figure 48: Overall project flow.

The different tasks in Figure 48 are explained below:

1: Prepare RAU-locations.

As described in chapter 3, it was necessary to create a fictional set of possible RAU and BS locations for the wireless networks. This set was to be used for planning of 3G, WiMAX and the DBWS. It is made by placing an RAU-location every 1000 meters in the area of Aalborg municipality (and every 200 meters in the downtown area). After this, the ones located in areas without any MTs are removed (e.g. in the middle of Limfjorden). This is done using the two scripts in the "1 – create grid" folder of the source code. "Gridmaker.py" creates the 1000-meter grid, whilst "add_urban_grid" adds the 200-meter grid.

Input: Start and stop x-coordinates for the grid

Output: Database table with x-y coordinates, and an identification number

The finished database used for further calculations in this project can be found in appendix 9 in the database on the appendix CD.

2: Prepare Segment Tables.

As described in chapter 5, the size of the segment-database had to be reduced in order to make calculations run faster. This was done by implementing the algorithm described in appendix 6. The program therefore requires a GIS-database containing information on segments, before it runs the algorithm and output a reduced GIS-database with a segment point table and a segment table. The program is located in the folder "2 - Prepare segment tables" in the source code.

Inputs: Original GIS-database with segment table

Output: Reduced GIS-database with segment and segment point table.

The finished database used for further calculations in this project can be found in appendix 9 in the database on the appendix CD.

3: Make Coverage Sets

In order to find out the best way of providing radio coverage in step 4, it was necessary to calculate who of the MTs are covered by each of the possible RAU-locations. This program therefore finds the id of each MT within the range of a possible RAU, and writes it to a text-file. The program is located in the "3 – create coverage sets"-folder on the CD.

Input: RAU locations and MT locations

Output: Text-file with coverage sets.

The finished text-files used for further calculations in this project can be found in "Results"-folder in the database on the appendix CD.

4: Radio Coverage Planning

When the RAU-locations are fixed, it is possible to find how many of these have to be "active" to provide coverage for a fixed percentage of the MTs. This was implemented by formulating it as a set-cover problem, and solved using the greedy and genetic algorithm. More information on implementation is found in section 4.5. Radio planning for the three different technologies all use the same program, but performs the planning according to parameters deciding what technology it is planning for. The program can be found in the folder "4 - Radio planning" in the source code.

4a: 3G Planning

Input: 3G-specific parameters, MT-locations, possible RAU-locations and its coverage sets.

Output: Database-table with "active" BSs for 3G

The finished database used for further calculations in this project can be found as table “3G” in the “RESULTS_DATABASE” on the appendix CD.

4b: WiMAX Planning

Input: WiMAX-specific parameters, MT-locations, possible RAU-locations and its coverage sets.

Output: Database-table with "active" BSs for WiMAX

The finished database used for further calculations in this project can be found as table “WIMAX” in the “RESULTS_DATABASE” on the appendix CD.

4c: MIMO Planning

Input: LTE-specific parameters, MT-locations, possible RAU-locations and its coverage sets. Locations of placed 3G and WiMAX BS.

Output: Database-table with "active" BS for LTE

The finished database used for further calculations in this project can be found as table “MIMO” in the “RESULTS_DATABASE” on the appendix CD.

5: Join Results

Since the fiber planning is supposed to combine the three radio networks in the same infrastructure, a program to combine the results of the radio planning into one table was made. The program can be found in the folder “5 - join” in the source code folder on the appendix cd.

Input: Results of 3G, WiMAX and MIMO-planning

Output: A single table with the same results

The finished database used for further calculations in this project can be found as table “joined” in the “RESULTS_DATABASE” on the appendix CD.

6: CU-Placement

When all RAUs and BS are located, it is necessary to find out where to place the CU's. This was done by formulating the task as a set-cover problem, like in the radio planning. Each RAU is assigned a range as described in section 4.4.2. It is assumed that if a CU is placed at the RAU, it will provide a CU-connection for all RAUs within this range. The number of CUs necessary to provide a CU-connection to all RAUs is found using GA after this each RAU is assigned to a CU using A* search. The program doing this is found in the “6 – CU placement”-folder in the source code on the CD.

Input: Joined result table

Output: Joined result table with CU information

The finished database used for further calculations in this project can be found as table “Automatic_CU” and “Manual_CU” in the “RESULTS_DATABASE” on the appendix CD.

7: CU-CU Planning

It is necessary to interconnect the CUs using a high-speed fiber-backbone. It is assumed in this project that a fiber-ring with logical point-to-point connections will provide enough reliability for this. The task was therefore implemented using A* search to find the best path between CUs, and a permutation-version of the GA to find the ring using the least fiber. The program is located in the “7 – CU_CU planning”-folder in the source code on the CD.

Input: Joined result-table (with cu-information), reduced segment tables

Output: The ring path and statistics

The finished database used for visualization in MapInfo can be found as table “Automatic_CU_CU_segments” and “Manual_CU_CU_segments” in the database on the appendix CD. In the “results”-folder the plots and statistics from this step can be found in the results of the manually and automatically placed CUs.

8: CU-RAU Planning

When the CUs are placed, it is necessary to make sure every RAU has a connection to a CU. This was implemented by creating MSTs from each CU to its assigned RAUs. The paths in the tree was found with A* search. In order to find the shortest fiber length and lowest amount of splitters needed for each MST, a simple GA was implemented. The program is located in the “8 – CU_RAU planning”-folder in the source code on the CD.

Input: Joined result-table (with cu-information), reduced segment tables

Output: Fiber paths and statistics.

The finished database used for visualization in MapInfo can be found as table “Automatic_CU_RAU_segments” and “Manual_CU_RAU_segments” in the “RESULTS_DATABASE” on the appendix CD. In the “results”-folder the plots and statistics from this step can be found in the results of the manually and automatically placed CUs.

9: Capacity Dimensioning

When the radio and fiber-network is in place, it is necessary to dimension the capacity in the different parts of the network. This was implemented by finding the capacity usage of each RAU using the wireless technology throughput, number of users using the service and MUSP. Using this information the RAU could be sectorized according to the bandwidth needs of each RAU. The bandwidth use of all the RAUs connected to a CU is summed up to the bandwidth use of that CU. The CU to CU network is then dimensioned according to the bandwidth use of each CU.

Input: Table stating the RAUs and number of users. A Table that stats the technology bandwidth and a table that stats the modulation areas of technologies.

Output: CU txt-file with the bandwidth from all the RAU combined into the respective CU

The finished database used for further calculations in this project can be found in appendix 9 in the database on the appendix CD.

10.2 Appendix 2: Path-finding Algorithms

Two pathfinding algorithms were implemented during the course of this project, with the object of finding the shortest path. The shortest path is the route using the least length from one location to another using the segment information available. Originally it was thought to use only Dijkstras algorithm, but this was exchanged with A* search later in the project due to speed. Both will be presented here.

10.2.1 Dijkstras Shortest Path

Dijkstras shortest path algorithm is named after the Dutch programmer Esdger Dijkstra, and computes the optimal result for a single source shortest path problem. The algorithm computes the shortest path from a start vertex to all other vertices in the graph, for connected graphs with positive weights. In network planning however, it is common to only be interested in the shortest path from source to one target. Because of this, the algorithm can be terminated when the target is found, to speed up the running time. The pseudocode for the Dijkstras algorithm can be seen in Text-Box 1.

```
Dijkstra (Graph, source, target)
    for vertex v in Graph:
        dist[v] = infinity          #Unknown distance from source
        parent[v] = none            #Unknown parent vertex
    dist[source = 0]
    Q = all vertices in Graph
    While Q not empty:
        u = vertex in Q with shortest dist[]
        remove u from Q
        if u == target:
            break
        for each neighbor v of u where v still in Q
            new_distance = dist[u] + distance_between(u,v)
            if new_distance < dist[v]:
                dist[v] = new_distance
                parent[v] = u
    return parent
```

Text-Box 1: Dijkstras Algorithm

When the algorithm has run, it is necessary to use the backtracking algorithm to find the path from source to target.

10.2.2 A* Search

The A* searach is a flexible search algorithm that uses two cost functions to limit the search space. This can be seen in Equation 29. In this formula, *f(x)* is the total cost*, g(x)* is the cost to get to the current location, while *h(x)* is the heuristic estimate of distance to goal.

$$f(x) = g(x) + h(x)$$

Equation 29: A* functions

If g(x) is set to 0, the algorithm becomes a greedy search. If h(x) is set to 0, the algorithm becomes Dijkstras shortest path.

For this project, g(x) was the length of segments from start location to location x, and h(x) was the eucledian distance to the goal. Using this heuristic ensures that the A* search gives the same result as Dijkstra's (optimal result).

The pseudocode for the A* search can be found in Text-Box 2.

```
A* (Graph, source, target)
    parent = []*vertices in Graph
    open = empty set         #Set of vertices to be evaluated
    closed = empty set       #Already evaluated vertices
    add source to open
    g_cost[source] = 0       #Distance from source along the path
    h_cost[source] = estimate_of_cost_to_target(source,target)
    f_cost[source] = g_cost[source] + h_cost[source]
    while open not empty:
        u = vertex in open with lowest f_cost
        if u == target:
             break
        remove u from open
        add u to closed
        for each neighbor v of u:
            if v in closed:
                continue
            elif v not in open:
                add v to open
                test_f_cost = g_cost[u]+dist_betw(u,v)+h_cost[v]
                if f_cost[v] > test_f_cost:
                    f_cost[v] = test_f_cost
                    parent[v] = u
                    g_cost[v] = g_cost[u]+dist_betw(u,v)
    return parent
```

Text-Box 2: A* algorithm[31].

When the algorithm has run, it is necessary to use the backtracking algorithm to find the path from source to target.

10.2.3 Backtracking

When the path-finding algorithm is finished, the path can be found by backtracking from the target to the source, using the parents. The pseudocode for this procedure can be found in Text-Box 3.

```
backtrack(parent, source, target)
    path = empty set
    add target to path
    vertice_in_path = parent[target]
    while vertice_in_path != source:
        add vertice_in_path to path
        vertice_in_path = parent[vertice_in_path]
    add source to path
    return path
```

Text-Box 3: Backtracking algorithm

10.3 Appendix 3: Fiber-optics

The fiber cables carry the data from source to destination in the form of light signals i.e. the data travels across the cables in the speed of light. Since the data travels in the form of light this gives the signal resistance to electromagnetic interferences. The fiber cable is made of a glass or plastic core covered by a cladding which is coated and surrounded by a buffer the cable itself is shielded by a PVC Jacket as shown in Figure 49, the light signal travels through the glass core. The different refractive index of the cladding causes the light signal to keep traveling through the core like can be seen in Figure 50, the buffer provides extra fiber protection it also preserves the fiber strength and absorbs shocks.

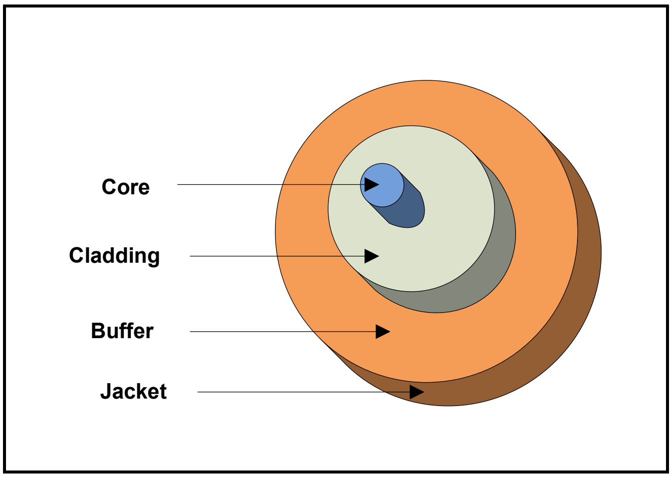

Figure 49: Fiber cable.

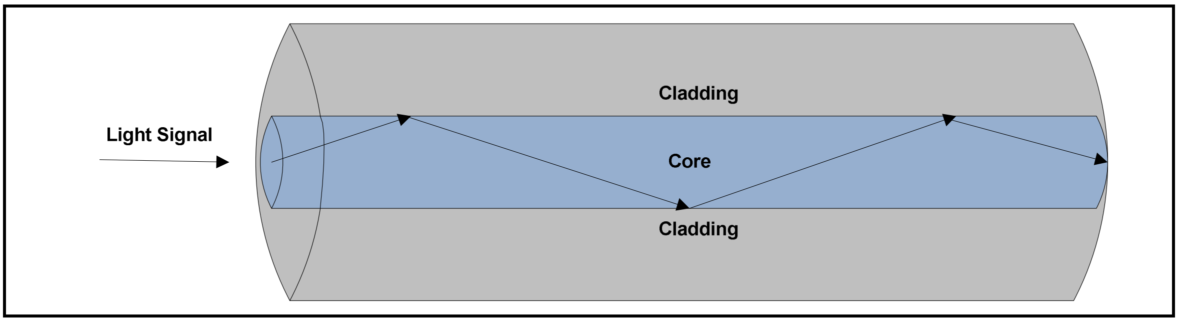

Figure 50: Fiber cable operation.

Advantages of Fiber Optics

Any network built on fiber technology is characterized by a number of befits and advantages such as:

- Fiber optics has very high potential bandwidth, very low latency and very short round trip times if compared to other telecommunications technologies.
- Due to fibers low dispersion it therefore uses either no or very few repeaters and signal generators.
- The fiber optics cable is not affected by the electromagnetic fields or corrosion unlike coaxial cables and copper wires.
- The fiber optics cable is not affected by rain, foliage or interferences [9].

Wavelength Division Multiplexing (WDM) in optical networks

WDM is a technology used to combine multiple wavelengths from different users on one single optical fiber it is quite similar to the frequency division multiplexing (FDM) used in microwave radio and satellite systems. To explain this technology the case of a point to point connection will be considered with w independent transmitters (Tx) and w independent receivers (Rx). Transmitters in this case are all light sources such as laser, the outputs of these transmitters are optical signals with different wavelengths (colors) λ_i where i=1, 2, 3⋯, w. A wave length multiplexer is then used to combine all wave lengths into one optical signal and the signal is transmitted over a single optical fiber. At the receiver's end the combined optical signal is then demultiplexed using a wave lengths de-multiplexer into w optical signals and each one is directed to the designated receiver (Rx) this operation is shown in Figure 51.

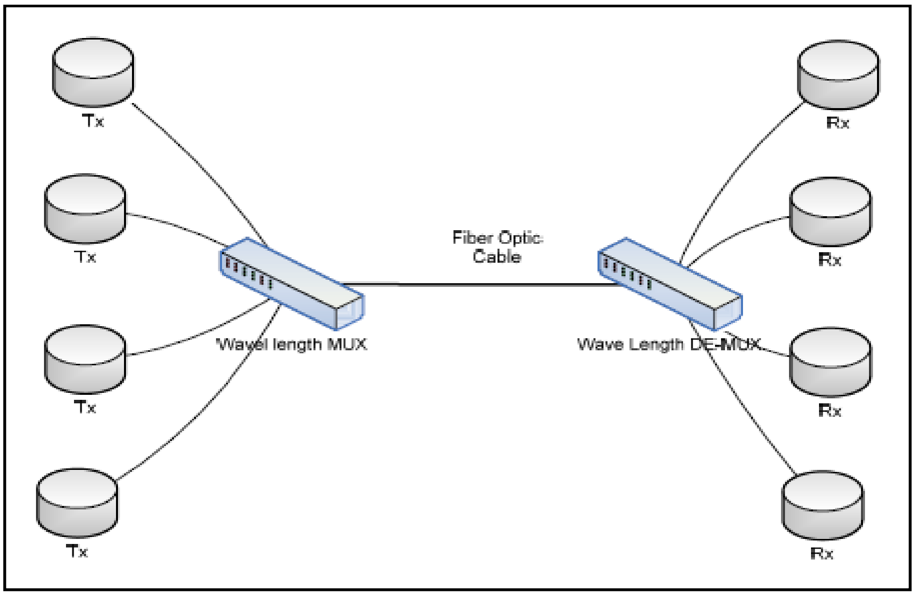

Figure 51: Wavedivision muliplexing.

Fiber Attenuation

Fiber attenuation is the reduction in signal strength over a distance. Attenuation in Fibers is much lower than in cables like coaxial cables which is one of the factors why fiber is desierable for comunication systems. Fiber attenuation is measured in dB/km and has a certain wavelenght area where the attenuation reaches its lowest values as can be seen in Figure 52. Attenuation is mostly caused by scattering and absorption [56]. Another thing that causes higher attenuation is the amount of water ions in the cable, the affect of the water ions can be seen in Figure 52 where it is shown as „Water Peak“. Newer and more advanced fiber cables are able to reduce this peak that helps to reduce the attenuation in the fiber.

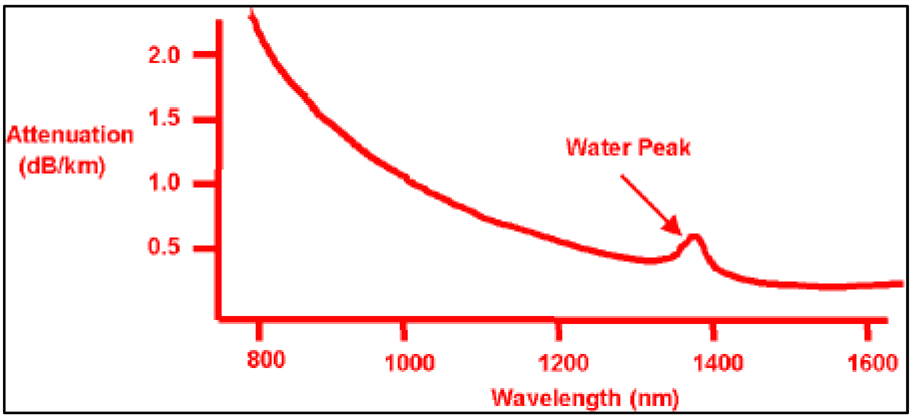

Figure 52: The fiber attenuation as a function of the wavelength [56].

10.4 Appendix 4: Wireless Terms and Definitions

This appendix will explain some of the terms and definitions used by many wireless technologies, and in planning of wireless networks.

10.4.1 Sectorization

When planning the cells in a wireless network, the number of users in a cell might be so high that the traffic load will exceed the capabilities of the cell. In this case it is necessary to sectorize the cell.

Sectorization is achieved by replacing the omnidirectional antennas with two or more directional antennas. The different sectors of a cell normally use different frequencies, in order to increase the total capacity in the cell. This means that the sectors combined can serve more people combined than a cell with an omnidirectional antenna.

When planning with honeycombs structures the sites can be seen as being put on the edges of the honeycomb facing three different honeycomb areas. Example of honeycomb setup using sectorizing can be seen in Figure 53.

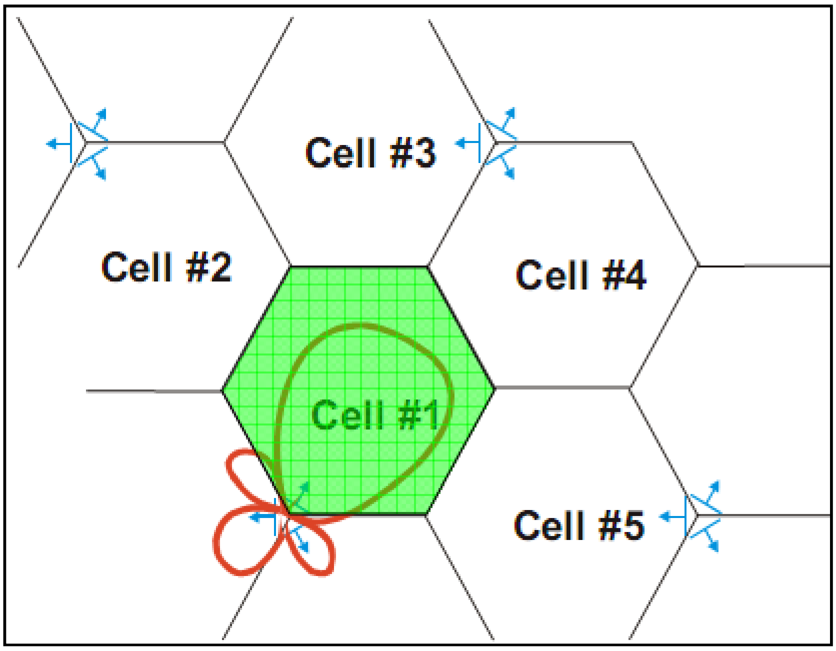

Figure 53: Sectorization.

10.4.2 Modulation Techniques

The process of modulating a signal is explained as mixing the signal with a sinusoid signal to produce a new mixed signal. The new signal will have certain benefits of an un-modulated signal during transmission. The benefit of modulating signals is the ability to send this signal over a bandpass frequency range. When every signal has its own frequency range, then transmission of multiple signals simultaneously over a single channel is possible since all signals are using different frequency ranges. There are several types of modulation techniques each giving a variety of coverage ranges based on the SNR. When a wireless system is said to be using adaptive modulation it means that the wireless system is allowed to choose the highest order modulation depending on the broadcast channel conditions. This means that when the user is far from the BS this gives lower modulation but as the user gets closer to the BS then higher order of modulations can be used to increase the throughput [57]. The different types of modulations are explained below.

BPSK

Binary Phase Shift Keying (BPSK) has two distinct phase shifts which are modulated the carrier. It is 180° opposed and can represent 1 bit per transition. There is no obligation that the phases start at 0° as long as the phase states are 180° apart. BPSK is shown in Figure 54.

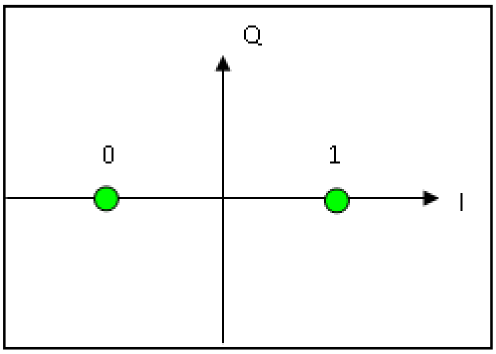

Figure 54: BPSK.

QPSK

More phases can be used although it requires more power to transmit over the same distance. Quadrature Phase Shift Keying (QPSK) uses 4 distinct phases separated by 90°. QPSK represents 2 bits per transition although it needs more signal power at the receiver to be able to recover the information accurately. As in BPSK the state doesn't necessarily need to start at 0°. Figure 55 shows QPSK.

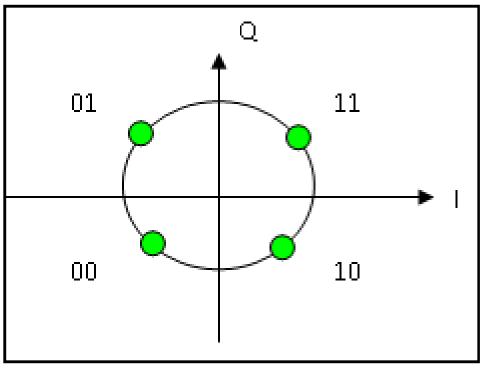

Figure 55: QPSK.

8PSK

The next step from QPSK is logically 8 PSK where eight distinct phases separated by 45°. 8 PSK can represent three bits per transition.

Although each of these modulations is more efficient since more bits can be transmitted each second it also increases the possibility of loss of information on a noisy transmission medium. Additions to 8 PSK continue to reduce the robustness of the radio channel. Therefore it is uncommon in practice to go higher than 8 PSK.

QAM

As spectrum have become more congested and the demand on amount throughput has increase even 8 PSK have become insufficient to provide enough channel capacity for many situations. This limitation has been overcome by using the carrier's amplitude to carry additional bits. That is on top of modulating the phase the amplitude is now being modulated as well. This is known as Quadrate Amplitude Modulation (QAM). QAM is formed by two phase states from BPSK adding two distinct amplitude states to each. QAM can be seen in Figure 56.

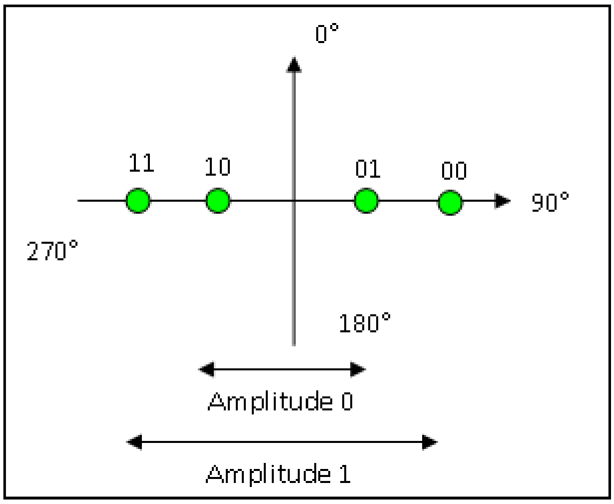

Figure 56: QAM.

This can be extended further. Adding two distinct amplitude shifts to a QPSK single 8 QAM is formed. This extends to 16, 32 and even up to 512 QAM.

Increasing the number of phases naturally increases the uncertainty of receiving and correctly interpreting each state when they increase as high as up to 512 states. Using 256 QAM the carrier must be 30 dB (1000 times) stronger than the noise in the channel so it can be sufficiently heard and demultiplexed at the receiver side. This can be put into consideration with BPSK that only needs to be 6 dB (4 times) stronger than the noise. Because of this designers use the simplest modulation suitable for their implementations. The balance equation here is the power versus spectrum bandwidth for a given throughput since simple modulation needs less power but delivers less throughput. Too complex modulation may result in the portable device needing too much power shortening the battery life extensively. It can also result in small coverage area and to high error rate for effective communication. Figure 57 shows trades-off that are associated with increasing modulation complexity.

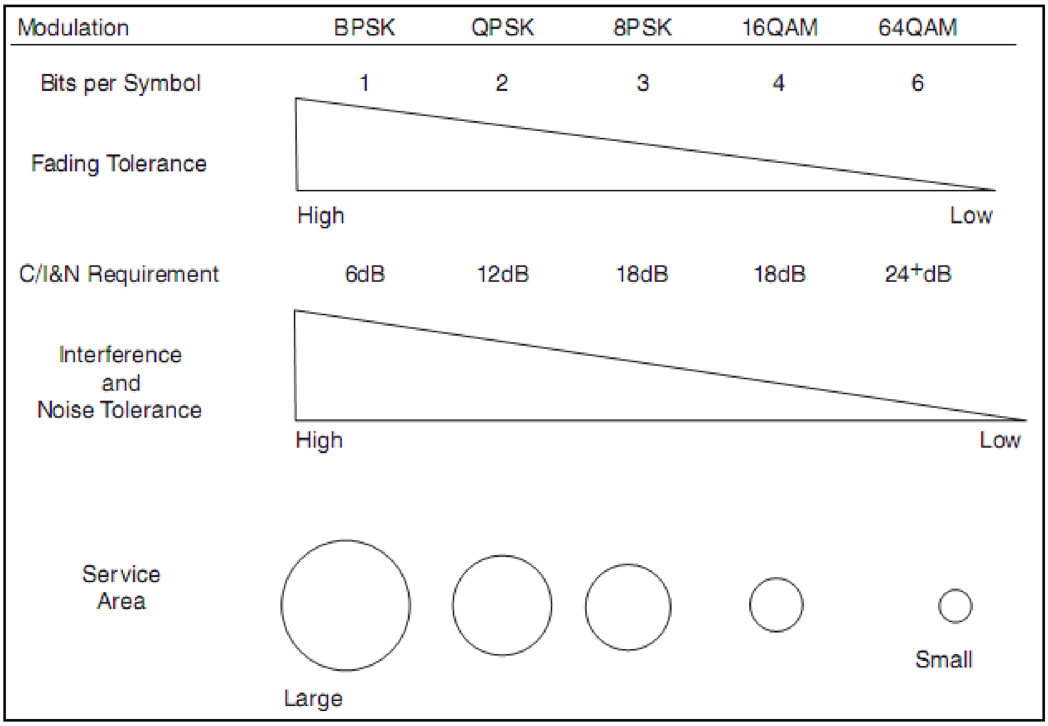

Figure 57: Overview of modulation & techniques. [58].

10.4.3 Coding Rate

The modulations are often given as e.g. QPSK ½ or 16QAM ¾. The fractions are used to describe the information rate of the forward error correction-code (FEC) in use. Depending on the FEC-method in use, the fraction can either refer to bits or blocks. In other words, it describes the number of useful bits or blocks divided by total number of bits or blocks. FEC is commonly used to achieve more reliable wireless channels.

In QPSK ½ and 16QAM ¾, one redundant bit/block is inserted after every first and third bit/block respectively. As more redundant bits/blocks are added, the channel becomes more reliable, but the throughput decreases [59].

10.4.4 Duplexing

In the modulation section it was assumed that the transmitter and receiver were standalone devices only capable of one-way communication. To be able to receive and acknowledge receipt of good information, ask for resend or report error a wireless data system needs to be two-way. Duplexing is performed in two ways. It can be either Frequency Division Duplexing or Time Division Duplexing.

FDD

Frequency Division Duplexing (FDD) has two distinct and separate frequencies allocated. The frequencies are used such that one is transmitted from the BS to the MT where it is received. The other frequency is transmitted from the MT and received by the BS. These two frequencies share a common antenna and therefore large separation needs to be between them, 45 MHZ or more so that the local transmitter energy can be filtered out of the local receiver. Systems requiring symmetric traffic benefit most by using FDD since the two channels have equal bandwidth.

TDD

Time Division Duplexing (TDD) uses a single frequency to accommodate both transmitting and receiving signals at both ends of the link. In order to do this the channel is divided into timeslots. This can be done in such a way that the transmitter and receiver see a continuous flow of information. The timeslots are divided into both transmit and receive time slots with small guard between them. Systems needing asymmetric traffic benefit most from using TDD since the slots can be allocated asymmetrically.

10.4.5 Multiple Access Technologies

In a wireless network there are usually many simultaneous users needing access to the network. In order to provide them access to the network a Multiple Access (MA) technique is needed.

FDMA

The original and simplest MA is Frequency Division Multiple Access (FDMA). It simply divides RF band into discrete channel allocation. Enough bandwidth to accommodate the modulation technique is assigned as well as enough space for sufficient information rate that the technology requires. One user can use each channel at a time. FDMA can be seen in Figure 58.

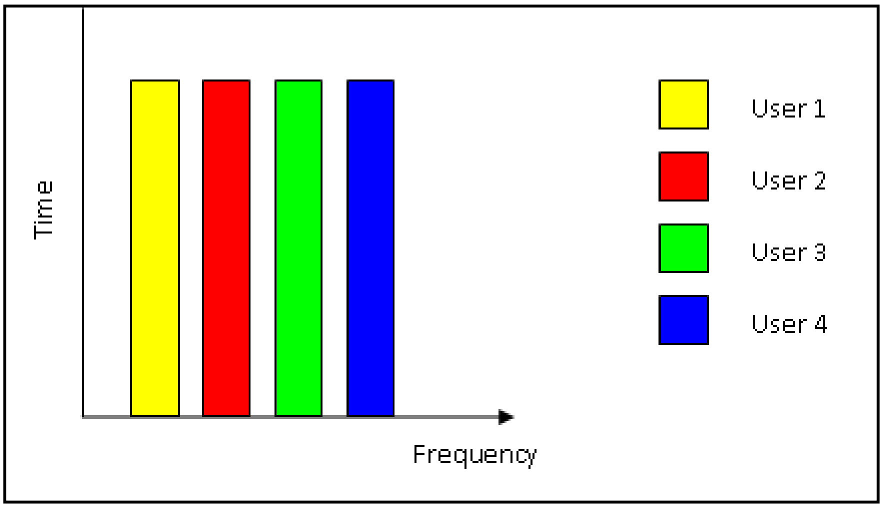

Figure 58: FDMA.

TDMA

Time division multiple Access (TDMA) is another simple method where users are allocated time slizes. The shared channel connection is switched so frequently that the user will not notice that he is sharing a channel with other users. TDMA divides each channel into many timeslots. The entire channel is occupied by these timeslots and assigned to users.

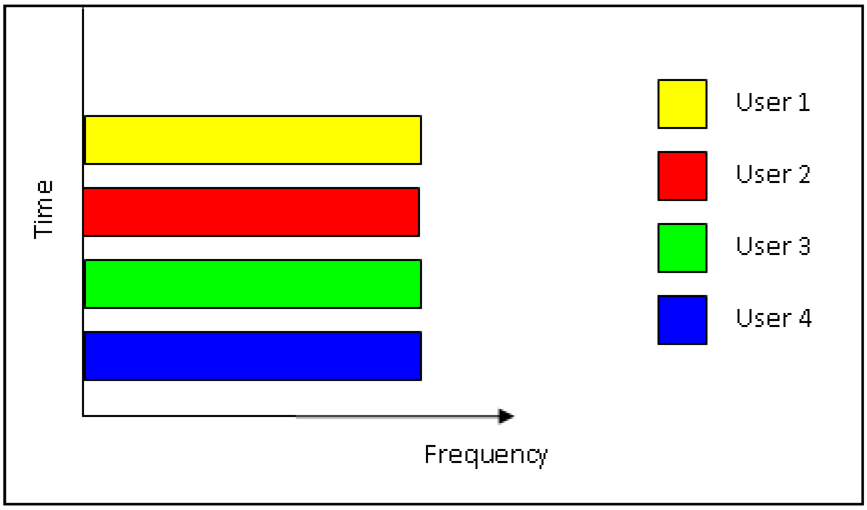

Figure 59: TDMA.

Spread Spectrum Technologies

For TDMA and FDMA to work well it requires good frequency management as well as good usage planning. If people in the area simultaneously use the same channels it causes interference. Because of this a reuse planning is needed. It is the matter of managing spectrum allocation in order to get the maximum capacity in an area that is to be served. It reuses the same channel in such a way that it minimizes interference. This means the location of the BS, height of the antenna and the transmitting power also needs to be put into consideration. Because FDMA and TDMA have problems to easily provide high throughput with many simultaneous users other modulation methods were perfected.

Spread spectrum one of the technologies built to overcome the shortcomings of FDMA and TDMA. Originally it was a method to provide secure communication and as the name implies it needs a much larger channel than the fundamental bandwidth requires.

CDMA

Code Division Multiple Access (CDMA) is an implementation of *Direct-Sequence Spread Spectrum (*DSSS). It uses characteristics from DSSS to provide multiple users access to the channel simultaneously. CDMA uses number of orthogonal codes as pseudo-random spreading codes. It can support multiple users on a common channel by associating unique code to each user using the channel, this results in the users being isolated from each other. CDMA can be seen in Figure 60.

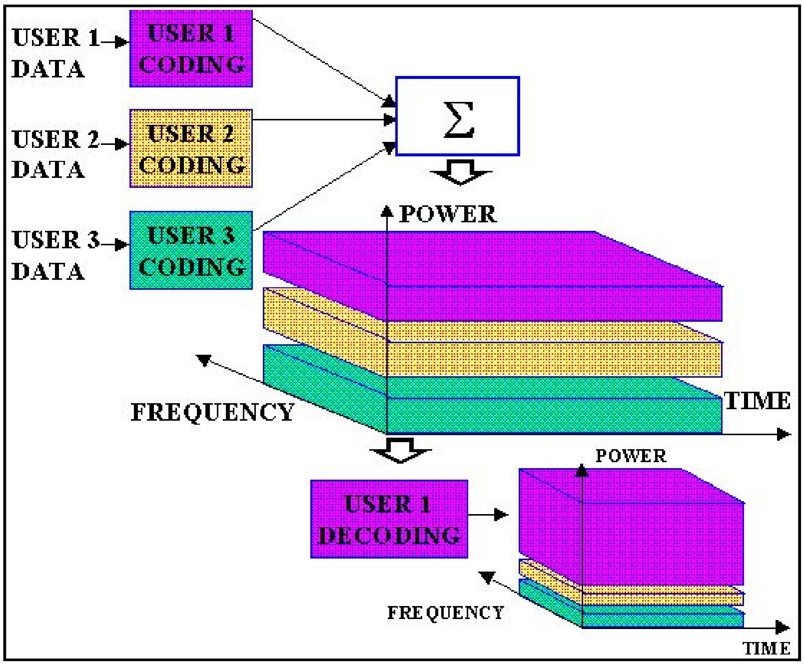

Figure 60: How different users share the same frequency over the same timeframe [60].

WCDMA

Wideband Code Division Multiple Access (WCDMA) is a wide spectrum implementation of CDMA using 5MHz spectrum. As in CDMA all users share the same time and frequency domain and individual users are separated using codes. Orthogonal codes are also used to separate the users. It uses both FDD and TDD.

WCDMA spreads the signal by directly combining the baseband information to the high chip rate binary code. The spreading gain is explain in dB and the chip rate for WCDMA chip is 3.84 Mchips/s. Equation 30 shows how the spreading factor and Figure 61 shows the difference between a signal that is not spread and a spread signal

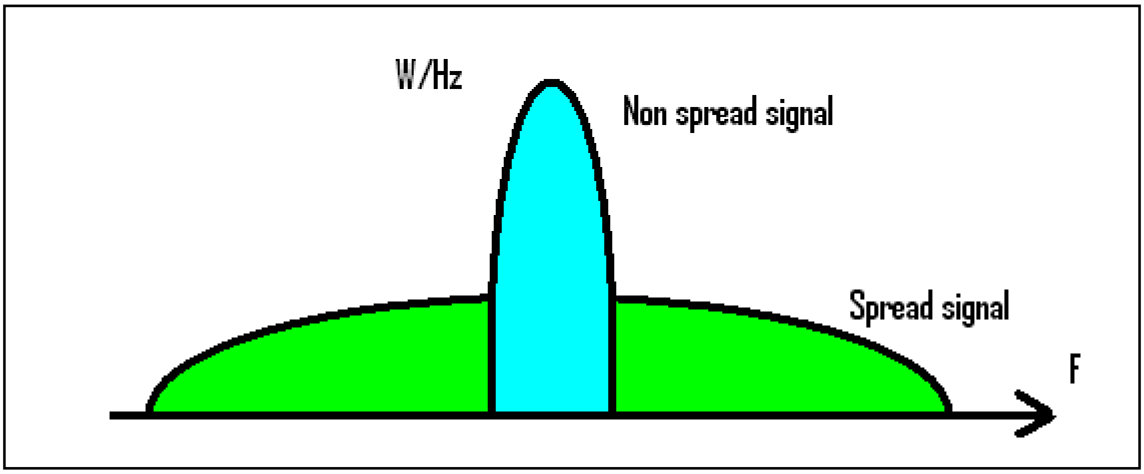

Figure 61: difference between a signal that is not spread and a spread signal.

$$Spreading\ Factor = \frac{Chip\ Rate}{Data\ Rate}$$

Equation 30: Spreading factor.

OFDMA

Orthogonal Frequency Division Multiple Access (OFDMA) is a multi-user Orthogonal Frequency Division Multiplexing (OFDM). OFDM uses a large number of small overlapping channels to transmit the data instead of a single carrier within a channel. The sub-channels each has an independent modem and seems like a independent carrier. Although the carriers overlap they are spaced apart at precise frequency providing the orthogonality. The modulated carriers center on the edge of the adjacent carriers. This way independent modulators only see their own frequencies. OFDM has high spectral efficiency, flexibility to adjust to available channel bandwidth and to lower susceptibility to multipath distribution.

ODFMA is used to allow multiple access for users on the same channel. OFDMA distributes subcarriers among users inorder for users to be able to transmit and receive at the same time within a single channel on what are called subchannels [76].

10.5 Appendix 5: Bandwidth Demands

Applications affect networks in very different ways. Some of the most important ways the applications affect the networks is the bandwidth demands they put on the network, the reliability they demand from the network and the response time the application requires. Table 39 shows some of the most common applications in networks today along with its relative bandwidth.

Application	Bandwidth
Mobile voice call	6 – 12 Kbit/s
Medium quality music stream	128 Kbit/s
High quality music stream	300 Kbit/s
Video conferencing	384 Kbit/s to 3 Mbit/s
Entry level, -high speed Internet (web browsing, e-mail etc.)	1 Mbit/s
Basic, -high speed Internet (web browsing, e-mail etc.)	5 Mbit/s
Enhanced, -high speed Internet (web browsing, e-mail etc.)	10 – 50 Mbit/s
Internet streaming video	1 Mbit/s
Gaming	1 – 10 Mbit/s
Standard definition TV (MPEG 4)	2 Mbit/s
High definition TV (MPEG 4)	7.5 – 9 Mbit/s

Table 39: Shows the bandwidth and response time demand as well as the transport protocol used to indicate the applicatons reliabilty [45].

Table 39 shows the bandwidth an application may require. But how much usage can be expected per month from this application and how much bandwidth will this usage consume?

Here below the expected bandwidth consumption of some of the most common applications will be examined.

Email can vary greatly in size depending on if it has attachment or not and the size of this attachment. Emails in essence consist of text and can be assumed to be at average 10 KB. Attachments vary from few Kbytes to 10 MB (most servers don’t allow much bigger attachments). If it’s assumed that a user receives 10 e-mails a day each of 10 KB in size and of these 5% has an attachment of size 1 MB. This results in a monthly usage of 19.7 MB.

Web browsing is another very popular application that can vary greatly in bandwidth demands. Light web browsing (no youtube or similar heavy web traffic) can be assumed to demand about 5 – 15 MB in average. Assuming a mobile device browsing news sites and social websites the lower limit will be chosen here. If it's assumed that the user spends by average 45 minutes each day of the month in browsing. This results in a monthly usage of 110 Mbytes.

Internet radio is another common application. If it's assumed to be a medium quality stream it can be expected to demand 128 Kbit/s. This calculates to 56 Mbytes an hour. If it's assumed that the user uses internet radio for 45 minutes every day of the month that results in a monthly usage of 1265.6 Mbytes.

Standard definition video streaming is a popular application (youtube, iTunes and Amazon Unbox). This streaming can require high bandwidth if continuous playtime is considered. It is assumed that users streams standard definition video content for half an hour a day at 1 Mbit/s. This results in monthly usage of 6750 Mbytes.

High definition video streaming is not yet very popular but a very likely candidate for a popular future application. This streaming today (using MPEG 4 compression) may require at least 7.5 Mbit/s. If the user watches 90 minute movie once a week it results in monthly usage of 21696.4 Mbytes.

10.6 Appendix 6: Data Normalization

Data normalization is the process of making the GIS data more suitable for planning large networks. The GIS data consists of a number of segments and Segment Points (SP) that are found in a table called the segment table. The idea is to reduce all the SP having a degree of 2. This process should be done without compromising the original network connectivity and shape.

The Segment Table

Contains all segments and nodes each segment is identified by a unique segment id, start and end segment points id, x-coordinates and y-coordinates for both start and end segment points and the lengths of the segment in meters. A sample of the segment table is shown is Table 40.

Segment Table											
sp_x1	**sp_x2**	**sp_y1**	**mid_id**	**sp_y2**	**sp_id1**	**s_id**	**sp_id2**	**komnr**	**lenght**	**ID**	**vejkode**
-219837	-219826	283585	20447	283590	1538320	1583960	1538529	837	13	1	1173
-219796	-219812	283463	20458	283464	1539021	1584206	1538773	837	16	2	1173
-219753	-219724	283602	20448	283607	1539754	1585768	1540261	837	30	3	1173
-219724	-219709	283607	20448	283608	1540261	1586033	1540511	837	14	4	1173
-219709	-219698	283608	20448	283607	1540511	1586234	1540709	837	11	5	1173
-219719	-219694	283595	20444	283600	1540342	1586307	1540782	837	26	6	1173
-219698	-219690	283607	20448	283604	1540709	1586376	1540851	837	9	7	1173
-219694	-219690	283600	20444	283604	1540782	1586377	1540851	837	6	8	1173
-219635	-219684	283435	20452	283444	1541680	1586478	1540948	837	50	9	1173

Table 40: Segment table.

The segment Point Table

The segment point table is a table containing all segment points used in the segment table each segment point is identified by a unique segment point number, x-coordinate, y-coordinate and degree of segment point. A sample of the segment point table is shown in Table 41.

Segment Point Table				
id	x	y	spid	degree
0	-219837	283585	1538320	2
1	-219826	283590	1538529	2
2	-219796	283463	1539021	2
3	-219812	283464	1538773	3
4	-219753	283602	1539754	2
5	-219724	283607	1540261	2
6	-219709	283608	1540511	2

Table 41: Segment point table.

RAU Table

The RAU table contains the locations of RAUs. Using this table it is possible to find the location of the closest SP and its distance from the RAU location. This is useful so the segment manipulation algorithm doesn't reduce the closest SP to the RAU is it is used in path-finding algorithm as described in section 5.1. The RAU table can be seen in Table 42.

fixed_grid							
id	x	y	radius	environment	counter	spid	distance
0	-238700	293300	0	0	1	1201801	7
1	-238500	293300	0	0	2	1205329	4
2	-238300	293300	0	0	3	1208151	24
3	-238100	293300	0	0	4	1211738	4
4	-237900	293300	0	0	5	1215321	40
5	-237700	293300	0	0	6	1217145	68
6	-237500	293300	0	0	7	1221723	87
7	-237300	293300	0	0	8	1224682	62
8	-237100	293300	0	0	9	1229105	47
9	-236900	293300	0	0	10	2486021	25
10	-236700	293300	0	0	11	1235007	68

Table 42: Grid table.

Segment Manipulation Algorithm

The segment manipulation algorithm can be seen in Text-Box 4.

```
For all SP∈ E(SP) do
      Select SPs where l_SP-grid=min
      Is SP selected then
            Flag==1
Else
            Flag==0
For all S ∈ E(s) do
      If Flag s(SP2)==1 then
            End for
      Else
            If degree of s(SP2)==2 then
                  Find s’ ∈ E(S) where s(SP1) connected
                  l_new=l(s’)+l(s)
                  Add s_new=(s(SP1),s’(SP”)) to E(s)
                  Remove s and s’ from E(s)
            Else
                  If degree of s(SP1)==2 then
                  Same as above for either side of s
                  UNTIL no further improvement
```

Text-Box 4: Segment manipulation algorithm.

10.7 Appendix 7: Genetic Algorithm

The genetic algorithms work by formulating a specific problem in a chromosome. In order to understand this, it is important to look at some biological terms. A chromosome is a string of DNA, which is a model for the entire organism. Each chromosome consists of genes which describes a specific trait, for example eye-color. The value of each gene is called allele, and could in the case with eye-color be blue, green or brown.

Encoding of the Problem

For the GA to be able to work on the problem it is necessary to encode it, so that the GA operators can be used to create better solutions. The encoding is a mapping from the problem itself into chromosome strings that can be manipulated by the GA. The chromosome is made up of genes, which is encoded parameters. The genes can be encoded in many ways, depending on the problem to solve. Some of the possible encodings is shown in Table 43.

Encoding	Gene 0	Gene 1	Gene 2	Gene 3	Gene 4
Binary	0	0	1	0	1
Permutation	3	0	1	4	2
Float	3.57	9.4	2.1	3.2	6.7
Chars	‘A’	‘D’	‘C’	‘C’	‘A’
Mixed	0110	9.2	‘ABC’	7	‘B’

Table 43: Different encodings.

The choice of encoding is depending on the task to optimize. The encoding normally has some sort of relevance to the underlying task. The binary encoding is often the simplest one to implement, as it yields simple implementations of the GA operators.

Population

The GA uses a collection of chromosomes (solutions) called population. The GA works by combining and mutating the chromosomes in the population, to produce better offsprings (new solutions). In order to find out which offsprings are better, an evaluation is made.

Evaluation

In the evaluation step, a fitness function evaluates the “goodness” of a solution, and assigns each solution in the population a fitness-score. The fitness score is a measure of how good each solution is at optimizing the objective function. The fitness-function therefore serves as the link connecting the physical problem being solved, and the GA. The fitness score is used in the selection process.

Selection

In order to create new populations, it is necessary to select parents from the existing population, and perform genetic operators on them. The selection of parents can be done in many ways, but this project uses one of the most common techniques, called roulette wheel selection (also known as fitness-proportional selection). This method works by assigning a probability to each chromosome, based on its fitness score. A random variable "R" is uniformly drawn between 0 and the total fitness F, and decides which parent is selected. Chromosomes with the best fitness score will then have the largest probabilities of being selected, at the same time as the other solutions also has a possibility of getting through to the next generation. Roulette wheel selection is illustrated in Figure 62.

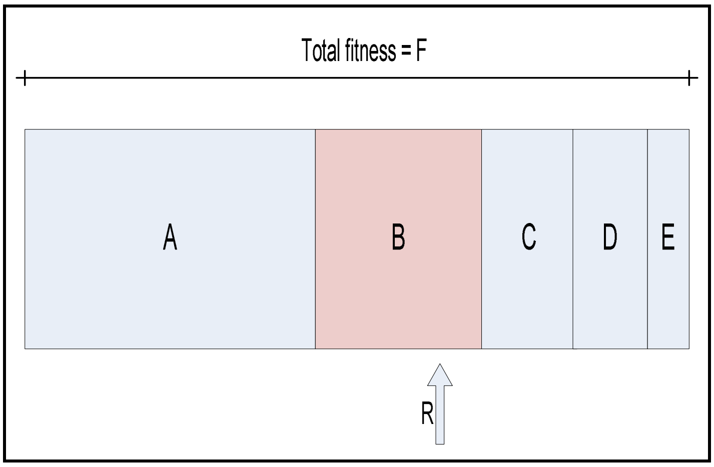

Figure 62: Roulette wheel selection.

When the selection is done, the genetic operators crossover and mutation can be performed on the selected individuals.

Crossover

Crossover is a simple operator that produces two offsprings from two parents. The new offsprings are created by first selecting a crossover-point. The offspring gets the genes before the crossoverpoint from parent nr 1, and the genes after the crossoverpoint from parent 2, or vice versa. This is illustrated in Table 44.

Parent 1	(a,b,c,d,e,f,g,h,,j)
Parent 2	(0,1,2,3,4,5,6,7,8,9)
Offspring 1	(a,b,c,d,4,5,6,7,8,9)
Offspring 2	(0,1,2,3,e,f,g,h,i,j)

Table 44: Crossover.

In Table 44, the crossover point is 4. The crossover point is normally drawn from a uniform distribution. It is also possible to use crossovers with multiple crossover points [61].

Mutation

The second operator of the GA is Mutation. The Mutation operator introduces some randomness into the algorithm, in order to investigate a larger portion of the search space, and limit the chance of getting stuck in a local optimum. Each gene in a chromosome has a small probability of being changed. This is illustrated in Table 45, where the fifth bit is mutated.

Original	(0,0,1,1,0,1)
Mutaded	(0,0,1,1,1,1,)

Table 45: Mutation.

Elitism

The chromosome with the best fitness rank is automatically included in the new solution, without performing crossover or mutation. This ensures that the algorithm only will generate better and better solutions, but may be a cause of too early convergence (stuck in local optimum) [61]

10.8 Appendix 8: Tools

This appendix describes the tools used in the project.

GIS

A Geographical Information System is a tool that allows for interaction and analysis of geographical data. GIS stores geometry and attributes of objects in the physical world. The geometry describes the shape and location of the object, and the attributes describe descriptive information about the objects.

There are many tools for this purpose, ranging from expensive software suites to free open source software. For this project MapInfo was used, which is a powerful application to create thematic maps, SQL queries and statistics from GIS-data [62]. Although there are many kinds of GIS, the common factor is the use of vector and/or raster data to present and describe features of an area [63].

- **Vector Data**

  Vector data is a term for spatial information being stored in vectors. This method used a x,y-coordinate system, arcs and vertices to describe the geographical features.

- **Raster Data**

  Raster data uses a grid-structure where the geographical area is divided into cells identified by row and column. Each cell is assigned attributes of the features they are describing.

The difference between them is illustrated in Figure 63:

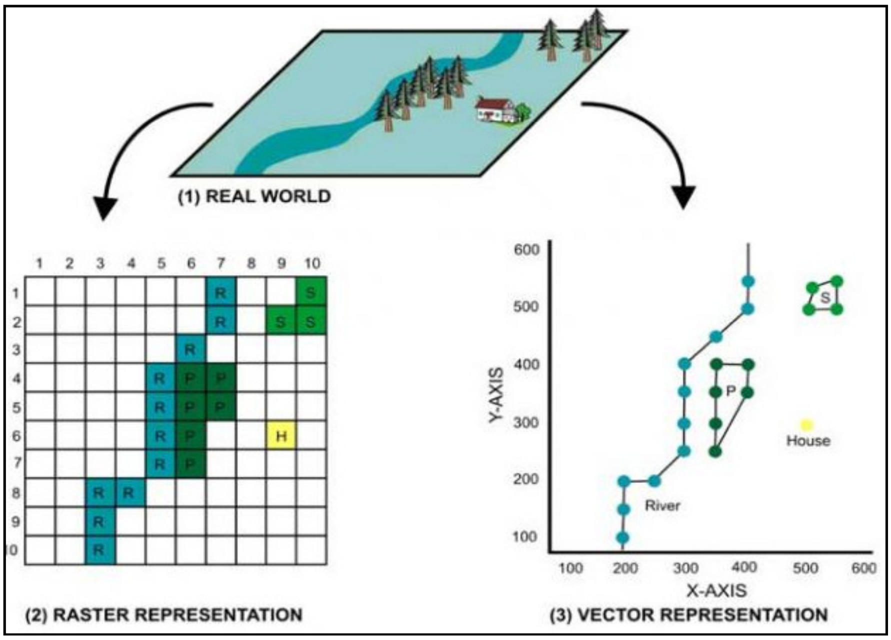

Figure 63: Difference between vector and raster representation [64].

For network planning, vector data is the most suited data type, and is what is used in the project [65]. The GIS-data provided to the group contains information about roads (segments and segment points), municipality borders, and NTs in Aalborg municipality. An example of how the information used in this project may look when presented in MapInfo can be seen in Figure 64.

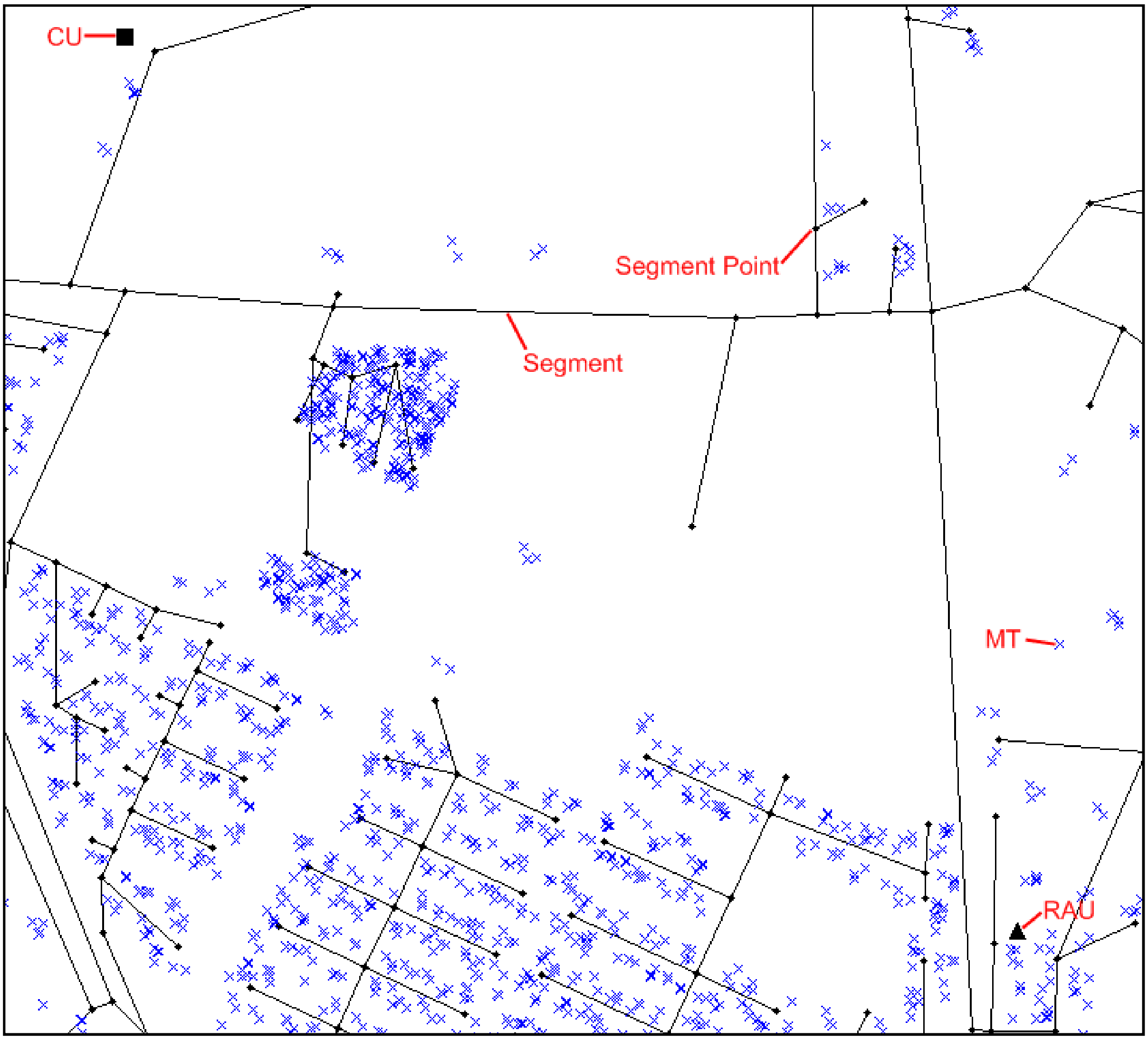

Figure 64: Geographical information displayed in MapInfo.

For more detailed information about the GIS-data used in this project, see appendix 6 on segment manipulation.

MapBasic

MapBasic is a programming language based on the BASIC-languages, developed to be used with MapInfo. It allows the user to customize the geographic functionality of MapInfo, automate repetitive operations, and integrate MapInfo with other applications. MapBasic was used in this project for displaying results of calculations in MapInfo [66].

Python

Python was used as the programming/scripting language for implementing methods of solving the problems in the project. Python was chosen because it is a powerful language with an easy syntax. In addition to this it is free and cross-platform. For more information on the Python programming language, the reader is referred to [67].

The programs made during the project use several modules which is not included in the standard python distribution. These modules can be downloaded separately, or alternatively use the "Python for Scientists"-distribution, which the group used during the project. This is an extended Python-distribution, containing modules commonly needed for scientific calculations. It is freely available for download at [68].

It should be noted if it is wanted to run the programs made during the project on another platform than Windows, the module for connecting to the ODBC-database needs to be changed. The odbc-module used by this project is only included in the windows binary installer, and not available on other platforms. There are however several other modules that can be used for this on other platforms.

MS Visio

Microsoft Visio is a diagramming tool for Windows. It uses vector graphics, and provides a simple way of creating flow-charts, diagrams and graphics. It was used for the charts and graphics in the thesis.

MS Word

Microsoft Word is the de-facto standard word processor on the market today. It comes as a part of the Microsoft Office software suite. Word was used for writing the thesis.

Paint.NET

Paint.NET is a free graphic editing program for Windows, often used as an alternative to Photoshop. It can be downloaded from [69]. It was used for editing of images for this thesis.