Design of a new IT Infrastructure for the Region of Nordjylland

Access Network

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Abstract

This master thesis describes the design of the access network for a new IT Infrastructure for the region of Nordjylland. The first chapter contains the statement of the problem and determines the aims of the project. The second and third chapters include an overview of Broadband Wireless Networks (2) and the WiMAX technology (3), which is the base of this project. After that, in the fourth chapter a description of the region together with a study of the population and its projections for the future are included. Chapter 5 describes all the methodology followed for placing the base stations of the network and the frequency planning for them is also explained. Chapter 6 deals with the traffic analysis of the network and the seventh chapter estimates the budget necessary for deploying the network. Finally, Chapter 8 presents the conclusion and gives some comments about possible future work lines.

Preface

The present report has been written at the Department of Electronic Systems of Aalborg University and documents a final thesis made by David Sevilla in Network Planning & Management between November 15th, 2007 and June 4th, 2008. It is intended to the supervisor, the examiner and all others interested in this subject.

The objective of this project has been the design of a new IT Infrastructure for the Region of Nordjylland, which has been divided into two different parts according to the backbone network (presented in Sergio Labeaga's thesis, 2008) and the access network, discussed in the present document.

A special effort has been made in order to separate the methodology from the final results. Therefore, applying the same methodology to other input data (e.g. a different area or region) should not present any inconvenience.

Furthermore, several figures, tables and graphs can be found throughout this report which main purpose is to complement the text for a better understanding.

This document has been written using Microsoft Word 2002 SP3. For calculations and data management Microsoft Excel 2002 SP3 and MapInfo Professional 7.5 softwares have been used. The figures and graphs that can be found throughout the report have been made using the three tools mentioned.

References to literature are given as [X] and listed at the end of the report. After this References section, several appendixes can be found which are referred when topical throughout the document.

There is a CD-ROM enclosed with the report which contains sources and data files used during the implementation of the project.

Any questions regarding this project can be directed to davidsevilla@gmail.com

David Sevilla Ferreiro

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Contents

INTRODUCTION

In this chapter the motivation for tackling this project together with its m objectives are provided. Besides, some initial assumptions are also introduced.

1.1 Motivation

Information technologies have a deep impact on several business applications and help to improve the service offered and to lower the costs. Technology plays an important role in the strategic plan of an organization.

The constant developments in the Communications field make existing infrastructures become obsolete in short periods of time: everyone wants the best technology (in terms of speed, quality, reliability,…) as soon as possible.

Moreover, the success of new technologies encourages people to start using the Internet instead of the traditional devices (TV, telephone,…) which have been more familiar to them until these days due to its constant improvement (possibilities such as video on-demand, interactive gaming or virtual reality). This demands a higher bandwidth, reliability, quality,… basically: better technologies.

However, a historical technological barrier can still be found: the traditional copper phone lines. The great and fast development in operating speeds becomes profitless as the connection capacity reminds unchanged and, thus, old-fashioned. This telephone network reaching every business and household simple does not have enough transmission capacity to provide these services to its customers. Therefore, a new and better technology must be used to replace these lines.

Nowadays, the brand-new technologies offering high bandwidth which are rising in Denmark are WiMAX and fibre optics (FTTH: Fibre To The Home). The objective of this project is to develop a new generation IT[1] infrastructure for the region of Nordjylland (in the north of Denmark) which uses these brand-new technologies as a possible replacement for the old local loop[2], allowing the final subscribers to have access to these new services.

Therefore, in order to design the best possibility for this new infrastructure, a strategy will be planned starting with the study of the current situation of the region, trying to find afterwards the best-fitting network evaluating its costs and other important features.

1.2 Project objectives

As already mentioned in the previous section, the main objective of this project is to design a new telecommunications network for the region of Nordjylland. This task is divided in two different parts: the backbone network, where S. Labeaga's project [0] is focused on, and the access network, which is discussed in this report.

[1] Information Technology
[2] Physical link or circuit which connects the customer to the provider

The proposed deployment should be able to work as a WiMAX access network in short-term and as an extra solution for providing mobility once FTTH is implemented in the future. When designing a WiMAX network several factors can influence in the final result, which makes this process become a really delicate matter. The requirements which will be taken into account for designing the network are the following:

- **Covering more than 95% of the Network Terminals (NTs).** It must be assured than most of the NTs in the region, independently of their location, have access to the new infrastructure.

- **Scalability.** Nowadays, future services demands are hard to predict and for this reason the new network must be as dynamic and scalable as possible, as it must be prepared for future improvements without the need of modifying the deployed model.

- **Balanced traffic between base stations.** BSs' load and the traffic among them must be evenly shared, which makes achieving the scalability objectives easier.

- **Reduced investment.** Cost-effective solutions to all these requirements must be found.

1.3 Methodology

The following tasks will be made throughout the implementation of the project:

1. Placement of Base Stations (5. Network design). The most suitable locations for the base stations will be discussed according to the NT distribution in the region and taking into account characteristics of WiMAX (3. WiMAX technology), regulations and economical and geographical factors.

2. Frequency planning (5. Network design). How the frequency spectrum is distributed among the base stations will be described according to regulations and different frequency assignment techniques.

3. Traffic study. The traffic in each base station will be estimated.

4. Budget. The total investment needed to carry out the network will be estimated.

1.4 Assumptions and notes

This section describes all the assumptions made during the development of the project and clarifies the solutions to the problems found throughout this process:

1. Unfortunately, there has been an unavailability to work with the data for the current region of Nordjylland (after the Municipal Reform in 2007, section 4.1), so it has been inevitable to deal with the data according to the old distribution of the region for performing the simulations. Anyway, the methods followed for designing the network would remain the same if these data were available.

2. An important error was found in the processed data as only businesses around Aalborg municipality were registered in the NTs database: the rest of businesses in other municipalities of Nordjylland were all tagged as households in this database. In order to solve this problem, 5% of the households of each municipality were “re-tagged” as small businesses.

3. Although the Access Network and the Backbone Network [0] are related, it may be possible to find some differences in the reports as further changes in [0] from April 14th, 2008 on have not been taken into account in this report in order to meet the date deadline.

4. Talking about bandwidth demand, small businesses will have on average similar requirements to the residential users’. Therefore, they will be provided an identical bandwidth.

2. BROADBAND WIRELESS NETWORKS

In this chapter an introduction to Broadband Wireless Networks is given and some important features related to them are described.

2.1 Introduction to Broadband Wireless Networks

Wireless Networks can be defined as the group of technologies which allow two or more devices to communicate between them without using any physical support, by transmission of electromagnetic waves in the radioelectric spectrum.

The main example of Broadband Wireless Access Networks (BWAN) would be the WLL (Wireless Local Loop), which refers to different technologies and systems allowing the final customer to access the PSTN (Public Switched Telephone Network) with low infrastructure costs and high speed of transmission.

The main feature these networks have is replacing the traditional copper pair which enables the final connection between customer and provider: they are a real alternative for the so-called wired 'last mile'.

The operation outline of Wireless Access Networks is similar to the one cellular communications are based on, except for the fact that the user's terminal is not a mobile device, being the receiver antenna located in a fixed position (typically on the top of buildings, for the moment).

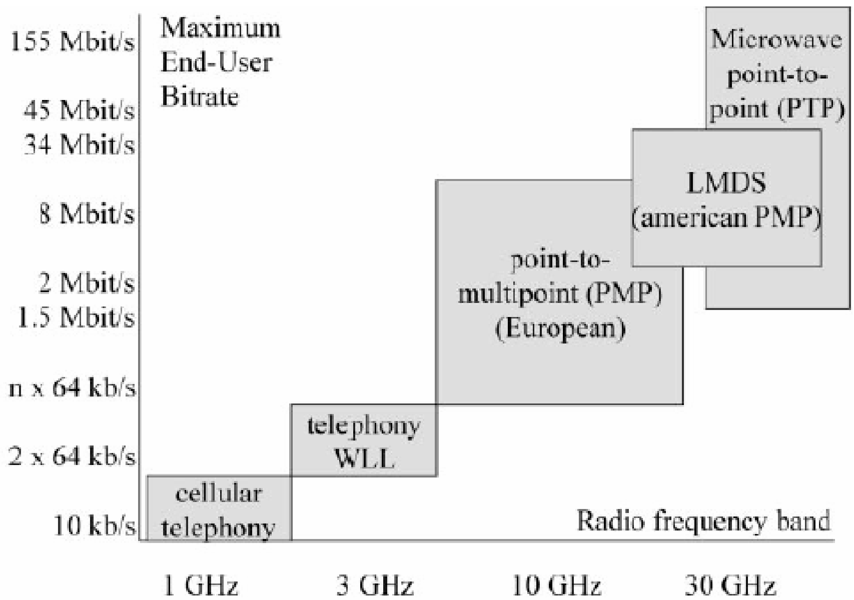

Figure 2.1: empirical relation between the radio layer and the bit rate supported by user in BWAN

Amongst all the technological possibilities for broadband network deployments, two are worth mentioning: LMDS (Local Multipoint Distribution System) and MMDS (Multichannel Multipoint Distribution System). Both systems are based on the use of microwave frequencies, so it is required that no physical obstacles between transmitter and receiver exist. Transmission is Point-to-Multipoint, which means that only one antenna transmits the signal to several receiver antennae inside a certain geographic area. Figure 2.1 can help to "locate" each technology.

A brief description of these two main variants is the following [1]:

LMDS (Local Multipoint Distribution System)

LMDS networks provide telecommunications services of high capacity: internet access up to 8 Mbps, fixed voice services, data communications in private networks and video on demand, for example.

The "Multipoint" term means that a transmission is made, via radio and in a limited coverage radius, to multiple subscriber installations from only one point (Base Station), while from the subscribers to the base it is made in a point-to-point way. A base station can have several sectors, and each of these sectors can have a coverage area of the multipoint system. They can operate in bands from 2 to 40 GHz, high-frequency bands which use is regulated and requires the payment of the corresponding license.

The main disadvantages of LMDS are:

- The bandwidth is shared among all users, so the service offered gets worse as the number of users increases.
- It requires Line of Sight (LOS) between the antennae to make the data transmission.
- The equipment needed for its deployment is not standardized.

These two last disadvantages make WiMAX become the main alternative to LMDS, as it allows Non-Line of Sight (NLOS) connections and it uses standardized equipment which can cut the costs of these installations, as it will be explained in the next chapter.

MMDS (Multichannel Multipoint Distribution System)

This technology works in a very similar way to LMDS and both of them have the same disadvantages. The main differences between them are the following:

- MMDS uses a different frequency band, also regulated, normally lower than 2.5 GHz, where LOS is not required.
- The distance between the Base Station and the customers can be higher than 10 km, while in LMDS it barely exceeds 5 km.

Nowadays, the BWAN industry is evolving towards the second generation of this kind of networks. This way, the rise of a new standard (IEEE 802.16) and the stated interest of the sector's industries and participants in promoting its use (WiMAX) generates new expectations in the creation of new high-capacity wireless access networks.

From this point of view, some of these standards are described in this chapter, especially analysing the IEEE 802.16 standard and the network this standard is focused on: a Metropolitan Area Network (MAN).

2.2 Broadband Wireless Standards

In any kind of communications technology, standards are the key to promote huge production volumes and, this way, reduce costs and make an increase of the market share possible, allowing a big number of users to access that technology. Furthermore, standardization simplifies the product testing and evaluation processes at the same time it reduces the development and introduction periods.

Therefore, IEEE has established a hierarchy of complementary wireless standards [2], which includes the 802.15 for Personal Area Networks (PAN), 802.11 for Local Area Networks (LAN) and 802.16 for Metropolitan Area Networks (MAN). Inside this last standard it is also included the 802.16e for mobile communications, which can be located into the Wide Area Networks (WAN), place also occupied by second and third generation cellular telephony technologies (GSM and UMTS). Each of the mentioned standards represents an optimized technology for a different market and model of use and it is designed for complimenting the others.

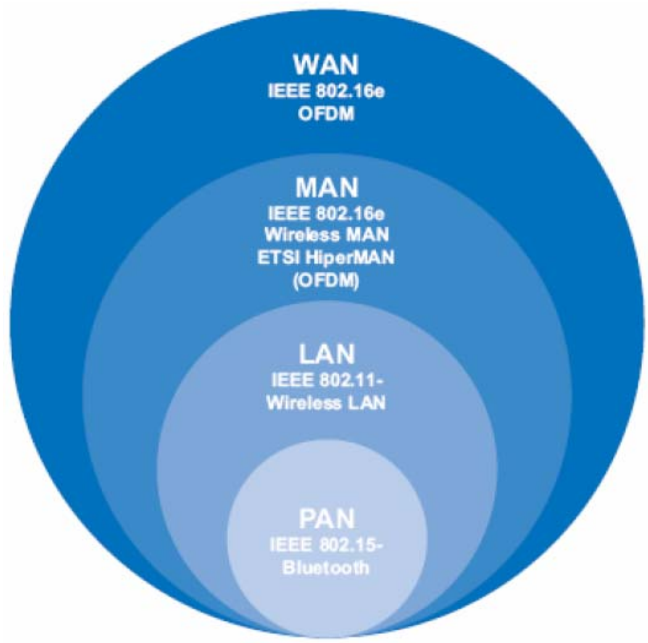

Figure 2.2: location of wireless standards

It is important to remark that when talking about broadband wireless networks it is normally referring to systems which provide, via radio, similar services to what can be offered by other (wired) technologies such as DSL, fibre optics and fibre/coaxial hybrid networks. Furthermore, transmissions are made between fixed locations, as it was defined before. However, on December 2005 IEEE approved the standard for mobile WiMAX (802.16e) [3], which allows using this system of wireless communications with moving terminals.

2.2.1 IEEE 802.15 – Personal Area Networks (PAN)

The wireless technologies based on the 802.15 standards family (Bluetooth, Zigbee) provide, at a low cost and low power, a short-range radio link for mobile devices. This way it allows establishing real-time voice and data connections by using the 2.4 – 2.483 GHz free band, reaching transfer rates of up to 1 Mbps.

2.2.2 IEEE 802.11 – Local Area Networks (LAN)

The 802.11 protocol, or Wi-Fi, is a standard of communications protocol which defines the use of the two lowest levels of the OSI architecture (physical and data link layers), specifying its operation rules in a Wireless Local Area Network (WLAN).

Currently, the 802.11 family includes six transmission by modulation techniques, all of them using the same access protocols. The original standard was published in 1997, but new versions are continuously being developed. Below these lines the different revisions to the standard since its first appearance can be seen.

Standard	Description
802.11	Original standard. It supports from 1 to 2 Mbps. 2.4 GHz band
802.11a	High-speed WLAN standard in the 5 GHz band. Up to 54 Mbps
802.11b	WLAN standard for the 2.4 GHz band. It supports 11 Mbps
802.11e	Focused on the QoS requirements for all the IEEE WLAN radio interfaces
802.11f	It defines the communication between access points to provide WLANs from different providers
802.11g	It sets an additional modulation technique for the 2.4 GHz band. Directed to providing speeds of up to 54 Mbps
802.11h	It defines the spectrum administration of the 5 GHz band for its use in Europe and Pacific Asia
802.11i	It is focused on knocking down the vulnerability in security for authentication and codification protocols

Table 2.1: standards of the 802.11 family

The 802.11a revision was made additionally to the ‘b’ version and it was not compatible with its products. Due to technical reasons very few products were developed.

Later on the ‘a’ revision for the same speed was introduced and it was compatible with the ‘b’ standard: it was called 802.11g [4]. Nowadays, the majority of products are from the ‘b’ or ‘g’ specifications.

The latest version of this standard is the 802.11n revision, which raises the theoretical limit up to 640 Mbps. Currently there are already some products which satisfy the first drafts for the ‘n’ standard, which is to be published during 2008 after some delays.

2.2.3 IEEE 802.16 – Metropolitan Area Networks (MAN)

The 802.16 standard refers to a BWA system providing high data transmission rates and long-range (up to 60 km). This system is scalable[3] and allows working in both licensed and unlicensed bands from the spectrum. Service, both fixed and mobile, is provided by using traditional sectorial antennae or adaptative antennae with flexible modulations allowing exchanges of bandwidth per range.

[3] Scalability [5]: desirable property of a system, a network, or a process which indicates its ability to either handle growing amounts of work in a graceful manner or to be readily enlarged.

The 802.16 standard is called *Air Interface for fixed Broadband Wireless Access Systems* [6], although it is also known by the name of *Wireless Metropolitan Area Network (WirelessMAN)*. It defines a channel access management mechanism (Medium Access Control, MAC) which supports several implementations of the radio layer. This multiplicity of radio layers is basically due to the wide frequential operation margin covered by this standard. Same way as other standards of the IEEE 802 group, 802.16 includes a working groups family which have been developing different aspects of the standard from its original specification on.

The initial standard became official in April 2002 and it mainly referred to fixed radio links requiring LOS between transmitter and receiver. It was planned to cover the 'last mile' (provider to customer) using effectively frequencies from the 10-66 GHz band. The fact of requiring LOS limited this standard to basically Point-to-Point (PTP) applications.

In March 2003 a new version for this standard (802.16a) was released and it became the real beginning of WiMAX as a wireless broadband technology. This revision was able to reach a 40-60 km range using frequencies from the 2-11 GHz band (some of these frequencies do not require license for their usage), but the most important improvement was that LOS was not required, which made this standard suitable for Point-to-Multipoint (PTMP) applications.

The next important revision of the 802.16 standard was presented in June 2004 and it was called 802.16d (it is also known as 802.16-2004). It set the base for fixed WiMAX.

Fixed WiMAX deployments do not provide handoff between Base Stations, which means that service providers can not offer mobility. In December 2005 the last revision (802.16e) was released and it solved this mobility problem, becoming the base for mobile WiMAX. These implementations can be used to deliver both fixed and mobile services and are currently being developed.

In Table 2.2 the main standards for the 802.16 family are described [7].

Standard	Description
802.16	Original standard. It specifies the MAC and radio layers for PTMP communications in the 10-66 GHz frequency range. LOS is required and it can reach up to 134 Mbps in cells from 2 to 5 km. It supports QoS. Published in April, 2002.
802.16a	Revision made towards the 2-11 GHz bands, with LOS and NLOS systems and PTP/PTMP protocols. Published in March, 2003.
802.16c	Expansion of the 802.16 standard focused on defining the features and specifications in the 10-66 GHz band. Published in January, 2003.
802.16d	New revision for adding the profiles approved by WiMAX Forum. Published in June, 2004. Approved as 802.16-2004.
802.16e	Expansion including the broadband connection for mobile devices. Published in December, 2005.

Table 2.2: standards of the 802.16 family

Therefore, two practical variants for the 802.16 standard can be found: 802.16d (fixed) and 802.16e (mobile). The 802.16e standard for mobile communications is not a case of study in this project.

In conclusion, the 802.16 standard can work in frequencies from 2 to 11 GHz with NLOS, offering ‘last mile’ connections, and in frequencies between 10 and 60 GHz for LOS communications between stations.

2.3 Metropolitan Area Network (MAN)

A metropolitan area network is a high-speed (broadband) network which, giving coverage in a vast geographic area, provides integration of multiple services capacity by data, voice and video transmissions through mediums such as fibre optics and twisted copper pair at speeds going from 2 to 155 Mbps.

The concept of MAN represents an evolution of the LAN concept to a wider field, embracing areas of a higher coverage that in some cases are not limited to a metropolitan environment but can reach to a regional (or even national) coverage by interconnecting different MANs.

2.3.1 Planning of a IEEE 802.16 network

A broadband wireless network adopts the shape of a cellular network, where each Base Station (BS) provides service to a number of subscribers located inside its coverage area. As customers’ locations are fixed, each user is assigned a predetermined base station (normally the closest one) and their directive antennae are pointed towards the server BS during the installation. The high gain obtained in the direction of the server BS reduces interferences and raises the cell’s coverage in that direction. In Figure 2.3 an example of rectangular cellular planning with 90º sectors can be seen, where the A, B, C and D labels show the 4 sectors used around each BS, as well as the channels used. As it can be seen in the picture, adjacent sectors use the same channels, which is because, besides, a discrimination by polarization technique is used. This technique will be explained later in this section.

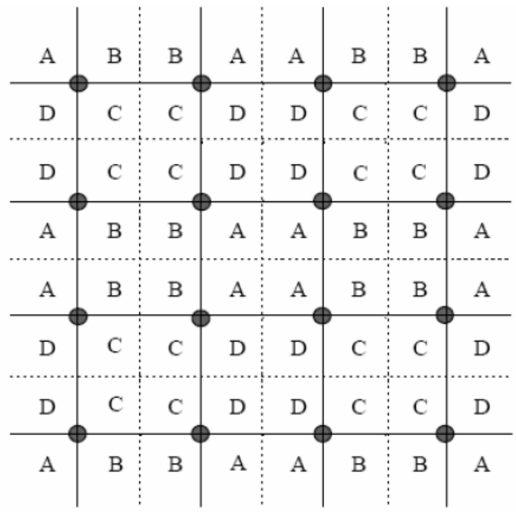

Figure 2.3: rectangular cellular planning with 90º sectors

In order to obtain a precise description of the planning some important facts must be considered: propagation losses, depending on the standard used and the type of service area (urban or rural), time dispersion of the radio channel (delay spread), time variation of the channel's reply (Doppler effect, which in the case of BWA networks is a very low value) and also the interferences due to adjacent channel and co-channel [8].

The cell planning and the frequency assignment are both especially critical aspects in the initial design of the 802.16 system because important modifications during successive phases of a deployment can involve the need of adjusting directly each one of the user terminals. Amongst the mechanisms which can provide a good level of scalability to the system, the following ones can be mentioned:

- **Sectorization.** The initial process of cellular planning must consider the use of sectorization as a key mechanism to increase system's capacity. The number of sectors per location can be raised to obtain a higher capacity. For example, changing from 4 to 8 sectors makes system's capacity almost double.

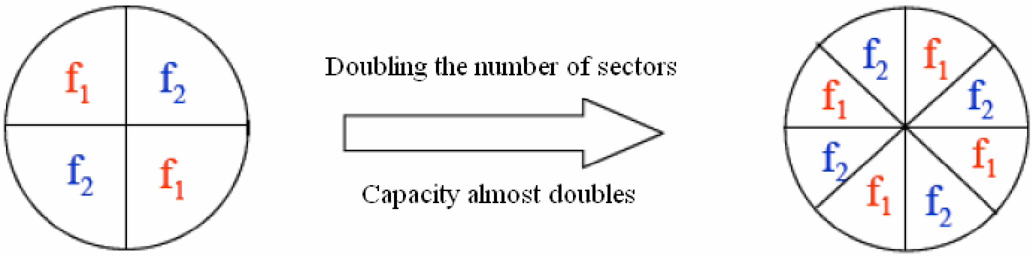

Figure 2.4: increasing system's capacity by using sectorization techniques

- **Adaptative modulation.** As it will be seen in section 3.7, the IEEE 802.16 standard allows adapting modulation and channel codification depending on the link conditions between the BS and any customer. The network capacity can increase directly in case of using higher spectral efficiency modulation schemes, but this will also involve a reduction in the coverage zone and better C/I (Carrier to Interference) requirements so it is able to work. In Figure 2.5 the use of this technique together with the sectorization technique is shown, where eight QPSK sectors provide access to the furthest stations, while four 16QAM sectors allow offering higher speeds to the closest ones.

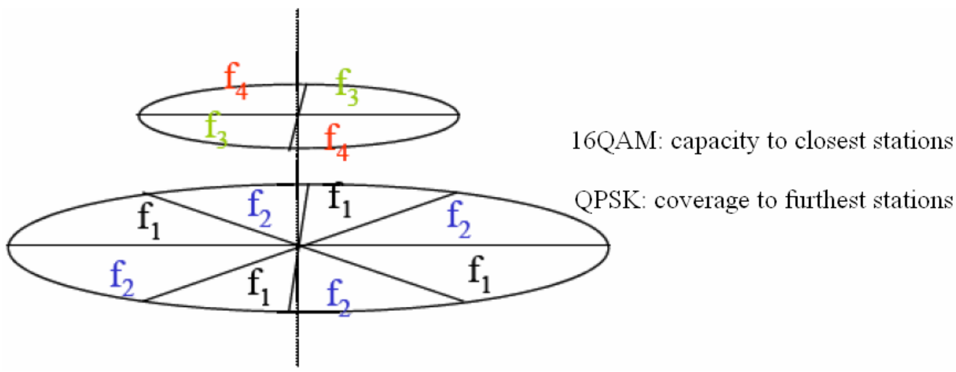

Figure 2.5: combination of adaptative modulation and sectorization techniques

- **Frequency reuse and polarization.** In Figure 2.3 this concept can be seen, where the BSs with coverage overlappings have to work to different frequencies for reducing the co-channel interferences (for using the same channel). Therefore, the task is to assign channels reducing to the maximum the interference level, taking into account that the availability of channels is limited. A very commonly used technique is to change the polarization of the antenna between adjacent sectors.

2.4 Summary

In this chapter an introduction to Broadband Wireless Networks has been given: the main wireless standards have been introduced and the areas where WiMAX technology (802.16 standard) is focused on (MANs) have been described. Therefore, a deeper introduction to the WiMAX technology can now be given.

3. WiMAX TECHNOLOGY

In this chapter the WiMAX technology is explained: the main characteristics of this standard as well as the organizations watching over its correct development are introduced. Some comparisons to different technologies can also be found throughout the chapter.

3.1 Introduction to WiMAX technology

WiMAX stands for Worldwide Interoperability for Microwave Access and it is a wireless data transmission standard (IEEE 802.16) designed for being used in MANs, providing broadband connectivity. Theoretically speaking, this technology is able to provide data rates up to 75 Mbps and it can reach distances up to 50-60 km. However, these distance and capacity figures are maximum orientative values and they can never be achieved simultaneously.

As it has already been mentioned, the initial expectations for WiMAX are focused on rural environments, with few accesses. In other words: it is oriented to all those people who can not have access to DSL and/or cable. Its design makes this technology really suitable for supporting connections in rural areas.

The WiMAX standard is totally compatible with Wi-Fi (IEEE 802.11) and their operation is similar, but at higher speeds, larger distances and for a bigger amount of users (talking about WiMAX).

WiMAX includes the IEEE 802.16 standards family and the HyperMAN standard from the European standardization organization, ETSI. Since the 802.16a, basis of the current 802.16-2004 standard where WiMAX is developed, was approved in the beginning of 2003, it has been evolving until the 802.16e version published in December 2005, which provides mobility. Below these lines there is a basic review of the evolution of the 802.16 standards as a quick reminder of the previous chapter:

- 802.16: from 10 to 66 GHz, with QAM modulation, LOS.
- 802.16a: from 2 to 11 GHz, OFDM and OFDMA, NLOS.
- 802.16b/c: interoperability and specification of certifications.
- 802.16-2004: it replaces previous versions.
- 802.16e: mobility.

WiMAX has the potential to impact all forms of telecommunications as it is able to provide at the same time ISP services and replacement for telephone copper wires and TV's coaxial cables. Using fixed wireless access (FWA) systems, cable operators can expand their footprint to new subscribers without the need to lay new cables: satellite operators can provide a full Triple-Play package by using WiMAX to deliver fast broadband access to subscribers who may otherwise be too far away from an exchange to benefit fully from high bandwidth DSL; TelCos can use WiMAX to provide a full digital service -incorporating video, data and voice- to potential customers, giving them a different business model and opportunity to compete with the more traditional operators [9]. Below these lines some examples of applications WiMAX can be used for can be found, both in its fixed and mobile versions.

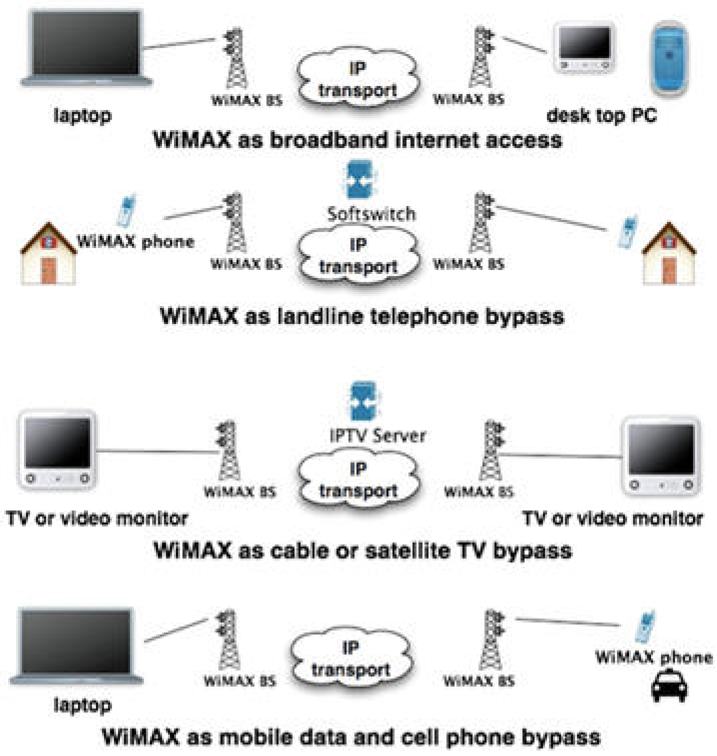

Figure 3.1: different applications of WiMAX [10]

3.1.1 Fixed WiMAX vs. Mobile WiMAX

Although Mobile WiMAX is out of the scope of this project, in this section a brief comparison between both standards will be introduced and compared.

As it was previously explained, Mobile WiMAX was developed in order to solve the impossibility of Fixed WiMAX to offer mobility. As seen in Figure 3.2a, Fixed WiMAX offers cost effective PTP (LOS) and PTMP (NLOS) solutions.

The Mobile revision provides roaming for portable devices within and between service areas, it allows any telecommunications to go mobile (Figure 3.2b).

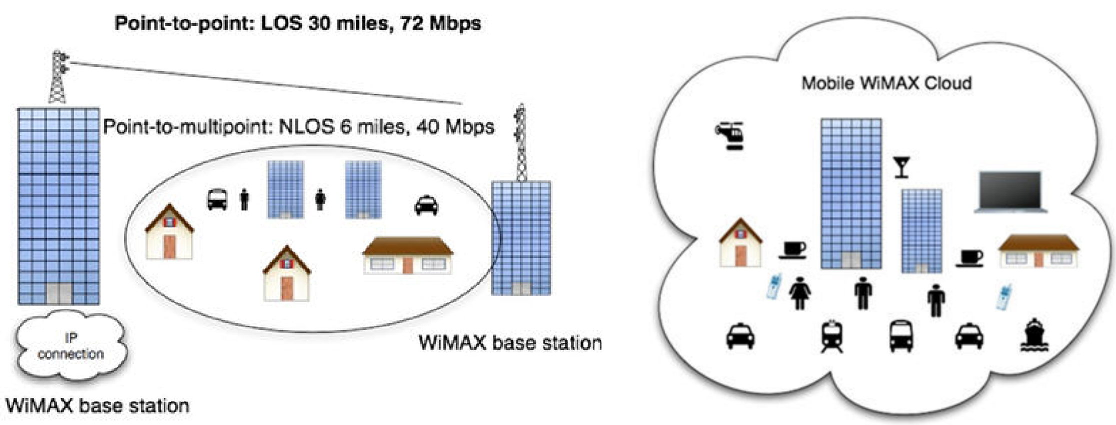

Figure 3.2: a) fixed WiMAX; b) mobile WiMAX [10]

In Table 3.1 a comparison table between both fixed and mobile standards can be seen. The most important features will be explained in following sections.

	802.16d	802.16e
Subscribers	Fixed/Portable	Fixed/Portable/Mobile
Channel conditions	LOS, Near-LOS, Non-LOS	
Modulation	OFDM-256	S-OFDMA (128-2000)
Duplexing	TDD/FDD	
Sub-carrier modulation	BPSK, QPSK, 16QAM, 64QAM	
Channel bandwidth	Scalable: 1.25 MHz – 20 MHz	
Data rate (peak)	75 Mbps @ 20 MHz 15-18 Mbps @ 5 MHz	15 Mbps @ 5 MHz
Cell Range	>20 km: rural 2 to 5 km: suburban, urban	3 km: indoor 5 km: outdoor

Table 3.1: fixed WiMAX vs. mobile WiMAX [11]

3.1.2 Main characteristics of WiMAX

Amongst the main characteristics of this technology, the following ones can be mentioned:

- It uses **OFDM** (Orthogonal Frequency Division Multiplexing) modulation, which allows transmitting in different frequencies simultaneously. This technology uses orthogonal spacing, so it can be guaranteed that there will not be interferences among the frequencies. OFDM technology is explained in Appendix A.

- It supports **Smart Antennae** mechanisms which improve the spectral efficiency in wireless systems and different types of antennae.

- It supports **PTMP** and **Mesh** networks.

- It has such a **QoS** for NLOS operators that the signal is not severely distorted because of the presence of buildings or other possible interference causes.

- It supports **TDM** and **FDM** multiplexing, which makes interoperability between cellular (FDM) and wireless (TDM) systems possible.

- As **security** measures, it includes its own cryptography and security systems.

- It has **voice, data and video** applications.

- It presents **adaptative modulation** techniques depending on the SNR conditions.

3.2 WiMAX Forum

In order to promote the use of WiMAX standards, it is desirable that all the manufacturers of electronic devices reach agreements to develop this technology, which leads to the creation of certifications that ensure the compatibility and interoperability of these devices. That is why the 'WiMAX Forum' [12] exists: it is a non-profit organization set by dozens of companies (67 in the beginning and more than 530 by these days) supporting the IEEE 802.16 and ETSI HyperMAN standards.

WiMAX Forum's main purpose is to guarantee the interoperability of BWA products so that systems from different manufacturers can work together with total compatibility. For accomplishing this purpose, WiMAX Forum tests these devices and if they pass testing they are given the *WiMAX Forum Certified* designation, which means that they meet all the requirements to interoperate with other WiMAX products.

In principle, it could easily be deduced that this technology involves a serious threat to the business of wireless short-range access technologies in which many companies are based on, but there are very important organizations behind this project. Some of these significant members of WiMAX Forum are: Cisco, Ericsson, Fujitsu, Intel, Motorola, Nokia, Samsung, Siemens, Vodafone,… most of them operators.

WiMAX Forum started the certification process in July, 2005. As the standards allow a considerable amount of possible configurations, WiMAX Forum specifies which are the features the devices have to meet in order to achieve the certification. This group of characteristics is known as *certification profile*. The profiles which have to be certified in first instance are the following [13], all of them based on IEEE 802.16-2004:

Freq Band (MHz)	Duplexing	Channelisation (MHz)
3400 - 3600	TDD	3.5
		7.0
	FDD	3.5
		7.0
5725 - 5850	TDD	10

Profiles are for PMP systems only and are for 256 OFDM

Table 3.2: "First Round" profiles currently identified for the initial certification process

The next certification is more focused on Mobile WiMAX and it includes systems able to work in the 2500-2690 MHz band with a 5 MHz bandwidth [14]:

SYSTEM PROFILES	CERTIFICATION PROFILES		
	Spectrum	Duplexing	Channel Width
Mobile WiMAX (IEEE 802.16e-2005, OFDMA)	2.496 - 2.690GHz	TDD	5, 10 MHz (dual)

Table 3.3: "Second Round" profiles for the certification process (IEEE 802.16e-2005)

The first companies and products in obtaining the WiMAX Forum Certification were Aperto Networks with their PacketMAX 5000 base station, Redline Communications with RedMAX AN-100U, SEQUANS Communications with SQN2010 and Wavesat with their miniMAX subscriber station.

This first round of certified products was developed according to the 3.5 GHz profile based on the IEEE 802.16-2004 standard. Nowadays (May, 2008) there are 20 certified base stations and 22 certified subscriber stations [15].

3.3 Applications of WiMAX networks

As it was previously mentioned, the WiMAX technology was developed mainly for providing 'last mile' BWA in MANs with similar features to other technologies having physical support.

Generally speaking, broadband radio technologies represent a physical connectivity alternative to the Telecommunications networks' expansion and their success compared to other technological options (DSL, cable, Wi-Fi) depends on the kind of environment where their deployment is proposed.

More concretely speaking, amongst all the market segments where the WiMAX development can become more interesting the following ones can be remarked:

Residential broadband access and SOHO (Small Offices Home Offices)

High-speed Internet access (voice + data), where multimedia services such as videoconference, video on-demand or TV can be included. In terms of capacity, it can be compared to the service currently offered by DSL or cable lines.

Telecommunications services for SMEs (Small and Medium-sized Enterprises)

Dedicated broadband access (2 Mbps) where it is not possible to provide access by physical means. In those areas where wired services exist, some studies of business models have been made which prove that WiMAX would be an efficient and competitive alternative against these services.

Backhaul networks for WLAN hotspots

WLAN islands interconnection network to broadband services. It allows interconnecting short-range (200 metres approximately) WLAN networks for creating huge telecommunications networks with a much higher range.

It can also become interesting as a backhaul alternative in cellular network deployments where currently dedicated lines or microwave links are used for getting to the base stations.

In Figure 3.3 these applications of WiMAX systems and some other possibilities are shown.

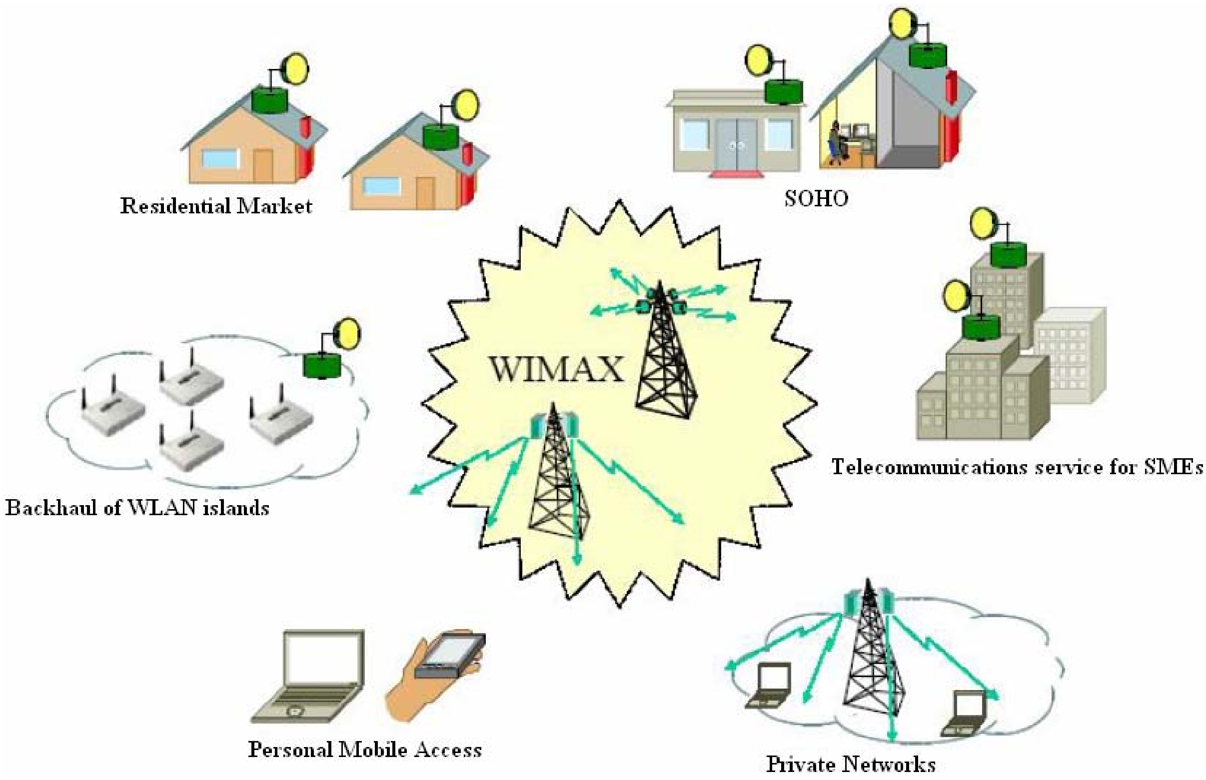

Figure 3.3: WiMAX applications

3.4 Elements and configurations of WiMAX networks

3.4.1 Elements included in a WiMAX network

A WiMAX network is part of a BWA network, so basically its elements are the ones mentioned before for 802.16 networks:

- **Customer Premises Equipment (CPE).** This is the name for the equipment including the functions for the Subscriber Stations (SS) identified in the operation of BWA networks. This equipment provides connectivity with the Base Station (BS) via radio. There are different types of equipment: they can be either indoors (auto-installable devices inside buildings) or outdoors (external antenna).

- **Base Station (BS).** It does not only allow connectivity with the SSs but also provides the control and management mechanisms for SS equipments. The BS is in charge of the transmission functions and has the transport elements needed to connect to the distribution system (core network).

3.4.2 Types of architecture for a WiMAX network

The standard 802.16-2004 [6] defines three different architectures compatible with WiMAX technology: PTP, PTMP and Mesh (MPTMP). Nowadays, PTP (for backhauls or radiolinks) and PTMP ('last mile' access) infrastructures are the most common ones, but Mesh networks also have their advantages.

3.4.2.1 Point-To-Point (PTP) Topology

In Figure 3.4 an example for this topology is shown and the two communicating elements (transmitter and receiver) can be easily identified. It is defined in the standard as a special case of the PTMP topology.

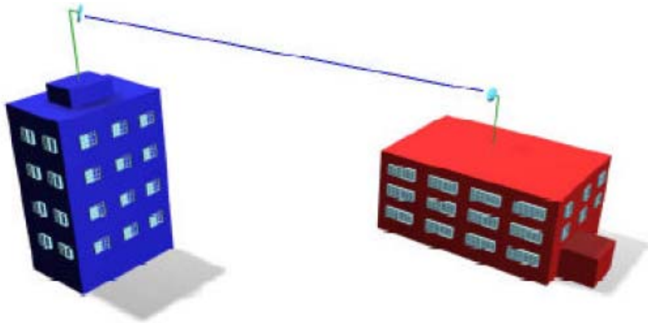

Figure 3.4: diagram of a network in PTP architecture

3.4.2.2 Point-To-Multipoint (PTMP) Topology

The network topology and architecture specified in IEEE 802.16 is shown in the next picture. The BS handles the interface between the wireless network and the connection network (core network). The SS allows the user to access the network by establishing connections with the BS.

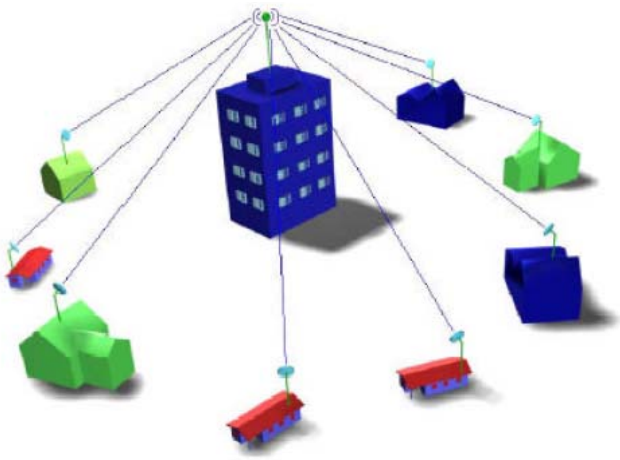

Figure 3.5: diagram of a network in PTMP architecture

In PTMP configurations, a WiMAX link is carried out from a central BS with sectorial antennae. In this kind of networks, stations with 2 sectors (180º), 4 sectors (90º) or 8 sectors (45º) can be found, depending on the type of antenna used and the area pretended to cover. Inside a sector, and for a determined frequency (channel), all the BSs receive the same power (or parts of it).

Transmissions in the downlink (DL) are usually broadcast, so all the user stations receive all the information and they choose the one directed to them. In the uplink (UL) the channel is shared by the user stations through demand management mechanisms (Figure 3.6).

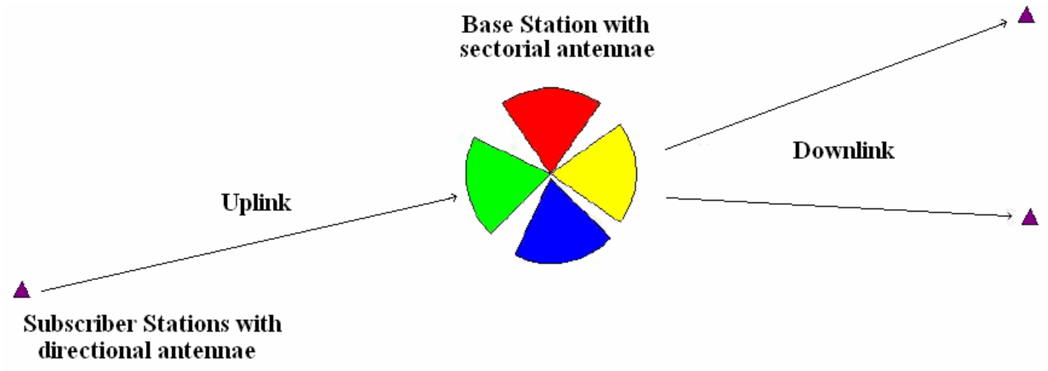

Figure 3.6: downlink and uplink in a PTMP configuration

3.4.2.3 Mesh Topology

The standard specifies this mesh topology as an alternative to the PTMP architecture. In this type of configuration, a SS can connect to one or more "messenger" SSs until it reaches the BS. This last case is an example of a multi-jump network, which represents an interesting possibility for expanding the total coverage area of the network without the need of a significant increase of BSs. This leads to a representative reduction of costs as the price of a SS is much lower than the cost of a BS.

What makes these networks special is that each user node is connected and communications are made through the nodes. These networks learn automatically and keep configurations in dynamic paths.

This kind of networks are used in Wi-Fi technologies, being considered in the 802.11s standard. These types of networks are also known as multi-jump networks.

In Mesh networks, the nodes act as routers installed in a vast surface. Each node transmits a low-power signal for reaching all the neighbour nodes, which forward the signal too. These networks allow adapting to the changes in topology as nodes can be added or deleted.

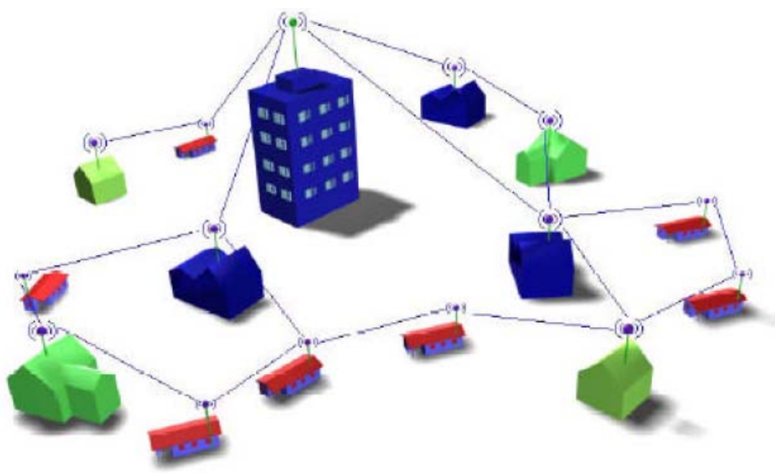

Figure 3.7: diagram of a network in Mesh architecture

As a review for this section, in Figure 3.8 an orientative diagram about the elements and configurations that can be found in a WiMAX network is introduced. The two elements explained (CPE and BS) can be easily identified as well as the possible connectivity configurations between them. Generally speaking, a WiMAX network has a similar architecture to the traditional cellular networks as it is based on a strategic distribution of a series of positions where the BSs will be located. Each BS uses a PTMP or PTP configuration for linking the customers' equipments. There is also the possibility that the SSs are linked between them in a mesh configuration.

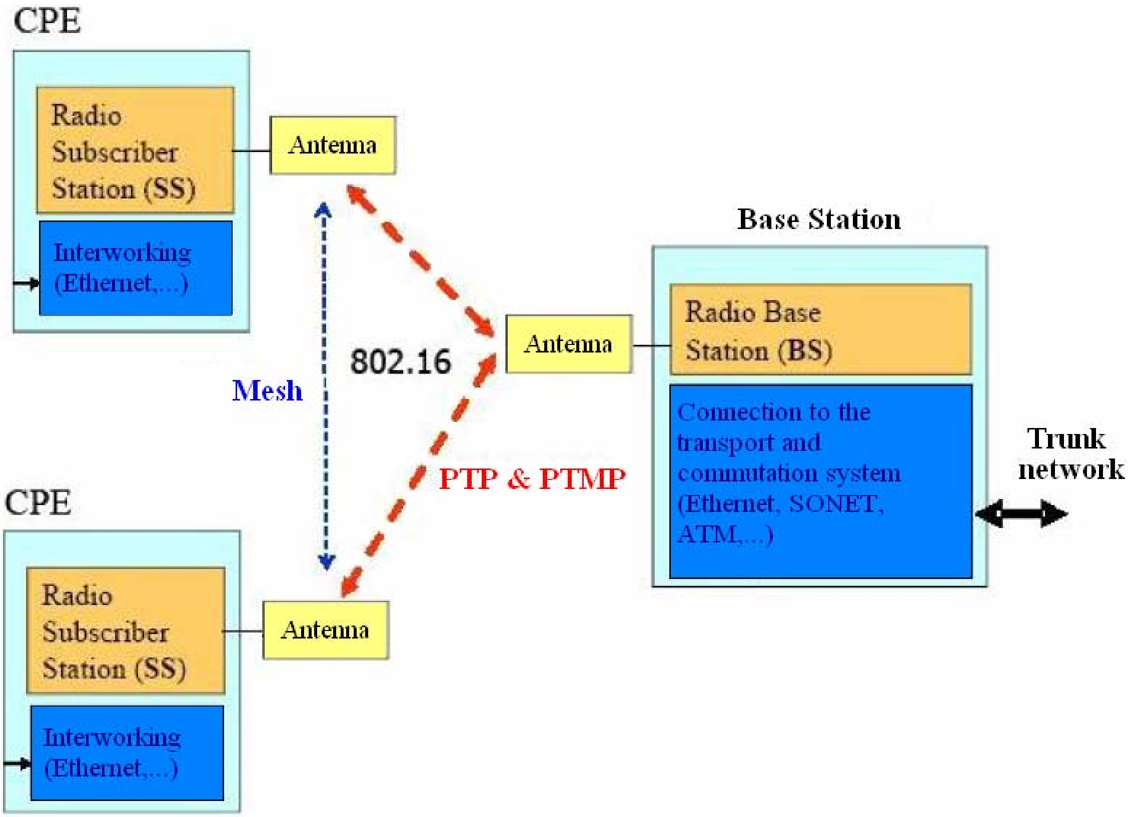

Figure 3.8: elements and possible configurations of a WiMAX network

3.5 Use of Spectrum

Governments all over the world recognize the value of innovations associated with open standards and license-exempt solutions and have established frequency bands available for use by licensed and license-exempt WiMAX technologies. However, to impose some control over unlicensed solutions to mitigate the potential for interference, some governments stipulate power requirements for high-power and low-power operations.

Each geographical region defines and regulates its own set of licensed and license-exempt bands, as shown in Figure 3.9. In order to meet global regulatory requirements and allow providers to use all available spectrums within these bands, the 802.16-2004 standard supports channel sizes between 1.5 MHz and 20 MHz.

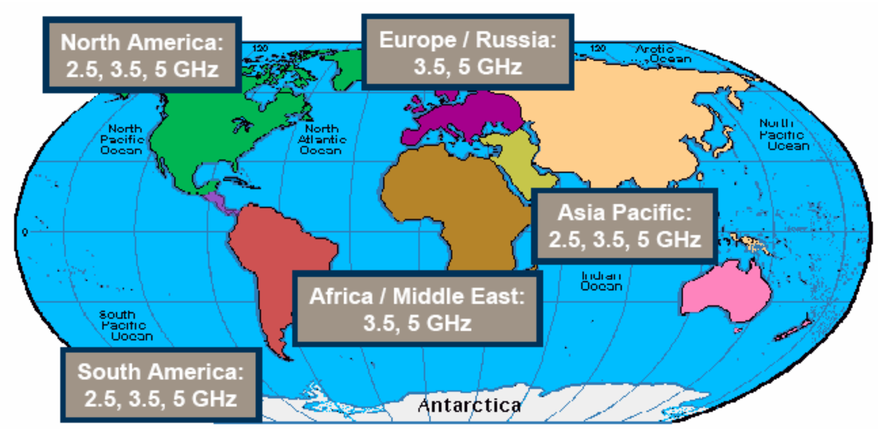

Figure 3.9: worldwide allocation of licensed and license-exempt bands [11]

Figure 3.10 shows the different available bands for BWA networks in the 2-6 GHz range [16]. It must be noticed how these bands are divided regarding the need of license or not.

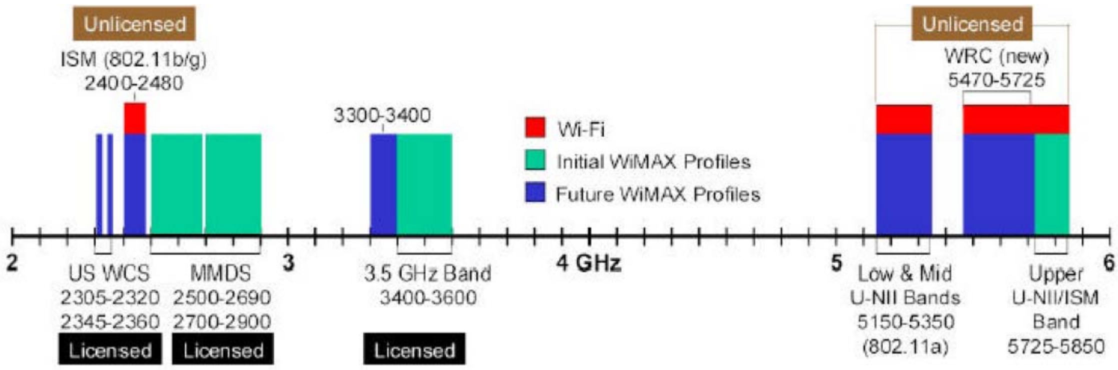

Figure 3.10: radioelectric spectrum representation

Below these lines a table for describing the available frequencies for the WiMAX technology is introduced.

Frequency	Description
3.5 GHz	Licensed band available for BWA systems (3.3-3.6 GHz)
Low U-NII	License-exempt band used in Wi-Fi (5150-5350 MHz)
Upper U-NII / ISM	Unlicensed band initially chosen by WiMAX Forum (5725-5850 MHz)
WCS	Two bands divided into 15 MHz slots (2305-2320 and 2345-2360 MHz)
WRC	License-exempt band (5470-5725 MHz)
2.4 GHz ISM	Licensed band with 80 MHz for BWA applications. It is used by Wi-Fi and 802.16e systems
MMDS	It includes 31 channels of 6 MHz (2500 to 2690 MHz). Range available for BWA applications in the US

Table 3.4: description of available frequencies for WiMAX

WiMAX Forum [12] [13] focused its initial objectives for certifying WiMAX systems on the MMDS and 3.5 GHz licensed bands and on the upper part of the 5 GHz U-NII unlicensed band, where less interferences can be found, allowed power levels are reasonable and a suitable bandwidth is available.

3.5.1 Licensed Bands: 2.5 GHz and 3.5 GHz

The 2.5 GHz band is used in much of the world. Each country assigns the band in a different way, so the spectrum allocated across regions can range from 2.6 GHz to 4.2 GHz. A system operating in the licensed band has an advantage over a system operating in an unlicensed band in that it provides an exclusive usage of the spectrum (more generous downlink power budget), and better QoS and NLOS reception at lower frequencies.

The main disadvantage of using the licensed spectrum is that some of the bands are in contention (3.5 GHz in the US and 2.5 in Europe because it is designated for 3G). In Europe, the ETSI has assigned the 3.5 GHz band, originally used for WLL, for licensed WiMAX solutions. There is also some trouble with the 2.3 GHz band, as the usage in adjacent channels limits the amount of available bandwidth. WiMAX Forum is currently petitioning regulators to change the current policy.

The usage of licensed bands is the most suitable solution for Point-to-Multipoint applications requiring large coverage.

3.5.2 License-exempt Band: 5 GHz

The majority of countries around the world have embraced the 5 GHz spectrum for unlicensed communications, mainly the 5.15 and 5.85 GHz bands. There are approximately 300 MHz of license-exempt spectrum available in many markets globally (an additional 255 MHz in highly populated markets like the US). Some governments and ISPs are concerned that interference resulting from the availability of too many license-exempt bands could affect critical public and government communication networks, so they have established limited control requirements for 5 GHz spectrums, such us restrictions on certain channels and enforcement of the use of the DFS (Dynamic Frequency Select) function.

The main advantages of using unlicensed bands are their fast rollout and their lower costs (there is no need to pay for the usage of the spectrum).

The main disadvantages of license-exempt bands are:

- Interference: other RF systems can also operate in the same spectrum.
- Increased competition: another operator could easily enter the market.
- Limited power due to government regulations.
- Availability: the 5.8 GHz spectrum is not available in some countries.

For all that, operators should carefully evaluate the potential use of license-exempt spectrum before rolling out a network. However, and exception could be made for rural and remote regions because there is less likelihood of interference and competitions.

3.5.3 Duplexing: technical differences between licensed and unlicensed bands

Both WiMAX licensed and license-exempt solutions are based on the IEEE 802.16d standard, which uses OFDM in the physical (PHY) layer.

Duplexing [17] refers to the process of creating bi-directional channels for uplink and downlink data transmissions. TDD (Time Division Duplexing) and FDD (Frequency Division Duplexing) are both supported by the 802.16d standard: licensed solutions use FDD while unlicensed solutions use TDD.

FDD requires two separated channel pairs to minimize interference, one for transmission and one for reception. It is used in 3G wireless networks, which operate at a known frequency and are designed for voice applications.

TDD provides a single channel for both upstream and downstream transmissions. A TDD system can dynamically allocate upstream and downstream bandwidth depending on the amount of traffic. This asymmetric transfer is well suited for Internet traffic where large amounts of data may be pulled across the downlink. TDD becomes useful in environments where channel pairs are not available due to regulation restrictions or where license-exempt frequencies can be used.

A TDD system operates by first transmitting downstream from the base station to the subscriber station. After a short guard time, typically 1ms, the subscriber station then transmits at the same frequency and in the upstream direction.

TDD and FDD solutions are not interoperable since they use different bands and duplexing techniques. A comparison between both techniques is shown below these lines.

	TDD	FDD
Advantages	- Enhanced flexibility (paired spectrum not required) - Easier to pair with smart antenna technologies - Asymmetrical	- Proven technology for voice (3G) - Designed for symmetrical traffic - Guard time not required - More efficient use of bandwidth - Improved QoS
Disadvantages	- Not able to transmit and receive at the same time	- Impossible to deploy where spectrum is unpaired - Spectrum usually licensed - Higher cost (spectrum purchase, hardware)
Usage	- Environments with varying traffic patterns - RF efficiency more important than cost	- Environments with predictable traffic patterns - Equipment costs more important than RF efficiency

Table 3.5: TDD vs. FDD

Summing up, FDD and TDD each serve a purpose. FDD operates in two separate channels, one for receiving traffic and the other one for transmitting traffic. The spectrum granted for FDD technologies is licensed in equal sized bands. Guard times between upstream and downstream bursts are not required, enabling a full duplex implementation.

In a TDD solution, one channel is used for both transmitting and receiving traffic. Guard times are required between upstream and downstream bursts.

Licensed solutions use FDD because of its robust duplex nature, as well as the fixed spectrum modulated by frequency. This enables carrier class QoS, which cannot be fully achieved in unlicensed solutions.

3.6 802.16 Protocol Architecture

The 802.16 standard, same way as the rest of standards from the IEEE 802 family, defines the specifications for the multiple physical layers (PHY) and the Medium Access Control (MAC) layer. In Figure 3.11 the protocol pile for this standard is introduced, where the MAC layer is composed by the following parts: *Convergence Sublayer* (CS), *MAC Common Part Sublayer* (MAC CPS) and *Privacy Sublayer* [18].

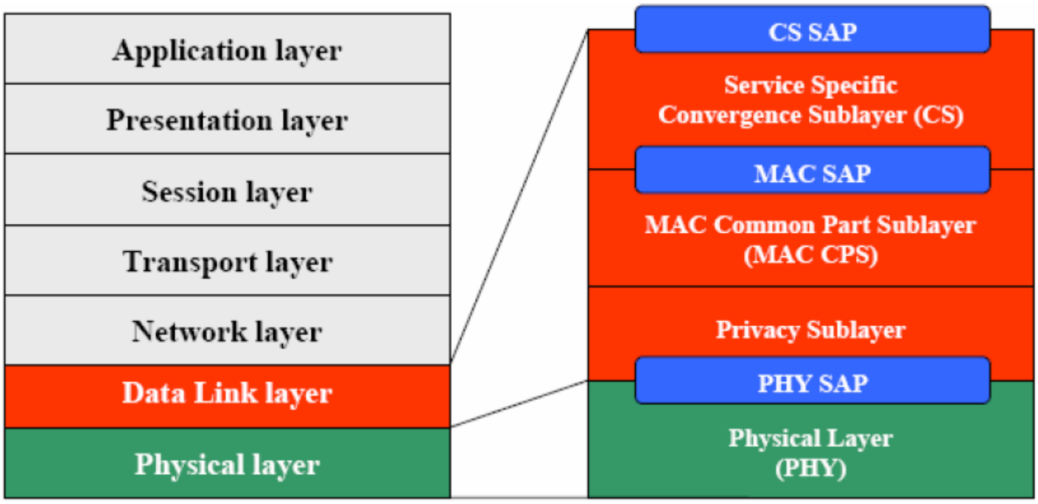

Figure 3.11: structure of the 802.16 protocols

Therefore, the layers and sublayers defined in the protocol are the following:

<u>Convergence Sublayer (CS)</u>

The 802.16 systems must support operation with ATM or IP systems. The CS is able to interact with these two operation modes through the *Service Access Point* (CS SAP), so that is why the function of this sublayer is interacting among the functions of the MAC and Network layers.

<u>MAC Common Part Sublayer (MAC CPS)</u>

It is the core of the MAC layer. It contains all the functions needed for doing the data exchange and for controlling the MAC layer. It is connected to the CS sublayer through the MAC SAP.

Privacy Sublayer

This layer implements all the privacy required elements due to the PHY layer. Some examples are the key exchange and the encrypting/decrypting processes. The PHY SAP is in charge of interconnecting it to the PHY layer.

Physical Layer (PHY)

It specifies the characteristics of the different modes of operation of the air interface: WirelessMAN SC, WirelessMAN SCa, WirelessMAN OFDM and WirelessMAN OFDMA.

3.7 Radio channel characteristics

The 802.16-2004 standard specifies up to 5 different radio layers, which are the result of the wide frequential operation and deployment environment margins it allows to cover. In Table 3.6 the main characteristics of these 5 radio layers are described; it is important to notice that WirelessHUMAN is not a concrete specification but that it comes from its application in unlicensed bands of the WirelessMAN-Sca, WirelessMAN-OFDM and WirelessMAN-OFDMA layers.

Physical layer	Range	Supported options	Duplexing mode
WirelessMAN-SC	10-66 GHz	-	TDD FDD
WirelessMAN-Sca	2-11 GHz (licensed bands)	AAS ARQ STC	TDD FDD
WirelessMAN-OFDM	2-11 GHz (licensed bands)	AAS ARQ Mesh STC	TDD FDD
WirelessMAN-OFDMA	2-11 GHz and (licensed bands)	AAS ARQ STC	TDD FDD
WirelessHUMAN	2-11 GHz and (unlicensed bands)	AAS ARQ Mesh STC	TDD

Table 3.6: characteristics of the different 802.16 physical layers [6]

As it can be appreciated in Table 3.6, all the radio layers except WirelessMAN-SC are designed for working in the 2-11 GHz range, where it is not necessary to have LOS conditions for the interconnection of the equipment. That is why 802.16 includes a series of techniques for compensating the effects of the multipath propagation. Some of these techniques are listed following these lines:

- **AAS (Adaptive Antenna Systems).** It allows using multiple antennae for adapting the radiation diagram to one or more certain directions.

- **STC (Space Time Coding).** Mechanisms making transmission diversity.

- **ARQ (Automatic Repeat-reQuest).** Protocol used for the error control which re-transmits the packets that did not arrive properly to their destination.

WiMAX also uses adaptative modulation techniques which lead to an upgrade to a stronger codification when channel conditions get worse. This way, the closer the SSs are to the BSs, the more probabilities they will get of being able to transmit at a higher speed. In Figure 3.12 these effects can be observed.

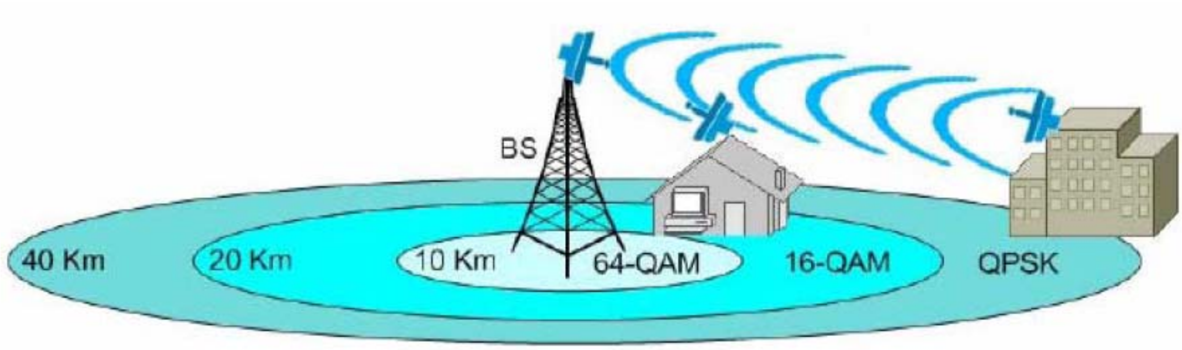

Figure 3.12: adaptative modulation effects

Following these lines, the characteristics of the 5 radio layers identified in the standard are listed:

WirelessMAN-SC

It is the 'single carrier' version made for LOS in the 10-66 GHz frequency band. This version is focused on applications with configuration flexibility, as the transmitter and receiver antennae must have LOS between them, which is a reason for locating the receiver antenna in high places.

WirelessMAN-Sca

'Single carrier' version for frequencies lower than 11 GHz. It includes the previously mentioned techniques for supporting NLOS operations.

WirelessMAN-OFDM – 256 FFT

It is focused on NLOS operations in frequency bands below 11 GHz and it is based on the OFDM orthogonal modulation. Apart from the typical functionalities of the WirelessMAN-SCa standard, this version supports mesh topologies and subchannelization in the uplink, which represents a great tool for optimizing the system's coverage.

WirelessMAN-OFDMA – 2048 FFT

It supports NLOS operations in frequencies lower than 11 GHz and it is based on the OFDMA (Orthogonal Frequency Division Multiple Access) multiple access scheme. This technique is an extension to OFDM for allowing the channel-sharing to multiple users. Apart from the typical functionalities of the WirelessMAN-SCa version, it supports subchannelization in both uplink and downlink.

WirelessHUMAN

This technique includes specific functionalities for working in unlicensed bands, which is why it is called *High-speed Unlicensed Metropolitan Area Network* (HUMAN). It specifies operation in 5 to 6 GHz bands, basing on a flexible channelization scheme including channels of 10 and 20 MHz with 5 MHz spaces.

3.8 Propagation models

In order to perform a WiMAX network the deployment type is really important. There are two different possibilities for the radio channel of a wireless communications system, and they are the following [19]:

Line of Sight (LOS)

The radio channel has direct line of sight between the BS and the SS. In these links the signal travels through a direct path, without obstacles from the transmitter to the receiver. A LOS link requires that 60% of the first Fresnel zone[4] is free of any kind of obstruction, avoiding this way any diffraction effect in the signal. If this requirement is not accomplished there will be a significant reduction in the intensity of the signal.

Therefore, when a link between two LOS points is created the distance and height of the obstacles must be known, as well as the height of the transmitter and the receiver. In Figure 3.13 the representation of the Fresnel zone can be observed; these zones set the points where the signal contribution through the direct and the diffracted paths are in phase and out of phase, being summed constructively or destructively in an alternate way.

---

[4]Fresnel zone [20]: In radio communications, one of a (theoretically infinite) number of concentric ellipsoids of revolution which define volumes in the radiation pattern of a (usually) circular aperture.

Note 1: The cross section of the first Fresnel zone is circular. Subsequent Fresnel zones are annular in cross section, and concentric with the first.

Note 2: Odd-numbered Fresnel zones have relatively intense field strengths, whereas even numbered Fresnel zones are nulls.

Note 3: Fresnel zones result from diffraction by the circular aperture.

To maximize receiver strength, one needs to minimize the effect of the out of phase signals by removing obstacles from the RF Line of Sight (RF LoS). The strongest signals are on the direct line between transmitter and receiver and always lie in the 1st Fresnel Zone.

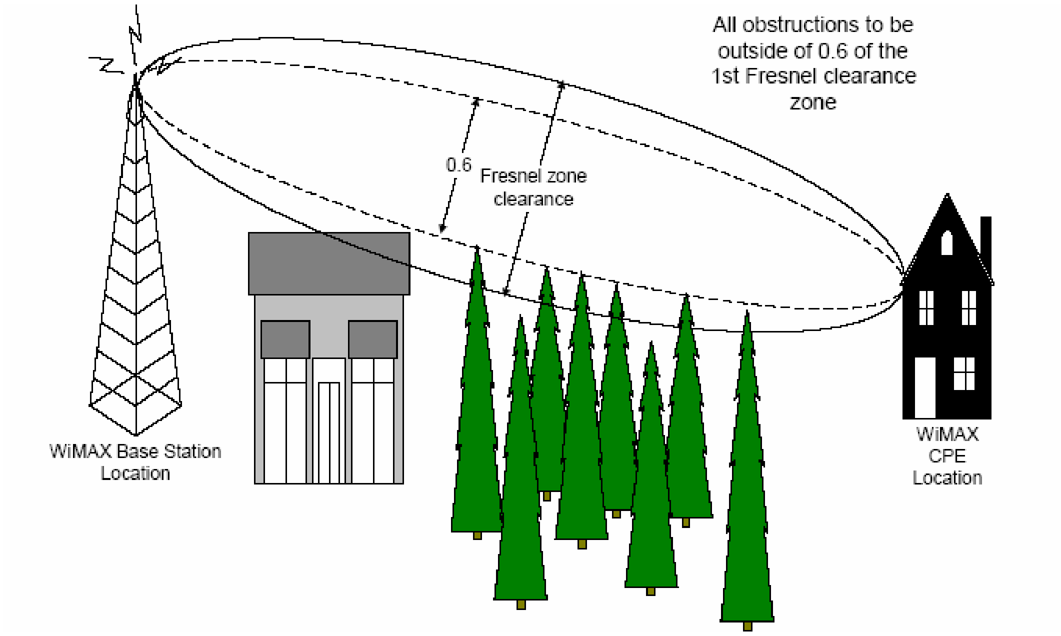

Figure 3.13: Fresnel zone

Non-Line of Sight (NLOS)

The radio channel has not direct line of sight between the BS and the SS. In these links the signal travels towards the receiver through reflections and diffractions (it must be clear that when referring to NLOS connections it does not mean that the signal can go through obstacles, but that the signal can be recovered thanks to its rebounds). The signals arriving to the receiver are composed by the direct signal, multiple lower-intensity reflected signals and different propagation paths caused by diffraction. These signals have different delays (*delay spread*), attenuation, polarization and stability compared to the direct signal. In Figure 3.14 an example of NLOS propagation is shown:

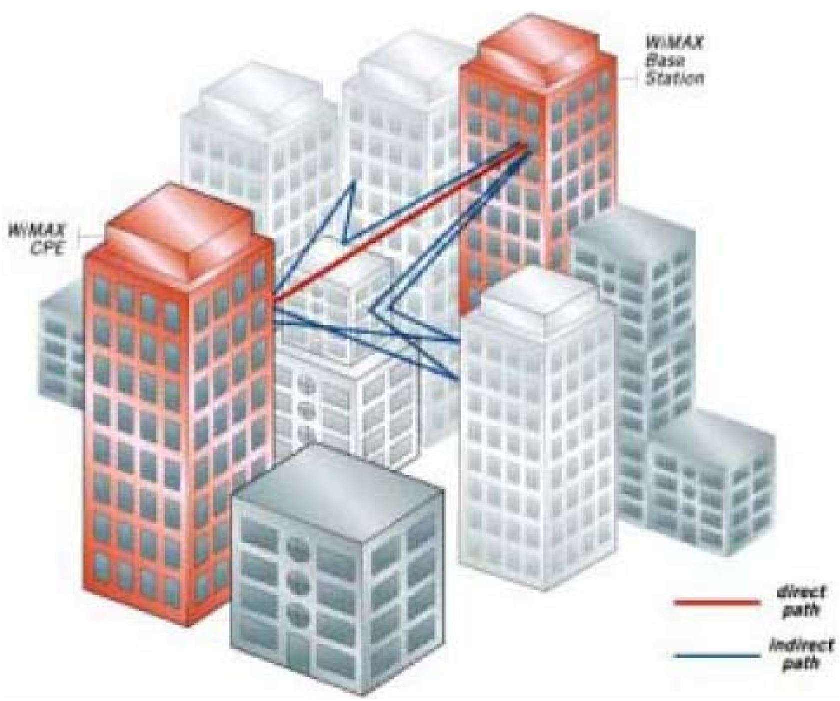

Figure 3.14: NLOS propagation

Some advantages of the NLOS propagation over LOS are the following:

- In many cases the deployment requirements do not allow locating the antenna according to the height restrictions needed for a LOS link. For large-scale cellular deployments, where the frequency re-usage is critical, reducing the height of the antenna can become an advantage as the co-channel interferences between adjacent cells are reduced. This fact forces the BSs to operate in NLOS conditions.

- The NLOS technology also reduces the installation costs, allowing an easy localization of the customer device.

- The NLOS technology and the WiMAX characteristics allow using indoor customer devices, which leads to two main challenges: on one hand beating the building penetration losses and, on the other hand, providing coverage to reasonable distances with reduced transmission powers and antenna gains.

The following table shows the characteristics of the link and the type of CPE antenna that must be used for different situations:

Type of system	**LOS (Line of Sight)**		**NLOS (Non-Line of Sight)**	
	LOS	**nLOS (near-LOS)**	**External NLOS**	**Internal NLOS**
Radio path	Direct, without obstructions	Direct, low-dense obstruction (e.g. trees)	Reflections, multipath propagation	Reflections, multipath propagation and penetration losses
Rx Antenna	Highly directive, installed outside the building	Highly directive, installed outside the building	Directional, installed outside the building	Omnidirectional, included in customer device, installed inside the building

Table 3.7: comparison between LOS and NLOS propagation models

WiMAX technology uses different techniques or technologies in order to reduce the effects of the NLOS links (multipath, diffractions, changes of polarization, etc.). Some of these technologies have been already described in section 3.7.

As a kind of summary for this section, in Figure 3.15 a picture explaining the differences between LOS, near-LOS and Non-LOS conditions is included:

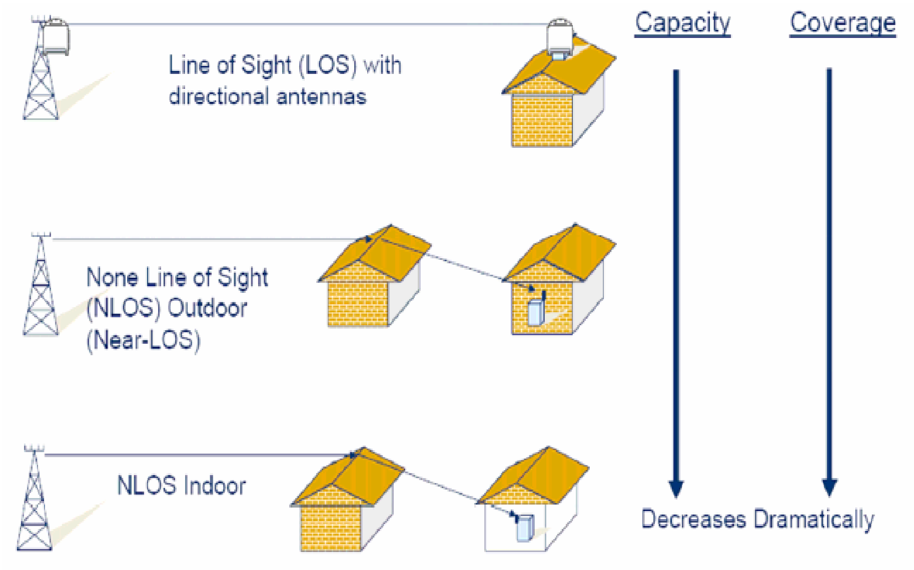

Figure 3.15: LOS vs. Near-LOS vs. Non-LOS

In the Figure it can be appreciated that capacity and coverage decrease dramatically from LOS conditions (for example, directional antennae mounted on the rooftop of a building) to NLOS conditions (an end user inside a building using his laptop), so obviously the ideal 60 km/75 Mbps features can not be taken into account in this case.

3.9 Summary

As a kind of review, below these lines a comparison table between WiMAX and some other different technologies is shown:

	WiMAX 802.16	**Wi-Fi 802.11**	**Mobile-Fi 802.20**	**UMTS & cdma2000**
Speed	124 Mbit/s	11-54 Mbit/s	16 Mbit/s	2 Mbit/s
Coverage	40-60 km	300 m	20 km	10 km
Licensed	Yes/No	No	Yes	Yes
Advantages	Speed and coverage	Speed and price	Speed and mobility	Range and mobility
Disadvantages	Possible interferences	Short-range	High cost	Slow and expensive

Table 3.8: Technology comparison

In conclusion, there are four important features that make WiMAX especial:

1. OFDM: it makes possible to provide connection in NLOS conditions.
2. Capacity: the bandwidth is important, but it is even more important the use of bandwidth (Mb/MHz), which is great in WiMAX.
3. Distance: high distances can be reached, but they are absolutely dependent on the transmitted power and the sensibility of the receiver.
4. Standardization: the most important one because it reduces the equipment costs.

The solution adopted for this project will be fixed WiMAX, which provides the following benefits:

- Scalability: improvements can be made without losing any quality in the services offered.
- Cost effectiveness: it provides a good relation between costs and outcomes.
- Flexibility: a wireless medium enables deployment of an access solution over long distances across a variety of terrains in different countries.
- Standard-based: WiMAX Forum.

4. THE REGION OF NORDJYLLAND

In this chapter different information regarding the Region of Nordjylland will be provided. An introduction to this region is given as well as some general information and a description of who could be interested in a future IT infrastructure and why.

4.1 General information

On January 1st, 2007 a Danish Municipal Reform took place and the entire country suffered a complete redistribution of its traditional regions and municipalities. This way, Denmark ended up divided into 5 regions and a total of 98 municipalities [21] by merging the previous divisions (13 countries and 270 municipalities) into larger units.

The country of Denmark (Figure 4.1) consists of a large peninsula, Jylland (Danish names for regions and cities will be used from now on), and hundreds of islands, being Sjælland (where the capital, København, is) and Fyn the biggest and most important ones. The Faroe Islands and Greenland are autonomous provinces of Denmark with home rule. Denmark is characterized for being a mainly "flat" country (the highest natural point is Møllehøj, a hill 170 metres tall), having an average height of just 31 metres above sea level.

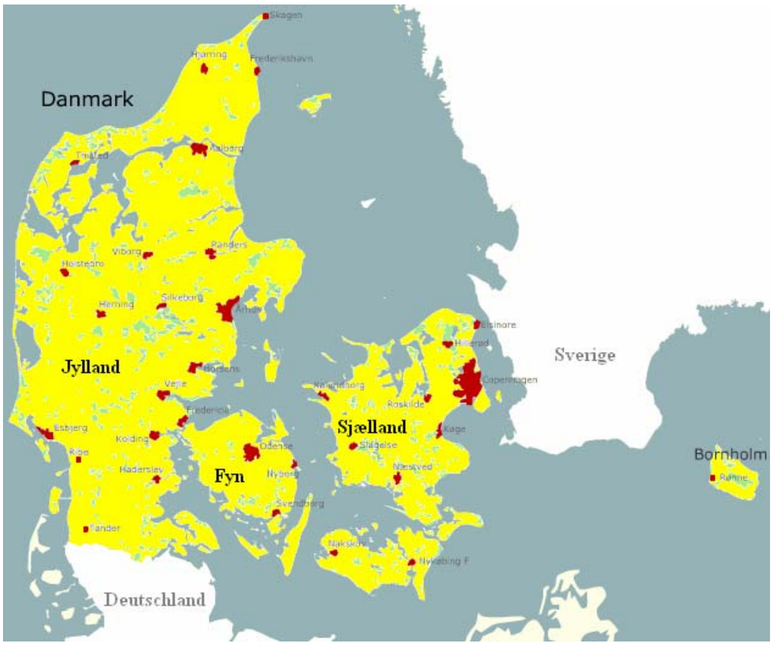

Figure 4.1: Map of Denmark

Focusing on the area this project is based on, after the municipal reform the region of Nordjylland became bigger and got finally composed by 11 municipalities, which can be seen in the map in Figure 4.2.

Nordjylland is the northern region of Denmark and it is also the less populated one of the five regions composing the country. Its largest city (and also the capital) is Aalborg, the fourth largest one in Denmark, which population on January 1st, 2007 was 100731 inhabitants. According to the total population of Nordjylland (576972), it means that the 17.46% of the inhabitants of the whole region live in Aalborg.

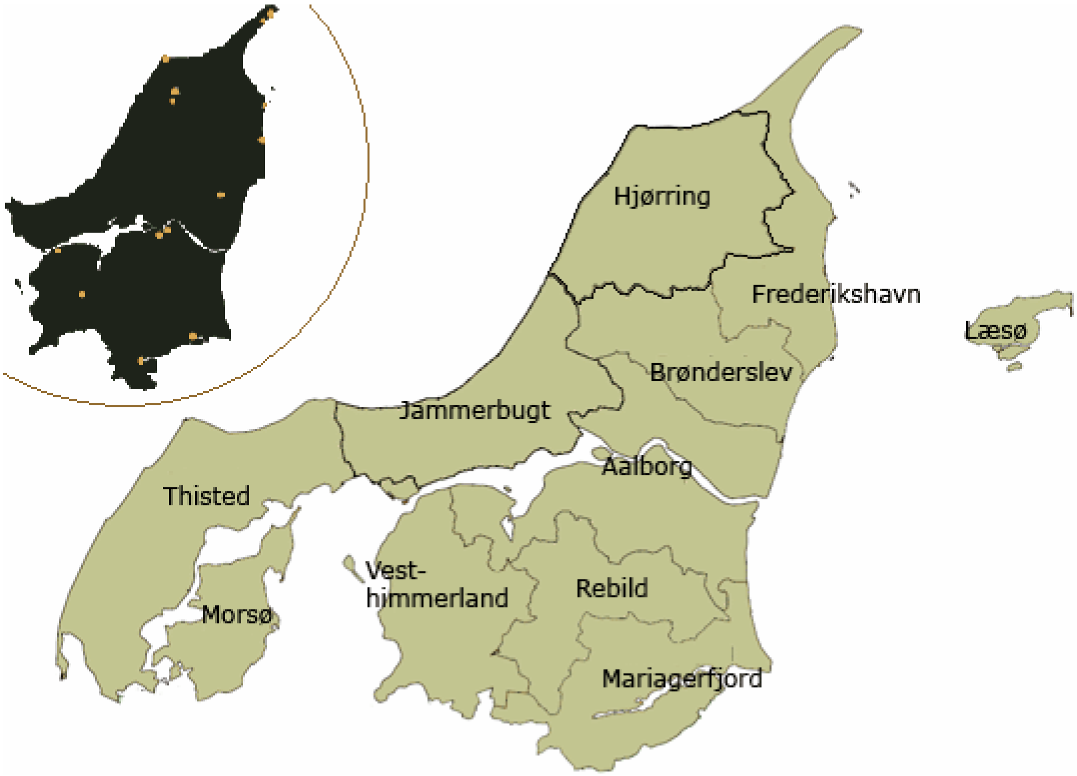

Figure 4.2: evolution of Nordjylland into 11 municipalities after the reform in 2007

Nordjylland covers an area of 8020 km^2, which means that its population density is about 72 inhabitants per km^2, the lowest one in the country by far in spite of being the third largest region.

The entire country of Denmark has a total population of 5447084 inhabitants, so the 576972 living in Nordjylland are 10.6% of the total population of the country. In Table 4.1 the population distribution per municipality together with the number of households in each of them is shown.

Municipality	Population	Households
Brønderslev	35 445	15 833
Frederikshavn	62 877	29 709
Hjørring	67 118	30 526
Jammerbugt	38 787	16 835
Læsø	2 058	1 050
Mariagerfjord	42 288	18 709
Morsø	22 196	10 188
Rebild	28 633	11 911
Thisted	45 580	20 432
Vesthimmerlands	37 841	16 943
Aalborg	194 149	95 277

Table 4.1: Population and households in the municipalities of Nordjylland

From Table 4.1 it can be easily appreciated that Aalborg is the most populated municipality (33.65% of the inhabitants in the whole region). This fact will be taken into account later on for designing the network.

4.2 Population projections

When building a new IT infrastructure, it is important to take into account that it should be operating for several years before it gets improved or replaced. This fact makes the study of population projections become important: migration fluxes and future urban sprawl must be considered as they have influence in the network design (Chapter 5).

According to [21], population in Nordjylland will grow around 2% from now to the year 2030 (Figure 4.3). This is such a slight change that, from a global perspective, current data will be perfectly valid for the network planning simulations.

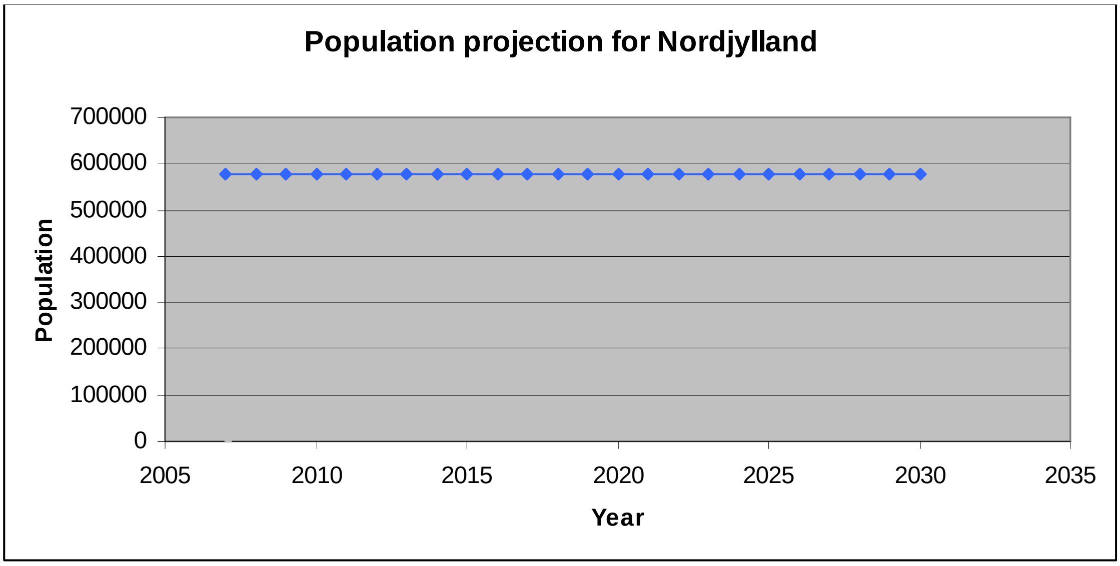

Figure 4.3: population projection for the region of Nordjylland until the year 2030

However, this information is not conclusive from a local perspective because it is only focused on the whole region and it does not consider possible migration fluxes between municipalities inside Nordjylland. Therefore, population projections by municipality have been also consulted (Figures 4.4 and 4.5).

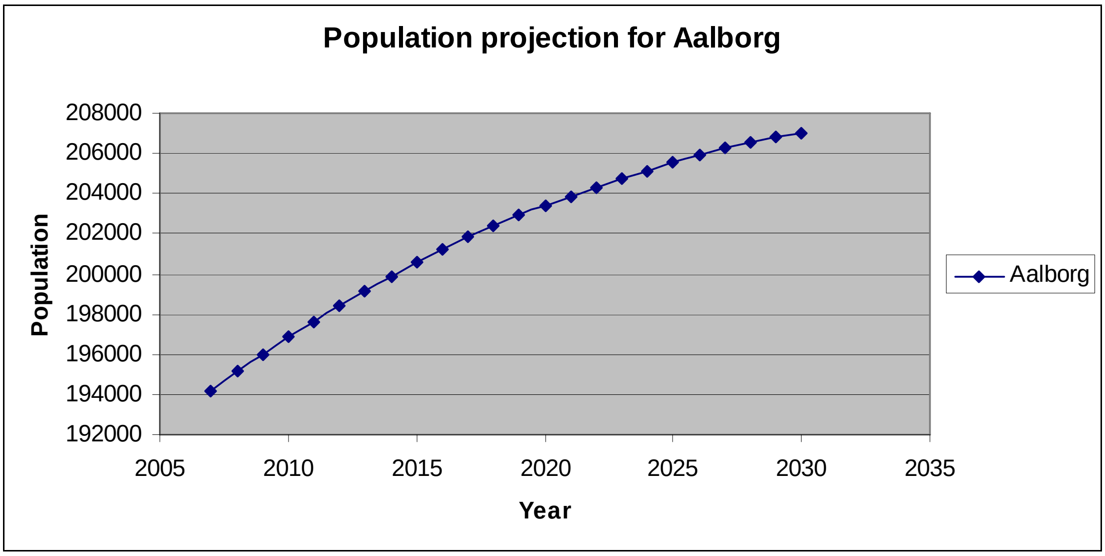

Figure 4.4: population projection for the region of Nordjylland until the year 2030

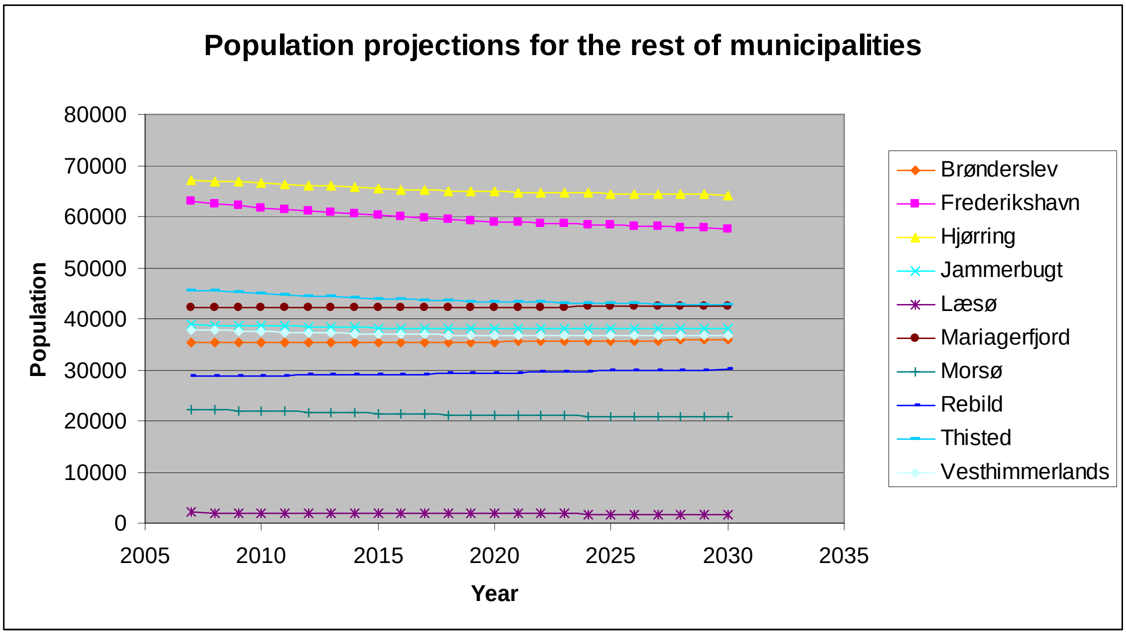

Figure 4.5: population projection for the rest of municipalities (excluding Aalborg)[5]

By taking a look at these graphs, it can be clearly appreciated that the only municipality which will register an important variation is Aalborg with an increase of 6.5% in the population between 2007 and 2030.

This demographic stability throughout the years makes the task of designing the network (placing the main nodes, Chapter 5) easier. If important changes had been predicted the planning procedure would have been a bit more difficult due to the need of taking into account these changes, causing an increase in the total budget too.

4.3 Interested Parties

In this section information about interested parties will be given. The following comments are the result of assumptions made according to the current situation of these parties in the region.

4.3.1 Service Providers

At first sight, building a new infrastructure in any place in Nordjylland different to Aalborg does not look very interesting for the Service Providers: it is not a very populated region and it would hardly be worth its –both construction and maintenance– costs. However, these low-populated cities in Nordjylland have a quite limited access to the Internet and if they had a high-tech infrastructure it would be very possible that the population could increase. The only fact of having an infrastructure able to give Triple Play services to the citizens in Nordjylland would not only be a good reclaim for new citizens to move in, but also a way to encourage any existing or new Service Provider to be the one offering that service.

[5] Aalborg has been placed in a different graph because the difference between this municipality and the others is so high that the graphs can not be clearly appreciated.

Furthermore, many existing ISPs do not have their own access infrastructure, being forced to rent connection from others. This fact makes building a new infrastructure become a good possibility for these providers.

More specifically, two important Danish ISPs could be suggested: on one hand there is TDC, Denmark's leading telecommunications provider, which have a really aggressive strategy according to their own words: they have money to invest and a hard motivation to become the most efficient operator not only in Denmark but also in the whole Nordic region. They pretend to invest DKK 3.9 billion annually in the Nordic business up to 2010.

On the other hand there is Skyline: they pretend to provide full internet coverage for the whole Denmark before 2010 and, as their plan includes Nordjylland too, they should be really interested on the development of this network.

Some other companies which could be interested are Clearwire –the leading WiMAX ISP in the U.S.A., whose division in Denmark is growing really fast–, Danske Telecom –which are paying a lot of attention to WiMAX technology, becoming one of the most important companies in the sector– and even Ceragon Networks after their multi-year agreement with Denmark's Sonofon.

4.3.2 Private Households

It is clear that one of the most interested parties in having access to this kind of technology are the citizens themselves, as it is known that they always look for the best service at the best price. With this technology their needs would be totally fulfilled for a reasonable future, otherwise the broadband access they are being offered nowadays –if they have any– would become obsolete really soon.

4.3.3 Businesses

It seems clear that a fast and secure access to the Internet is something the businesses in Nordjylland should be interested in: if they participated in the construction of this infrastructure they would have advantages on a national and even international business area. The possibility of having access to the Triple Play technology should be very attractive for these businesses because they would easily increase their benefits, widen their market and even increase exports.

Furthermore, agriculture is an important business in Nordjylland and it is not often offered a proper Internet access due to geographical reasons. Thanks to WiMAX technology this fact would not be a problem due to the large coverage a WiMAX station can offer on its own. That way the agricultural sector, which usually uses the best access technology offered, would be a very important customer and probably one of the most interested parties in having access to this infrastructure. In addition, nowadays more and more new technologies are becoming available for the agriculture and they will continue this way in the future, so by participating in this infrastructure the agricultural businesses in Nordjylland would have access to these developments and they would be given the opportunity of not being left behind.

5. NETWORK DESIGN

In this chapter the steps followed to design the WiMAX network will be explained (including the location of the base stations and the frequency planning), as well as the tools used and the criteria taken into account for this deployment.

5.1 Tools used

For working in this section of the project, two important tools have been needed: some data to base on and a tool for handling that data.

The data used for this research belong to some GIS[6] databases for the region of Nordjylland. Up to three databases have been used: the first one provides information about all the NTs (Network Terminals) in the region, which include households, businesses, farming, etc.; the other two databases contain data for the roads and the location of all the COs (Central Offices) of TDC in Nordjylland. As mentioned in assumption 1 back in section 1.4, the data for the current region of Nordjylland (after the Municipal Reform in 2007) have been unavailable for its use in this project. Therefore, all simulations have been made according to the data referring to the old distribution of the region.

The software used to work with this database is MapInfo Professional 7.5, from MapInfo Corporation, which is a powerful mapping application that enables business analysts and GIS professionals to easily visualize the relationships between data and geography [23].

Below these lines there are some examples of how do these databases look like once loaded into MapInfo (Figures 5.1, 5.2 and 5.3).

Figure 5.1: NTs loaded into MapInfo: a) The whole region. b) A closer look at the north part of the region, where the important cities can be easily appreciated

[6] A Geographic Information System (GIS) integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information [22].

Figure 5.2: roads loaded into MapInfo: a) The whole region. b) A closer look at the north part of the region, where the important cities can be easily appreciated

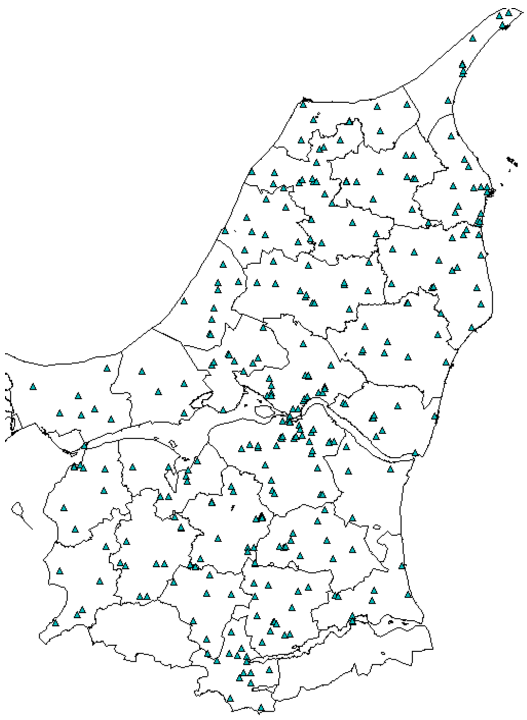

Figure 5.3: main COs of TDC loaded into MapInfo

Just as an orientation, below these lines a graphical description about the NT data available for the project in comparison with the distribution of the current Nordjylland is shown (Figure 5.4).

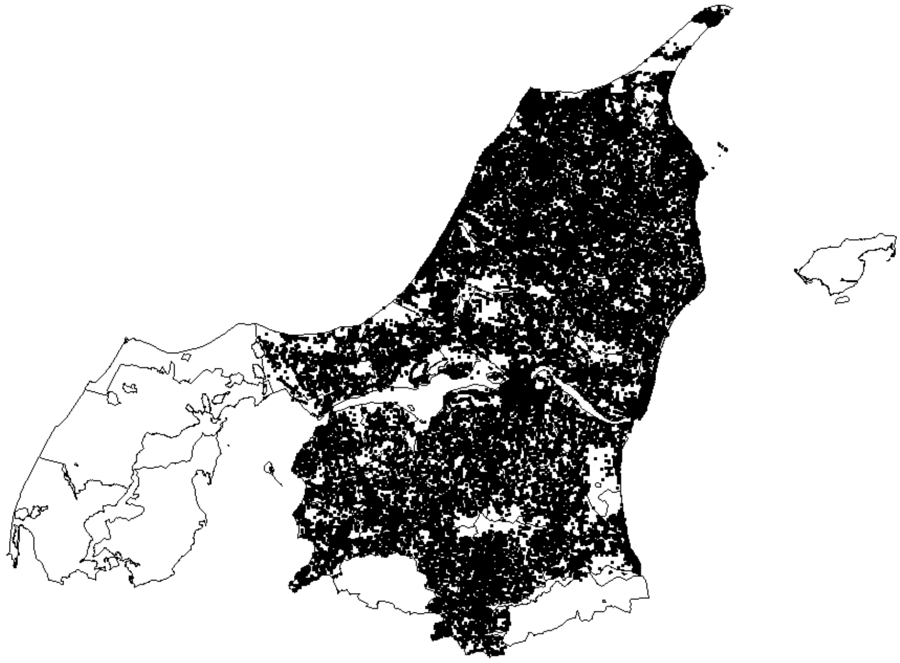

Figure 5.4: NTs from old Nordjylland vs. current Nordjylland distribution

5.2 Background

5.2.1 Situation in Denmark

In Denmark [24] many licenses for the 3.5 GHz have been sold during these last years. In 2004 [25], the largest recipient of 3.5 GHz licenses was Clearwire. In May 2004 a company named Flux Europe Sarl won a 3.5 GHz license for Copenhagen, at a cost of US$267,205. In November 2004 Flux asked the Ministry to transfer the licence to a new wholly-owned Danish subsidiary called Clearwire Denmark ApS. Shortly thereafter, Clearwire also acquired a local broadband operator named Danske Telecom A/S for a reported US$16.7 million. Since then, Danske Telecom has become the leading provider of fixed wireless in Denmark.

The WiMAX Spectrum Auction in Denmark is 3.4 – 3.6 GHz [26].

5.2.2 Followed criteria

5.2.2.1 Duplexing mode and propagation model

As seen in Table 3.2 for the WiMAX Forum profile, the 3.4 – 3.6 GHz band can use both TDD and FDD duplexing. However, as this is a licensed band the FDD solution (in section 3.5.3 it was explained that FDD is more suitable for the licensed spectrum) with dual 3.5MHz bandwidth channels (one for the UL, one for the DL) will be used.

An important requirement for assessing technology for Broadband FWA is to have an accurate description of the wireless channel. Channel models are heavily dependent upon the radio architecture. For example [27], in first generation systems, a super-cell or "single-stick" architecture is used where the BS and the SS are in LOS conditions and the system uses a single cell with no co-channel interference. For second generation systems, a scalable multi-cell architecture with NLOS conditions becomes necessary.

This way, the next step to follow should be to determine the propagation model so it is possible to predict the range. Some years ago, Stanford University developed a group of channel models for simulating the multipath phenomenon in LMDS systems. They are known as Stanford University Interim (SUI) models and they are the most commonly applied models for WiMAX deployments. They cover three different terrain categories [28]:

- **Type A**: a hilly terrain with moderate-to-heavy tree density ~ urban environments (highest path-loss).

- **Type B:** either a hilly terrain with light tree densities or a mostly flat terrain with moderate-to-heavy tree densities ~ suburban environments.

- **Type C:** a flat terrain with light tree densities ~ rural environments (lowest path-loss).

These terrain categories provide a simple method to more accurately estimate the path-loss of the RF channel in NLOS conditions.

Treating these terrain categories as urban, suburban, and rural respectively is a suitable assumption for the purposes of this project due to the geographical characteristics of Nordjylland, but it would not be unusual in other regions to, for example, find a rural area which features are closer to Type A terrains rather than to Type C's. In this case each environment should be assessed on its specific characteristics.

The SUI channel models were selected for the design, development and testing of WiMAX technologies in six different scenarios, SUI-1 to SUI-6, described in [29]. By using these channel models, it becomes possible to predict more accurately the coverage probability that can be achieved within a base station site sector [19]. The coverage probability estimates can then be used for further planning efforts. For example, they can be used to determine the number of base station sites necessary to provide service to a geographic area. These models do not replace the detailed site planning efforts but can provide an estimate before real planning begins. It is important to perform RF planning activities to consider specific environment factors, co-channel interference, and actual clutter and terrain effects.

Table 5.1 [28] provides a summary of the key downlink radio characteristics that are used in later sections of this report. The system gain in Table 5.1 is typical of med-performance WiMAX-compliant equipment solutions offered by vendors.

As it can be appreciated in the Table, the DL system gain for indoor self-installable CPE units is approximately 6 dB lower than the system gain for outdoor CPEs, primarily due to the difference in antenna gain. There is also an additional path loss with indoor CPEs due to wall penetrations and non-optimal installation locations that will typically be off bore-sight to the base station antenna. This excess path loss is estimated to be about 15 dB.

However, these parameters for indoor CPEs are only included as an orientation because 100% outdoor CPEs will be assumed for the deployment of the WiMAX BSs in the area. The reason of this assumption is mainly a matter of costs, as it is cheaper to deploy outdoor equipment than indoor.

Attribute	3.5 GHz Band
Duplexing	FDD
Channel Bandwidth	2 x 3.5 MHz
Adaptive Modulation	BPSK, QPSK, 16QAM, 64QAM (COFDM-256)
Nominal System Gain for Outdoor CPEs	164 dB at BPSK
Nominal System Gain for Indoor Self-Installable CPEs	158 dB at BPSK
Excess Path Loss for Indoor CPEs	15 dB
Propagation Conditions	Urban, Suburban, and Rural. LOS/NLOS

Table 5.1: relevant radio parameters for the 3.5 GHz band

Therefore, the typical scenario for this deployment would be the following:

- Cells up to 25 km radius.
- Rooftop installed directional antennae (2 – 10 m) at the receiver.
- 15 – 60 m height BS antennae.
- High cell coverage requirement (90-100%).

The wireless channel is characterized by:

- Path loss (including shadowing).
- Multipath delay spread.
- Fading characteristics.
- Doppler spread.
- Co-channel and adjacent channel interference.

Some of these parameters are explained in Appendix B. It must be noticed that they are random and only a statistical characterization is possible. Typically, the mean and variance of parameters are specified.

The above propagation model parameters depend upon terrain, tree density, antenna height and beamwidth, wind speed, and season of the year.

However, these data have been unavailable during the implementation of this project and assumptions have been made in order to take them into account.

The use of adaptive modulation (2.3.1) and adaptive coding enables each end-user link to dynamically adapt to the propagation path conditions for that concrete link. When the received signal levels are low (e.g. the case of users more distant from the BS), the link automatically "downgrades" itself to a more robust, but less efficient, modulation scheme. Since each modulation scheme has a different efficiency, the effective channel capacity can only be obtained by knowing the modulation and coding schemes of each end-user link sharing that particular channel. This can be done by assuming that the active subscribers on any given channel are uniformly distributed over its coverage area and, additionally, that each end-user is under the same conditions, i.e. all outdoor CPEs and NLOS [28].

5.2.2.2 Range and capacity limits for WiMAX deployments

WiMAX deployments can be either range-limited or capacity-limited. In the case of a range-limited deployment, and assuming a uniform distribution of active subscribers with outdoor CPEs, more than 60% of active users will be operating at either QPSK or BPSK modulation, while only 15% will operate at 64QAM. An example of this can be seen in the 90º sector shown in Figure 5.5.

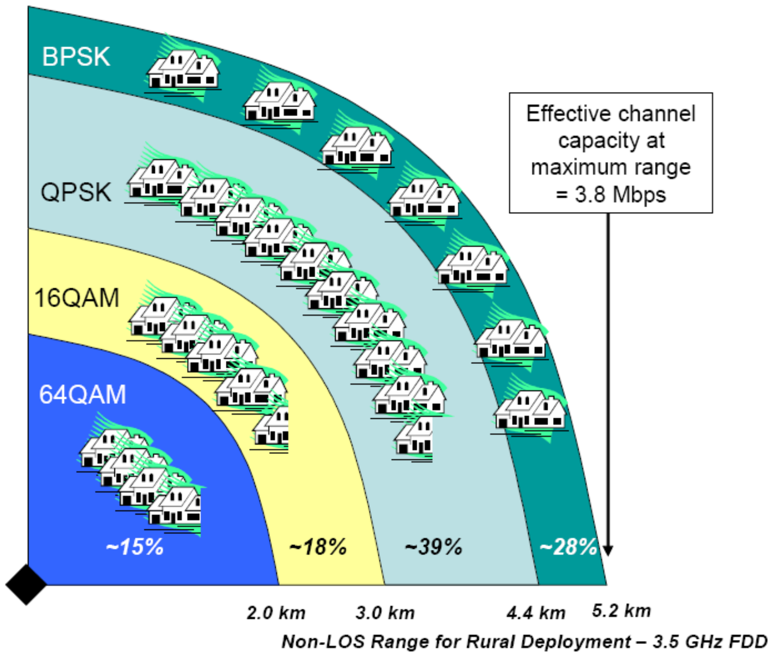

Figure 5.5: typical subscriber density for a 3.5 GHz Rural Deployment [28]

The range estimates shown in Figure 5.5 apply to a 3.5 GHz deployment in a rural environment with all outdoor, NLOS CPEs. As it can be appreciated in the picture, with the shown distribution of users the effective DL channel capacity (net user data rate) for a range-limited deployment is 3.8 Mbps, clearly lower than the 9.7 Mbps for the capacity-limited case with all end-users operating at 64QAM. That is because the fact of assuming that all users are NLOS is a worse-case situation. In practice, it is reasonable to expect that some outdoor installations will be within LOS or near-LOS to the BS antenna.

Since the 64QAM range for LOS or near-LOS exceeds that of BPSK for NLOS, in practice some distant end-users will actually be operating at 64QAM instead of BPSK, which will increase the effective DL channel capacity from the 3.8 Mbps shown.

Another factor not taken into account in the Figure is an allowance for Co-Channel Interference (CCI) from adjacent cells which, in a multi-cellular network, is an added consideration. Excessive interference will also cause the affected link to move to a different type of modulation, thus reducing the effective channel capacity. Anyway, the approach used in Figure 5.5 for estimating channel capacity represents a very adequate first order estimate for effective DL channel capacity since these two effects (LOS and CCI) tend to offset one another.

For fixed services, due to license assignments with limited spectrum, most deployments are usually capacity-limited rather than range-limited. However, very low density rural areas can be considered as exceptions, particularly those ones which could be classified as terrains with high propagation losses. This way, and focusing on this project, taken into account the characteristics of Nordjylland, the first criterion for placing the base stations will be to locate them in the most densely populated areas, based on this capacity limitation, and then the range criterion will be used for the areas with lower population density.

Therefore, for capacity-limited deployment scenarios it is necessary to deploy base stations with enough BS-to-BS spacing in order to match the expected density of end-customers. Data density is an excellent metric for matching BS capacity to market requirements. With the demographic information (including population, households and businesses per km^2) of the objective area and the expected services to be offered along with the expected market penetration, data density requirements can be easily calculated. This process is described below:

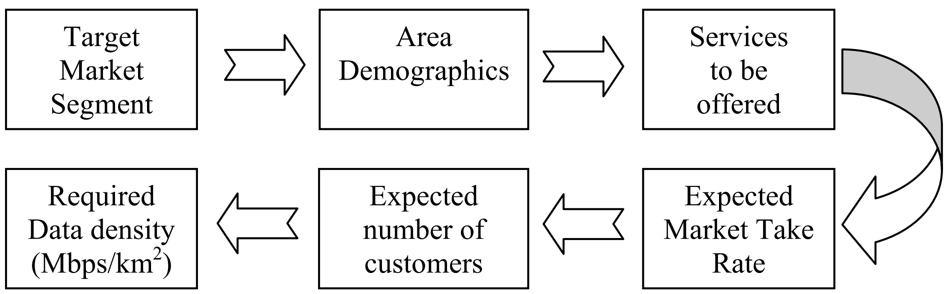

Figure 5.6: determining market driven capacity requirements

Furthermore, in fixed wireless networks it is also important to project market requirements some years into the future and deploy BSs according to what those projections say. The assumed market segments and services to be offered are summarized in Table 5.2.

Customer Type	Service Description	Overbooking Factor
Residential	384 kbps Average	20:1
Residential VOIP (20% of users)	128 kbps Average	4:1
SME Premium (25%)	1.0 Mbps CIR, 5 Mbps PIR	1:1 (CIR)
SME Regular (75%)	0.5 Mbps CIR, 1 Mbps PIR	1:1 (CIR)

Table 5.2: metrics used to calculate Market Data Rate Requirements [28]

Table 5.3 represents a typical range of data density requirements for urban, suburban and rural environments for an average metropolitan area based on the service definitions in Table 5.2:

	Urban	Suburban	Rural
Residential Density Penetration	4,000 to 8,000 5 to 10%	800 to 1,500 5 to 10%	200 to 600 5 to 10%
SME Density Penetration	400 to 600 2 to 5%	50 to 100 2 to 5%	10 to 30 2 to 5%
Data Density Range	10 to 40 $Mbps/km^2$	2 to 7 $Mbps/km^2$	0.5 to 2 $Mbps/km^2$

Table 5.3: typical data rate requirements for an average Metropolitan Area [28]

Therefore, focusing on the deployment of the WiMAX BSs assuming all outdoor CPEs, Table 5.4 becomes interesting as it shows the demographics and anticipated number of residential and SME customers along with the data density required to serve the anticipated number of end-customers:

	Urban	Suburban	Rural
Geographical Area to be Covered	60 sq-km	120 sq-km	200 sq-km
Expected Number of Residential Customers	30,000	20,000	5,000
Expected Number of SME Customers	1,500	500	150
Required Data Density	29 $Mbps/km^2$	5.9 $Mbps/km^2$	1.0 $Mbps/km^2$

Table 5.4: demographics for Deployment Examples [28]

All the deployment criteria to this point have been capacity-limited with the desired BS capacity determined by projected market requirements based on services offered, demographics and projected market penetration. However, as it was mentioned before, there is another possible deployment scenario, which is to deploy the minimum number of base stations necessary to get ubiquitous coverage over a particular area at the outset and only add additional capacity as the need arises to serve a growing number of customers. This additional capacity can be achieved by adding BS channels to the already deployed base stations assuming sufficient spectrum is available; or by inserting additional base stations if the spectrum is not available.

Deploying for coverage without regard for projected capacity requirements is a viable deployment strategy where the market requirements are uncertain and hence difficult to quantify accurately. For instance, this would certainly be a reasonable deployment approach for an operator wanting to provide ubiquitous outdoor internet access for nomadic customers over a wide geographical area. When the initial network is operational the operator will be in a better position to assess and predict traffic patterns, customer acceptance and market penetration expectations.

5.2.2.3 Summary of criteria/assumptions

As a review, the most important features taken into account for designing the network are listed once more below these lines:

- Frequency band: 3.5 GHz.
- FDD duplexing with dual 3.5MHz bandwidth channel.
- SUI models.
- Outdoor CPEs. Assumptions for LOS/NLOS.
- Range (low density) or capacity-limited (high) deployments.
- 1st: capacity-limited: Tables 5.2, 5.3.
- 2nd: range-limited: Table 5.4.
- Range-limited: additional capacity can be achieved by adding BS channels (enough spectrum available) or by inserting additional BSs (spectrum not available).

5.3 Network design

In this section all the information regarding the placement of the WiMAX Base Stations (BSs) and their characteristics will be explained.

5.3.1 Objectives

As it was mentioned in the introduction, the main objective of this project is to design a telecommunications network which provides Triple Play services to the whole region of Nordjylland. The goal is to provide full WiMAX coverage to the region; however, a 95% minimum will be taken into account for the deployment.

5.3.2 Population distribution

The first step followed for calculating the placement of the BSs was creating a thematic map in MapInfo which showed the population distribution all along the region. To that purpose, previously a grid covering the whole region was created; the cell-size chosen for this grid was 3 km x 3 km, which as a result divided the region in 1564 cells of 9 km^2. The reason for choosing this size for the cells is just because if a bigger area was chosen the cells did not have enough resolution, while if the size was smaller the simulations were really laborious and they took too long or made the software crash.

Once the grid was obtained, a simulation was run in MapInfo in order to obtain a thematic map which described the population density in the whole region. In Figure 5.7 the result of this simulation is shown: it can be easily noticed that the areas with higher NT density are displayed in red and orange and the lower-density zones are drawn in green or blue, according to the legend.

The reason for doing this process is because the first criterion followed for placing the base stations is that the most populated cities in the region must have a BS located nearby, as they are going to be the ones handling more traffic. Therefore, the base stations for these "main" cities will be located in these most-densely populated zones, as it is explained in the next section.

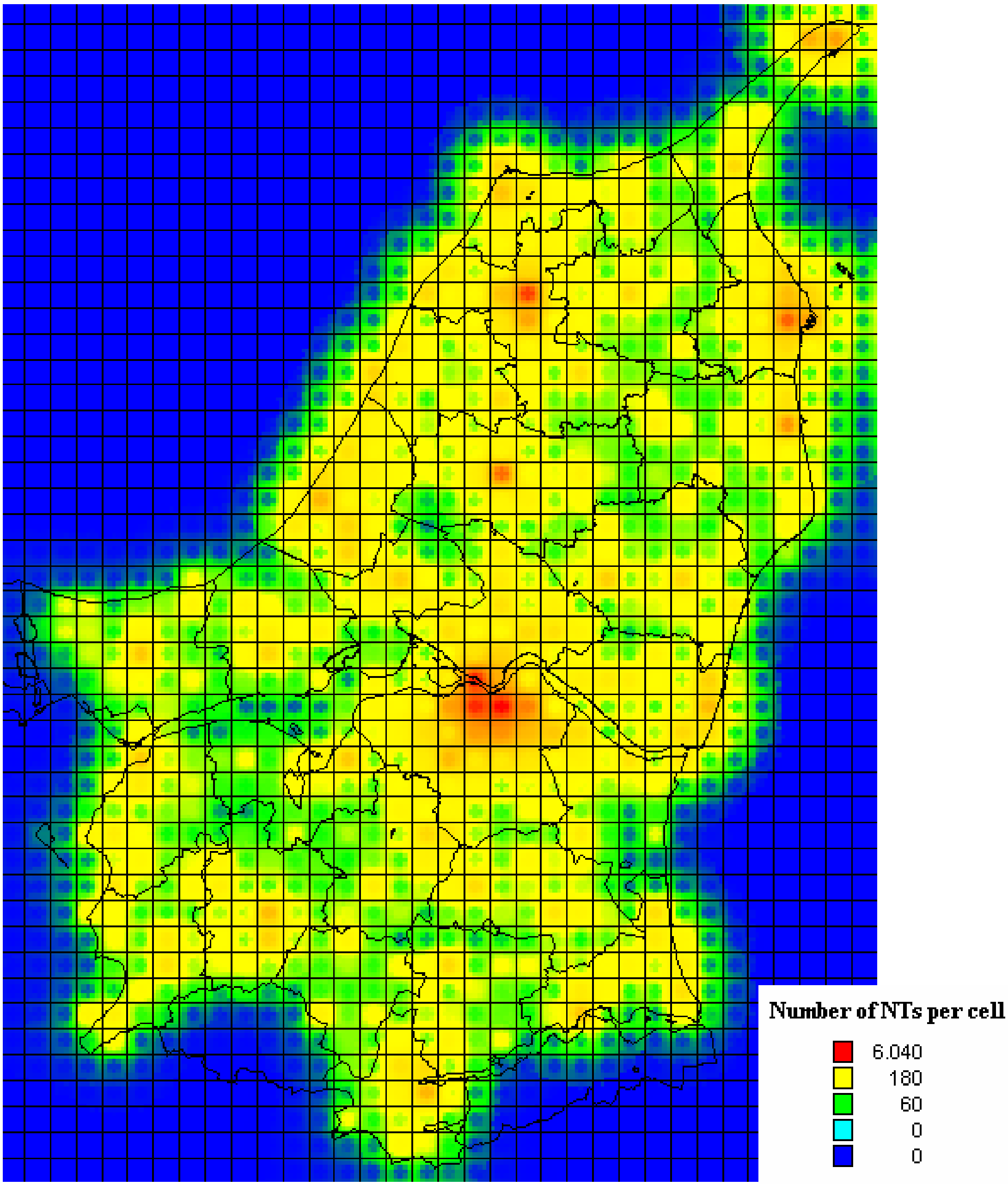

Figure 5.7: NT density map

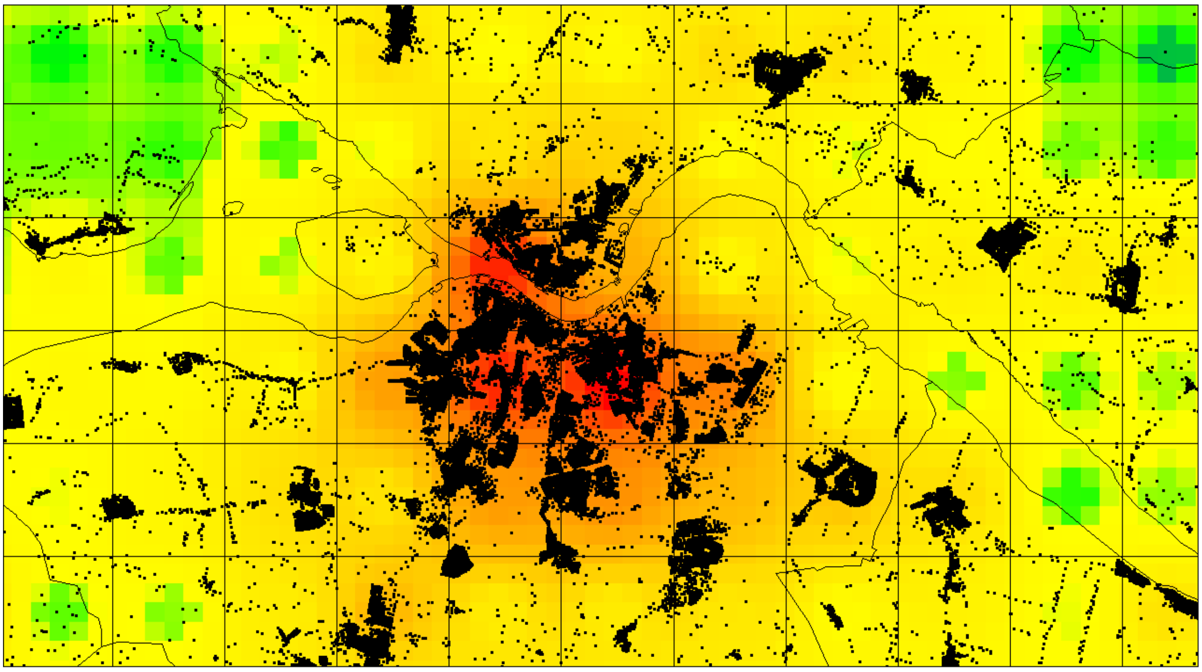
Figure 5.7b: a closer look into Aalborg

5.3.3 Main nodes

After obtaining the density map for the region, the next step was calculating the points with a higher population density. This one is the most important part this project has in common with S. Labeaga's.

As explained in S. Labeaga's report [0], a lower number of nodes reduces the costs of the backbone network: less equipment is needed but more powerful and expensive because each node has to process a higher amount of data; in other words: by decreasing the number of nodes the costs of the backbone network are lower but, on the other hand, the price of the access network increases. Furthermore, assuming equally distributed traffic in the network (balanced network), the less the number of nodes, the more the traffic they have to process, which implies worse consequences in case of a node-failure because the traffic will be concentrated in a smaller amount of nodes.

The solution to this task was to find a compromise between both interests, which, translated to MapInfo, consisted in a query that returned the cells from the grid which had more than 3000 NTs in them. The reason for choosing 3000 NTs is that if a query related to cells with more than 3000 was made it only returned cells located in Aalborg, while if the query was made by taking into account cells which had less than 3000 NTs it returned a much higher number of cells, which were not really valuable for defining the main nodes of the network but were noted down and used for placing further "not-main" stations.

As a result, 8 cells out of 1564 were obtained (4 of them in the city of Aalborg). These 8 cells were used as the main nodes for S. Labeaga's backbone network [0] and were used in this project as 5 areas which should have BSs located nearby: Aalborg, Frederikshavn, Hjørring, Sæby and Brønderslev.

The results of this query are shown in Figure 5.8.

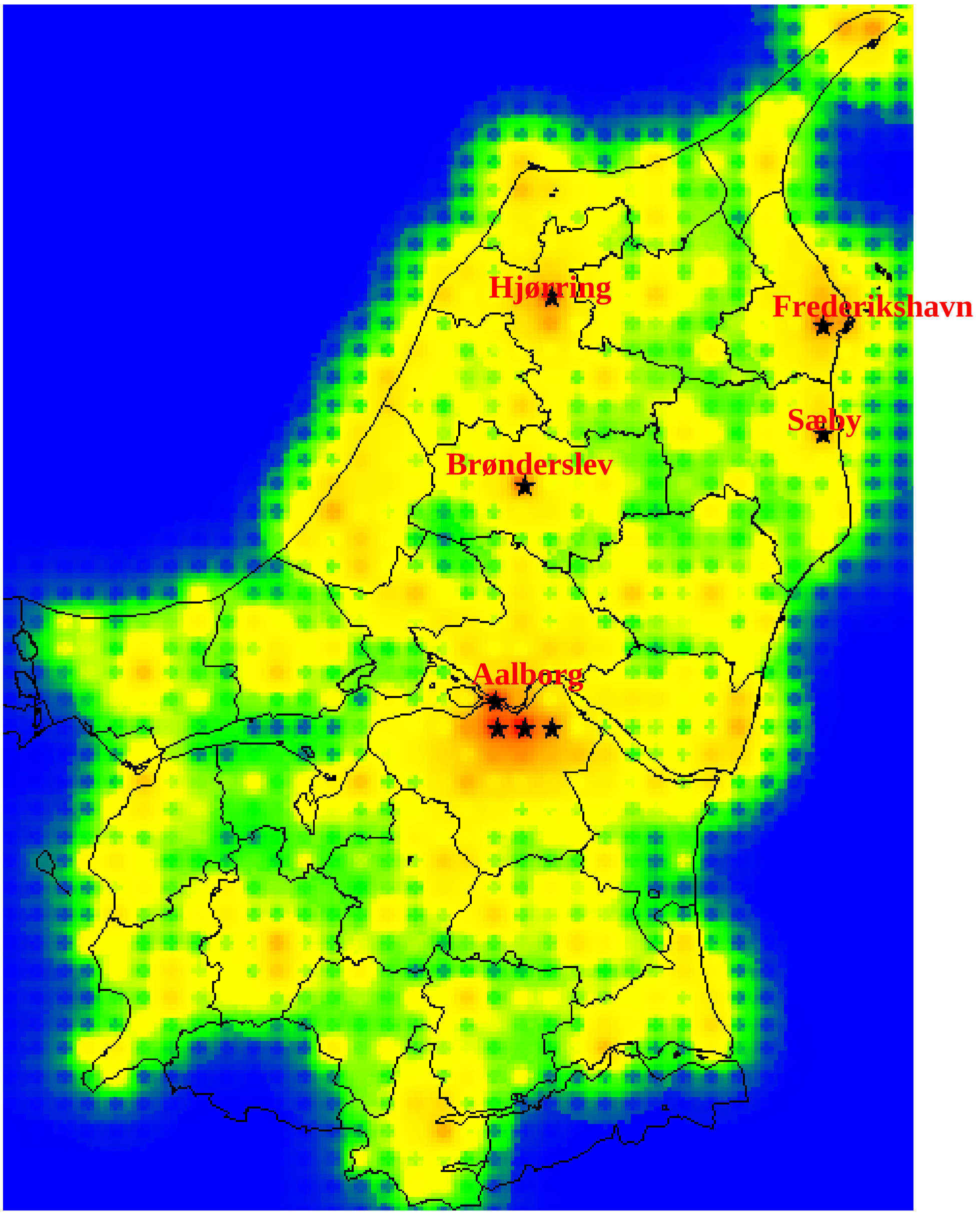

Figure 5.8: the stars show the cells of the grid which have more than 3000 NTs in them

5.3.4 Placement of Base Stations

As said before, by the calculation of cells with more than 3000 NTs, 5 areas were obtained, which have been considered as the main locations for the BSs. However, it would be impossible to give WiMAX coverage to the whole region of Nordjylland with just these 5 spots, so more BSs are needed in order to accomplish the objective of giving coverage to the whole region.

Going back to Table 5.4 and the SUI model, the information about the area to be covered can be translated, taking into account the 9 km^2 cell-division, into 7 cells for urban areas (Type A), 13 for suburban (Type B) and 22 for rural areas (Type C). The only city which will be considered as an urban area is Aalborg, the most populated one (almost 100000 inhabitants). It will also be assumed that, from the other "main nodes", just Frederikshavn and Hjørring are suburban (Sæby and

Brønderslev are not as populated as these two) and the rest of the region will be considered as rural. This way, when drawing the coverage circles it will be taken into account that the radius from the BSs will be 5 km (for covering 7 cells) for urban areas, 10 km for suburban and 15-20 km for the rural ones (typical radii values for 100%, 75% and 50% NLOS conditions respectively).

For being more specific about these "coverage circles" the following picture can be used as an orientation:

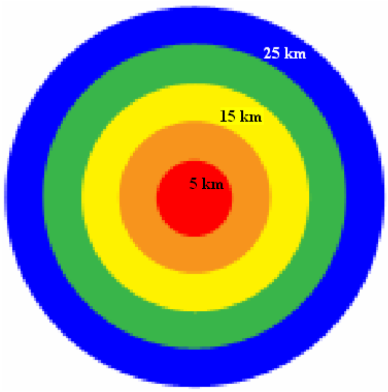

Figure 5.9: structure of a coverage circle

As seen in Figure 5.9, a coverage circle is divided into different categories according to its radius. In previous chapters it was explained that fixed WiMAX is designed so that it is able to reach distances up to 50-60 km. However, it was also pretty clear that these ranges could only be achieved in very good conditions: LOS and good equipment, so these "ideal" distances will not be taken into account for the placement of the BSs although Nordjylland is mainly a rural area and the conditions can be very close to ideal.

According to the structure of a coverage circle seen in Figure 5.9, depending on the zone a NT is located in it will receive a better or worst service from the BS. In other words: the closer the NT is to the BS (red zone), the better service it gets, while a NT located in the blue zone will see it can not reach the same service rates. Anyway, the adaptative modulation technique (section 2.3.1) also helps, making the connection more robust so distant points to the BS can be provided a minimum quality access.

The objective when placing the base stations is that the most populated areas are included in the red zone of these coverage circles drawn around the stations. These circles can also be related to LOS/NLOS conditions by assuming that the red zone has 100% NLOS conditions and the further zones have a higher percentage of near-LOS and LOS conditions (but always lower than NLOS, trying to approach to worst-case solutions).

5.3.4.1 Main Base Stations

First of all, and according to the first criterion mentioned for the placement of base stations, there will be some "main" BSs which are going to be located in areas next to the main nodes calculated before in order to give service to the most populated cities in the region. These BSs will be 4 (the reason for them not being 5 is explained below), as shown in Figure 5.10:

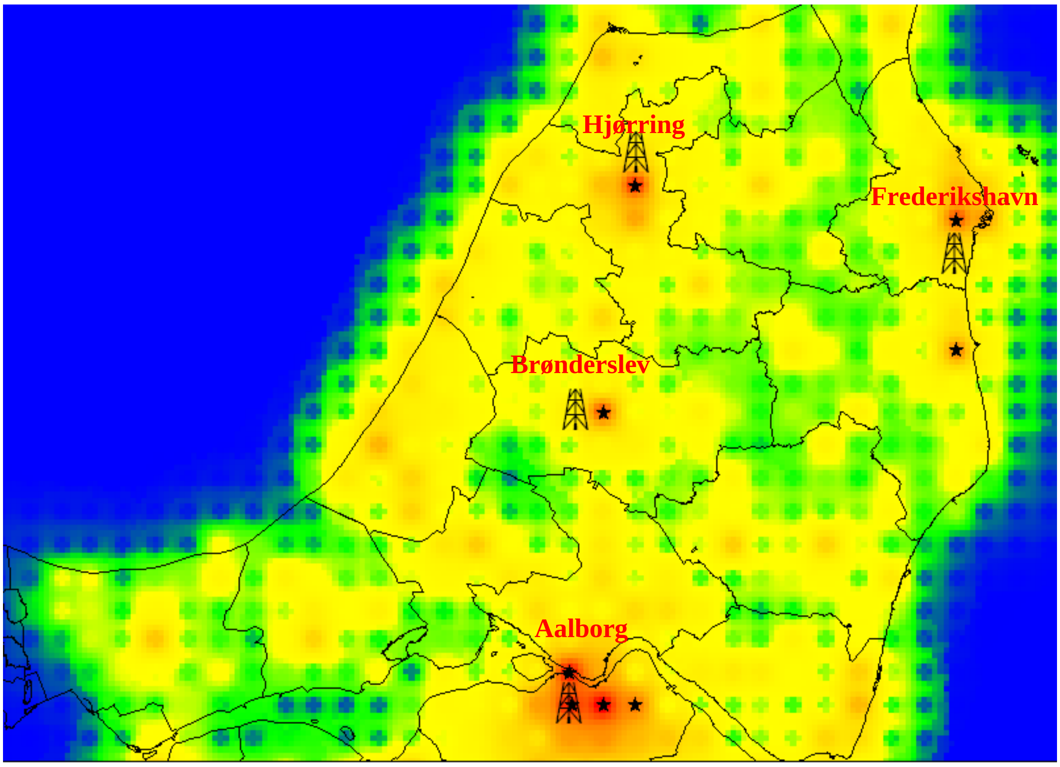

Figure 5.10: "main" Base Stations located in Aalborg, Brønderslev, Hjørring and Frederikshavn

As it can be appreciated in the picture, 4 main base stations have been placed in Nordjylland for the most populated areas obtained by the study of the NT density in the whole region.

After the first criterion (placement in most populated areas) is fulfilled, another criterion is taken into account for an optimized location of the antenna: based on the COs of TDC loaded in MapInfo (Figure 5.3), the BSs are placed relatively close to these COs because here is where the backbone nodes from S. Labeaga's network are placed [0]. The BSs are connected to these nodes by fibre optics in a PTP configuration and the distances between them are small. By using this method a lot of money is saved because the creation of a new infrastructure for the nodes would raise dramatically the cost. In the future a second link between the BSs and these nodes could be implemented for offering redundancy.

Following these lines a deeper description of the networks implemented in these cities is reported for a better understanding of the network configuration:

- **Aalborg:** the "main" base station will be, of course, for the capital of Nordjylland and most populated city in the region. In order to offer reliability to the network (to solve possible cuts in the service or prevent possible traffic overloads) and increasing its capacity, a mesh structure (section 2.4.2.3) has been implemented in the city. This

Aalborg network will be composed of the main base station and 3 additional Subscriber Stations (SSs) distributed as shown in Figure 5.11.

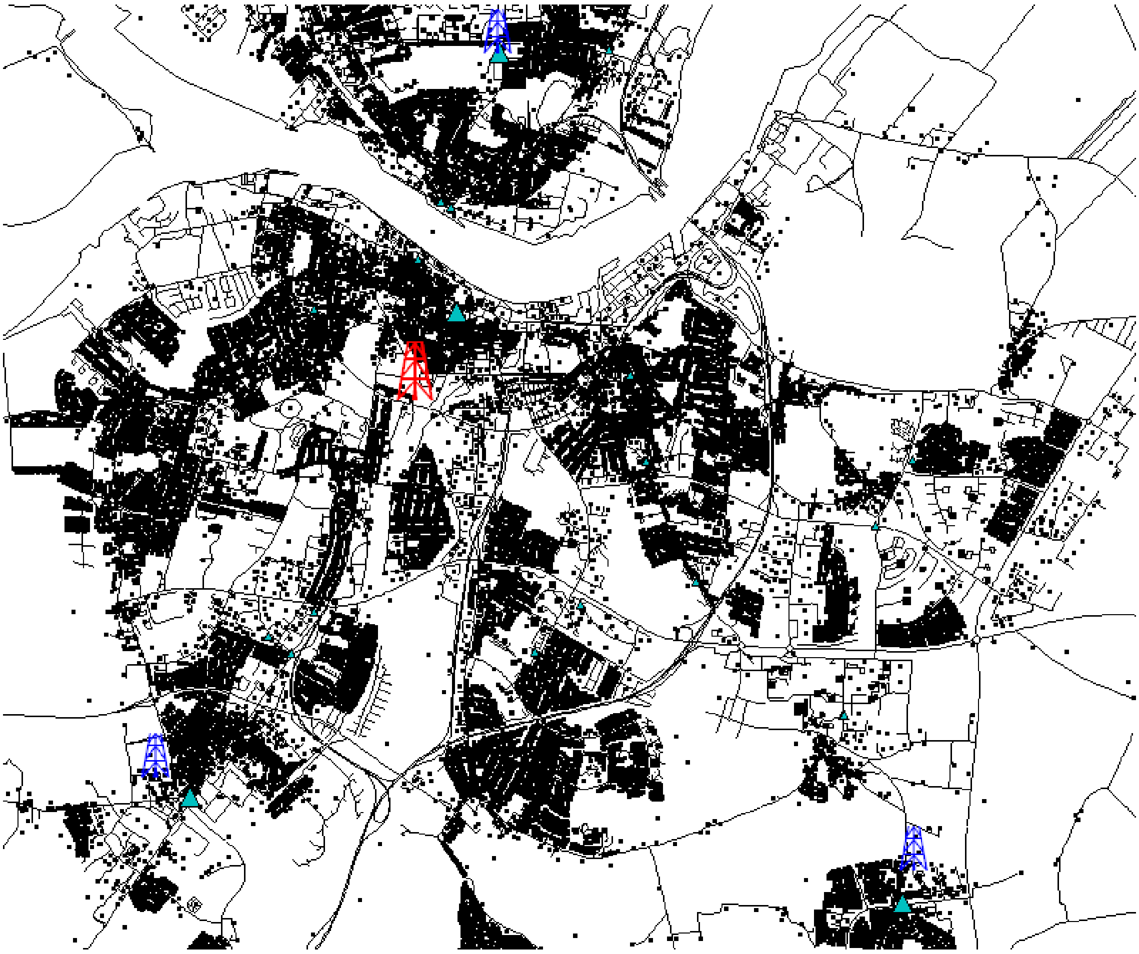

Figure 5.11: location of Base Stations in Aalborg. The red antenna is the main BS and the blue ones are the SSs; the big triangles show the location of the closest CO to each BS

It can be appreciated in the picture how the stations have been placed close to TDC's Central Offices in order to make further connections to these offices easier. As mentioned before, this link between the base stations and the TDC offices is implemented in fibre optics and it is the connection between the access network and the backbone network.

- **Frederikshavn:** there will be another BS in this city which will cover both Frederikshavn and Sæby (2 of the 5 main nodes) due to their proximity (only 12 km between them). The reason for setting the BS in Frederikshavn and not in Sæby is just because Frederikshavn has a higher number of NTs. As Frederikshavn is also a highly populated city, another mesh network will be placed in this area, which will count on two additional SSs for offering additional capacity and reliability for both Frederikshavn and Sæby.

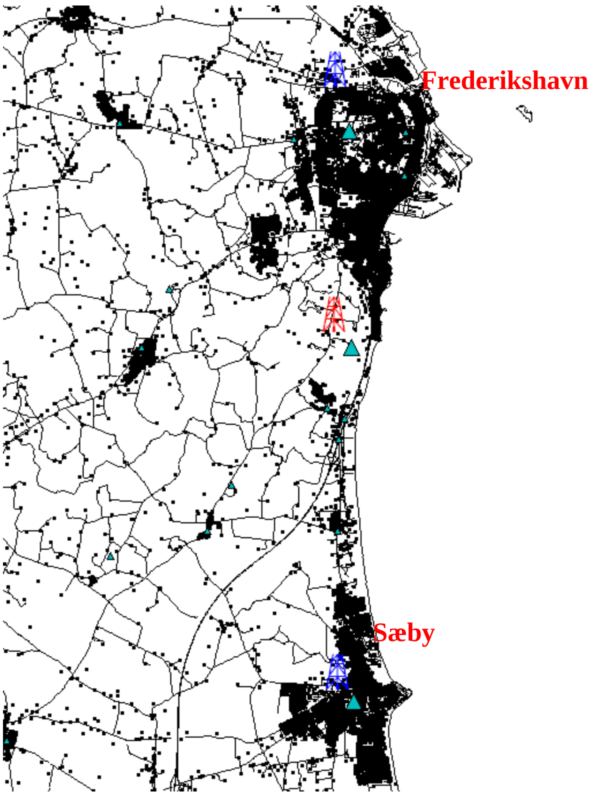

Figure 5.12: location of Base Stations in Frederikshavn and Sæby

- **Hjørring:** this town located in the northwest side of Nordjylland will also be an "important" BS because of having more than 3000 NTs and because it can easily cover the northwest seaside of the region (only 15 km to Hirtshals, the last city in the seaside). An additional SS will be deployed in this also highly-populated town. In Figure 5.13 the distribution of the BSs in Hjørring is shown.

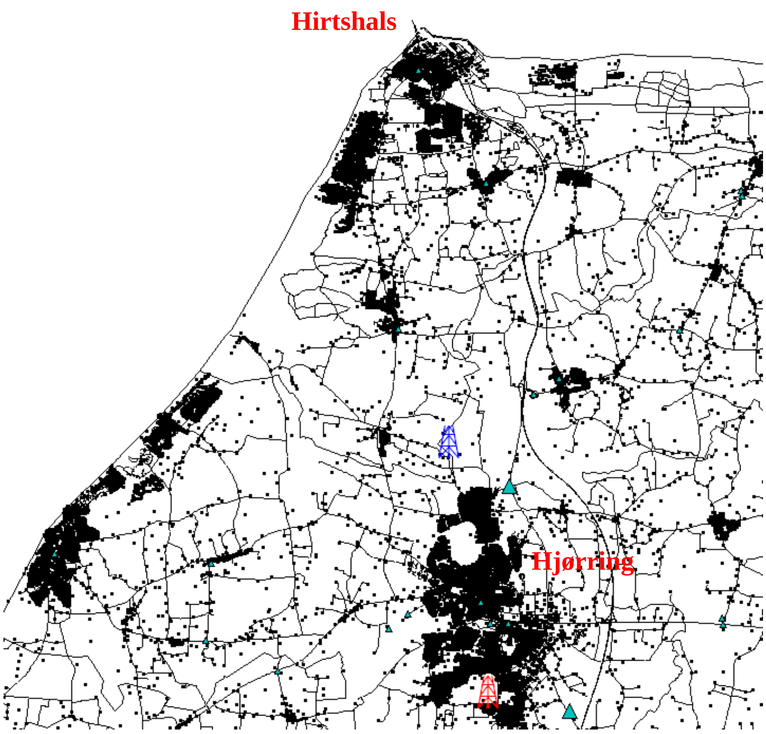

Figure 5.13: location of Base Stations in Hjørring

- **Brønderslev:** this village located between Aalborg and Hjørring will have the last "important" BS. It will be placed at the west of the town so it can also cover the seaside.

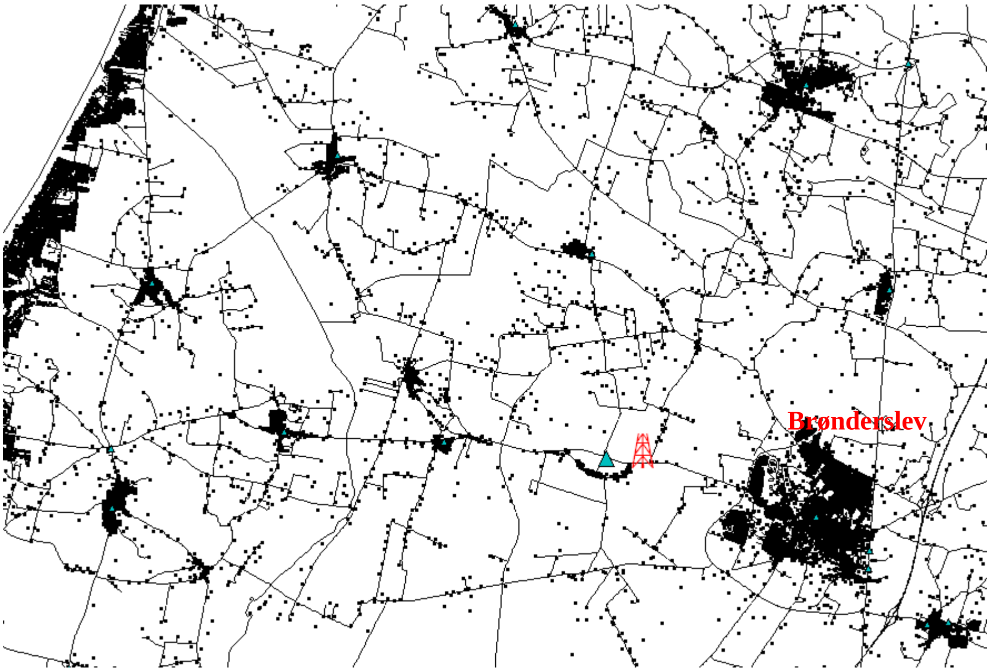

Figure 5.14: location of Base Station in Brønderslev

5.3.4.2 Rest of Base Stations

Now the rest of BSs will be placed around these 4 "main" stations (using the range-limited solution) in order to cover the whole region. The criterion followed for the location of these remaining base stations has been placing them in cities outside the range of the coverage circles for the main stations in a way the can cover the whole region. In other words: after knowing the location of the main base stations, their respective coverage circles have been drawn and, out of them, the most suitable cities (the ones noted down before when counting the NTs) for covering the remaining area have been chosen as an adaptation of the first criterion, so each base station is located in a city. The final result is that with 10 BSs (plus the 6 SSs) it is possible to cover the whole Nordjylland. Following these lines, the final location for the 10 BSs –and the 6 SSs– can be seen (from north to south and west to east):

BS1: between Skagen and Ålbæk, Figure 5.15.
BS2: south of Hjørring (SS1 at the north of the town), Figure 5.13.
BS3: south of Frederikshavn (SS2 at the north of the town and SS3 in Sæby), Figure 5.12.
BS4: west of Brønderslev, Figure 5.14.
BS5: Jammerbugt, Figure 5.16.
BS6: south of Aså, next to Dronninglund, Figure 5.17.
BS7: Aalborg (SS4 in the north, SS5 in the southwest, SS6 in the southeast), Figure 5.11.
BS8: southwest, between Vesthimmerland, Farsø and Aars, Figure 5.18.
BS9: south, north of Hobro, Figure 5.18.
BS10: southeast, in Veddum, northeast of Hadsund, Figure 5.18.

These will be the names used for referring to the BSs in following chapters. The general distribution of all these BSs all over the region can be seen in Figure 5.19.

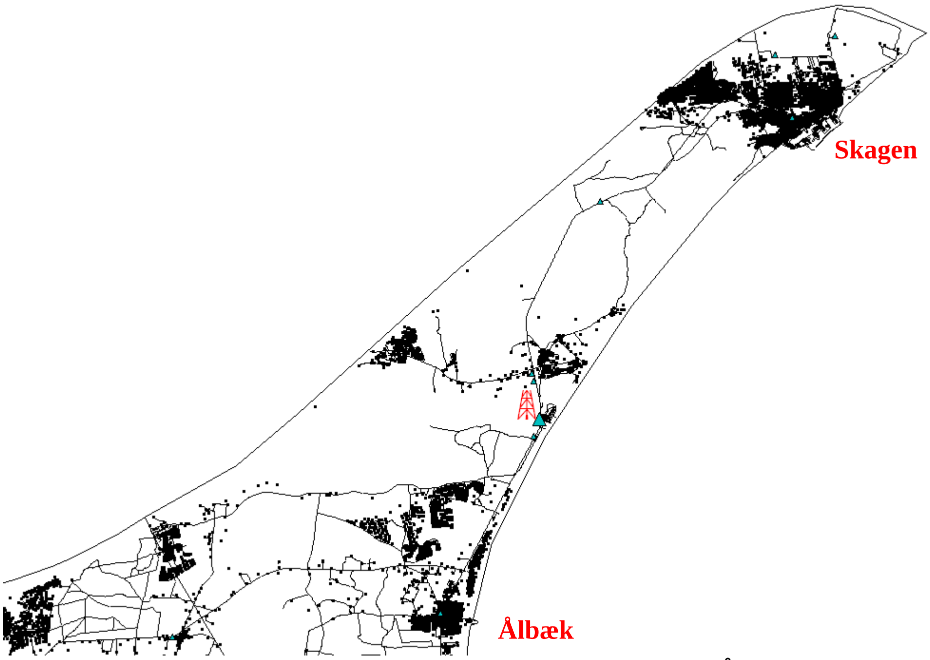

Figure 5.15: Location of BS1 (between Skagen and Ålbæk)

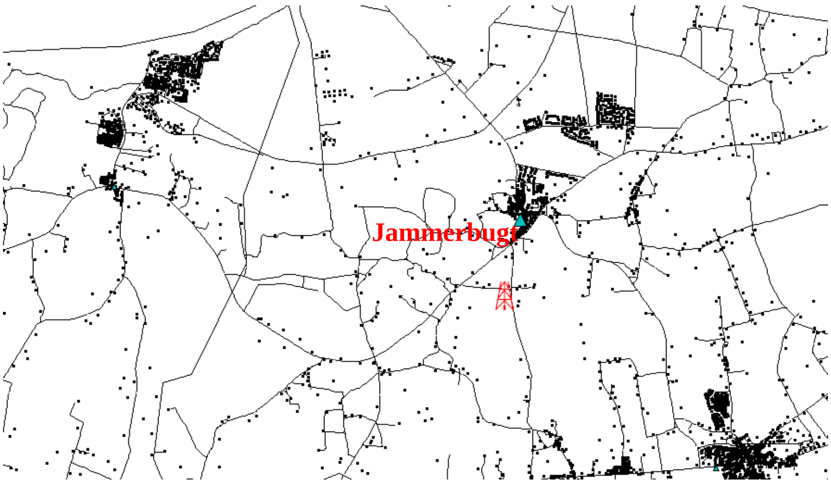

Figure 5.16: Location of BS5 (Jammerbugt)

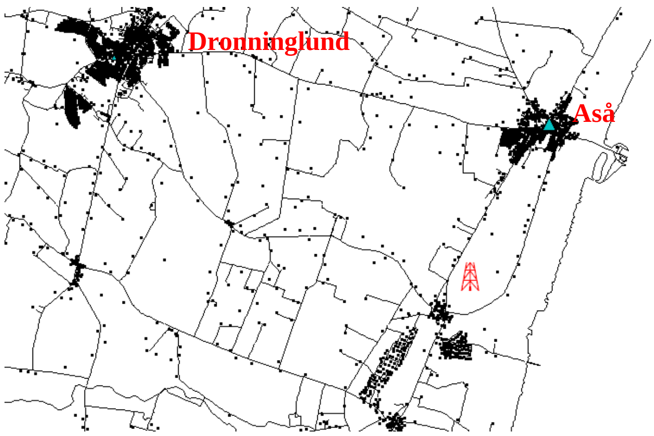

Figure 5.17: Location of BS6 (south of Aså)

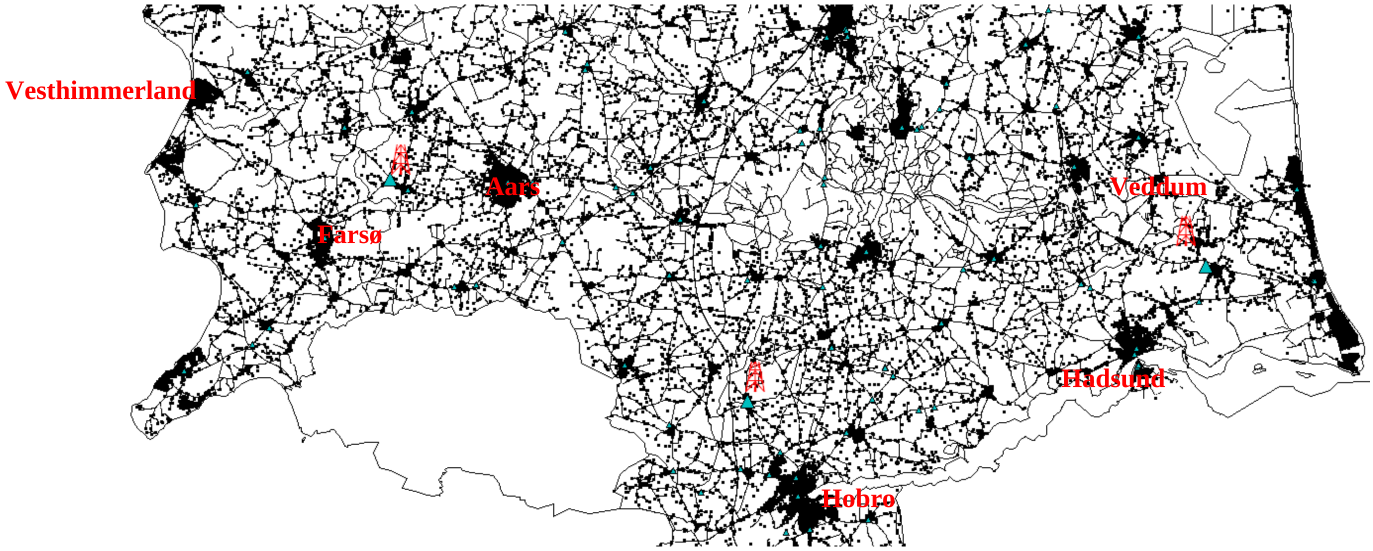

Figure 5.18: Location of BS8, BS9 and BS10

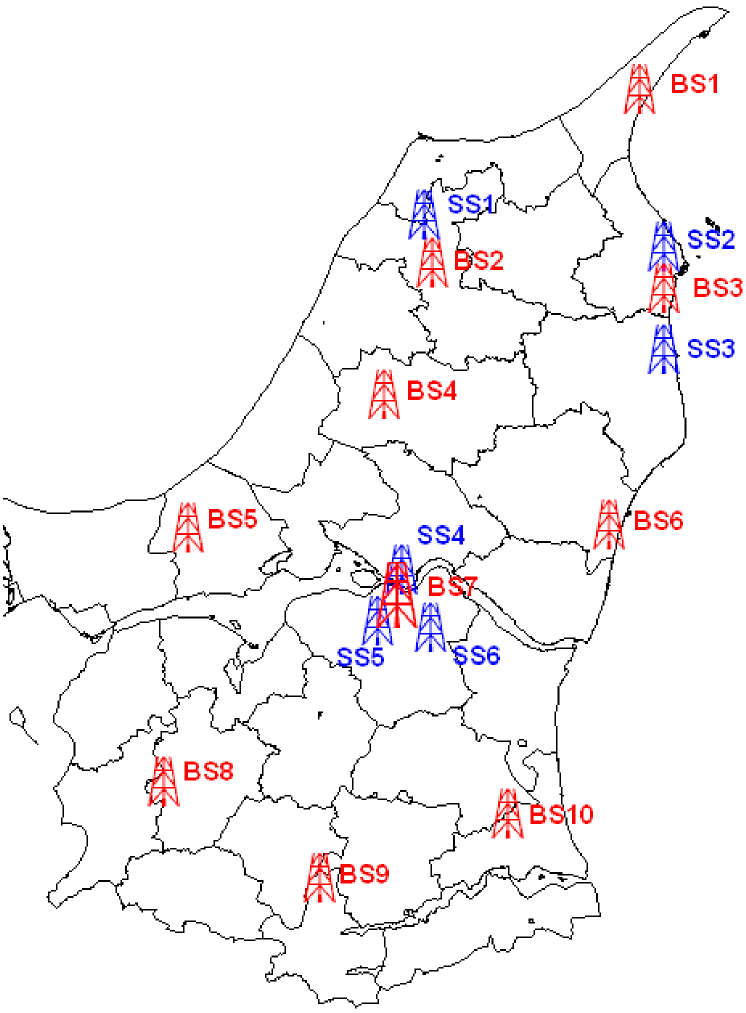

Figure 5.19: Placement of Base Stations all over Nordjylland and their names

By placing these Base Stations as explained, the WiMAX coverage in the whole region of Nordjylland can be guaranteed at least in the demanded 95% minimum. In Figure 5.20 the coverage of each Station can be seen.

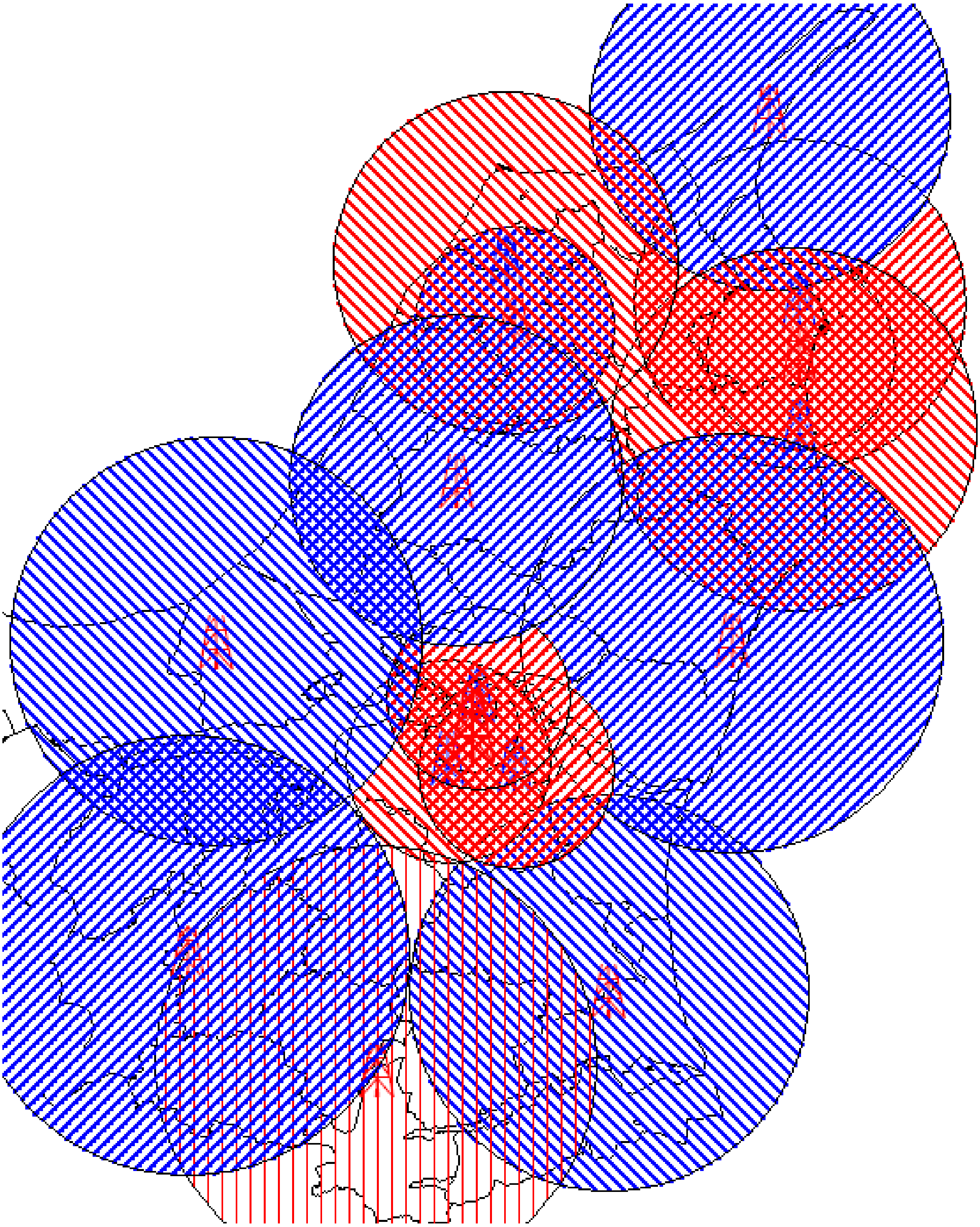

Figure 5.20: Location of all Base Stations for Nordjylland and their respective coverage

It must be taken into account that all these circles show the total coverage of the antennae, but the service offered to the customers is not the same in the whole circle.

As mentioned before, the radii for these circles of coverage can be 5 km (urban areas: BS7), 10 km (suburban areas: BS2, BS3) or 15-20 km (rural areas: the rest of BSs). About the SSs for the "main nodes", all of them have "lost a level" according to their BS because of being located in the outskirts of the cities, so they will not handle as much traffic as the main ones and their "reliable" coverage can be higher. In other words: being Aalborg's BS (BS7) urban, its SSs (SS4, SS5, SS6) have been considered as stations for providing coverage to suburban areas (10 km coverage); the same has been applied to Frederikshavn (BS3) and Hjørring's (BS2) BSs: they are suburban but their SSs have been considered as rural.

Talking about the rural areas, two different categories (referring to their coverage circles) have been considered: the first group has 15 km radius and the second one 20. The stations included in the first category are the SSs for the suburban nodes, BS1 (enough for covering the northeast region) and BS4 (Brønderslev, one of the "main nodes"). The rest of rural nodes have been considered as 20 km-radius ones because the population in these places is much lower.

To sum up and for leaving it clear, here is a list of the different sizes used for the coverage circles and their respective stations:

- 5 km coverage: BS7.
- 10 km coverage: BS2, BS3, SS4, SS5 and SS6.
- 15 km coverage: BS1, BS4, SS1, SS2 and SS3.
- 20 km coverage: BS5, BS6, BS8, BS9 and BS10.

5.3.5 Frequency Planning

As said in chapter 2, the cell and frequency planning are especially critical aspects in the initial design of the system, so it becomes necessary that it is done in a proper way. For this task some important concepts previously described (such as sectorization, adaptative modulation and frequency reuse) will be used.

The frequency band the planning is based on is the 3.5 GHz (3.4-3.6) licensed band, and it was said that FDD duplexing with dual 3.5MHz bandwidth channel was used. A cell frequency re-use factor of 1 is assumed for determining the amount of spectrum required. By taking a look at Table 5.4, the number of channels per base station needed to meet the data density requirements in the frequency band can be obtained (Table 5.5):

Terrain	Channels/BS	Spectrum required	Coverage	Condition
Urban	8	56 MHz	60 km^2	NLOS
Suburban	4	28 MHz	120 km^2	70% NLOS
Rural	3	21 MHz	200 km^2	50% NLOS

Table 5.5: number of channels per BS and spectrum required

In Figure 5.21 how the sectorization technique for each type of terrain would look like is shown. As it was mentioned before, adjacent sectors can not have the same frequency but adjacent channels from different cells do.

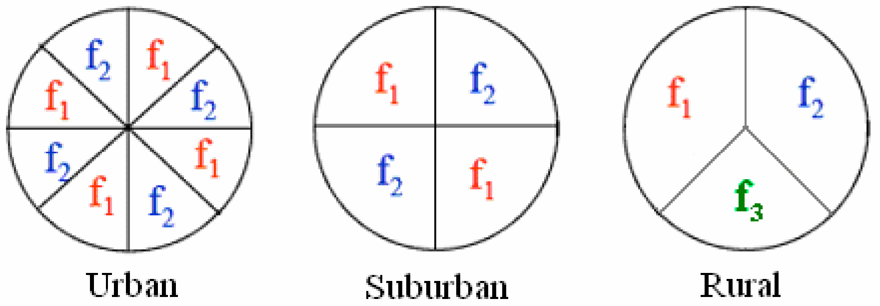

Figure 5.21: number of channels depending on the terrain

As it could be expected, there is value in having more spectrum available since, in general, due to the relatively high base station fixed costs it is more economical to deploy fewer high capacity base stations as opposed to a larger number of low capacity base stations. If the added spectrum has to be acquired through an auction process however, some of this infrastructure cost benefit will be offset by higher spectrum license fees and should be taken into account for a more accurate cost comparison.

Focusing on the network being planned, the cell types of each base station are yet to be determined. For drawing the coverage circles Aalborg's BS (BS7) was the only one considered as urban, while Frederikshavn's (BS3) and Hjørring's (BS2) were suburban and the remaining BSs rural. If these criteria were used again for the frequency planning, 8-sector cells would be assigned to BS7, 4-sector cells to BS2 and BS3 and 3-sector cells to the rest of BSs. However, as the option of inserting additional BSs (and so creating mesh networks) for saving spectrum was used for increasing the capacity of BSs in most populated areas (instead of the "increasing number of channels" solution, section 5.2.2.2), a re-designation of BS types should be made.

Therefore, the inclusion of additional BSs for the mesh networks allows using a lower number of sectors for the cells. This way, 3-sector and 4-sector cells will be used for the base stations and they will provide them enough capacity for covering all the NTs. Aalborg (BS7), Frederikshavn (BS3) and Hjørring (BS2) base stations will be divided in 4 sectors as shown in the suburban configuration of Figure 5.21 while the rest of stations will be distributed in 3 channels according to the rural configuration of the same Figure.

In Figure 5.22 a graphical description of how each cell is configured is shown. It must be complemented with Table 5.6 because recognizing each part of the diagram can become a bit hard, especially in the zones where the mesh networks are deployed due to the existence of several BSs in those areas. The steps followed for this frequency planning procedure are the following:

1. The 4-sector cells (which represent the mesh subnetworks) are drawn in first place and assigned 2 channels each (suburban configuration in Figure 5.21).

2. After that, the 3-sector cells start to be drawn around these already placed cells, taken into account the following criteria for the overlapping coverages between base stations:

    - Adjacent sectors in a cell use different channels in order to avoid or reduce the CCI. The objective is to assign channels reducing to the maximum the interference level, keeping in mind that the number of channels is limited.
    - Adjacent sectors between cells can either be assigned a different channel or use the same one by changing the polarization of the antenna. This technique was introduced in section 2.3.1.

3. By following the previous criteria, the rest of cells are drawn manually, orienting the antennae as desired in order to obtain better coverage for the sectors (including a bigger portion of the adjacent sectors using the same channel, for example).

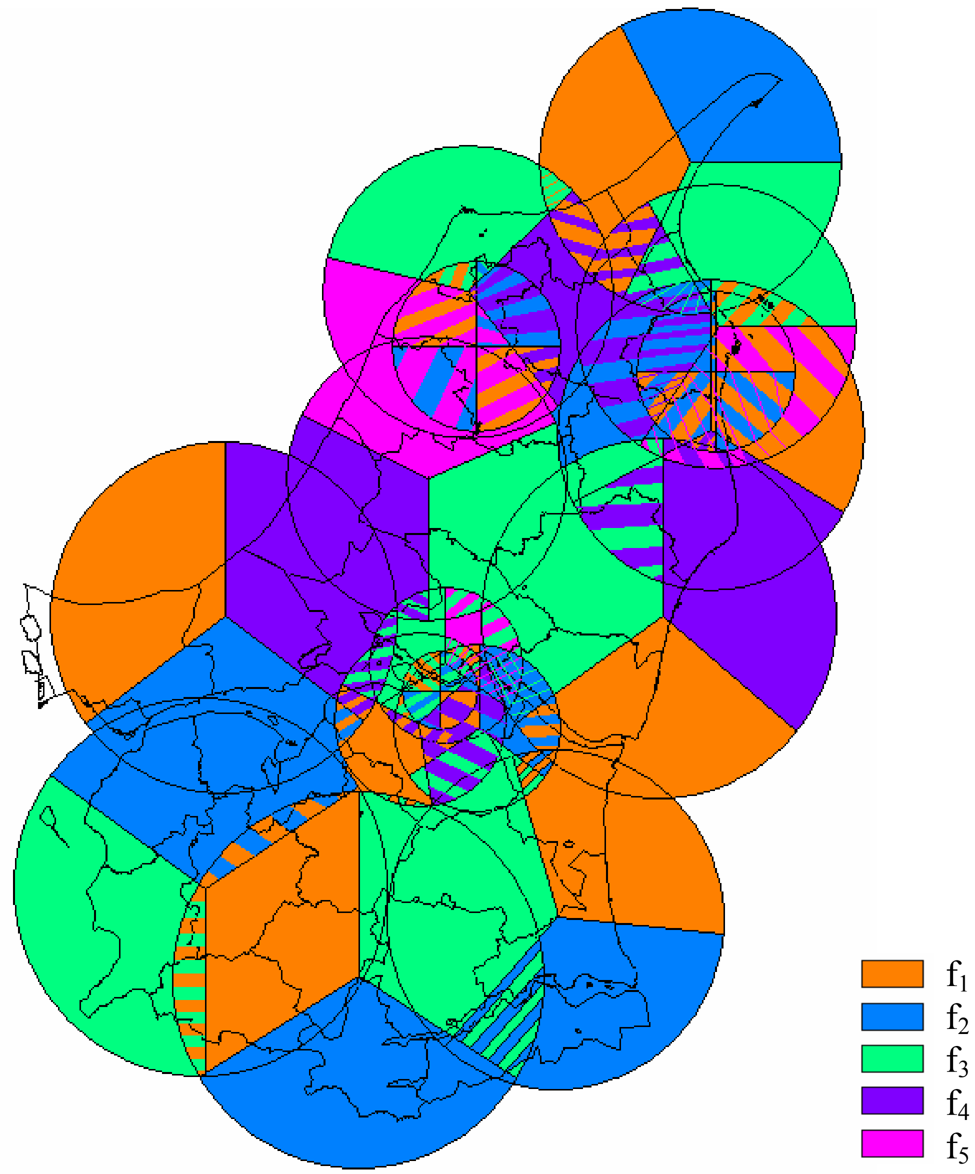

Figure 5.22: frequency planning

Station	# of channels	Polarization	Channel 1	Channel 2	Channel 3	Channel 4
BS1	3	V	f_2	f_1	f_3	-
BS2	4	H	f_1	f_2	f_2	f_1
BS3	4	V	f_2	f_1	f_1	f_2
BS4	3	H	f_5	f_4	f_3	-
BS5	3	V	f_1	f_4	f_2	-
BS6	3	V	f_3	f_4	f_1	-
BS7	4	H	f_1	f_2	f_2	f_1
BS8	3	H	f_2	f_3	f_1	-
BS9	3	V	f_1	f_3	f_2	-
BS10	3	H	f_3	f_1	f_2	-
SS1	3	V	f_3	f_4	f_5	-
SS2	3	H	f_4	f_3	f_5	-
SS3	3	H	f_2	f_1	f_4	-
SS4	3	V	f_3	f_5	f_4	-
SS5	3	H	f_1	f_3	f_4	-
SS6	3	V	f_1	f_2	f_3	-

Table 5.6: configuration of each base station according to the frequency planning

As it can be appreciated in the table, there are no interfering channels with the same polarization between adjacent sectors, which means that there will not be losses due to the CCI. In addition, the frequency planning has been possible by using 5 different channels (f_1 to f_5), which means that 35 MHz (5 * 7 MHz) are needed from the spectrum.

5.4 Summary

In this chapter everything related to the placement of the BSs has been explained.

First, the steps and criteria followed to identify the main nodes were explained, obtaining 5 locations for them.

After that, and based on WiMAX Forum documentation, the radii which would be used for the coverage circles were introduced: 5 km - urban areas, 10 km - suburban areas, 15-20 km - rural areas.

The next step was to locate the main Base Stations close to the main nodes and, afterwards, the placement of the rest of the BSs could be achieved based on the coverage criterion from WiMAX Forum. For highly populated areas the deployment of Subscriber Stations became necessary in order to prevent traffic overloads in these cities (increased capacity).

Finally, it turned out that with 16 stations (10 BSs + 6 SSs) it was possible to cover the whole region, so the final location of all of them and their respective coverage circles were drawn.

After the base stations were placed the frequency planning was tackled, using 3 and 4-sectored cells and changing the polarization of the antennae to avoid co-channel interferences. As a result, 5 different channels (35 MHz) were obtained for the planning.

6. TRAFFIC ESTIMATION

In this chapter the overall traffic each base station will have to handle is estimated. This is a very important stage for planning the network because it allows identifying future critical points (bottlenecks) and it can show how balanced the network is. The assumptions taken into account for evaluating the traffic and the methods followed for obtaining the final results are included in this chapter.

6.1 Initial assumptions

In order to calculate the traffic in each BS some assumptions and requirements have been taken into account:

1. From the total traffic in a base station, 5% of the connections of a NT will be directed to another NT covered by the same BS (local or internal traffic), another 5% will be assumed that has a different BS as destination (regional traffic) and the rest (90%) will be oriented to NTs placed in external networks/Internet [30]. This way, **5% internal traffic** (remaining in the same BS) and **95% external traffic** (going out of the BS) will be taken into account for traffic calculations[7].

2. **20% penetration** will be assumed. Consulted statistics [24] show that, excluding TDC, the rest of ISPs in Denmark do not have more than 10% penetration in the market. Therefore, an optimistic maximum penetration margin of 20% has been chosen for the designed network (Appendix C: Traffic statistics).

3. Another important factor to take into account would be the number of users connected at the same time to the network. As an orientation, 10% of the total users were connected simultaneously in the USA in 1999. In a short-term view, this percentage has been almost doubled and it will be gradually increasing in the next years. Therefore, a maximum of **40% of the users simultaneously connected** to the network will be estimated in long-term [31].

6.2 Methodology

In order to figure out the traffic in the whole Nordjylland an analysis of the distribution of NTs in the region has been made, using MapInfo for calculating the number of NTs each Base Station gives access to. These estimations may only be valid in a limited period of time due to traffic growth and distribution changes.

[7] The reason for including the regional traffic inside the external traffic is because the study of this regional traffic can become a tough task due to the huge amount of possibilities: there are 16 base stations in the network and each one of them can send/receive data to/from the others, which makes 16*15 = 240 different communication paths. Besides, only 5% of the total traffic is considered as regional, so it becomes non-significant compared to the rest of traffic handled by the network. Therefore, regional traffic has not been taking into account for deciding the approach and it has been considered as a part of the external traffic.

The bandwidth demand required by each subscriber is a very important matter for studying the traffic in the network and an estimation must be made for helping these traffic calculations.

Demanded bandwidth by residential subscribers increases every year. Among the most common services, Voice over IP (VoIP) is the one consuming a lower bandwidth (~ 0.1 Mbps), "fluent" surfing on the Internet requires from 5 to 10 Mbps, Peer-to-Peer (P2P) applications require around 20 Mbps and four HDTV channels using H.264 encoder need around 30 Mbps [32] [33]. Therefore, it becomes essential to provide the customers a bandwidth between 25 and 100 Mbps (or even more) for usage in new generation services [33]. This way, an average bandwidth of 25 Mbps per user will be estimated for WiMAX traffic calculations according to the consulted sources, which agrees with Scenario A explained in [0], section 3.2.

Note: as it was mentioned in assumption 4 in section 1.4, small businesses and residential users will be provided an identical bandwidth.

The following steps have been followed for estimating the amount of traffic per base station:

1. The number of NTs covered by each base station is extracted from the NTs data layer in MapInfo and then multiplied by the bandwidth (25 Mbps) guaranteed to the customers.

2. Some additional reduction coefficients are applied to these results by taking into account assumptions 2 and 3 from 6.1: 20 % penetration and 40% of users connected simultaneously. As a result, the total traffic per BS is multiplied by a 0.08 (0.2 * 0.4) reduction coefficient.

By applying these two steps the estimated traffic for each base station will be obtained. As said before (assumption 1 in section 6.1), 5% of this traffic will remain in the BS (internal traffic) and the remaining 95% will be directed to the backbone by the fibre connection between the BS and the closer node from the backbone network (5.3.4.1, [0]).

6.3 Results

6.3.1 Additional assumptions for defining the traffic for each Base Station

In this section, the traffic held by each WiMAX base station will be estimated. In the previous chapter the placement of BSs and their respective coverage circles were determined. These will be the data used for analysing the traffic (Figure 6.1), taking also into account the assumptions made in section 6.1 and the methods explained in section 6.2. Furthermore, some additional assumptions will be described in order to define the traffic handled by each BS.

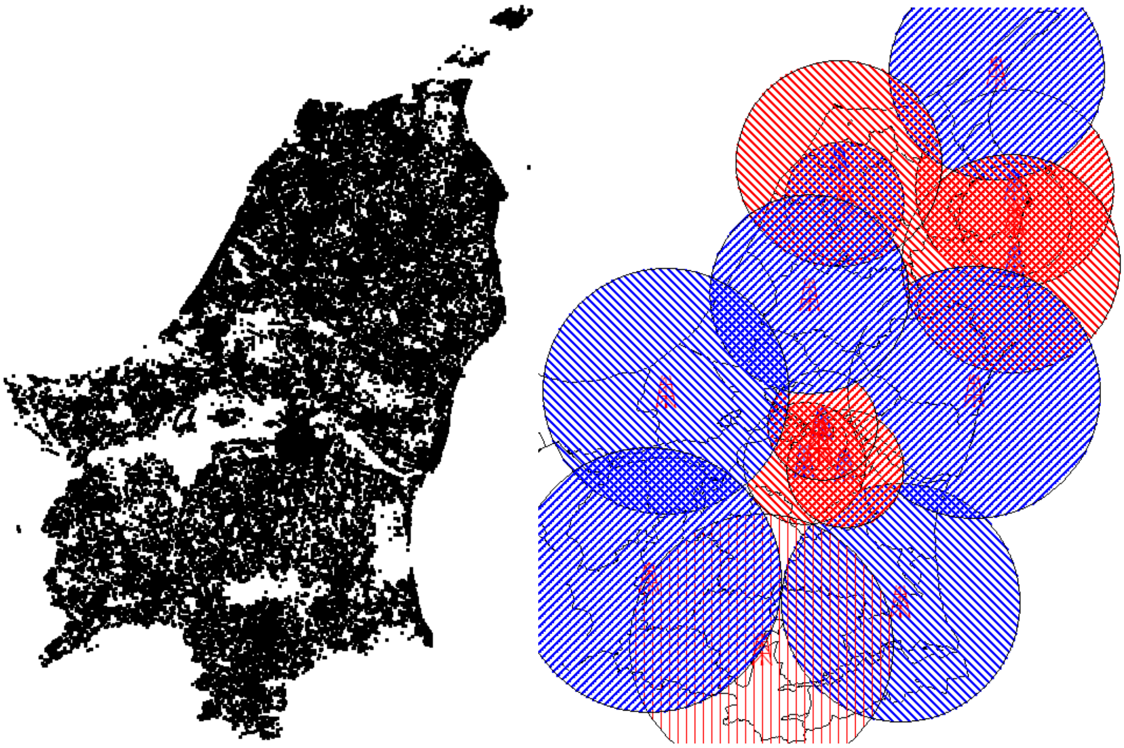

Figure 6.1: data used for traffic estimation: NTs in Nordjylland and coverage of BSs

After loading the NT database in MapInfo, all the NTs from the region are displayed on the map; they are 241434 NTs in total. Now the amount of NTs inside the coverage circles for each BS is calculated by making queries in MapInfo. In Table 6.1 a list of all the BSs and their respective NTs can be seen. However, this is not accurate because of the intersections between the coverage circles, which make some NTs be counted two, three or even more times. It can be seen that the total number of NTs using these simple queries is 492531, a bit more than two times the quantity of NTs which actually exist in Nordjylland.

Station	Number of NTs
BS1	15943
BS2	19268
BS3	19778
BS4	37648
BS5	34593
BS6	29193
BS7	31410
BS8	26752
BS9	29616
BS10	20054
SS1	34407
SS2	27187
SS3	28801
SS4	44980
SS5	46265
SS6	46636
Total	**492531**

Table 1: preliminary counting of NTs in Nordjylland

As the results obtained in Table 6.1 are not accurate, more complex queries will have to be made in order to reduce this amount to the correct number, determining which station will cover each NT in these intersection areas by divisions of the coverage area or even by establishing priorities among the base stations. This task has been done station by station.

About this task, some important facts must be taken into account in order to determine which station covers which NT:

1. As it was mentioned in section 5.3.4, the further a NT is to the BS, the worst signal it receives. Here is where the adaptative modulation technique becomes useful, strengthening the connection so these distant points can be provided quality access. From the structure of a coverage circle seen in Figure 5.9, it will be considered that all NTs included in the first two levels (10 km radius) from a BS must be provided access by that BS, excluding the mesh "subnetworks" deployed in the most populated areas as the distance between stations is lower than 10 km.

2. For NTs outside these 10 km-radius circles different criteria will be taken into account too:

    a. If the two closest BSs to the NT have similar amounts of traffic, then the coverage area will be splitted between them.
    b. If the two closest BSs to the NT have a noticeable difference regarding handled traffic, the BS with lower traffic will be given priority.
    c. If the NT is equally far from the two "closest" BSs (in the fourth or fifth level of the coverage circle), then any of the options (priority or splitting) can be used as there will not be an appreciable difference in the final result.

3. For mesh subnetworks mentioned in point 1, as they will be the ones handling higher traffic and as their stations are very close to each other, "equal divisions" (this term is an orientation) will be made in the coverage circles for the stations.

6.3.2 Defining the traffic per Base Station

Below these lines the MapInfo querying task is described for each base station and all the assumptions seen in this chapter are applied in the process:

- **BS1.** Its coverage circle intersects with the ones from SS1, SS2, SS3 and BS3. By taking a look at the table and the number of NTs for each of these stations, it is pretty clear that BS1 is the one with a lower density of NTs, so it will be given priority and all the NTs included in its circle will be supported by this station (assumption 2b). In Figure 6.2 a graphical example of the final distribution of all the coverage circles for traffic estimation can be found which can help to understand this description.

- **BS2.** The coverage circle for BS2 is included into the one for SS1 and it also intersects with the circle for BS4. According to assumption 3, the traffic among BS2 and SS1 will be “splitted”. This can also be seen in Figure 6.2.

- **BS3.** Similar to BS2. The only difference is that the area intersecting with the BS1 circle must be subtracted because it was already said that BS1 has priority over its surrounding circles. The rest of the circle will be “shared” by BS2, SS2 and SS3.

- **SS2.** After subtracting from SS2 circle the intersection with BS1 and defining the division with BS3, there are other two intersections to care about: for the intersection with SS3 the 2a criteria will be applied and for the one with SS1 priority will be given to SS2 as it can be considered as the case 2c and it has a lower traffic than SS1.

- **SS1.** This station has intersections with all the stations mentioned above (with priority over SS1) plus SS3 and BS4. For both cases the splitting solution will be used (in the case of the SS1+SS3 intersection the solution adopted does not really matter as it is a really small area).

- **SS3.** Its circle is cut by the circles of all the stations mentioned above except BS2’s (the solutions adopted are already known then) and by the BS4 (worthless) and BS6 circles. For this SS3+BS6 intersection the splitting procedure will be applied again.

- **BS7, SS4, SS5, SS6.** All these stations set the mesh network for Aalborg and surroundings and the same solution used for the other mesh networks (assumption 3) is used in this case: splitting. All these stations in Aalborg surroundings have been given priority over any other intersecting station.

- **BS6.** Its circle crosses with the ones from all the SSs in Aalborg (with priority over BS6, as mentioned), the ones in Frederikshavn and the base stations BS4 and BS10. The procedure for the SSs has already been explained, while for these two last BSs the splitting solution will be used again.

- **BS4.** Similar to BS6, with many intersections and almost all of them already listed. The “sharing” solution is also used between BS4 and BS5.

- **BS5.** Almost the same case than BS4, with subtractions from higher priority stations and shared coverage in intersection zones; the only difference is that it also has shared coverage with BS8.

- **BS8.** The same situation as BS5 (shared coverage with BS5 and BS9) but without any subtractions because of the SSs in Aalborg.

- **BS9 and BS10.** The same solutions applied for BS4 and BS5 can also be used for these southern stations.

All these assumptions have been translated into more complex MapInfo queries in order to determine the estimated traffic for each station. Below these lines a graphical example of the final distribution of all the coverage circles for traffic estimation can be seen together with the table (Table 6.2) of the final number of NTs per station. It can be easily appreciated in this table that the total number of NTs is correct because it fits the number obtained when loading the NT data in MapInfo.

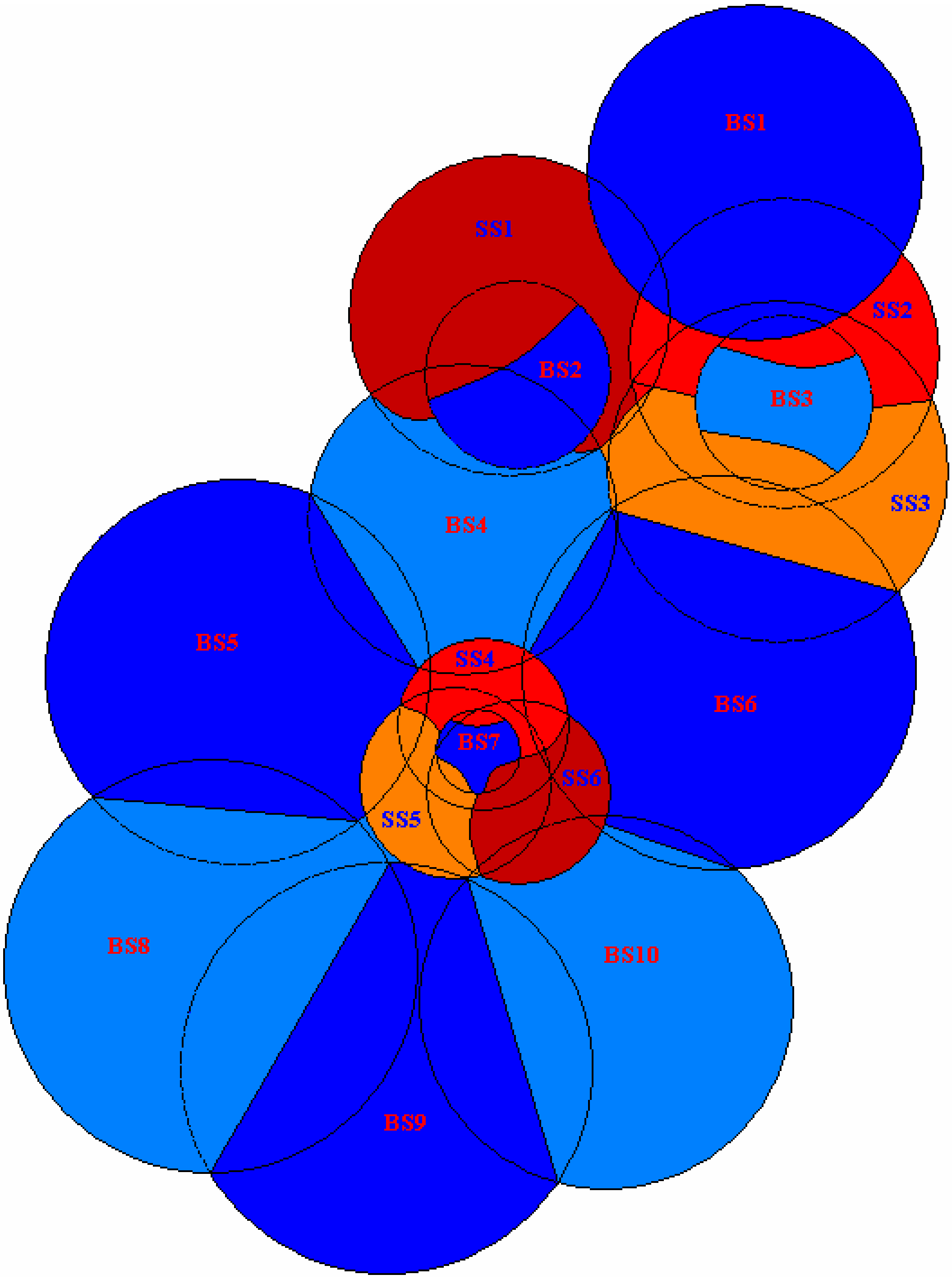

Figure 6.2: distribution of estimated traffic in Nordjylland

Station	Number of NTs	Percentage
BS1	15943	6.60%
BS2	16057	6.65%
BS3	11720	4.85%
BS4	21052	8.72%
BS5	22529	9.33%
BS6	14781	6.12%
BS7	15705	6.50%
BS8	18149	7.52%
BS9	19727	8.17%
BS10	13383	5.54%
SS1	14544	6.02%
SS2	7524	3.12%
SS3	10404	4.31%
SS4	12223	5.06%
SS5	13317	5.52%
SS6	14376	5.95%
Total	**241434**	**100.00%**

Table 6.2: traffic per Base Station in Nordjylland

Below these lines, in Table 6.3, the calculation of the maximum traffic generated per node, according to the methods explained in 6.2, can be found:

Station	Number of NTs	Gross Traffic [Mbps]	Clear Traffic [Mbps]		
			Total	Internal Traffic	External Traffic
BS1	15943	398575	31886	1594,3	30291,7
BS2	16057	401425	32114	1605,7	30508,3
BS3	11720	293000	23440	1172	22268
BS4	21052	526300	42104	2105,2	39998,8
BS5	22529	563225	45058	2252,9	42805,1
BS6	14781	369525	29562	1478,1	28083,9
BS7	15705	392625	31410	1570,5	29839,5
BS8	18149	453725	36298	1814,9	34483,1
BS9	19727	493175	39454	1972,7	37481,3
BS10	13383	334575	26766	1338,3	25427,7
SS1	14544	363600	29088	1454,4	27633,6
SS2	7524	188100	15048	752,4	14295,6
SS3	10404	260100	20808	1040,4	19767,6
SS4	12223	305575	24446	1222,3	23223,7
SS5	13317	332925	26634	1331,7	25302,3
SS6	14376	359400	28752	1437,6	27314,4
Total	241434	6035850	482868	24143,4	458724,6

Table 6.3: traffic per Base Station

Furthermore, each base station has been sectorized in the frequency planning procedure, so it is also possible to obtain the expected traffic per sector for each one of the base stations; this way the traffic supported by each channel can be seen. These results are shown in Table 6.4.

Station	Number of channels	Number of NTs/channel	Gross Traffic [Mbps/channel]	Clear Traffic [Mbps]
BS1	3	5314	132858	10629
BS2	4	4014	100356	8029
BS3	4	2930	73250	5860
BS4	3	7017	175433	14035
BS5	3	7510	187742	15019
BS6	3	4927	123175	9854
BS7	4	3926	98156	7853
BS8	3	6050	151242	12099
BS9	3	6576	164392	13151
BS10	3	4461	111525	8922
SS1	3	4848	121200	9696
SS2	3	2508	62700	5016
SS3	3	3468	86700	6936
SS4	3	4074	101858	8149
SS5	3	4439	110975	8878
SS6	3	4792	119800	9584

Table 6.4: traffic per sector for each Base Station

7. BUDGET ESTIMATION

The proposed IT infrastructure includes 16 stations (10 BSs + 6 SSs) and the distribution network for connecting the stations to the TDC offices. In this chapter, estimates of the economy related to this network will be provided. Therefore, the proposed solution can be compared with further possible solutions in terms of cost.

7.1 Assumptions

Normally, the network investments can be divided into two parts: construction and operation costs.

The construction costs refer to the initial expenses of implementing such an IT infrastructure and will be the only costs estimated in this report. Basically, they include the price of the base stations and the fibres for interconnecting BSs and TDC COs.

The operational costs have both positive and negative expenses; the positive operational costs will be the income obtained from the subscribers using the network, while the negative costs consist of expenses fro the management, fault repair, administrative staff, etc.

Some additional costs which must also be taken into account are those regarding the spectrum license purchase.

The price of the elements needed to build the proposed infrastructure will be introduced in this chapter.

In Table 7.1 all the information regarding costs for WiMAX deployments can be found [34].

Component	Price in 2006	Price evolution
Spectrum license fee (e.g. 8 x 7 MHz)	175 000 DKK (25 000 €)	-
WiMAX 3.5 GHz BS	70 000 DKK (10 000 €)	-15% per year
WiMAX 3.5 GHz BS sector	49 000 DKK (7 000 €)	-15% per year
BS installation cost	5 000 €/BS + $500/sector	-
BS site rental	1 800 €/BS per year + 1 200 €/sector per year	-
Transmission link equipment (P2P radio link + port in core switch)	25 000 € per BS	-10% per year
P2P radio link site rental	2 400 € per BS per year	-
WiMAX 3.5 GHz indoor CPE	2 100 DKK (300 €)	-20% per year
WiMAX 3.5 GHz outdoor CPE	2 800 DKK (400 €)	-20% per year
Outdoor CPE installation cost	100 € per installation	-
Network equipment administration and maintenance costs	20% of cumulative investments	-

Table 7.1: cost assumptions for WiMAX deployments

The cost of the ditch would be around 200 DKK (28 €)/metre, including ditch, duct, fibre and labour costs [35]. Costs relative to electricity maintenance and other concepts have not been considered.

7.2 Investment projection

Now that the cost assumptions for WiMAX deployments are clear, they will be applied to this network:

Component	**Calculations**	**Final Price**
10 WiMAX 3.5 GHz BSs	10 * 10 000 € * 0.7	70 000 €
Installation costs for 10 BSs	10 * 5 000 €	50 000 €
51 WiMAX 3.5 GHz BS sectors	51 * 7 000 € * 0.7	249 900 €
6 WiMAX 3.5 GHz outdoor CPEs	6 * 400 € * 0.6	1 440 €
Installation costs for 6 outdoor CPEs	6 * 100 €	600 €
	Total	371 940 €

Table 7.2: calculating costs for installation of the WiMAX stations

1. For calculating the cost of 10 BSs and their respective sectors, they are multiplied by their prices in Table 7.1 and then by their estimated value in 2008 (2 years = 30 % reduction on the price in both cases).

2. A similar calculation is made for the outdoor CPEs which are going to be used as SSs taking part in a mesh network. The reduction coefficient is now 40% for two years.

After these calculations, an estimated investment of 122 040 € (854 280 DKK) for placing the WiMAX base stations has been obtained as a result.

Now the cost of the distribution network (between the BSs and the TDC COs) will be calculated. It is known (7.1) that the price of the ditch is 28€/m. In Table 7.3 the distances from all the stations to their respective COs (main nodes in [0]) are shown.

Note: it is obvious that fibre ducts can not be installed (physically) everywhere; normally they must follow the roads infrastructure. Therefore, there is a need to correct the distances measured in straight line. It has been assumed that, on average, real distances (across the roads) are √2 times straight-line distances [36].

Station	**Distance to CO (m)**	**Corrected distance (m)**
BS1	505	714.18
BS2	2186	3091.47
BS3	830	1173.80
BS4	808	1142.68
BS5	1252	1770.60
BS6	2840	4016.37
BS7	683	965.91
BS8	1290	1824.34
BS9	1380	1951.61
BS10	2260	3196.12
SS1	1970	2786.00
SS2	1420	2008.18
SS3	810	1145.51
SS4	177	250.32
SS5	495	700.04
SS6	517	731.15
Total	**19423**	**27468.27**

Table 7.3: BS-CO distances and their corrected value

Therefore, a total of 27468.27 metres of fibre are needed for the distribution network, which multiplied by 28 €/m gives as a result an investment of 769 112 €.

The last investment that must be taken into account is the purchase of the spectrum needed for the base stations. In Table 7.1 it is shown that the price is 25 000 € for a 7 MHz channel, so by multiplying this value by the 5 channels needed for the frequency planning of the network a total investment of 125 000 € for license fees is obtained.

Therefore, the total investment for deploying the planned network would be:

371940 (WiMAX) + 769112 (fibre) + 125000 (licenses) = 1 266 052 € (8 862 364 DKK)

The estimated price per NT can also be calculated by just dividing this price by the total number of NTs in Nordjylland: 1 266 052 € / 241 434 NTs ≈ 6 €/NT.

This price is very cheap because not all the factors which can influence the network have been taken into account for these calculations; just the basic elements of the network have been considered.

8. CONCLUSION AND FUTURE LINES

This chapter contains the conclusion of the thesis and it also gives an overview of the future lines of action for the network planned.

8.1 Conclusion

Many parameters have influence in the methodology of a network planning process, so it is impossible to obtain the perfect solution for a deployment. Some approximations can be made by reaching compromises between these parameters (cost, capacity, scalability,...); these trade-offs have allowed to achieve the solution proposed in this report, which accomplishes all the initial requirements suggested at the beginning.

- **Covering more than 95% of the NTs.** The final solution covers more than the 95% of the NTs required thanks to the characteristics of WiMAX technology.

- **Scalability.** Improvements can be easily made without losing any quality in the services offered. On the contrary, any addition to the network will not make other thing than improving the service.

- **Balanced traffic between base stations.** It can be said that the BSs' load and the traffic among them is more or less evenly shared, with all the BSs handling between 3 and 10% of the total traffic (Table 6.2). This makes achieving the scalability objectives easier too.

- **Reduced investment.** Since the beginning of the project, maintaining a reduced cost has been one of the main objectives for this deployment, as there was always a criterion related to costs for every decision which had to be made. Some examples are the implementation of mesh networks in the most populated areas of the region (using SSs as "messengers" between BSs) and the assumption of outdoor CPEs for the customers.

Talking about the methods applied to the project, MapInfo has been an important tool for achieving the results. This software has been used to manage the network terminals data, essential to locate the nodes in the areas with higher NT density (5. Network Design).

8.2 Future lines

Network planning processes involve many cases of study and not all of them have been tackled. Some work proposals, omitted parts in this project and assumptions that could be made in a different way are listed below these lines:

- One of the first future objectives anyone could think about is expanding the work done to the whole Denmark (or to a different region in the country). To that purpose, special attention must be paid to the connection with external and international networks.

- Changing the placement of base stations method: instead of the “manual” methodology used in this project, an algorithm for placing the BSs according to several parameters could be designed. Some of these parameters could be the criteria mentioned throughout the report or all the effects related to wireless channels that could not be taken into account (path loss, multipath delay spread, fading characteristics, Doppler spread, etc.). For some of these parameters, new data should be available, like for example the characteristics of the terrain (presence of hills, trees, deserted zones,…).

- The study of different scenarios for the deployment could also be an interesting add-on to this project, offering the possibility to present different solutions and then have the possibility to choose the most suitable one.

- Another improvement to this project would be to determine more strict criteria (more than 25 Mbps per user, different percentage assumptions for studying the traffic,…).

- A deployment for working in a different frequency band (a license-exempt band, for example) could also be studied.

- Environmental studies. Studying the environmental impact of the new network (placement of the antennae, use of outdoor CPEs instead of indoor,…).

- A more precise budget could also be estimated taking into account the following recommendations:

    - WiMAX Base Stations: different equipment could be studied to see which solution would involve lower costs (some scenarios could be considered too in order to obtain different objectives).
    - Fibre distribution network: instead of assuming approximations for distance calculations the real distances could be determined somehow, but it is probably a much more interesting topic for [0].
    - As it was mentioned a few lines above, the network could be planned for working in unlicensed bands, which would lower costs because of not having to purchase any spectrum. This solution could become interesting for a rural region like Nordjylland due to the lack of possible interferences, which is the main problem of using unlicensed bands.

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Appendix A: WiMAX characteristics

In this section the main features of WiMAX will be introduced.

OFDM Modulation

OFDM stands for Orthogonal Frequency Division Multiplexing and it is the main reason of being able to reach so high speeds with WiMAX. Using 256 subcarriers it is able to cover a 48 km area, allowing Non-LOS connections, and it is capable of transmitting data up to 75 Mbps with a spectral efficiency of 5 bps/Hz, supporting thousands of users with a channel scalability of 1.5-5 MHz. This modulation technique is the same one used in WiFi and Digital/Cable/Satellite TV, so it is sufficiently tested.

OFDM supports hundreds of users per channel with a great bandwidth, it is suitable for both continuous and bursty traffic, not depending of the protocol used (it can transport either IP, Ethernet, ATM,…), and it supports multiple services simultaneously, such as SLA[8] and QoS[9].

The main advantage of OFDM over single-carrier schemes is its ability to cope with severe channel conditions (for example, attenuation of high frequencies in a long copper wire, narrowband interference and frequency-selective fading due to multipath) without complex equalization filters.

Some other important characteristics about OFDM are that it increases the SNR of subscriber stations, it improves the resistance to multipath interference and outdoor environments and it supports FDD and TDD (explained later) for making interoperability between other systems easier.

[8] SLA (Service Level Agreement): that part of a service contract where the level of service is formally defined. The provider is compromised to offer the customer that level of service.
[9] QoS (Quality of Service): ability to provide different priority to different applications, users, or data flows, or to guarantee a certain level of performance to a data flow.

Appendix B: Wireless channel characteristics [27]

Suburban Path Loss Model

The most widely used path loss model for signal strength prediction and simulation in macrocellular environments is the Hata-Okumura model. This model is valid for the 500-1500 MHz frequency range, receiver distances greater than 1 km from the base station, and base station antenna heights greater than 30 m. There exists an elaboration on the Hata-Okumura model that extends the frequency range up to 2000 MHz. It was found that these models are not suitable for lower base station antenna heights, and hilly or moderate-to-heavy wooded terrain. To correct for these limitations, a model which covers the three most common terrain categories found across the United States is presented. However, other sub-categories and different terrain types can be found around the world.

The maximum path loss category is hilly terrain with moderate-to-heavy tree densities (Category A from SUI model). The minimum path loss category is mostly flat terrain with light tree densities (Category C). Intermediate path loss condition is captured in Category B. The extensive experimental data was collected by AT&T Wireless Services across the United States in 95 existing macrocells at 1.9 GHz. For a given close-in distance d0, the median path loss (PL in dB) is given by

$$PL = A + 10\,\gamma \log_{10}(d/d_0) + s \quad \text{for } d > d_0,$$

where $A = 20 \log_{10}(4\ \pi\ d_0\ /\ \lambda)$ (λ being the wavelength in m), γ is the path-loss exponent with $\lambda = (a - b\ h_b + c\ /\ h_b)$ for h_b between 10 m and 80 m (h_b is the height of the base station in m), d_0 = 100m and a, b, c are constants dependent on the terrain category reproduced below.

Model parameter	Terrain Type A	Terrain Type B	Terrain Type C
A	4.6	4	3.6
B	0.0075	0.0065	0.005
C	12.6	17.1	20

The shadowing effect is represented by s, which follows lognormal distribution. The typical value of the standard deviation for s is between 8.2 and 10.6 dB, depending on the terrain/tree density type.

Receive Antenna Height and Frequency Correction Terms

The above path loss model is based on published literature for frequencies close to 2 GHz and for receive antenna heights close to 2 m. In order to use the model for other frequencies and for receive antenna heights between 2 m and 10 m, correction terms have to be included. The path loss model (in dB) with the correction terms would be

$$PL_{modified} = PL + \Delta\ PL_f + \Delta\ PL_h,$$

where PL is the path loss given in [4], ΔPL_f (in dB) is the frequency correction term given by

$\Delta PL_f = 6 \log (f / 2000)$,

where f is the frequency in MHz, and ΔPL_h (in dB) is the receive antenna height correction term given by

$\Delta PL_h = - 10.8 \log (h / 2)$; for Categories A and B;
$\Delta PL_h = - 20 \log (h / 2)$; for Category C,

where h is the receive antenna height between 2 and 10 m.

Urban (Alternative Flat Suburban) Path Loss Model

The Cost 231 Walfish-Ikegami (W-I) model matches extensive experimental data for flat suburban and urban areas with uniform building height. It has been also found that the model presented in the previous section for the Category C (flat terrain, light tree density) is in a good agreement with the Cost 231 W-I model for suburban areas, providing continuity between the two proposed models.

Figure C.1 compares a number of published path loss models for suburban morphology with an empirical model based on drive tests in the Dallas-Fort Worth area. The Cost 231 Walfisch-Ikegami model was used with the following parameter settings:

Frequency = 1.9 GHz
Mobile Height = 2 m
Base Height = 30 m
Building spacing = 50 m
Street width = 30 m
Street orientation = 90º

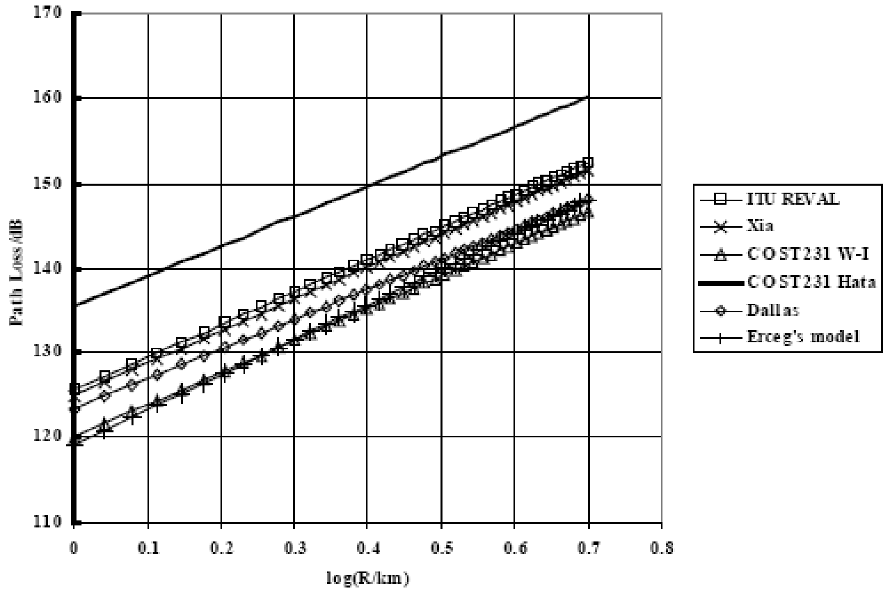

Figure B.1: Comparison of suburban path loss models

Note: COST 231 W-I, ITU Reval and Xia models all have a Hata correction term added for modeling the path loss variation with mobile height.

It has also been found that the Cost 231 W-I model agrees well with measured results for urban areas, provided the appropriate building spacing and rooftop heights are used. It can therefore be used for both suburban and urban areas, and can allow for variations of these general categories between and within different countries.

Flat terrain models in conjunction with terrain diffraction modelling for hilly areas can be used in computer based propagation tools that use digital terrain databases. The weighting term for knife-edge diffraction should be set to 0.5 to minimize the lognormal standard deviation of the path loss.

Multipath Delay Profile

Due to the scattering environment, the channel has a multipath delay profile. For directive antennas, the delay profile can be represented by a spike-plus-exponential shape. It is characterized by τrms (RMS delay spread of the entire delay profile) which is defined as

$$\tau^2_{rms} = \Sigma_j \; P_j \, \tau^2_j - (\tau_{avg})^2$$

where

$\tau avg = \Sigma j \; Pj \; \tau j$,

τj is the delay of the j th delay component of the profile and Pj is given by

Pj = (power in the j th delay component) / (total power in all components).

The delay profile has been modeled using a spike-plus-exponential shape given by

$$P(\tau) = A \; \delta(\tau) + B \sum^{\infty}_{i=0} \exp(-i\Delta\tau/\tau_0) \; \delta(\tau - i\Delta\tau),$$

where A, B and $\Delta\tau$=are experimentally determined.

RMS Delay Spread

In a proposed delay spread model based on a large body of published reports. It was found that the rms delay spread follows lognormal distribution and that the median of this distribution grows as some power of distance. The model was developed for rural, suburban, urban, and mountainous environments. The model is of the following form

$\tau rms = T_1 \, d^{\varepsilon} \, y$,

where τrms is the rms delay spread, d is the distance in km, T_1 is the median value of τ_{rms} at d = 1 km, ε is an exponent that lies between 0.5-1.0, and y is a lognormal variate. However, these results are valid only for omnidirectional antennas. It was shown that 32o and 10o directive antennas reduce the median τ_{rms} values for omnidirectional antennas by factors of 2.3 and 2.6, respectively.

Depending on the terrain, distances, antenna directivity and other factors, the rms delay spread values can span from very small values (tens of nanoseconds) to large values (microseconds).

Fading Characteristics

Fade Distribution, K-Factor

The narrow band received signal fading can be characterized by a Ricean distribution. The key parameter of this distribution is the K-factor, defined as the ratio of the "fixed" component power and the "scatter" component power. An empirical model was derived from a 1.9 GHz experimental data set collected in typical suburban environments for transmitter antenna heights of approximately 20 m. An excellent agreement with the model was reported using an independent set of experimental data collected in San Francisco Bay Area at 2.4 GHz and similar antenna heights. The narowband K-factor distribution was found to be lognormal, with the median as a simple function of season, antenna height, antenna beamwidth, and distance. The standard deviation was found to be approximately 8 dB.

The model presented is as follows

$K = F_s F_h F_b K_o d^{\gamma} u$,

where:

F_s is a seasonal factor, F_s=1.0 in summer (leaves); 2.5 in winter (no leaves)

F_h is the receive antenna height factor, F_h= $(h/3)_{0.46}$; (h is the receive antenna height in meters)

F_b is the beamwidth factor, F_b = $(b/17)_{-0.62}$; (b in degrees)

K_o and γ are regression coefficients, K_o = 10; γ = -0.5

u is a lognormal variable which has zero dB mean and a std. deviation of 8.0 dB.

Using this model, one can observe that the K-factor decreases as the distance increases and as antenna beamwidth increases. We would like to determine K-factors that meet the requirement that 90% of all locations within a cell have to be services with 99.9% reliability. The calculation of K-factors for this scenario is rather complex since it also involves path loss, delay spread, antenna correlation (if applicable), specific modem characteristics, and other parameters that influence system performance. However, we can obtain an approximate value as follows: First we select 90% of the users with the highest K-factors over the cell area. Then we obtain the approximate value by selecting the minimum K-factor within the set. For a typical deployment scenario (see later section on SUI channel models) this value of K-factor can be close or equal to 0.

Figure B.2 shows fading cumulative distribution functions (CDFs) for various K factors. For example, for K = 0 dB (linear K = 1) a 30 dB fade occurs 10-3 of the time, very similar to a Rayleigh fading case (linear K = 0). For a K factor of 6 dB, the probability of a 30 dB fade drops to 10-4. The significance of these fade probabilities depends on the system design, for example whether diversity or retransmission (ARQ) is provided, and the quality of service (QoS) being offered.

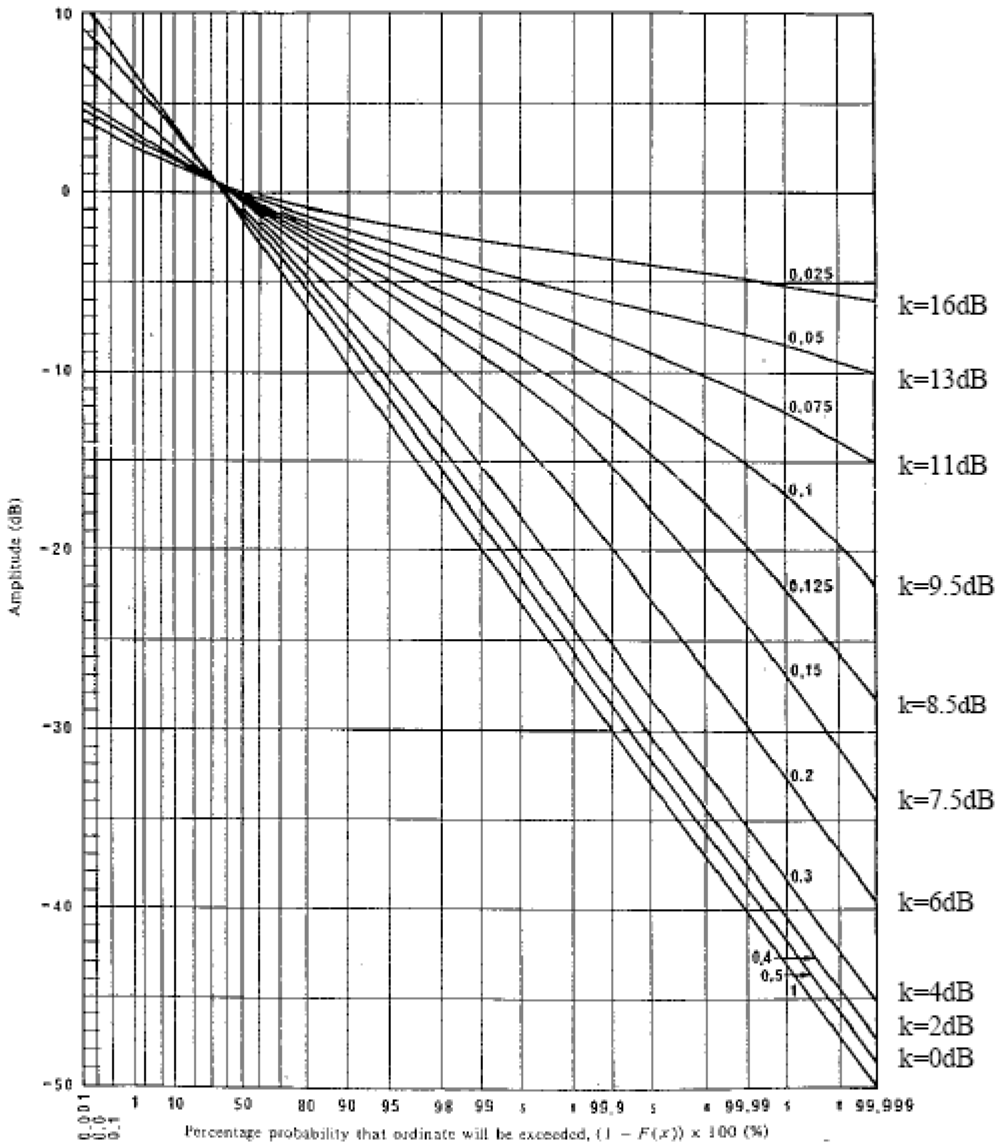

Figure B.2: Ricean fading distributions.

Doppler Spectrum

Following the Ricean power spectral density (PSD) model in COST 207, we define scatter and fixed Doppler spectrum components. In fixed wireless channels the Doppler PSD of the scatter (variable) component is mainly distributed around f = 0 Hz (Fig. B.3a). The shape of the spectrum is therefore different than the classical Jake's spectrum for mobile channels. A rounded shape as shown in Fig. B.3b can be used as a rough approximation to the Doppler PSD which has the advantage that it is readily available in most existing radio frequency (RF) channel simulators. It can be approximated by:

$$S(f) = \begin{cases} 1 - 1.72 f_0^2 + 0.785 f_0^4 & f_0 \le 1 \\ 0 & f_0 > 1 \end{cases} \qquad \text{where} \quad f_0 = \frac{f}{f_m}$$

The function is parameterized by a maximum Doppler frequency fm. Alternatively, the –3dB point can be used as a parameter, where f_{-3dB} can be related to fm using the above equation. Measurements at 2.5 GHz center frequency show maximum f_{-3dB} values of about 2 Hz. A better approximation of fixed wireless PSD shapes are close to exponential functions. Wind speed combined with foliage (trees), carrier frequency, and traffic influence the Doppler spectrum.

The PSD function of the fixed component is a Dirac impulse at f = 0 Hz.

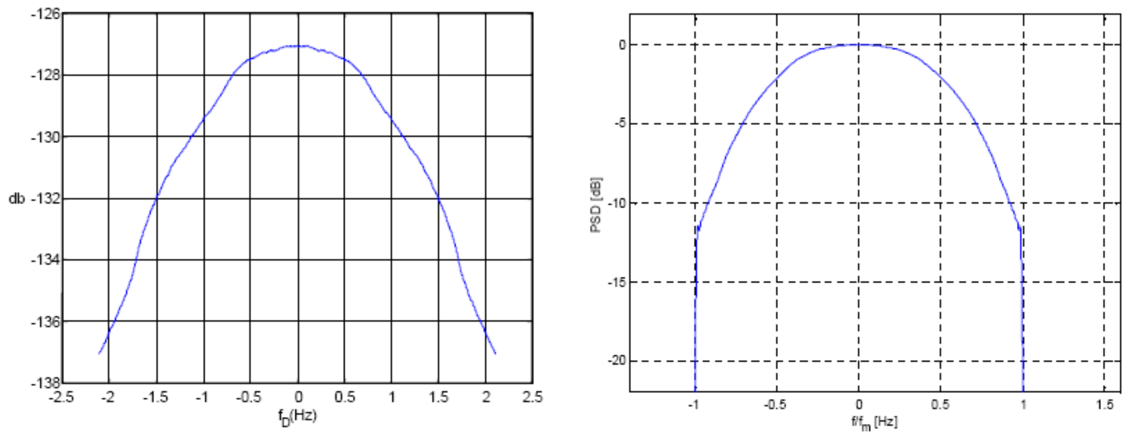

Figure B.3. a) Measured Doppler spectrum at 2.5 GHz center frequency (left)
b) Rounded Doppler PSD model (right)

Spatial Characteristics, Coherence Distance

Coherence distance is the minimum distance between points in space for which the signals are mostly uncorrelated. This distance is usually grater than 0.5 wavelengths, depending on antenna beamwidth and angle of arrival distribution. At the BTS, it is common practice to use spacing of about 10 and 20 wavelengths for low-medium and high antenna heights, respectively (120º sector antennae).

Co-Channel Interference

C/I calculations use a path loss model that accounts for median path loss and lognormal fading, but not for 'fast' temporal fading. In the example shown in Fig. B.4, a particular reuse pattern has been simulated with r^2 or r^3 signal strength distance dependency, with apparently better C/I for the latter. However, for non-LOS cases, temporal fading requires us to allow for a fade margin. The value of this margin depends on the Ricean K-factor of the fading, the QoS required and the use of any fade mitigation measures in the system. Two ways of allowing for the fade margin then arise; either the C/I cdf is shifted left as shown below or the C/I required for a non-fading channel is increased by the fade margin. For example, if QPSK requires a C/I of 14 dB without fading, this becomes 24 dB with a fade margin of 10 dB.

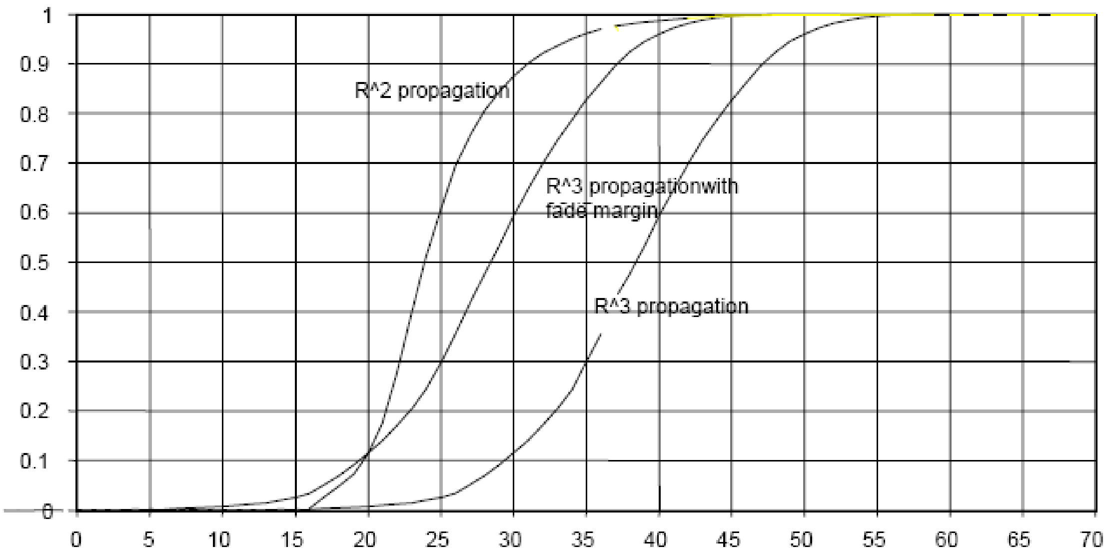

Figure B.4: Effects of fade margin on C/I distributions

Appendix C: Traffic statistics

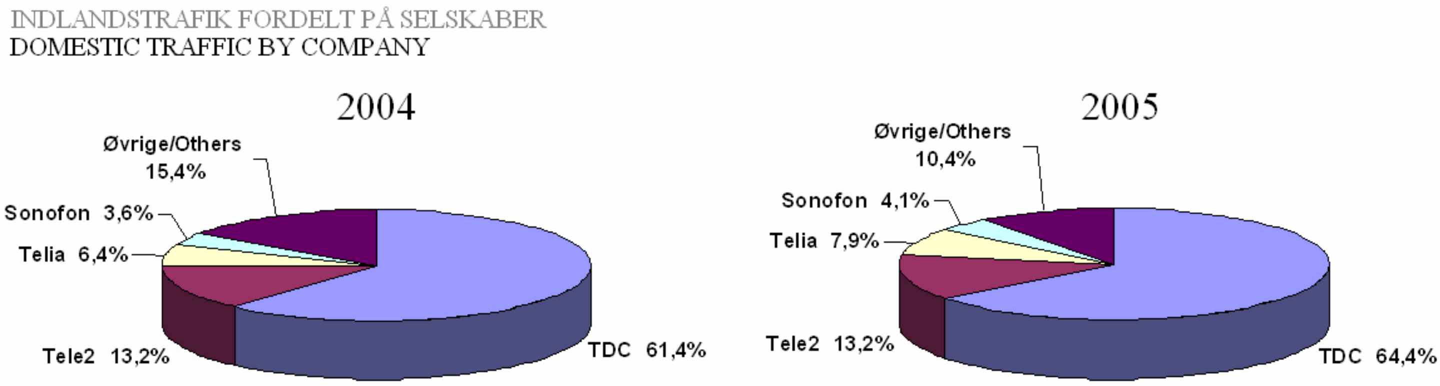

Figure C.1: Domestic traffic by company (Denmark) [24]

Ultimo perioden End of period					Markedsandele Market shares			
	2002	2003	2004	2005	2002	2003	2004	2005
Cybercity	95.107	92.335	115.671	144.698	6,2%	5,5%	6,9%	8,1%
Dansk Kabel-TV	•	•	•	50.371	•	•	•	2,8%
Orange	56.385	39.695	21.914	•	3,7%	2,4%	1,3%	•
TDC	881.255	1.014.207	1.074.892	1.102.283	57,5%	60,4%	63,9%	61,5%
Tele 2	178.701	164.290	132.755	158.637	11,7%	9,8%	7,9%	8,9%
Telia	129.018	141.729	151.888	34.487	8,4%	8,4%	9,0%	1,9%
TeliaStofa	...	...	...	146.727	...	...	...	8,2%
Tiscali	146.400	150.068	88.279	•	9,5%	8,9%	5,2%	•
Øvrige[2] Others[2]	46.183	75.987	97.236**	264.509	3,0%	4,5%	5,8%**	8,6%
Abonnementer i alt **Subscriptions in total**	1.533.049	1.678.311	1.682.635**	1.791.341	100%	100%	100%	100%
- heraf erhverv - of which businesses	139.236	235.438	295.963**	360.893	•	•	•	20,2%
- heraf privat - of which private	1.393.786	1.442.873	1.400.169**	1.430.448	•	•	•	79,8%
Tilslutningsmetode[3] **Type of connection[3]**								
- dial-up - dial-up	1.825.973	1.987.093	696.655	467.863	•	•	•	26,2%
- direkte opkobling - direct connection	468.730	733.858	1.027.993	1.313.186	•	•	•	73,2%
Abonnementer pr. 100 indbyggere Subscriptions per 100 inhabitants	28,5	31,1	31,3	32,9	•	•	•	•

Table C.1: ISP market shares (Denmark) [24]