

Design of Backbone for Wireless Citywide Networks like Wireless Trondheim

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Problem Description

The student should draw up principles and solutions for backbone for wireless citywide networks. The student should use Wireless Trondheim as basis and will participate in the design of the backbone for the coming deployment. A central part of the assignment will be to get updated on various technologies for backbone such as fiber, licensed radio solutions (e.g. WiMAX) and unlicensed radio, and evaluate these technologies according to costs and applications. An important element in the assignment will be to take into consideration future capacity demands, research activity and make models with scalability. NTNU, The City of Trondheim and Sør-Trøndelag county municipality have fiber in the development area, and it will be an important part of the assignment to consider how this existing fiber infrastructure may be used and if it will be cost saving. The assignment presuppose some practical work, survey and practical thinking to take part in the deployment of the backbone for Wireless Trondheim

Assignment given: 20. January 2006
Supervisor: Steinar Andresen, ITEM

Preface

This thesis is part of the study in Master of Science at the Norwegian University of Science and Technology. The work has been carried out at the Department of Telematics, in the period January 2006 to June 2006.

I would like to thank Professor Steinar Andresen for his cooperation in connection with the definition of the problem description. I also want to thank my supervisor Thomas Jelle for all his support and suggestions, with definition of problem description and during my work. He has been very willing to help, and has made it easy for me to keep a good progression during the whole period.

Trondheim, June 2006

Asgeir Torstensen

Abstract

This master's thesis will investigate some of the technological solutions available for the construction of a backbone for a wireless citywide network (CWN), such as Wireless Trondheim, and a special attention is given to the possible advantages of using infrastructure already in place.

There are several different technologies which can be used as a backbone for the wireless CWN, and in this thesis strengths and weaknesses of the various solutions will be discussed. Some requirements, such as scalability to handle increased capacity demand from future access technologies, may be more important to satisfy than others, and the discussion will see how this might rule out or favor some technology choices. In addition to demands from regular traffic to be carried in the network, also research traffic should be allowed. It is discussed how different requirements as a consequence of this research traffic will set limitations to which technology to use.

While the performance of each of the technologies are relatively constant for all cases and easy to determine, the cost of using the different technologies is not. For this reason most effort is put into the analysis of this decision factor. Different possible scenarios are introduced, and the costs of using various technologies in the different scenarios are calculated.

The results from the calculations are then discussed in more detail, and an important part of this discussion is sensitivity analysis. The values for several of the parameters used in the calculations will be changed, and the various analyses show how the change of one parameter will affect the result of the calculations.

Based on the calculation results and the discussion of the results, some principles which can be used as guidelines in planning and deployment of a backbone for a wireless CWN will be suggested.

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List of Abbreviations

ADSL	- Asynchronous Digital Subscriber Line
AP	- Access Point
COE	- Central Office Equipment
CPE	- Customer Premises Equipment
CWDM	- Coarse Wavelength Division Multiplexing
CWN	- CityWide Network
DSL	- Digital Subscriber Line
DSLAM	- Digital Subscriber Line Access Multiplexer
DWDM	- Dense Wavelength Division Multiplexing
FSO	- Free Space Optics
GHz	- GigaHertz (10^9 Hz)
GSM	- Global System for Mobile Communications
LAN	- Local Area Network
LOS	- Line-Of-Sight
NLOS	- None-Line-Of-Sight
PDH	- Plesiochronous Digital Hierarchy
POF	- Plastic Optical Fiber
PTP	- Point-To-Point
PTM	- Point-To-Multipoint
PV	- Present Value
SDH	- Synchronous Digital Hierarchy
SFP	- Small Form Pluggable
SHDSL	- Synchronous High-bitrate Digital Subscriber Line
SONET	- Synchronous Optical Network
UMTS	- Universal Mobile Telecommunications System
WDM	- Wavelength Division Multiplexing
WDS	- Wireless Distribution System
Wi-Fi	- Wireless Fidelity
WiMAX	- Worldwide Interoperability for Microwave Access
WT	- Wireless Trondheim

Definitions

- Access Radio** - Is used only to refer to the Access Points in the access network, i.e. Wi-Fi access points or the like.
- Backbone** - Network feeding the APs of the CWN, i.e. connecting the APs to the Internet.
- Trunk** - A trunk is a link in the backbone network carrying traffic from two or more APs
- Spreading** - The part of the backbone bridging the gap from trunk termination to each single AP
- Availability** - The system is operational at a given instant of time
- Reliability** - The system performs its specified task correctly
- Depreciation time** - The economical life time of an investment, i.e. after a time equal to the depreciation time the value of an investment is assumed to be zero. In this thesis it is sometimes referred to as *time period*.

Chapter 1

Introduction

1.1 Background

On the 26th of April 2005 the board at the Norwegian University of Technology and Science (NTNU) decided support the deployment of a wireless data network covering all its campus, the bus route between the two biggest campus, Gløshaugen and Dragvoll, and Trondheim city centre. This marked the start of a project called "Trådløse Trondheim" (Wireless Trondheim), where NTNU is the most important driving force. The vision for this project is:

- Construct a world class large scale wireless test laboratory for R&D
- Make Trondheim and NTNU more attractive to students and technology based industry and commerce.
- Offer wireless access to all citizen in the centre of Trondheim

An important task in the deployment of a wireless CityWide Network (CWN) like this, is the planning and deployment of the backbone connecting the access points to the Internet. There are several different technologies with different performance and different costs which can be used in the construction of such a backbone, and which services it will be possible to offer in the CWN depends very much on the technology chosen in the backbone.

This diversity of technologies and consequences of different choices make the background for this thesis, which has the title "Design of backbone for wireless Citywide networks like Wireless Trondheim". The objective of this thesis is then to give an introduction to the possibilities and limitations of different technologies, and identify some decision factors when

choosing which technology to use. One very important decision factor is the cost of the various solutions, and much attention has been given to the task of estimating the cost in different situations.

1.2 Scope

The focus in this thesis is on the physical layer of the backbone construction, and no attention is given to how different solutions may result in different implementation for the layers on top of this. Also the focus is given to installation and leasing costs, i.e. the costs of maintenance and operation are left out of the calculations. Since it is the backbone which is discussed the costs of Wi-Fi access points in the access network and the installation of these are not included in the calculations.

1.3 Method

Initially most efforts was put into the studies of different technologies, and much time was spent to gather information about performance for the various xDSL technologies, radio solutions and fiber optics solutions. Much of this information has been found searching the Internet, but some books on fiber optics have also been useful. When time came to start with gathering of price information the Internet was not that helpful any more, and I had to start contacting persons within different companies to get price estimates. Most of them were very helpful, but especially for fiber solutions it was difficult to obtain "general" price estimates since the price varies a lot from case to case. In this phase also my supervisor Thomas Jelle was most helpful to give me price estimates on equipment and cost of work.

With several different price estimates for different xDSL solutions, radio equipment for different suppliers and fiber solutions in hand, next step was to decide on price estimates for the different solutions to use in the calculations. Since all the prices are combined with more or less uncertainty, the results of the calculations are discussed, and the effect of changes in different parameters are investigated through several sensitivity analysis.

1.4 Thesis outline

Chapter 2 will give an introduction to different technologies and solutions which could be used in the backbone network for a wireless CWN. It also gives a discussion of different network topologies presenting pros and cons of different choices.

Chapter 3 presents some decision factors, but costs are left to a separate chapter.

Chapter 4 first presents the basis for the calculations, and then follows the calculations.

Chapter 5 is a discussion of the calculations from previous chapter, and several sensitivity analysis are performed in this chapter.

Chapter 6 contains some concrete suggestions to how the cost of the backbone network may be minimized, and summarizes how different factors limit the opportunity set of technologies.

Chapter 7 concludes the project.

Chapter 2

Technologies and topologies

This chapter gives an overview over the most relevant technologies to use in a backbone network for a wireless CityWide Network (CWN).

2.1 Radio

Microwave radio transmission uses the air as the transmission medium and this represents both the biggest advantage and the biggest disadvantage of the radio technologies. The benefit is obvious as no cabling between transmitter and receiver means that the very high costs connected to cabling are avoided. The drawback is the unpredictable behavior of the medium and the lack of control. One uncontrollable factor is the weather, with both day to day variations like fog, rain and snow and seasonal variations like leaves on the trees and ice on waters affecting the transmission conditions. How much the transmission is affected by changing weather conditions depends on the modulation used and the frequency of the signal, but in any case the weather will effect the quality of the signal transmission.

The topology of the surroundings is also an important issue within radio communication. Forests, hilly terrain, open fields and cities result in different channel properties, and different topologies will affect the range and capacity of a radio system. Line-Of-Sight (LOS) is an expression much used within radio transmission, and whether there is LOS or not between transmitter and receiver will affect both the possible distance between these and the capacity of the link. In general systems operating at low frequencies handle None-LOS (NLOS) better than systems operating at higher frequencies.

2.1.1 Licensed versus unlicensed

Another problem with radio communication is the interference between different information signals. An example is locations where there are many Wi-Fi access points (APs) operating in the 2.4 GHz frequency band. These may be deployed without any frequency planning so the quality of service delivered from each AP may be significantly reduced by interference from other APs. The gravity of the interference problem depends on the frequencies used, and a major factor is whether the frequencies are licensed or unlicensed.

Unlicensed frequency bands

The 2.4 GHz frequency band used by Wi-Fi and several other applications is an example of an *unlicensed* frequency band. Apart from regulations regarding permissible radiated power, the unlicensed frequency bands are free to use. The great benefit by using unlicensed frequencies is that there is no need to apply for concession to use them, and there is no license fee to be paid. This enables a fast deployment if needed, and generally at a lower cost since no license fees are to be paid.

The major drawback is the lack of control. The frequency spectrum is free for everyone to use, so there is little or no control with regards to who transmits, where it is transmitted and how much transmission there is. Of course it is possible to do measurements to get an impression of the present interference level, but even though the interference level is unlikely to change during days or weeks, it is often likely to do so during months or a few years. The result is that the use of unlicensed frequencies makes it more difficult to do radio planning and to keep a given service level over time.

Licensed frequency bands

To keep control over the use of frequencies and thereby reassure a more efficient use of them, a very big portion of the frequencies are licensed and administrated by national regulators. The big advantage of licensed frequency bands is the increased control. Still there are the troubles related to topology, day to day variations and seasonal variations, but the level of interference is controllable. With the elimination of this variable it will be easier to do the radio planning.

The disadvantages are potentially time consuming bureaucracy and additional costs related to the acquisition of the license. The price of a

license depends on the frequency band and in some cases this could form a significant part of the total costs. Although some licenses for the 3.5 GHz band used by WiMAX have been very expensive, high license fees is a bigger problem within the industry of mobile communication systems like GSM and UMTS than for fixed wireless links.

2.1.2 Radio equipment

There are several different producers of equipment for radio communication, and just as there are several producers there are also many different products on the market. A first distinction can be made between access points which deliver access to the end user, and backhaul equipment delivering access to these access points. In this thesis the focus is on the backhaul equipment.

Standards versus proprietary solutions

Wi-Fi is now the dominant standard for wireless access, and virtually all laptops produced today has an integrated network card which supports Wi-Fi. The emergence of the Wi-Fi standard increased the market for wireless access equipment and opened up for mass productions, and as a consequence the prices have been pushed down. Although Wi-Fi is a technology for wireless access, it can also be suitable as a backhaul solution in many cases. Long distances should be covered by other technologies, i.e. other radio solutions, fiber or xDSL, but the last meters of the connection to the access point can be delivered using Wi-Fi. Wi-Fi uses two different frequency bands, 2,4 GHz and 5 GHz. They are both unlicensed bands, but while the 2,4 GHz band is used by a lot of Wi-Fi users and other applications, the 5 GHz band is much less utilized, has more available channels and higher radiated power is allowed [1]. 5 GHz links could therefore be good and cheap alternatives to other radio solutions or cabling for the last meters to the access points.

In the wireless backhaul market there has been no common standard, so each producer has used its own proprietary standard. Therefore there has been no room for mass production, and equipment prices have been kept relatively high. This situation will probably change during the next years as WiMAX equipment will be produced. WiMAX is a technology based on the IEEE 802.16 standards, and should offer good performance both as an access technology and as backhaul technology [2]. WiMAX is a new technology still under development, and producers have just started to deliver equipment that support WiMAX. What many people hope and

predict is that WiMAX should become a dominant standard, and that increased competition and the possibility for economics of scale will push down the price of equipment [3].

Today's solutions

The performance of a radio link depends on several factors which are all connected to each other, as does all other communication systems regardless of transmission technology. The complexity of the electronic in the transceivers is clearly an important factor, and of course closely connected to the price. Apart from technical issues, there are some physical relations between transmission properties. The Shannon Law shows how an increase in transmission capacity will lead to higher bandwidth consumption and/or smaller coverage [4].

Because of these tradeoffs which have to be made between complexity, bitrate, bandwidth and coverage, the suppliers offer products with different combinations of these properties. Most products are based on proprietary standards which often result in slightly different performance and unfortunately incompatibility. Still, a quick look at the properties and performance of equipment from different producers has indicated that equipment from different producers have similar qualities. For this reason, and because it would be too extensive to give an overview of all the products, this discussion will introduce a few products from a couple of leading producers, i.e. Proxim and Nera. Proxim has its base in the United States while Nera has its base in Norway, and their products are representative for what is available in the market today. The products introduced here represents just a small fraction of what is available on the market, and they are just meant to give a picture of the possibilities of radio.

Proxim solutions

Two families of Proxim equipment will be presented, the Proxim Tsunami and the Proxim TeraBridge.

The *Proxim Tsunami* family includes i.a. Tsunami.GX32, Tsunami.GX200 and Tsunami 480, which offer aggregate capacities of 32 Mbit/s, 216 Mbit/s and 872 Mbit/s respectively. The full duplex capacities are approximately half of the aggregates. The Tsunami equipment operate in the 5.8 GHz license free frequency band (ISM band), and in addition the Tsunami 480 uses the frequency band around 5.3 GHz (UNII band) which is also license free in many countries. Split-box design is common for all the Tsunami products, i.e. they all have an indoor unit and an outdoor radio unit. The

indoor and the outdoor units are connected with a coaxial cable, and the distance between the two units should not exceed 300m. The Tsunami family is the latest generation of high capacity wireless bridges from Proxim, and extension of fiber network and network backhaul is among the intended applications for this equipment [5, 6, 7].

Proxim TeraBridge is available in two versions, TeraBridge 5345 and TeraBridge 5845. The 5345 uses the UNII frequency band around 5.3 GHz, while the 5845 uses the ISM frequency band around 5.8 GHz. They both have a capacity of 45 Mbit/s full duplex, but while the 5345 is defined as being suited for short to medium range links the 5845 should support radio links up to 64 km (40 miles). While the Tsunami family, and also the products from Nera presented later, have a split box design with an indoor and an outdoor unit, the TeraBridge is an all outdoor radio [8].

Nera solutions

This section will present two of the solutions available from Nera which are the most relevant to use as backbone in a citywide wireless network, one solution for low and medium capacity and the other for relatively high capacities.

Nera FlexLink is the solution for low and medium transmission capacity networks, and it covers capacities from 2x2 to 16x2 Mbit/s. It uses a PDH radio and it is possible to choose between the 7, 8, 13, 15, 18, 23, 26, 32 and 38 GHz frequency bands which are all licensed frequency bands [9]. Channel bandwidth varies from 3.5 MHz to 28 MHz depending on set up and the chosen frequency band. The FlexLink indoor and outdoor units are connected by a single coaxial cable which carries data and power to the outdoor unit. Maximum distance between indoor and outdoor unit is 300 meters. Three different configurations are possible with the FlexLink to adjust to the required availability. The different configurations available are 1+0, 1+1 Hot Standby and 1+1 Hot Standby with Space Diversity [10].

Nera Evolution Metro is the Nera alternative for higher transmission capacity and it supports bitrates up to 622 Mbit/s. Bitrates up to 311 Mbit/s is achieved using one outdoor unit, while two outdoor units are necessary to deliver 622 Mbit/s [11]. The Evolution Metro uses a SDH/SONET radio, and several different licensed frequency bands between 5 and 38 GHz are available [12].

As for the FlexLink it is possible to use a protected configuration (1+1 Hot Standby) to increase the availability of the system [13].

2.2 xDSL

Digital Subscriber Line (DSL) is a broadband access technology which uses the existing copper wires in the PSTN network to offer broadband access to residential and business subscribers. The "x" simply means that there are several different implementations of the DSL technology. Figure 2.1 shows the components used to supply DSL services. The "splitter"

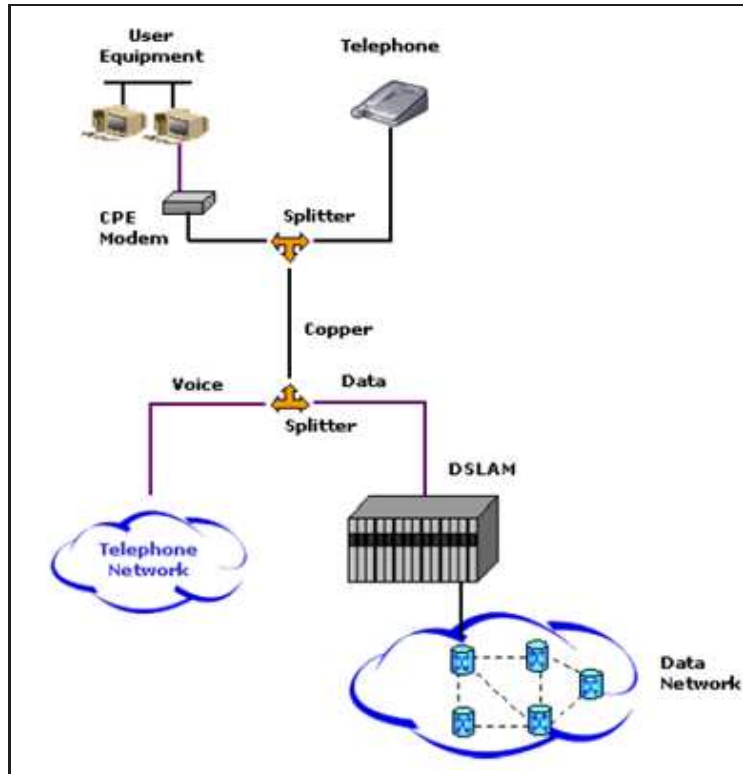


Figure 2.1: *DSL Environment*. Figure modified from [14]

shown as part of the Customer Premises Equipment (CPE) can be omitted in the G.Lite (G.992.2) standard [15], and this allows for easier installation in homes and businesses. The DSLAM (DSL Access Multiplexer) is part of the Central Office Equipment (COE), and aggregates traffic from different CPEs and switches them to the data network. The CPE Modem, also called the DSL Modem, is the part of the CPE which communicate with the DSLAM. Though there are several different variations of DSL, they all have a structure as the one presented here. The difference is how the equipment operate, and the different operation alternatives may be divided into two families, i.e. *Symmetric DSL* and *Asymmetric DSL* [14].

Symmetric DSL

Symmetric DSL means that the bitrates are equal for downstream and upstream transmission. Within the symmetric DSL family there are several different variations, but the most important ones are:

HDSL (High bitrate DSL)

This is the first of the symmetrical DSL technologies, and it uses 2 or 3 wire pairs to achieve the high bit rates [14].

HDSL2 (High bitrate DSL)

A further development of the HDSL which uses just a single wire pair and thus enables use of less copper pairs [14].

SDSL (Symmetrical DSL)

SDSL is also an improved version of HDSL and it uses a single wire pair for transmission. In addition it offers different bitrates, while HDSL2 offers just one alternative.

SHDSL (Symmetric High-speed DSL)

Just like the SDSL technology the SHDSL is similar to HDSL2 while offering a variety of bitrates, but compared to SDSL it is capable of delivering both higher data rates and longer range [14, 16].

Asymmetric DSL

The asymmetric DSL technologies delivers different downstream and upstream bitrates, i.e. the downstream is faster than the upstream rate. The argument for the asymmetric DSL technologies is that most users have a much higher downstream capacity demand than upstream, because applications like web browsing, radio streaming and Video on Demand result in much downstream traffic and less upstream. As for the symmetric family there are several different variations of asymmetric DSL, and the most important ones are:

ADSL (Asymmetric DSL)

ADSL is the broadband solutions for most homes and businesses, and it has a portion of more than 60% of the broadband market [17].

ADSL2/ADSL2+ (Asymmetric DSL)

These upgrades of the ADSL technology was standardized in 2004, and offers both higher bitrates and longer range than ADSL.

VDSL/VDSL2 (Very high bitrate DSL)

When it comes to capacity the VDSL is superior to the other DSL technologies, but the price to pay is a shorter range. The newest standardization, VDSL2, is also capable of delivering very high symmetrical bitrates.

2.2.1 Range and Capacities

Table 2.1 gives an overview of the capacities and ranges of different DSL technologies. The ranges given in the table are just meant to give an indication of how long distances between COE and CPE the technologies support when delivering maximum bitrates. These range values may be much higher for lower bitrates, and also the quality of the copper wires together with the surroundings will affect the ranges.

DSL Type	Downstream	Upstream	Range in meters
ADSL	7 Mbit/s	800 kbit/s	3000
ADSL2	8 Mbit/s	1 Mbit/s	3500
ADSL2+	24 Mbit/s	1 Mbit/s	1500
HDSL/HDSL2	2 Mbit/s	2 Mbit/s	3500
SDSL	2 Mbit/s	2 Mbit/s	3000
SHDSL	4.6 Mbit/s	4.6 Mbit/s	4000
VDSL	55 Mbit/s	15 Mbit/s	300
VDSL2	100 Mbit/s	100 Mbit/s	400

Table 2.1: *DSL types, maximum capacities and corresponding ranges. Values evaluated from [14, 17, 18, 19, 20]*

2.3 Fiber optics

Figure 2.2 on the following page shows a simple illustration of the structure in a fiber optic transmission system.

The optical transmitter converts an electrical input signal to an optical signal. The optical signal is (in most cases) created by a light emitting diode (LED) or a solid state laser diode (LD) [21].

The fiber optic cable is the transmission medium for the optical signal. There are different types of optical fibers, and these will be described in

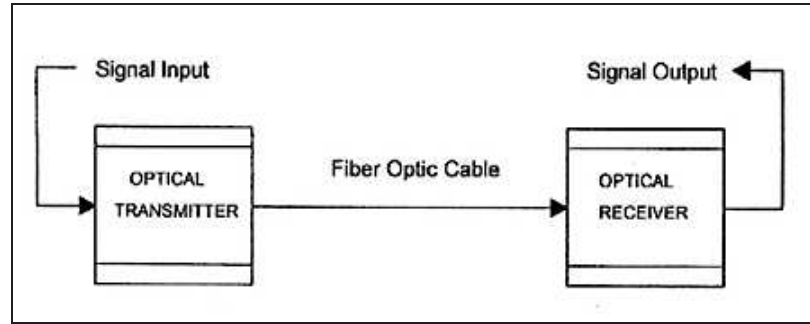


Figure 2.2: *Simple fiber optic transmission system.* Figure taken from [21].

more detail in section 2.3.1.

The optical receiver contains a photodiode that detects the optical signal and converts it back to an electrical signal.

Today the fiber optical cable (henceforth referred to as fiber) is the superior transmission medium. The upper limit of fiber capacity is not known, but researchers have tried to determine it, and according to [22] the two researchers Partha Mitra and Jason Stark at Lucent Technologies have found that one single fiber can carry at least 100 Tbit/s. So today it is not the fiber itself which limits the capacity, but the equipment at either end of it. The performance of this end equipment increase every year though, and with the ongoing development of the Dense Wavelength Division Multiplexing (DWDM) technology (see section 2.3.2 on page 14), scientists succeed to utilize more and more of the theoretical capacity of the fiber. According to [23], transmission of 10 Tbit/s has been achieved in laboratories in 2001 using the DWDM technology. Outside the laboratories equipment supporting 2.56 Tbit/s for distances up to 1000 km without the need of electrical regenerators can be bought today [24].

2.3.1 Types of fiber

The quality of the fiber is of vital importance for how high bitrates one can transmit and over how long distances. Figure 2.3 on the next page shows the general structure of a fiber. The core is where the optical signal is transmitted. The light is kept in the core because the cladding is made from a material with higher refraction index than the core, thus leading to total reflection, i.e. all the light hitting the joint face of core and cladding is reflected back into the core [26]. In most fibers both the

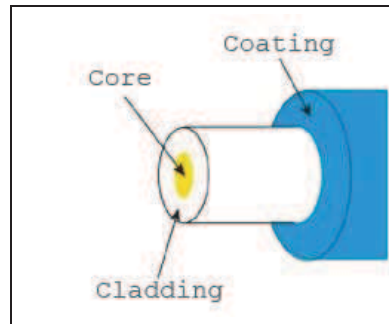


Figure 2.3: *The structure of the fiber.* Figure taken from [25].

core and the cladding are normally made from very clear glass, however there are fibers with both made from plastic, so-called Plastic Optical Fiber (POF) or with a glass core and a plastic cladding [25]. The coating surrounding the cladding should protect the core and cladding from moisture and other damage. It is normal to categorize fibers in two categories, multimode fibers and singlemode fibers.

Multimode Fiber

A mode refers to a light path in the fiber [27], so in a multimode fiber there are several possible paths for the light to travel. This is illustrated in figure 2.4. The multimode fiber has a relatively large core, typically $62.5 \mu\text{m}$

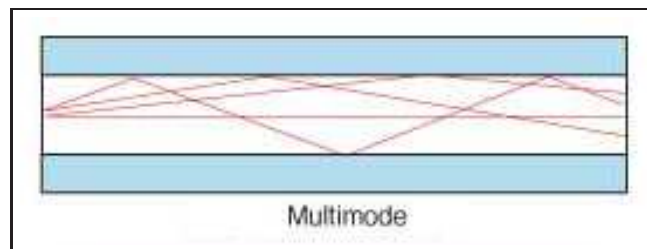


Figure 2.4: *Lightwaves in a multimode fiber.* Figure taken from [25].

(microns), and this allows several different modes to propagate within the core. Each of the light pulses will experience modal dispersion as they travel along the fiber, i.e. each pulse is spread out. Because of this modal dispersion the different pulses will interfere with each other and make it impossible to receive each single signal if they are sent without sufficient time spacing. Although there are several other factors affecting the

maximum data rate which can be sent through a multimode fiber, modal dispersion is a very important one [26].

Singlemode Fiber

The core in a single mode fiber is much smaller than the core in a multimode fiber, only 8-9 microns. Because of this thin core, all the light pulses have to travel along the same path in the fiber, as shown in figure 2.5 [26] For this reason the singlemode fiber does not exhibit the modal dispersion

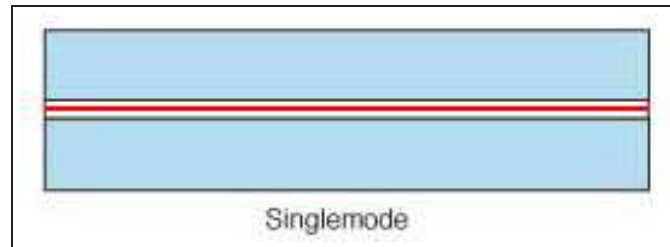


Figure 2.5: *Lightwave in a singlemode fiber.* Figure taken from [25].

caused by multiple modes, and it allows for much higher transmission speeds over longer distances than the multimode fiber. The two types of fiber are therefore suited for different purposes, with singlemode fiber as the clear choice in backbone networks with long distances and high demands to capacity, and multimode for network with more moderate distances and capacity demands, e.g. LANs.

There are two other types of optical fiber, the POF and very large core diameter silica, but the areas of application for these would normally not include data transmission networks, and they are therefore left out of the discussion on fiber types [21].

2.3.2 Dense Wavelength Division Multiplexing

As mentioned before it is the technology utilizing the fiber rather than the fiber in itself which limits the amount of data one can send through the fiber. So far the most promising technique for the utilization of the fiber is the Dense Wavelength Division Multiplexing (DWDM). It is with this technology the speeds of 10 Tbit/s referred to earlier has been achieved.

DWDM is an advanced form of Wavelength Division Multiplexing (WDM). In a fiber one wavelength represents one channel, and a single channel can carry several Gbit/s. The basic idea of WDM is to send several different

channels through one single fiber, e.g. in a two channel system one channel uses a wavelength of 1310 nm and the other a wavelength of 1550 nm. In this two channel system there is a relatively large difference between the two wavelengths used, and in traditional WDM the spacing between channels is in the range of several 10 nm. When the spacing between the different channels is reduced we start to talk about Dense WDM. In DWDM the spacing between channels can be as small as 0.4 nm, and possibly even smaller as the technology develops [23].

DWDM and fiber attenuation

The dense spacing in DWDM increases the overall spectral density of the transmitted signal, i.e. more information is transmitted using a smaller fraction of the available frequencies compared to traditional WDM¹. This is important because fibers have so-called "sweet spots" [28] which is the wavelength for which the fiber is optimized, i.e. the attenuation is the least for frequencies close to the sweet spot. Typically the fibers have their sweet spots around 1300 nm or 1550 nm.

As a result of the changing fiber properties for different wavelengths, the use of many channels in WDM will result in several channels using wavelengths far away from the sweet spot of the fiber which will then lead to worse performance in these channels. So to really take advantage of the high capacities possible with fiber one needs to use DWDM. It should be mentioned though that capacities high enough for most purposes can be achieved using single channel or two channel systems which is obtained using the cheaper technology of CWDM¹.

2.3.3 The optical transmission system

The optical transmission system is more complex than illustrated in the simple sketch in figure 2.2 on page 12. The structure in figure 2.6 on the next page shows some of the most common elements needed in an optical network. The bidirectional links are either a fiber pair or one duplex fiber.

When the distance between transmitter and receiver (or two transceivers) is sufficiently long, amplifiers are needed to amplify the signal in the fiber. Amplifiers simply re-amplify the optical signal, so any noise will be amplified just as much as the original signal. For really long distances it is there-

¹Sometimes DWDM is referred to as just WDM and the traditional WDM is called "coarse WDM (CWDM)"

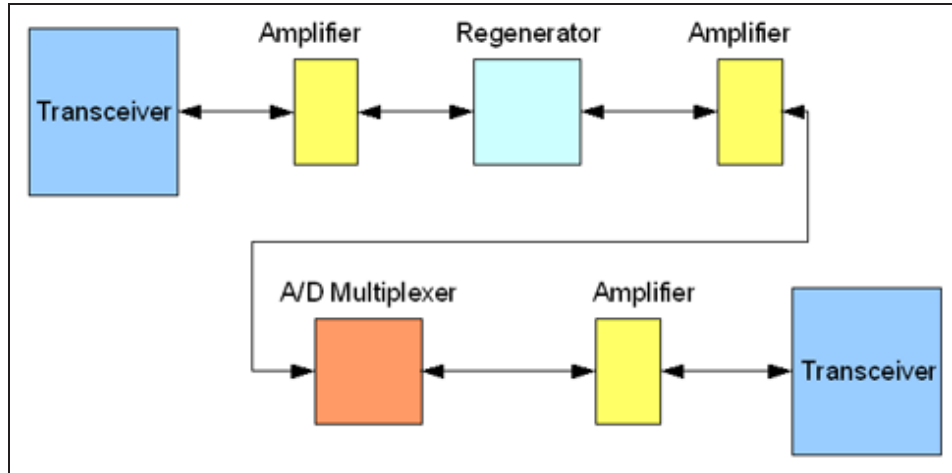


Figure 2.6: *Optical transmission system.*

fore necessary to introduce regenerators. A regenerator reconstructs the original electrical signal which is then used to make a new optical signal. The noise in the signal is removed and from the regenerator a new signal are sent which are re-amplified, reshaped and retimed. In a multichannel (wavelength division multiplexing, WDM) system these regenerators become quite complex and expensive, and should be avoided if possible [23].

The Add/Drop multiplexer is only needed in multichannel systems as its purpose is to add or drop only specific wavelengths from a joint optical signal [23]. The transceivers transmit and receive an optical signal. If it is a multichannel system the transceivers also have to multiplex and demultiplex the different signals.

Sometimes two fibers have to be connected without passing any of the network equipment shown in figure 2.6. There are two ways of doing this. One option is to splice the two fibers, i.e. to make a permanent joint between the two fibers. The other option is two use a connector which is a device used to make a non-permanent connection between two fibers. The connector should be used if the fibers are expected to be disconnected occasionally for testing or rerouting [25].

2.4 Free space optics

Free space optics (FSO) is a technology based on optical signals just like fiber optics, and the principles of the two technologies are more or less

the same. The major difference is the transmission medium, which in the FSO case is the air. The FSO can be seen as an attempt to combine the best from wireless with the best from fiber optics, i.e. get the flexibility and cost advantages of wireless communication as well as reaching capacities close to those of fiber.

One supplier of equipment for FSO equipment is LightPointe, and they have among others a product series named FlightStrata. The equipment in this family can deliver bit rates from 155 Mbit/s to 1.25 Gbit/s full duplex, with ranges from 4800 to 2000 meters respectively. These distances are given as the maximum distances, while the recommended distances are 3000 m in the case of 155 Mbit/s and 750 m in the case of 1.25 Gbit/s [29].

For the highest bit rates the recommended range for FlightStrata is 750 m, and even though that is rather short, it could be sufficient in many cases for a citywide backbone network. Also, even though it is wireless there are no requirements for licenses, and it is not troubled by radio interference. However, FSO is still considered a new technology and it has some major disadvantages. The biggest problem is that it is absolutely necessary with a line of sight between transmitter and receiver. Helicopters, construction cranes and even small objects like birds sitting in front of a transmitter or receiver or just flying through the line between them, will block the transmission. Also weather conditions like heavy rain, snow and in particular fog has a great impact on the range of FSO systems, and therefore it is necessary to keep the distances between transceivers very low compared to the range possible under good conditions [30].

Other factors also affecting the availability of a FSO link is scintillation, window attenuation (when the transceivers are placed indoor) and problems related to the alignment of transceivers. Altogether these factors reduces the availability of the system.

For networks carrying voice traffic it is normal for carriers to require "five nines" (99.999%) availability. In the case of FSO it is more common to talk of 99.9% availability, and even for this it will often be needed to reduce the link distances considerably, maybe to as short as 200 meters [31]. To achieve the desired availability of 99.999% the link distance can be no more than 150 m [32], and this reduces the possible applications for FSO. Because of these availability issues FSO equipment suppliers still focus mainly on the enterprise market where high bit rates and price often are more important than availability.

FSO has a great potential and could be a widely used technology also by carriers in the future, but because of the shortages mentioned above further discussions in this thesis will focus on the three other technologies introduced earlier; radio, xDSL and fiber optics.

2.5 Leased line

Leased line is not a technology but a service offered by different operators which gives the possibility to lease a line offering a given capacity available between two locations. Typical capacities for digital leased lines are between 64 Kbps and 155 Mbps, and this service is often used by clients with a high demand for availability and security. Fiber connections will be discussed separately and is not included in the concept of leased lines in this thesis.

With fiber removed from the equations, some preliminary investigations were enough to rule out leased lines as an alternative for backbone in a wireless CWN. A comparison of leased line and radio as regards to performance and price was enough to conclude that radio would be a better solution. During one year the expensed of a leased 155 Mbit/s line for less than 1 km would cost more than the establishing of a radio link with the same capacity using Nera CityLink [33, 9]. Because of these high costs of leased lines, this alternative is not discussed further in this thesis.

2.6 Network Topologies

This section will give a brief description of five major network topologies. A network topology refers to the shape of the network, i.e. how the different nodes in the network are connected, The topology is independent of the transmission technology chosen, although different topologies possess qualities which makes them more suited for one transmission technology than another.

Larger networks will often be a hybrid of two or more of the network topologies presented below, but it is useful to understand the basic structures and be aware of the pros and cons connected to each of them.

2.6.1 Bus Topology

A simple sketch of the bus topology is shown in figure 2.7 on the next page. In such a network all the nodes are connected by a shared medium. In the wired case this medium (the bus) will be a backbone cable, while in the wireless case it will be a specific radio frequency.

One important property of the bus topology is that all the data signals are broadcasted to all the nodes connected to the bus, so each of the nodes has to decide whether it should use a message or just ignore it.

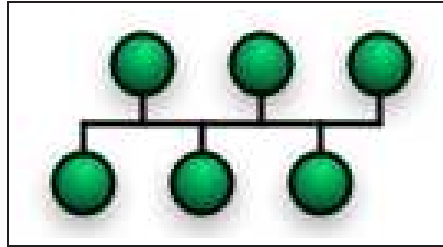


Figure 2.7: *Bus topology.*

The bus alternative is very simple, easy to understand and easy to deploy. The span of the network will be close to a minimum, which means that the costs of deployment are low compared to more extensive topologies presented later in this discussion.

The major drawbacks are collisions as a consequence of two or more nodes transmitting on the common medium at the same time, and the fault vulnerability. Because of the common medium all the nodes in the network may be affected by any network problem [34].

2.6.2 Ring Topology

In a ring topology all the nodes are connected by a single loop (see figure 2.8) consisting of several point-to-point links, and the data signals travels in one direction only. As the signal travels through the loop each node amplifies the signal before it passes it on. A message should always go the whole round so when it comes back to the sender this knows that the signal has reached the receiver.

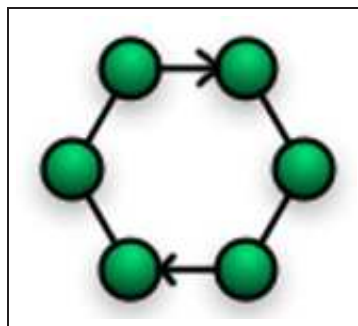


Figure 2.8: *Ring topology.*

An advantage of the ring topology is that each node in the ring regenerates

the signal so that there is very little signal degradation, and this makes it possible with rather long distances between successive nodes.

One big disadvantage of the ring topology is the fact that a broken link between any two nodes or a failed node will disable the entire network. Adding or removing a node in the ring will also disable the entire network, so the structure is also rather inflexible. To reduce the effect of broken nodes/links and increase the flexibility a ring is usually constructed with networks elements capable of sending the traffic in both directions so that a single node failure will not affect the operation of the entire ring [34, 35, 1]

2.6.3 Star Topology

The star topology is a popular networks solution, and its configuration is shown in figure 2.9. All the network nodes are connected to a centralized unit with point-to-point links. The centralized unit is often referred to as *hub*. This hub may be passive, active or intelligent. Passive and active hubs simply split the incoming signal to all the nodes, with the advantage of a active hub being that this regenerates and retransmit the information while the passive hubs simply split the signal. An intelligent hub will not send all the data to all the nodes, but only send data on the branch leading to the receiving node. In the case of redundant paths, the intelligent hub can select the best path at any time. A switch is an example of an intelligent hub.

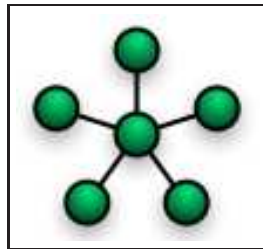


Figure 2.9: *Star topology.*

There are several benefits with this approach to network configuration. Each of the nodes is connected via its own point-to-point link, which makes it easy to isolate one signal node from the network if necessary, and it is easy to add or remove nodes without affecting the rest of the network. All the data pass through the hub, which makes it easier to trouble shoot and manage the network.

The downsides are connected to single-point-of-failure and increased costs compared to the previously presented topologies. The central hub is a very critical part of the network, and should this have a failure the whole network will fail. Increased costs is a result of the point-to-point links between the hub and the nodes in the network [34, 35].

2.6.4 Tree Topology

The tree topology is really just several star topologies connected together in a hierarchy, where each node in the tree acts like a central hub for its "children", i.e. the nodes in the next level of the tree connected to it. The structure of a tree is as shown in figure 2.10. Since the tree is merely a

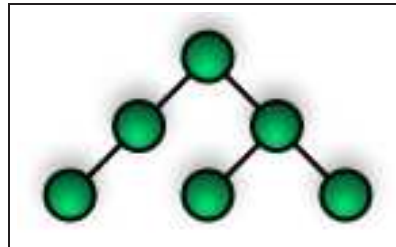


Figure 2.10: *Tree topology.*

combination of star networks, it possesses the same advantages and disadvantages as the star.

2.6.5 Mesh Topology

For mesh networks it is often made a distinction between full meshed networks and meshed networks. In a full-meshed network all the nodes have

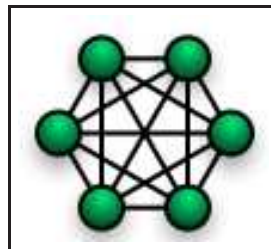


Figure 2.11: *Mesh topology.*

a physical connection to all the other nodes in the network (see figure 2.11 on the previous page), while a meshed network means that some nodes have physical connections to more than two other nodes. Some times mesh network is used in the meaning full mesh network, but in this thesis the presented distinction between mesh and full mesh will be used.

It is obvious that a mesh network with all its redundant links will offer high performance and better reliability than the alternatives with single point-to-point links. The price to pay is increased complexity and in many cases an increase in deployment costs. The complexity of a mesh network increases rapidly with the number of nodes. In the case of a full mesh network, the number of links needed is $n*(n-1)/2$, where n is the number of nodes. The costs connected to the construction of a mesh network depend on the technology used. For cabled solutions like fiber it will be very expensive to deploy several independent links to each node, while for radio the setup of alternative links can be done automatically when needed. Without spare resources in the radio network the establishment of an alternative link will reduce the capacity of the access points affected, but the extra cost connected to deployment of redundant links is avoided.

Chapter 3

Decision Factors

There are several factors to consider before a choice is made about which technology to use at the given locations. This chapter will discuss topics like current and future capacity needs, scalability, performance requirements and time perspective. The costs connected to each technology is also a very important decision factor, and chapter 4 on page 33 gives a thoroughly evaluation of the cost implications of different technology choices.

3.1 Time perspective

Time can be a very critical factor in the deployment of networks, especially if the network is a backbone for a wireless citywide network. The technology of choice for a wireless access network is Wi-Fi, which uses the license free frequency bands of 2.4 GHz and 5 GHz. The frequency bands are unlicensed, but it would not make sense for an operator to build a Citywide Network (CWN) using Wi-Fi technology in an area already occupied by another operator. The result of this would be much interference and the two networks could end up delivering far less capacity combined than one network alone [1].

For someone building a wireless CWN it will therefore be important to be the first to deploy the access network, and therefore it will also be important to build the backbone network fast. Other CWNs are not the only threat to a potential deployment. There might be a higher risk that the most popular areas could be covered by smaller wireless Local Area Networks (LANs) or Wi-Fi hot spots, leaving the CWN operator with a network just covering the less attractive places.

3.1.1 Radio and xDSL

In most situations it will be possible to deploy both radio and xDSL solutions very fast, sometimes as fast as within a few days, and these technologies will therefore be very attractive choices if time is a critical factor. However, it is not always radio or xDSL will be possible to deploy in a short time.

xDSL

In the case of xDSL it is mainly a question of whether it is possible to get a given xDSL solution at a given location or not, which depends on the services supported by the central serving the location. If the central in question does not support the requested xDSL service, then xDSL is not an option. Most telecom operators do upgrade their centrals to support at least ADSL, but to wait for such an upgrade is likely to be unacceptable for the schedule for many deployments. It would be possible for the builder of the wireless CWN to deploy its own backbone using xDSL technologies. However, the main purpose of xDSL is to utilize the copper infrastructure already available, and given the rather limited capacity of xDSL new deployment of infrastructure to support xDSL is left out of this discussion.

Radio

If the decision is made to use radio the deployment time depends very much of the specific solution selected. There is a possibly significant difference between the use of licensed versus unlicensed frequency bands. If unlicensed frequency bands are selected, it will be possible to start the deployment as soon as the equipment is in place.

If the choice is to use licensed frequencies, it will be necessary to acquire the license. To obtain a license it is often required to send an application to the national regulator. How much time this process will take depends on how the national operator handles the application. In Norway most licenses are given by Norwegian Post and Telecommunication Authority (NPT), and the time they need to process a license depends on the frequencies in question. If the application is for licenses given after the principle of "first come first served", the process should take no more than six weeks. However, in some cases it is necessary to make publication of an application to give others a chance to report their interest, and the time will in this case depend on the time limit set for others to report their interest [36].

3.1.2 Fiber optics

For fiber there are four different scenarios, each with a very different time perspective:

- Fiber is available at the location with draw-off point².
- Fiber is available at the location without draw-off point².
- Microduct tube for blowing fiber is available at the location.
- No fiber infrastructure is available at the location.

Fiber available with draw-off point

In this situation it will be possible to establish the connection very fast. Some preparations may have to be done, depending on the use of the available fiber and equipment already installed. In best case all the needed termination equipment is available and with free resources so that an additional line can be connected. In this case just the cabling from the termination till the access point need to be done. Other situations could be dark fiber with no termination equipment, or fiber already in use but with insufficient termination equipment. The different situation involves different costs, and will be discussed in more detail in the chapter 4 on page 33. Regarding time there are small differences, and establishment may always be fast in the case of fiber with draw-off point available.

Fiber available without draw-off point

In this case there is a fiber passing by close to the location, but with no draw-off point available, and such a point will then have to be established. One possibility is to cut the fiber, and put in place the necessary equipment like a switch or a multiplexer. Redirection of unused fiber is another option, i.e. remove the fiber from its current path and instead direct it to the desired location. Regardless of how it is done, the procedure is likely to require some digging to access the fiber and also to cable the last meters to the location in question, and as a consequence of this deployment can be relatively time consuming.

²A draw-off point is a point where one or more fibers are terminated, e.g. switches or fiber ends

Microduct tube for blowing fiber available

In the deployment of a fiber optic infrastructure, the installation of the fiber cable is the most time consuming and the most expensive process [27]. If there are microduct tubes already in place, this makes the job much easier, and both time and costs are considerably reduced. Buy the fiber and blow it, and then there is fiber at the location with a draw-off point where the fiber exits the microduct tube. The time perspective in this situation will therefore be much like the time perspective in the first case of fiber available with draw-off point.

No fiber infrastructure available

In this case there is no fiber infrastructure available close to the location, so a new fiber path will have to be made. A permission to do digging will have to be acquired, and the job should be planned and performed. All together a process which could be very time consuming, and with this case will impose a time delay to the deployment which will be much longer than for xDSL, radio and the other fiber scenarios. It is also very expensive to establish a fiber infrastructure from scratch, but this is discussed more in chapter 4 on page 33

3.2 Performance

There are several different parameters defining the performance of a network, and capacity and availability are a couple of very important factors discussed in more detail in this section.

3.2.1 Capacity requirements

The different technologies discussed in this thesis have very different bit rate capacities, and in general xDSL technologies offer low capacity, radio offers medium capacity and fiber optics offers high capacity. See chapter 2 on page 4 for more details on capacities of the different technologies.

The backbone network could be heterogeneous, i.e. different technologies may be used in different parts of the network to satisfy different capacity requirements. To survey the current capacity needs is not necessarily an easy task, but it should be possible to obtain a good guess just by calculating the number of access points supported by each of the different links in the backbone. However, it is not sufficient to know the current

capacity needs to decide which technology to choose. It is just as important to consider future capacity demands for capacity, and this is not an easy task. [37] shows that estimation of future capacity requirements is very important for the choice of technology, and that erroneous estimates can result in the wrong choice and thereby reducing the profitability of the investment.

Estimation of future capacity requirements

Estimation of future traffic in the citywide backbone can be everything but an easy task, and it is outside the scope of this thesis to go into details on how to do this. However, as shown in [37], estimation of future demand may be very critical to the value of the investment and will therefore be given some attention in this section.

A possible approach to estimation of traffic is to look at the development and predictions made for the global Internet traffic and make use of these. For the period from 1997 to 2003 Internet traffic grew very fast, approximately doubling each year [38], and though the growth is still fast it now shows signs of slowing down [39]. Forecasts are that the volume of traffic will continue to grow through the next years, but at a decreasing rate.

To use traffic measurements and predictions from overall Internet traffic to estimate future capacity needs in the CWN backbone, one will have to assume that traffic in the wireless CWN has the same characteristics as the Internet traffic. Table 3.1 shows the composition of traffic in a part of the Sprint backbone in February 2004 [40].

Category	Bytes (approximate values in %)
Web	30
File sharing	25
Other TCP traffic	35
Streaming	5
Miscellaneous	5

Table 3.1: *Composition of Internet traffic in Sprint backbone February 2004* Values are calculated from [40]

Most data networks today are fixed wired networks or wireless networks with a limited degree of mobility, and most traffic is generated from desktops and laptops. A wireless CWN will offer outdoor coverage and possibly also support mobility. As a result of this, desktops will not be the

preferred user equipment and laptops and smaller, more mobile user terminals will dominate. With the change of user equipment also the area of application may change, and as a result traffic in the wireless CWN may have characteristics very different from those given in table 3.1 on the previous page. In stead of web browsing and file sharing as the dominant applications, services like Voice over IP (VoIP), video telephony and streaming might become dominant, and could result in a very different traffic pattern.

Scalability

Given the differences in maximum capacity of the various backbone technologies, it is obvious that they also have different scalability. Scalability is an important property of any technology because it makes it more robust to unpredicted changes in capacity requirements. The various xDSL technologies offers some degree of scalability. As shown in table 2.1 on page 11 there is quite a big difference between the capacity delivered by ADSL and VDSL, and the upgrade from one xDSL technology to another may be achieved by upgrading the equipment at either end of the connection. However, the high bit rate xDSL solutions are restricted by the distance from central to delivery location, so an infrastructure build for the lower bit rates is likely to be insufficient to support the highest rates. With the relatively low capacities of xDSL a significant increase in capacity demand is therefore likely to render the xDSL solution obsolete.

Radio can deliver higher bit rates over longer distances than xDSL. In addition radio communication is not bound by a fixed wired infrastructure, which makes it quicker and often cheaper to take down and/or establish new links. An equipment supplier like Nera delivers equipment which can upgrade bit rate capacities by simply updating the software of the base station [10, 41]. With the absence of wired infrastructure and the possibility to upgrade bit rate capacities by upgrading the software, radio has good scalability. Still, the maximum capacities of radio communication is rather limited, and if much traffic is accumulated also radio could prove to be insufficient.

Fiber optics is by far the most robust technology, and it is superior also when it comes to scalability. As mentioned in chapter 2 on page 4, the capacity of a fiber is limited by the end equipment. So with the fiber infrastructure in place all conceivable upgrades may be made simply by replacing the equipment at either end of the fiber link [42].

3.2.2 Availability

The availability of the system is defined as the probability that the system (network) is in an operating state at a given instant of time. For telecommunications systems it is common to require an availability of 99.999%, i.e. the network should not be unavailable more than approximately five minutes in one year. With the growing use of voice over IP, voice and data network integrate, and the requirement for availability will be decided by the application with the most stringent demand for availability i.e. voice. The unavailability of a network or a component may be given in stead of the availability, and often this unavailability is given as minutes of unavailability per year.

There are several factors influencing the availability of the network, and four of them are [43]:

- reliability of the network components
- maintenance procedures
- routing and protection
- protection switching

It is an engineering task to construct a network so that a given availability is achieved. The reliability of the network components is given, and the nature and consequences of the maintenance procedures are also very much given by the equipment in use.

The level of protection against equipment failure is decided by the level of redundancy, i.e. the possibility to use alternative routes and/or components, and how the protection is activated, i.e. automatic or manual switching. The redundancy in a network is closely connected to the choice of network topology (see section 2.6 on page 18). In a full mesh network there will be several different routes from one node to another, so one or a few failed links will not necessarily affect the availability for any of the nodes since there are alternative routes. For the same reason the failure of one node will not necessarily affect the availability for other nodes in the network. The downside of the mesh network approach is the complexity and the high costs. To make use of the potential flexibility of the meshed network the different nodes become quite complex as they have to find the best routes available from one node to another, and discover broken links and nodes and shift traffic to new routes. This complexity induces higher costs, and will also affect the reliability of the nodes. A contrast to the full

mesh network is a simple one-directional ring network. In this case the whole network will break down if just one link or one node should fail.

Regardless of the topology used for the design, the introduction of redundant equipment is used to increase the system availability. There are two major principles for the use of redundant equipment; Modular redundancy and Stand-by redundancy [44].

In modular redundancy all the equipment installed is active, so a failure in one of the active elements will be masked by the other. With modular redundancy there will be no actual switching among different elements and the service will be delivered continuously. In stead it will be necessary to introduce a decision mechanism which will decide what data to use in the case of an error [44].

The stand-by redundancy is implemented with active and passive copies. The active copies deliver the service, and the passive are just for backup and will be switched into operation should any of the active copies fail. Stand-by systems can be divided into three main groups [44]:

Cold standbys which means that there is (are) an unpowered copy(ies) of the system which can be started and but into operation if the active copy fails. This kind of standby is applied when it is tolerated to loose state information and if it is acceptable with loss of service which will occur during the start-up of the passive copy.

Hot standbys are standbys which are powered up and ready to take over operation when the active copy fails. This kind of standby is used is the service delivery is required to be continuous or only a short interruption is allowed.

Loadshare systems are not pure stand-by systems, but are more like overdimensioned systems meaning that all the copies are active and the load is shared between them. Protection is achieved because the number of active copies is high enough to allow for one (or more) of them to fail without the performance of the system to go below the required level.

3.2.3 Equipment reliability

The above discussion shows that the specifications of the components in the network is just one of more factors deciding the availability of the network. So by designing a network in the right way, most technologies may deliver the required availability. The difference is how much protection that is needed for the different technologies.

According to [42], fiber is the best technology also as regards to operational reliability, i.e. the use of fiber will give less need for protection than any of the other technologies. It is difficult to obtain a "standard number" for the availability of links, regardless of the transmission technology, because this depends on the number of elements constituting the link and the quality of these elements.

Common for all the technologies is that the transmission medium is contributing heavily to the unavailability time. For cable networks the (copper) cable faults can in some cases be responsible for as much as 95% of the unavailability time [43]. Experience also show that the fiber cable in optical networks have a greater impact on the unavailability than the terminals and repeaters [45], but while copper cables may get problems with ElectroMagnetic Interference (EMI) this is no problem for fiber cables.

Just as xDSL and fiber are vulnerable to cable failures, the availability of radio is heavily affected by the quality of the transmission medium, and sundry phenomena will affect the radio transmission in various ways for different frequencies used. Rain fading is one example. For lower frequencies (below 10 GHz), rain fading is not a major problem, but the problem increases rapidly for frequencies above 10 GHz and when the frequency is 15 GHz or higher, rain fading is the dominant fading mechanism [46]. This goes for all radio equipment, and one example of the effects of rain intensity on radio transmission is given in [47]. The Nera CityLink may operate in the 18 GHz frequency band, and given that the link should have a 99.99% availability, the link distance will vary from less than 6 km in parts of the world with high rain intensity to 25 km in areas with low rain intensity.

3.3 Possibility for research activity

In the case of Wireless Trondheim it is requested that the wireless network should be available for research activity, so the backbone network will need the resources to support such activity. A typical area of research is testing of new radio technologies, e.g. WiMAX, which will support bit rates of 50 - 100 Mbit/s. To do a realistic test of new technologies with such bit rates also the backbone network will have to support such bit rates. Regardless of the nature of the research, it will generate traffic that the backbone should be able to carry in addition to the traffic generated from the regular users.

One problem with research activity for the backbone network is the increased capacity demand, and this is likely to render useless the xDSL

technologies and the low and medium rate radio technologies. Fiber optics is far better than all other technologies when it comes to capacity, so extra traffic generated from research activity will make fiber a more attractive solution.

Also the reliability and the availability of the network are important properties of a network used to carry research activity. If new technologies or products should be tested with these properties as important test factors, it is crucial that the backbone network can deliver a service good enough to not affect the test results considerably.

Research has the potential to increase the load and quality requirements of the backbone very much and thereby reduce the number of applicable solutions. A restriction of research traffic to certain areas will leave open the possibilities to use technologies with lower bit rates capacity and inferior quality of service at locations not hampered with the load of research traffic.

Chapter 4

Costs

The preceding chapters have shown how fiber is the best performing technology. Radio and xDSL will often be faster to get into operation, but when it comes to performance the fiber optics score far better than all the alternatives primarily because of its huge bit rate capacity. If two or all three of the technologies discussed here possess the qualities needed, the economics of the different choices will be the deciding factor. This chapter will present some economical analyses for different situations.

4.1 Topology

The topologies discussed in section 2.6 on page 18 have very different properties, including very different costs of deployment. In this thesis the calculations will be based on deployment using a tree topology. There might be several levels in this tree, but it will be possible to divide it into two major parts. The upper part consists of the trunks, and the lower level consists of the spreading links. The trunks carry traffic from two or more access points, while the spreading links carry traffic from a single access point to the trunk.

With this network topology it is possible to use different technologies in the trunk and spreading part of the network, so for each link it will be possible to choose the technology which is best suited. One of the major advantages of this topology is that it gives a good balance between costs and vulnerability.

4.2 The different scenarios

For each location there are several possible scenarios, and this section will give an overview of the various situations discussed further in this thesis.

xDSL

As mentioned before the xDSL technologies are better ways to utilize the existing copper access network, and deployment of new infrastructure to support the delivery of one or more of the xDSL technologies is not discussed as an option. In the case of xDSL there is therefore two possibilities, *xDSL is available* or *xDSL is not available*.

Because of the very limited range of the high capacity VDSL technologies and the capacity limitations of ADSL, ADSL2, HDSL and SDSL (see table 2.1 on page 11), ADSL2+ and SHDSL is the two most interesting technologies. While ADSL2+ can offer high downstream bitrates, the upstream is rather limited. SHDSL on the other side offers moderate capacity in both directions, but the price is much higher for this kind of connection than for ADSL2+. The typical user generates more downstream traffic than upstream, and the moderate synchronous capacity of SHDSL may result in lacking downstream capacity while there will be spare upstream capacity.

Because of the asynchronous traffic pattern and the advantageous price of ADSL2+ compared to SHDSL, ADSL2+ will be used as the main representative for xDSL technologies and in the following economic evaluations price estimates for ADSL2+ will be used. However, it is important to keep in mind the considerations from section 3.2.1 on page 27 regarding potential changes in the traffic pattern as a consequence of e.g. VoIP, and therefore some calculations will be done also on the costs of SHDSL to see if it may be an alternative.

Radio

With radio it is unlikely that it is possible to make use of infrastructure already deployed, so the use of radio will result in the deployment of new infrastructure. As mentioned before the backbone for the CWN could be divided into two levels, trunks and spreading, and radio could be used in one or both of the levels. In the case illustrated in figure 4.1 on the following page radio technology is used to do the whole job. Radio links connect the access points to a radio backbone access point, and trunked traffic are

sent further in the network using radio technology. The connections between backbone radios are typically point-to-point (PTP) links, and the connections to the access points are typically lower capacity PTP links or point-to-multipoint (PTM).

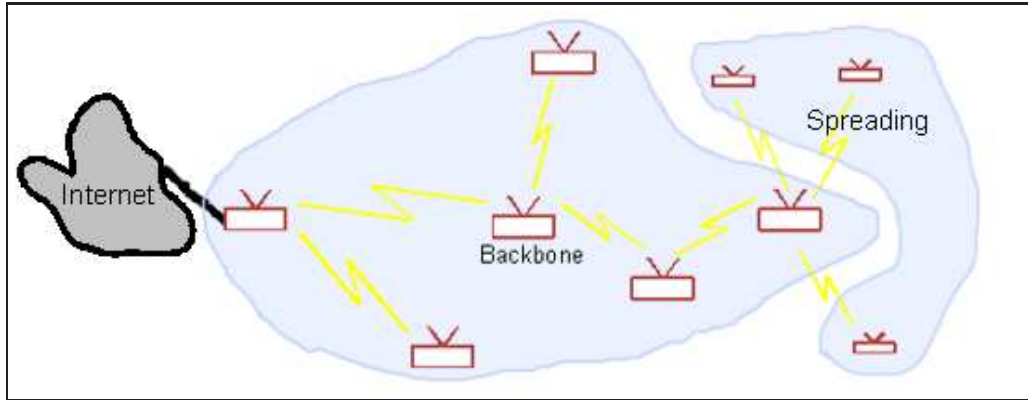


Figure 4.1: Radio carrying trunked traffic.

Figure 4.2 illustrates a situation where the trunked traffic is carried by fiber and radio is used just to bridge the gap from the fiber termination to the access points, the spreading.

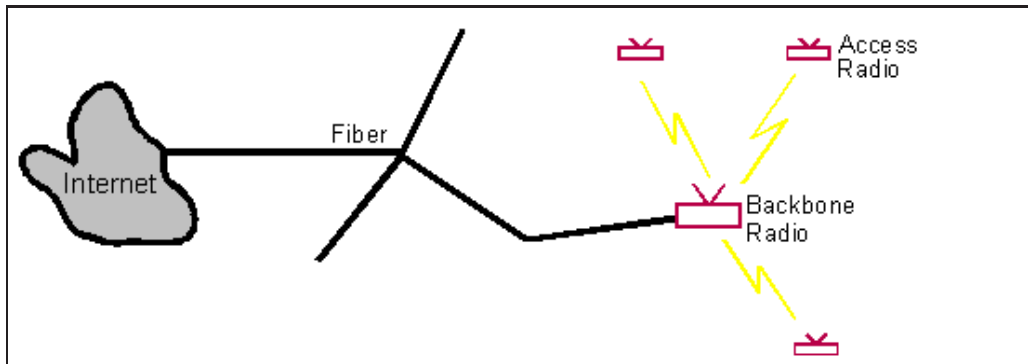


Figure 4.2: Trunked traffic in fiber and single connections with radio

A third alternative is to use radio to carry the trunked traffic while wired solutions are used for the single connections to the access points.

Fiber

For fiber the situation is a little more complicated than for xDSL and radio. In section 3.1.2 on page 25 four different scenarios for fiber is described:

- Fiber is available at the location with draw-off point³.
- Fiber is available at the location without draw-off point³.
- Microduct tube for blowing fiber is available at the location.
- No fiber infrastructure is available at the location.

It is clear that the costs connected to the use of fiber to a location will vary significantly depending on the different scenarios above, and all the different cases will be considered in the economic evaluations. Fiber is likely to be used only for trunking of traffic, for example in such a way as illustrated in figure 4.2 on the previous page

4.3 Prices

There are a lot of different suppliers of both the xDSL services and the equipment to be used in radio and fiber optics, and therefore also a variety of quality and price. This section will introduce the price estimates used in the later calculations for the different services. All the prices will be given in Norwegian Krone (NOK), and the prices used are from the Norwegian market.

4.3.1 xDSL

The main xDSL technology to be considered is the ADSL2+. ADSL2+ is still in an early deployment face, but actors like NextGenTel and Ventelo deliver this service in Norway. The price estimate used in the calculations will be *NOK 1000 per month*. This is based on the price charged by NextGenTel per 08.06.2006 for the delivery of this service [48]. In the cases when also SHDSL is considered, a price of *NOK 6500 per month* for 8 Mbit/s will be used. This price is based on the rates of Telenor per 08.06.2006 for the delivery of this service [49].

³A draw-off point is a point where one or more fibers are terminated, e.g. switches and fiber ends

4.3.2 Radio

Last section introduced the two levels of the backbone network, and showed how radio may be used in one or both of those levels. However, the technologies used are likely to be different for the two levels, with high capacity PTP links carrying the trunked traffic and PTM or lower capacity PTP links for the traffic from single access points. PTP solutions for trunked traffic will be discussed here, while the spreading will be discussed further in section 4.3.4 on page 40

Trunked traffic

There are several different suppliers of equipment for radio trunks. Nera and Proxim are two of these, and the products discussed in section 2.1 on page 4 from these two suppliers are all PTP solutions. Three equipment suppliers operating in Norway are ArcIT, Nera and Witelcom. Nera and Witelcom develop and produce their own radio equipment while ArcIT is a distributor for among others Proxim and Orthogon Systems. Table 4.1 gives an overview over prices given for links of different capacities from each of these suppliers, where OS Spectra links from Orthogon Systems is provided by ArcIT. The equipment from Nera operates in licensed fre-

Product	Capacity	Price (complete link)
Nera FlexLink	32 Mbit/s	NOK 95 000
Nera CityLink	155 Mbit/s	NOK 185 000
Witelcom for links up to 8 km	35 Mbit/s	NOK 14 000
Witelcom for links up to 15 km	35 Mbit/s	NOK 18 000
OS Spectra Lite	150 Mbit/s	NOK 100 000
OS Spectra	300 Mbit/s	NOK 125 000

Table 4.1: *Price estimates for different PTP radio links.* Estimates given by [9, 11, 50, 51]

quency bands, while the two others use license free frequencies. The Nera CityLink is currently being phased out and replaced by the a new series called Nera Evolution Metro. Area of application is the same for Evolution Metro as for CityLink, but the new product will offer more flexibility at a lower price [11].

The new Evolution Metro will be software upgradeable to 310 Mbit/s, and with an extra outdoor unit it could deliver up to 620 Mbit/s. The prices for these upgrades are not yet decided, but somewhere between 50

and 70 per cent of the initial investment for each upgrade [11]. Also the OS Spectra Lite is software upgradeable to OS Spectra and its 300 Mbit/s capacity. This upgrade costs NOK 25 000, the exact price difference between OS Spectra Lite and OS Spectra [51].

The products delivering 30-40 Mbit/s will not be considered more in this thesis since this capacity is likely to be too low to support trunked traffic from several Wi-Fi access points. In the calculations it will be assumed an initial deployment of equipment with a capacity of ca. 150 Mbit/s. As the overview shows there are considerable price differences between the product from Nera and the product from Orthogon Systems, but with these two prices as basis the price estimate used in the calculation for 150 Mbit/s radio PTP links will be set to *NOK 130 000*.

4.3.3 Fiber

There are several factors which all together constitute the total expenses of a fiber network, but the major factor is the cost of digging the ditch for the fiber. According to [20, 27] digging and closing of the ditch accounts for approximately 70% of the total expenses of a fiber network deployment. The remaining 30% include expenses for cable, roll out of cable and network equipment. There is a big difference in cost of fiber deployment in areas without roads or buildings compared to city centres with much other infrastructure already in place. Since the price is so dependent of the situation in each single deployment, it is difficult to give a general estimate of the cost of deploying one meter of fiber. Different projects operate with different prices, and the prices from the following example is based on prices given by [52, 53]:

Cost of digging the ditch	NOK 136,00
+ Cost of tube and the deployment of this	NOK 30,00
+ Cost of fiber, G24, 9/125 SM	NOK 35,00
+ Asphalt work (width ca. 50 cm)	NOK 130,00
<hr/>	<hr/>
= Price for one meter of fiber	NOK 336,00

Other price estimates given by [54, 20] are NOK 800 - 1000 and NOK 300 - 1000 respectively. The first estimate assumes establishment of new fiber route in a city, and the latter is for the establishment of new route in an asphalted street. Based on this information it is difficult set a price estimate, but since this thesis is about establishment of backbone in a city the price given which assumes establishment in a city will weigh a little more

than the other estimates and a price of *NOK 700,00 per meter* of fiber will be used when estimating the costs of fiber deployment.

Even though the fiber deployment is dominating other costs in a fiber network, termination and network equipment also represent considerable expenses. Table 4.2 shows the price estimates which will be used in the coming calculations. The estimates is based on prices given by [52, 53] and on equipment prices in web shops like TechLife.no and Advance.no [55, 56].

Equipment type and/or job performed	Price in NOK
Blowing of fiber in existing tube(per meter)	8,00
Cost of fiber cable, G24, 9/125 SM	30,00
Termination of fiber (per fiber)	500,00
Switch	10 000,00
GigaBit Interface Converter, GBIC (1310 nm)	5 000,00
GigaBit Interface Converter, GBIC (1550 nm)	20 000,00
MUX equipment (passive) for an extra CWDM channel	4 000,00

Table 4.2: *Price estimates fiber equipment.*

Leased fiber

Because of the high costs of deploying fiber, it may be an alternative to lease fiber from operators with an existing network. One such option is to lease dark fiber, i.e. unused fiber without termination equipment. In Norway there are two main operators which offer this service, Telenor and BaneTele. Prices for rent of dark fiber from these operators will vary from case to case, but estimates given are:

Operator	Establishment	Monthly fee (NOK)
Telenor ⁴	NOK 30 000 ⁵	3246 + 754 for each commenced 250 meter
BaneTele	NOK 50 000	10 000 ⁶

It should be possible to achieve considerable discounts for an operator constructing a backbone for a wireless CWN if it is interested in leasing

⁴Discounts up to 15% can be achieved if contracts are made for a period of 5 years.

⁵For connections longer than 1000 meter the establishment cost is NOK 50000.

⁶Price given by [57]. Actual prices given to Wireless Trondheim have a much lower monthly fee with an average of approximately NOK 4 000.

several dark fiber connections. If the establishment is also a part of a research project, like in the case of Wireless Trondheim, there will be possibilities to achieve discounted prices (academical prices). On the other side there will often be different factors not considered in these price estimates from the operators, so the actual price for a given link may turn out to be higher than indicated here. The price estimates used in the calculations for leased fiber will be *NOK 30 000 for establishment, and a monthly fee of NOK 3 200 plus 750 for each commenced 250 meter.*

4.3.4 Spreading to the access points

Whether xDSL, radio or fiber is used to carry trunked traffic, each of the Wi-Fi access points has to connect to the point of termination of the trunked traffic. This spreading to the Wi-Fi access points may be done using radio or cable.

Product or Operation	Price
50 m of cabling from e.g. fiber termination to access point, work and cable. Assumes no digging needed.	NOK 2750,00
Antenna at Wi-Fi side of radio spreading link	NOK 500,00
Installation of antenna at Wi-Fi side	NOK 500,00
Sector antenna at trunked side of radio spreading link	NOK 1000,00
Access point at trunked side for feeding Wi-Fi access points	NOK 5800,00
Installation of backhaul access point and antenna	NOK 500,00

Table 4.3: *Prices for spreading for radio and cable*

The prices provided in table 4.3 is based on price estimates for Wireless Trondheim provided by [1]. The equipment prices are based on recommended prices, and the installation costs are general estimates and will in practice vary depending on the situation at the site of installation. Spreading with radio is based on the use of 5 GHz Wi-Fi (IEEE 802.11a), and it is assumed that the Wi-Fi access points have two antenna interfaces and that they support Wireless Distribution System (WDS), MESH or Bridge operation. The spreading with this radio solution support PTM, but it will be assumed that also the spreading radio links are PTP.

4.4 Calculations

In this section the prices introduced above will be used to evaluate the costs of using the different technologies in each of the scenarios introduced in the beginning of this chapter. All the present values (PVs) presented in this section are the PVs of the costs of the various solutions. For more on how the PVs are calculated see appendix B on page 87

Assumptions and limitations

Some assumptions about technology choice and capacity have already been made, and here is a list of some more assumptions and limitations needed to get a basis for the calculations:

- Each Wi-Fi access point should have a guaranteed bandwidth of at least 10 Mbit/s, i.e. a 50 Mbit/s trunk can carry traffic from at most 5 Wi-Fi access points.
- A trunk will be assumed to carry traffic from 8 Wi-Fi access points if the capacity of the trunk is 80 Mbit/s or higher. This assumption represents the logistical restriction on how many access point that can be served by a single trunk regardless of the capacity of the trunk.
- The time periods (depreciation times) considered will be 3, 5 and 10 years, and the discount rate used is 7%.
- Only upgrades from xDSL to fiber (deployment) is considered, not from xDSL to radio.
- Radio is assumed to have an initial capacity of 150 Mbit/s and two possible upgrade scenarios: Increase the radio capacity or upgrade to fiber. Because of the many different possibilities for radio capacity upgrade, e.g. change the equipment, software upgrades, additional outdoor unit etc., an increase of the radio capacity is simply assumed to cost the same as the initial radio equipment investment. This will in most cases overestimate the cost if the capacity is doubled, but underestimate the cost in most cases if the capacity is quadrupled, but when assuming that only one upgrade of radio capacity will take place it will represent an average of the upgrade cost.
- Use of radio is assumed to require a license, and the price estimate for the license will be NOK 2 000 per year [1].

- In the calculations of present values the costs of establishment/deployment are assumed to be paid in the beginning of the year, while recurring expenses are assumed to be paid at the end of each year.
- Power Over Ethernet (PoE) is assumed to be used when cable connect an access point to trunk termination.
- Planning, maintenance and some deployment costs are omitted in the calculations (see section 5.4 on page 59).
- Microduct tubes are assumed to be available at no cost.
- All prices are given exclusive Value Added Tax (VAT).

From these assumptions we get that an ADSL2+ connection can carry traffic from 2 Wi-Fi access points, while radio and fiber trunks can carry traffic from 8 Wi-Fi access points.

4.4.1 Costs of the trunks

There are several things to consider in the calculations of the cost of a trunk, such as the importance of spare capacity to absorb future increase in capacity requirements as a consequences of research activity or upgrade of the access technology. It is also important to find reasonable time periods (depreciation times) to use in the calculations since the technologies in question have very different depreciation times. The possibility to lease trunk capacity increases the importance of the time period as leasing alternatives will become less attractive when leasing expenses accumulate over longer time. Together with the different depreciation times of the different technologies, also the uncertainty affects the choice of time period to use in the evaluations. When the time period becomes too long there will be so much uncertainty connected to future traffic pattern, capacity demand and possible technical solutions that the results from the calculations will be to uncertain to use in decision making.

One more important factor is the number of access points that is supported by one trunk. While an ADSL2+ link is assumed to support 2 access points, the radio and fiber links are assumed to support 8. The higher number of APs connected to a trunk will increase the value of this trunk, but at the it might increase the cost of the spreading network. This is because more APs connected to one trunk is likely to increase the average distance from trunk termination to the APs, and more expensive technologies (e.g. radio instead of cable) must be used to bridge the gap.

xDSL

As mentioned before the preferred xDSL technology is ADSL2+. Because of the possibility of a change in traffic pattern from asynchronous to synchronous, also the synchronous SHDSL technology is included in these first calculations on xDSL technologies. Table 4.4 shows the Present Val-

Scenario	Time period (years)		
	3	5	10
PV of cost of ADSL2+ link (in NOK)	31 492	49 202	84 283
PV of cost of ADSL2+ per access point (in NOK)	15 746	24 601	42 141
PV of cost of SHDSL link (in NOK)	204 697	319 815	547 839

Table 4.4: *The costs of an ADSL2+ and a SHDSL link over different time periods*

ues (PVs) for an ADSL2+ and a SHDSL link over different time periods, and it clearly shows that the SHDSL solution is very expensive compared to ADSL2+. Considering the fact that one ADSL2+ link can support two Wi-Fi access points while one SHDSL connection with its limited downstream capacity compared to ADSL2+ can support just one Wi-Fi access point, the cost difference per access point becomes even higher.

Radio

With the assumptions presented earlier in this chapter the cost of a radio link evaluated for different time periods will be as shown in table 4.5.

Scenario	Time period (years)		
	3	5	10
PV of cost of radio link (in NOK)	135 249	138 200	144 047
PV of cost of radio per access point (in NOK)	16 906	17 275	18 006

Table 4.5: *The cost of a radio link calculated for different time periods*

Fiber

The costs connected to the use of fiber is very different for the various availability situations described earlier. Table 4.6 on the next page presents the results from the calculations from the various situation when fiber is deployed, while table 4.7 on the following page presents the results from the calculations on leasing fiber.

Scenario		Total cost	Per AP
PV of cost for fiber with draw-off point available	Without WDM	30 000	3 750
	With WDM	48 000	6 000
PV of cost for fiber available without draw-off point		103 000	12 875
PV of cost when microduct is available		92 000	11 500
PV of cost of complete infrastructure deployment		754 000	94 250

Table 4.6: *The costs of using fiber in different situations*

In addition to the assumptions introduced earlier, the results in table 4.6 and 4.7 is based on use of 1310 nm GBIC in all cases except when fiber with draw-off point is available and WDM is needed. In the calculations it is also assumed that when no fiber is available or when only a microduct tube is available the distance of the fiber link is 1 000 meters, and in the case of fiber available without draw-off point the distance from the location where the draw-off point is created to fiber termination is set to 70 meters.

Scenario		Time period (years)		
		3	5	10
PV of cost of leasing fiber	Total cost	255 249	365 055	582 554
	Per AP	31 906	45 632	72 819

Table 4.7: *The costs of leasing fiber*

The results presented in table 4.6 are independent of the time perspective as all the investments are made initially. When no fiber infrastructure is available, in stead of deploying own fiber and undertake the expenses given in the last row in the table above, it is a possibility to lease fiber in stead. The expenses of leasing fiber is dependent of the time period, and these calculations is therefore given in the separate table 4.7.

Upgrades

For both ADSL2+ and radio there is the possibility that upgrading will be necessary during the time periods evaluated, and it is important to investigate how this will affect the present value of the total costs. The results presented in table 4.8 on the next page are based on a 10 years time perspective, and indicate how the costs vary with upgrade at different times.

In the case of an upgrade the number of access points per trunk becomes very significant, as the ADSL2+ trunk initially support just 2 access

Year of upgrade	xDSL	Radio	
	From ADSL2+ to fiber	Improved radio	From radio to fiber
1	765 215	274 047	885 869
2	726 369	265 542	838 289
3	690 065	257 594	793 821
4	656 135	250 166	752 263
5	624 425	243 224	713 423
6	594 790	236 735	677 125
7	567 094	230 672	643 201
8	541 209	225 005	611 496
9	517 018	219 708	581 865
10	494 409	214 759	554 173

Table 4.8: *The PV of cost of an ADSL2+ and a radio link when upgraded after a given time*

points. Assuming that the number of supported access points is the same also after the upgrade, both for radio and ADSL2+, we get the link costs per access point given in table 4.9.

Year of upgrade	xDSL (per AP)	Radio (per AP)	
	From ADSL2+ to fiber	Improved radio	From radio to fiber
1	382 607	34 256	110 734
2	363 185	33 193	104 786
3	345 032	32 199	99 228
4	328 068	31 271	94 033
5	312 213	30 403	89 178
6	297 395	29 592	84 641
7	283 547	28 834	80 400
8	270 604	28 126	76 437
9	258 509	27 464	72 733
10	247 205	26 845	69 272

Table 4.9: *The PV of cost per access point of an ADSL2+ and a radio link when upgraded after a given time*

4.4.2 Costs of spreading

The choice of radio or cable for the spreading from the trunk to the Wi-Fi access point is independent of the choice made for carrying the trunked

traffic. Wired solution are restricted to cable runs of approximately 100 and 150 meters⁷ for capacities of 100 Mbit/s and 10 Mbit/s respectively (using Ethernet over CAT 5 rated cable) [58], but longer distances can quite easily be achieved by introducing a switch / regenerator. A switch element will cost typically NOK 400 [1]. Using fiber cables (multimode) can also increase the distances quite a lot without very high costs, so the biggest problem of cabling is extra costs like digging which might be needed when a cable is deployed outdoor.

For radio there are several different solutions with very different capacities, and for the spreading links a capacity of approximately 15 Mbit/s delivered over 400-500 meters will be sufficient. With higher capacity needs or longer distances, price increases quite much. The price overview in table 4.1 on page 37 shows that with Witelcom equipment a complete link with a capacity of 35 Mbit/s up to 8 km will cost ca. NOK 14 000 (not including installation work). This is relatively cheap, but compared to equipment with the lower capacities of ca. 15 Mbit/s used in the example below it is still expensive. The equipment in the following example can, with the right configuration and line-of-sight, deliver capacities of 15 Mbit/s over distances of at least 400 meters [1].

Examples

If a Wi-Fi access point should be placed so that a cable connection between the access point and the trunk termination is a possibility and the distance is 100 meters, the costs will include only the cabling. With the price given for cabling in table 4.3 on page 40 the price will be $2 * \text{NOK } 2\,750,00 = \text{NOK } 5\,500,00$.

In another situation it might be necessary to use radio, and assuming a length of 70 meters from trunk termination to location of trunk side access point, the costs will be:

Cabling to trunk side access point	NOK	3 850,00
+ Wi-Fi radio at the trunk side	NOK	5 800,00
+ Sector antenna trunk side	NOK	1 000,00
+ Installation work trunk side	NOK	500,00
+ Antenna Wi-Fi side	NOK	500,00
+ Installation of antenna Wi-Fi side	NOK	500,00
<hr/> = Total cost of the radio spreading link	NOK	<hr/> 12 150,00

⁷With cable runs of 150 meters PoE may not work, and some extra costs should be expected for the establishment of power supply for the AP.

From the calculations it is quite clear that it is cost saving to locate the access point so that as many as possible can have a wired connection (at the given cost) to a trunk termination, which will often mean that the trunk is terminated in the same building where the access points are located. With ADSL2+ used to carry trunked traffic it is likely that the average distance from trunk to access point is smaller than in the case of radio and fiber, as ADSL2+ can only support 2 access points and it is easier to find a trunk location suitable for 2 access points than for 8. This should also enable wider use of cable to connect to the access point, so ADSL2+ will have the potential to make the last meter connections cheaper than radio and fiber. So even though the technology for the spreading network can be chosen independent from the technology used for the trunking, different choices for the trunk will favor different technologies for the spreading.

Research and upgrades

The calculations in the example above is based on a capacity demand of approximately 10 Mbit/s synchronous to each of the Wi-Fi access points (even though ADSL2+ trunks will not support this synchronous capacity). If a link should be used for research on higher capacity radio technologies (e.g. WiMAX), a capacity of 10 Mbit/s will not be sufficient. With a wired connection over a distance limited to ca. 100 meters, it will be possible to deliver at least 100 Mbit/s while with the low capacity radios from the price example above it will not be possible regardless of link distance.

Much the same is the case in an upgrade situation. If the technology in the access network is upgraded to support higher bit rates, the backbone will have to respond to this, both the trunk part and the spreading part. With cable over limited distances there will be spare capacity, while the low capacity radios will not satisfy the increase in capacity demand and will have to be replaced.

Chapter 5

Discussion

The results from the previous chapter are based on price estimates and fixed values of i.a. variables like average link distance and number of access points served by each trunk. In this chapter these results will be discussed, and the effects of variations in several of the variables will be investigated.

5.1 Result comparisons

The present values for the cost of a trunk link calculated per access point are summarised in table 5.1.

Scenario	Time period (years)		
	3	5	10
ADSL2+	15 746	24 601	42 141
SHDSL	204 697	319 815	547 839
Radio	19 530	21 375	25 029
Fiber available and no need for WDM	3 750	3 750	3 750
Fiber available and WDM needed	6 000	6 000	6 000
Fiber available without draw-off point	12 875	12 875	12 875
Microduct tube available	11 500	11 500	11 500
Deployment of fiber infrastructure	94 250	94 250	94 250
Lease of fiber	31 906	45 632	72 819

Table 5.1: *Present values of costs for links per access point*

These results show why SHDSL is not a good alternative. Over a period of 10 years the SHDSL solution will result in costs per access point

which is more than five times higher than the second most expensive solution, deployment of fiber. Because of the very high price SHDSL is considered to be unsuitable as a part of the backbone for a wireless CWN with the capacity requirements considered in this thesis, and is therefore left out of the discussion from now on.

The results in table 5.1 on the preceding page also show that when fiber is available with or without draw-off point or a microduct tube is available, the use of fiber is more economical than both radio and ADSL2+ even for the three year period. The costs found for these fiber scenarios may be underestimating the actual costs of these solutions because of other costs not included in the calculations. However, this is the case for all the other scenarios as well, and in section 5.4 on page 59 various sources of error and how they may affect the rating of the different technologies are discussed.

Since fiber is the cheapest solution whenever fiber infrastructure is available at or near the location or when a microduct tube is available, and since fiber is also the best performing technology it is the clear choice in these situations. The question is then what to choose when no fiber is available; ADSL2+, radio, deploy fiber or lease fiber. Figure 5.1 shows a

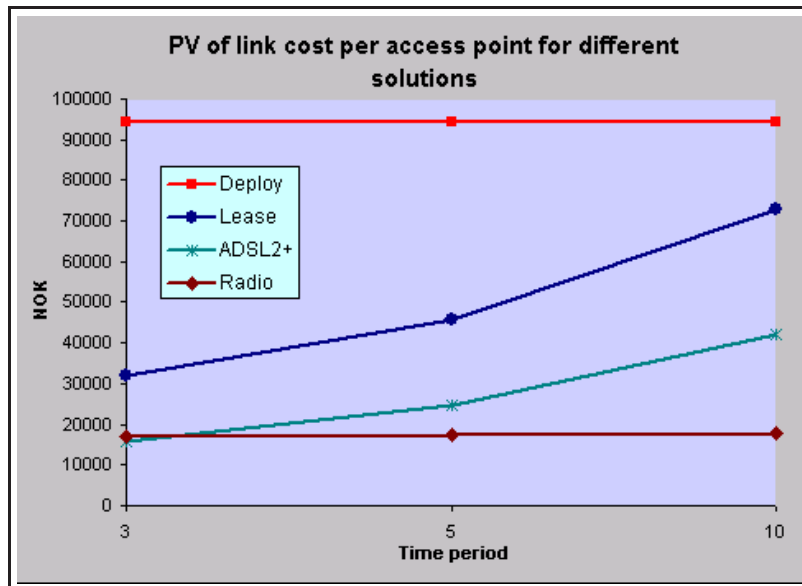


Figure 5.1: Price comparison of possible solutions when no fiber is available.

graphical representation of the results for the possible solutions when no fiber is available.

If radio and ADSL2+ for some reasons are not possible solutions, the conclusion to draw from the graphics in the figure is that lease of fiber is the best economical choice. However, the graphics show, not surprisingly, that the economical gain of leasing fiber decreases as the time period increases, and if the depreciation time is increased sufficiently the deployment of fiber will become cheaper than leasing. In section 5.2 on page 53 this is discussed further and calculations are made for time periods beyond ten years.

Now considering the case when ADSL2+ and/or radio can deliver the service in a satisfying way. In this case these two solutions are both more economical than both lease and deployment of fiber. For the choice between radio and ADSL2+ the results are ambiguous, as ADSL2+ shows to be cheapest if the time perspective is 3 years, while radio becomes the preferred choice when the time periods are extended to 5 and 10 years.

5.1.1 Upgrades

Figure 5.2 illustrates costs (calculated per access point) for the upgrade of ADSL2+ and radio at a given time compared to the costs of initial fiber deployment. The present values are calculated using a ten year time period. The curve representing an upgrade of ADSL2+ shows a cost level much

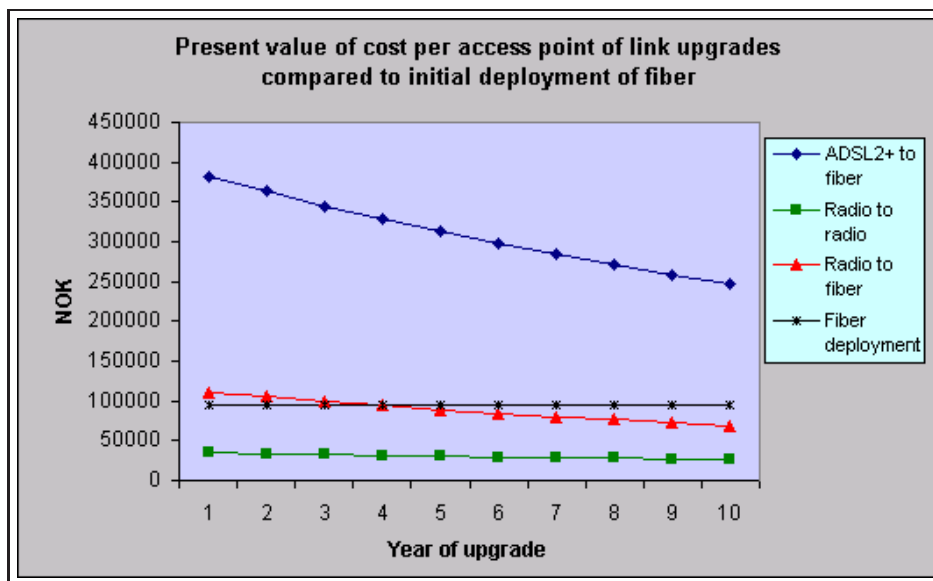


Figure 5.2: Cost of upgrade compared to initial fiber deployment.

higher than the other curves. The reason for this extremely high upgrade

cost of ADSL2+ compared to upgrade of radio and initial deployment of fiber is the assumptions made on the number of access points connected to each trunk. The cost curves in figure 5.2 on the previous page represent the link costs calculated per access point connected to the link, and with the assumption that only two access points are connected to an ADSL2+ trunk, the cost of upgrade from ADSL2+ to fiber is divided on only two access points while a radio trunk supports eight access points and the upgrade costs are therefore divided on these eight.

The reason for an ADSL2+ upgrade

When the upgrade from ADSL2+ to fiber is needed because more trunk capacity is needed to support the two access points initially connected to the trunk, the result is a fiber trunk serving just two access points, and therefore a very expensive fiber link.

If the upgrade is needed as a result of an increase in the number of access points that should be served by the trunk, e.g. because of a coverage extension, then the cost of the upgrade will be divided on more access points, and the curve in figure 5.2 on the preceding page will be shifted down. How big the shift will be depends on the number of added access points, and an analysis with the number of added access points as the variable shows that:

Total number of access points after upgrade			
<=5	6	7	8
ADSL2+ always the most expensive solution	ADSL2+ always more expensive than radio, but cheaper than fiber if upgraded after more than 7 years	ADSL2+ always slightly cheaper than radio if radio is upgraded to fiber and cheaper than fiber if upgraded after more than 3 years	ADSL2+ always cheaper than radio if radio is upgraded to fiber and cheaper than fiber if upgraded after more than 1 year

So use of ADSL2+ in areas of the network where upgrades are likely to occur because of increased capacity demand from the existing access points is not a good solution. ADSL2+ should therefore be used only when upgrading is unlikely to be necessary in the foreseeable future, or when upgrade might be needed but then as a consequence of an increase of the number of access points connected to the trunk.

The radio upgrades

As mentioned before there are two options for radio upgrade, i.e. upgrade the radio capacity or upgrade from radio to fiber. The curves in figure 5.2 on page 50 show that upgrading the radio capacity is a relatively cheap alternative. The suppliers of radio equipment often claim the flexibility, and in particular the possibility to "pay as you grow", as one of the major advances of radio, and these calculations show that this is the case. Even if an upgrade to fiber should be necessary in the future, an initial deployment of radio is cheaper than initial fiber deployment if the upgrade is done after more than four years.

Omitted upgrade scenarios

There are several other possible upgrade scenarios, such as upgrade from ADSL2+ to leased fiber, ADSL2+ to VDSL, radio to leased fiber and two times upgrade of radio (first improved radio then upgrade to fiber). ADSL2+ to VDSL is not an option with the availability and prices of VDSL today, but if the development of VDSL availability and price should be as it has been for the ADSL-technologies, then VDSL may become an alternative during a ten year period. The two times upgrade of radio is not discussed because it is unlikely that two upgrades should be necessary during a time period of ten years. With upgrades to improved radio it is possible to increase the radio capacity at least four-fold from the initial capacity of 150 Mbit/s, and such an increase of capacity should be capable of absorbing increase in capacity demands for quite a few years.

The upgrades to fiber are assumed to involve deployment of fiber and the cost of an upgrade is also compared to the cost of an initial fiber deployment. This might seem a little strange given that the calculation results in table 5.1 on page 48 shows that during a ten year period the lease of fiber is cheaper than deployment of fiber. However, as indicated earlier the time period is a critical parameter which has a great impact on the profitability of fiber deployment versus lease of fiber, and this will be discussed more in section 5.2 on the next page.

5.1.2 The spreading network

The calculations from the spreading example in previous chapter suggests that cable used in the spreading will cost ca. NOK 5 500 with 100 meters between trunk termination and the access point, while the radio solution will cost ca. NOK 12 150. Given that the capacity of cable is also superior

to the that of the radio used in the price example, cable is the best choice. However, length from trunk termination to Wi-Fi access point will often exceed 100 meters which means higher costs, and in a city it will often be needed to cross streets on the way from trunk termination to the Wi-Fi access point. When crossing of streets is required, or digging is needed for some other reason, radio link will be a good alternative. The calculations from last chapter is based on the use of Wi-Fi technology in the access network and the radio solution in the spreading network is also using Wi-Fi. There are several good reasons to use the same technology in the spreading network as in the access network:

- The capacity of the links in the spreading network will always match the capacity of the access points in the access network if PTP links are used.
- Less equipment needed as some components can be used in both the spreading network and the access network, e.g. radios with two antenna interfaces, one for the spreading link and one for the access network.
- The technology used in the access network should be mass-produced to assure a large potential customer base, and therefore cheap.

Upgrade

A disadvantage with the use of Wi-Fi in the spreading part of the backbone network is that there is little spare capacity to handle more traffic as a result of increased traffic after an upgrade of the access technology. With an upgrade of the access technology the capacity requirement is increased for all parts of the backbone, and the Wi-Fi links will probably be insufficient. But much of the installations which is part of the Wi-Fi links may be used also when the technology is changed, so the cost of changing all the radios will be limited to little more than the cost of the radio equipment. Given that the technology is based on a standard and that the radio equipment therefore is mass produced and relatively cheap, an upgrade will not necessarily cost that much.

5.2 Sensitivity analyses

The calculation results are based on several assumptions and variables which have been fixed. In this section the values on some of the variables will be altered to see what effects this will have on the results.

5.2.1 Cost per meter of fiber

One of the parameters with the widest distribution is the price estimate for the deployment of one meter of fiber. This estimate in itself is composed of several unities like cost of fiber cable and cost of digging the ditch, but it is the uncertainty connected to the costs of work which makes the interval of possible values so wide.

Figure 5.3 shows how the cost (per access point) of a link changes with changing costs per meter of fiber deployment. For fiber deployment to

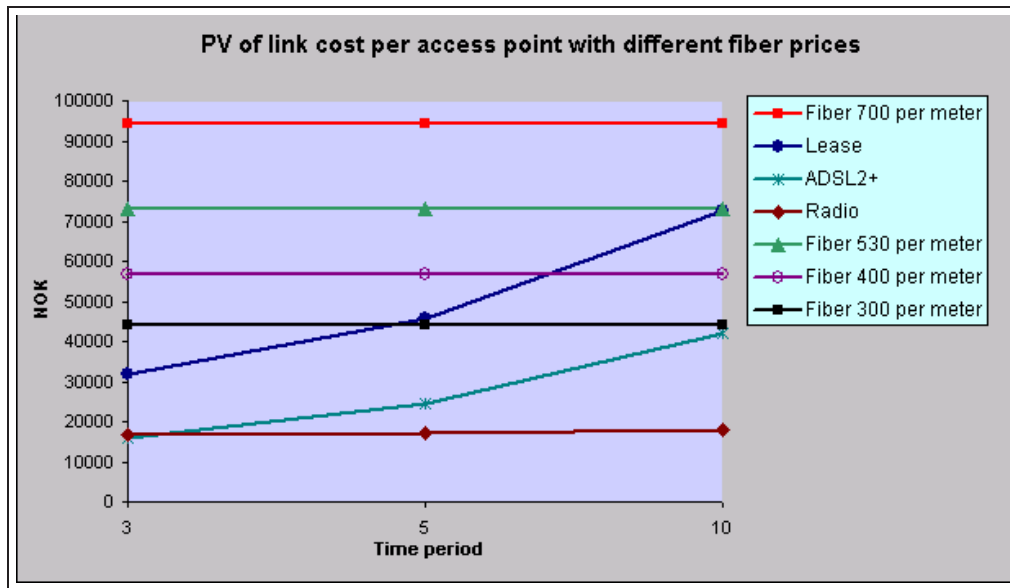


Figure 5.3: Link costs for different costs per meter of fiber

cost the same as lease of fiber, when the time period is set to ten years, the price per meter will have to be as low as NOK 530 per meter. If the price should be as low as NOK 300 per meter, fiber deployment will also be competitive on price with ADSL2+ evaluated over a period of ten years. However, it is unlikely that the average price of fiber deployment in a city will be as low as NOK 300 per meter so the most interesting result of this analysis is that price of fiber need to be as low as NOK 530 per meter to be competitive with leasing fiber when the depreciation time is ten years.

5.2.2 Length of the fiber links

With xDSL there is no price difference depending on the location of the termination, it is just a question of how much capacity it is possible to

achieve at given distances from a central. For radio there is some correlation between link distance and link cost, but with the high capacity radio solutions distances of several kilometers can be covered and there will be little or no price difference between a link of 500 meters and a link of 1 500 meters.

When it comes to fiber there is a much higher correlation between link distance and costs. Figure 5.4 illustrates how the costs of fiber deployment and lease of dark fiber vary with different link lengths. The figure shows

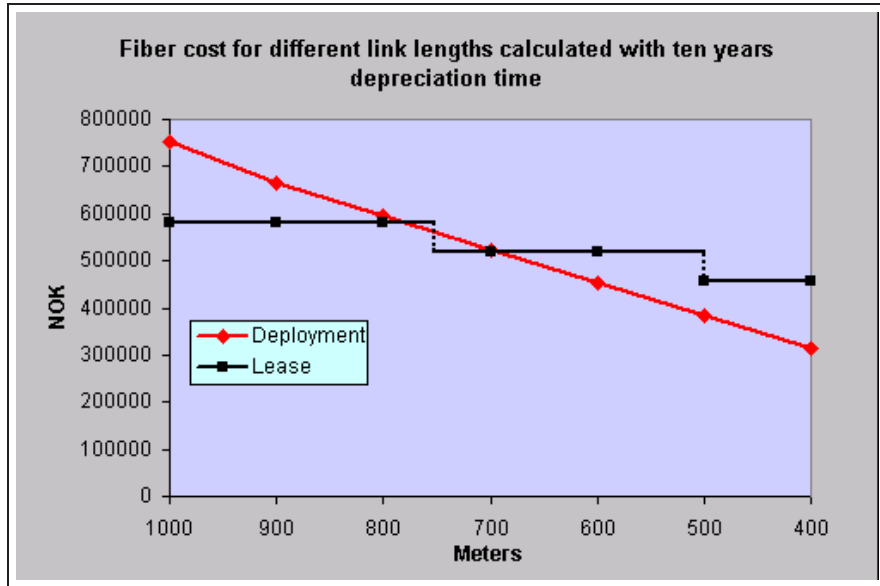


Figure 5.4: Link costs for different fiber link lengths

that even though both alternatives have positive correlation with the link distance, the deployment of fiber has the strongest correlation. The cost of fiber deployment decreases linearly as the distance decreases, while lease of fiber decreases in steps for every 250 meter decrease in distance. Because of the different characteristics of the two graphs there are more than one crossing point, but for distances shorter than ca 700 meters the deployment of fiber becomes cheaper than lease of fiber and the profitability of deployment increases as the distance decreases further.

The correlation between cost and distance is the same regardless of the distance interval considered, so for distances longer and shorter than the interval in the illustration the tendency will be the same; increased distance makes leasing more favorable while decreased distance makes deployment more favorable.

This analysis shows that the assumption about link distance is a very important factor and that relatively small variations in this variable can affect the cost of both lease and deployment considerably, the relation between the costs of the two alternatives and possibly the relation between the costs of fiber and the costs of xDSL and radio solutions.

5.2.3 Discounts

Regardless of the technology used it should be possible for a big customer like an operator of a wireless CWN to achieve some discounts, and as mentioned before this is possibly easier to achieve if the deployment of the CWN is also part of a research project. However, for xDSL and radio there is limited room for discounts as these two alternatives are already relatively cheap, and for deployment of fiber the effect of price changes has already been discussed and the effect of discounts will be the same as already found.

What remains is then to look at the consequences of discount on lease of fiber. Figure 5.5 shows how the cost of leased fiber change for different discounts.

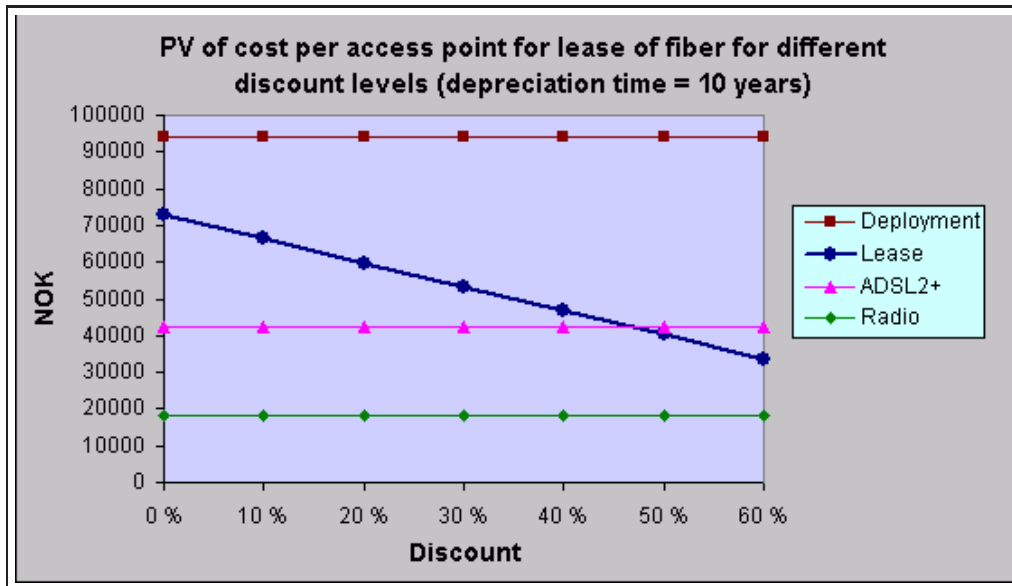


Figure 5.5: PV of cost of leased fiber with different discounts

The maximum discount available from Telenor with a contract for 5 years is 15%. As the graphs show this is far from sufficient to make leased

fiber competitive on price compared to ADSL2+ and radio. A discount of almost 50 % is needed to reach the price level of ADSL2+, and further calculations show that a discount of ca 84 % is needed to make it competitive on price with radio.

5.2.4 Depreciation time

The depreciation time is different for different technologies, and is therefore a parameter which is difficult to set in this case where technologies as diverse as radio and fiber are discussed. According to [42] it is normal to operate with a depreciation time for fiber of 20 - 30 years, while in calculations for wireless equipment depreciation times as low as 3 years are used [59]. The time intervals considered in this thesis is mainly 3, 5 and 10

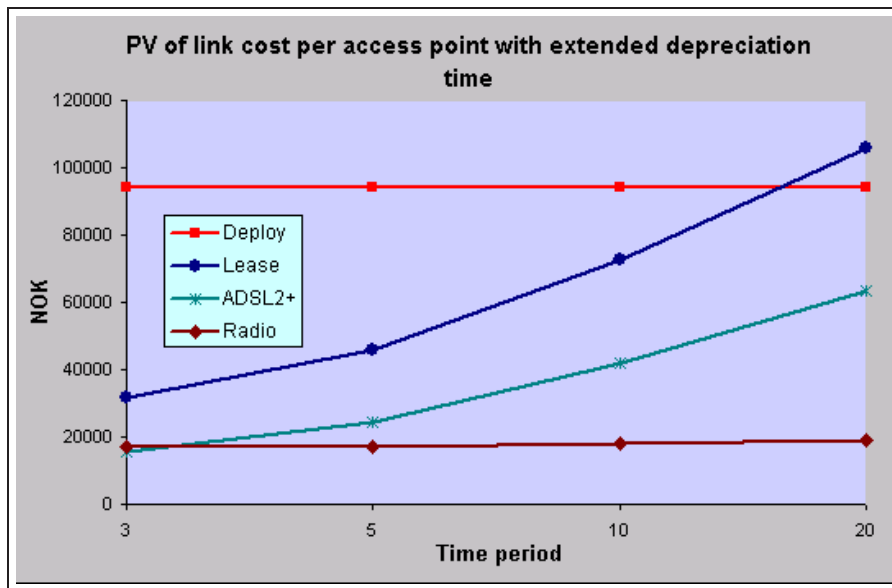


Figure 5.6: PV of cost per access point of different link with long depreciation time

years. When fiber is discussed the most attention is given to the 10 year period, given a normal depreciation time for fiber as high as 20 - 30 years.

Figure 5.6 shows the same graphs as presented in figure 5.1 on page 49, but with the extension of the time period to 20 years. As suggested earlier the graphs show that with a depreciation time of 20 years, the total costs of leasing fiber exceed those of deploying own fiber infrastructure. Radio and ADSL2+ show the same tendency as previously, but they do

not cross any of the other graphs. However, when the time perspective is 20 years it is likely that both ADSL2+ and radio links will have to be replaced/upgraded during that time, and the graphs for these technologies are therefore not so interesting when exceeding 10 years.

This shows that the choice of depreciation time in the calculation also is a critical factor, and for all the previously results it should be kept in mind that deployment of fiber infrastructure has a cost that is more or less independent of time because of the long lifetime, while lease of fiber, radio and ADSL2+ are not, and fiber is therefore increasingly attractive as the time period is increased.

5.2.5 Trunking costs versus spreading costs

In this thesis the backbone network has been divided into two parts, trunking and spreading, and most emphasize has been given to the trunk costs and calculations of these since a trunk is quite expensive compared to a spreading link, except from the cases where fiber infrastructure is available initially. Even when trunk costs are divided on the number of connected access points, a trunk is still more expensive per access point given the assumptions of 8 AP connected to fiber and radio trunks and 2 AP connected to a ADSL2+ trunk. The reason why the spreading links are as cheap as they are, is that it is assumed that they are located in such a way that inexpensive solutions can be used to bridge the gap between the trunk termination and the access points, which implies criteria like relatively short distances, line-of-sight or near-line-of-sight and limited interference levels.

Therefore there will be a trade-off between the number of access points connected to each trunk and the cost of each link. More APs connected to a trunk will decrease the relative cost of that trunk, but it may increase the average cost of the link between the APs and trunk termination because cheap technology is no longer sufficient to bridge the gap.

Since the number of links in the spreading part of the network is much higher than the number of trunks (≈ 8 times higher), a relatively small change in the cost of each link in the spreading part has the potential to affect the total costs much more than small changes in the price of the trunks.

5.3 Research's impact on costs

Research is a factor which has the potential to have the most considerable impact on the costs of the backbone network. The important thing to consider here is the type of research. If the research is restricted to activities which can do with the service quality which is satisfactory for the "normal" users and do not introduce a lot of extra traffic in the network, then research may not affect the choice of technology and therefore will not affect the cost of a deployment.

However, it is likely that it will be of interest to do research on new and alternative radio technologies with higher bandwidth consumption, or services which require a network with an extremely high availability. The consequence of such research activity will be a need for better performing solutions in the backbone, and will probably lead to higher costs of the deployment.

Higher performance requirements may result in fiber being the only possible solution for the trunks, or maybe also radio but then with a reduction in the number of access points which can be supported by each trunk, and thereby raising the real costs of the link. For the spreading part of the backbone the impact on costs will probably be more significant than for the trunks. This is because the calculations in previous chapter is based on the use of relatively cheap technology with little or no extra capacity. If these solutions are no longer sufficient, it will be necessary to use better equipment in the spreading part of the backbone, and this will cost significantly more. Since the number of links in the spreading part is high, i.e. equal to the number of APs in the access network, the total costs of the backbone will increase much as a consequence of this. Given 200 access points in the CWN, an increase of NOK 15 000 in installation cost per spreading link will increase the cost of the backbone with NOK 3 000 000. This increase is equal to the cost of deploying 4 fiber links each of 1 000 meters.

5.4 Sources of error

The previous section investigated how sensitive the calculation results are to changes in some of the variables used in the calculations. This section will present some factors which have been omitted from the calculations and which have the potential to change the results, and discuss the effect of some of the simplifying assumptions applied in this thesis.

5.4.1 Radio antenna placement

The radio antennas should preferably be placed outdoor, and although there are radio options which do not require line-of-sight between the transceivers, it is always to prefer. So the antennas should be placed outdoor and as high as possible to reduce the number of obstacles. This means that the possibilities for location of the radio antennas are limited, and there is the chance that the property owners, if these allows for a placement of the antenna altogether, will require some compensation for this. This could typically be a annual fee which will add up to the total expenses for the radio alternative, and thereby making radio less competitive on price.

5.4.2 Microduct tubes

The microduct tubes have been assumed to be available free of charge, which will in most cases mean that the builder of the backbone already has deployed these tubes. Another possibility is to partner with someone who has a network of such tubes, e.g. a municipality, which can place at disposal these tubes in return of e.g. access to a fiber pair or some other form of reciprocity which will give the owner of the tubes good utility value and induce no or very small extra costs for the builder.

If the access to microduct tubes can not be arranged in any of the way suggested above, one will probably have to pay a considerable fee for leasing the tubes, and the calculations for microduct tubes will naturally give much less attractive results. What the price of such microduct lease will be is very difficult to tell since there is no market for this.

5.4.3 Time of payments

There are various ways in which payments can be done, e.g. leasing fees are paid every month, every quarter, twice a year or once a year, in advance or after delivery etc. In the calculations it has been assumed that investments are paid in the beginning of the year, and that recurring expenses are paid at the end of each year.

The fees for leasing of fiber and ADSL2+ are actually paid monthly, and in these cases the assumption of payments in the end of each year make these alternatives more attractive than they actually are. In the case of leasing fiber for ten years the result from the calculations shows a cost with a present value of NOK 582 554 per link. If calculated with payments

each month the present value of the cost is NOK 597 129 per link, which correspond to a cost increase of approximately 2.5 %.

So the simplification of yearly payments will give a quite limited error, and compared to some of the other sources of error and the consequences of relatively small changes in variables like cost per meter of fiber, the effect of this simplification is almost negligible.

5.4.4 Constant prices

The prices are assumed to have the same nominal values over the years. It is difficult to decide what effect this will have on the relationship between the different alternatives, because it is unknown how the prices will develop. Over the latest years the prices for xDSL have decreased, while prices for fiber has increased. If the prices for the various technologies should develop in different ways over the next years, it is clear that this will affect the relationship between the technologies and may lead to other conclusions than those found in this thesis.

5.4.5 Cost of work

There are several expenses connected to work of different nature which have been omitted from the calculations, and here it will be discussed how this might make some choices look better than others.

Planning

The planning process will include the identification of the values for several of the parameters used in the calculations, and is therefore necessary to do before any decisions are made on which technology to use. Much of these costs are therefore independent of the technology chosen, and omitting them will not cause any of the technologies to appear considerably more or less attractive.

Deployment

It is difficult to estimate the price of deployment because it depends so much on the surroundings, especially for cabled solutions where e.g. need for digging will raise the expenses, while e.g. cable bridges or the like inside buildings will decrease the costs.

In the calculations regarding costs of the spreading network the cost of deployment is included for both the cabled solution and the radio solution, but this is not the case for all the trunked solutions. It is only the price estimate for one meter of fiber deployment which include work costs, while other costs like deploying radios and antennas are not included in the calculations. These costs are omitted because it is very difficult to make usable price estimates on what the cost will be for the different solutions, and the installation costs will often be small compared to the equipment costs in the case of trunks. The effect on the relative costs of ADSL2+, radio and fiber of including all the deployment costs will be very limited as it will lead to an upwards shift of the cost curve for all the technologies. However, the work needed on the radio links is probably more extensive and costly than for the others, so the omission of some of the deployment costs is likely to make the radio alternative look better compared to the others.

The big differences in the price estimates for deployment of fiber, varying from NOK 300 to NOK 1 000 is a result of different work cost in different environments, and show how difficult it is to make a price estimate for the deployment of cables and equipment.

Operation

The need for operation of own infrastructure make a significant difference between deploying own infrastructure as opposed to leasing access to infrastructure. Operation involves tasks like configuring the links (e.g. planning of frequency use in the case of radio), performing scheduled maintenance work and repair work whenever it should be needed.

It is difficult to estimate also these costs, but in [60] it is assumed that the cost of operation will be an annual costs which is 15 % of the initial investment costs. While this may be a good estimate for the operational costs of radio connections, it is probably much too high for fiber connections. According to [42] the reduced operational costs is one of the advantages of fiber.

The operational costs will be different for the various solutions, but for the deployment of own infrastructure they will be considerably higher than for leasing. How much higher depends on the chosen technology, how much competence which is already in place in the organization to take care of the tasks connected to operation and etc.

The introduction of the operational costs in the calculations will make the leasing alternatives more attractive compared to the others. Once again it might be the cost of radio which have been underestimated the most as

a result of leaving out the operational costs, but also ADSL2+, which have a relatively high unavailability, will induce some extra work because it might take some time to establish that it is the ADSL2+ link and not other equipment which has failed.

Chapter 6

Recommendations

This chapter will summarize some of the results from the two previous chapters, and some suggestions will be made of how to minimize the total costs of a deployment of a backbone for a wireless CWN.

6.1 Use of existing infrastructure

The calculations show very clear just how much money can be saved when sharing the capacity available on existing fiber infrastructure. If one fiber pair is already in use, applying WDM another user can also utilize the same fiber pair at a cost of only NOK 48 000. Some extra attenuation of the signal might be the case as a result of the introduction of more equipment, but the difference in quality of service will be negligible. The price for the deployment of 1000 meter of fiber with the parameters used in the calculations is NOK 754 000, which means that *savings of more than NOK 700 000 can be achieved using existing fiber pairs*, and that is just for one link. If an unused fiber pair is available the cost of taking this to use is even lower than with the use of WDM.

The discussions in chapter 2 on page 4 showed that fiber is the technology with the best performance and with no digging needed it is relatively fast to get up and going. When it is also competitive on price with ADSL2+ and radio, it is the clear best choice. For the builder of the wireless CWN it can therefore be a very good investment to use some time to find collaborating partners with an existing fiber infrastructure. Because of the almost infinite capacity of the fiber cables, the cost of sharing fiber capacity is very low compared to the gain for the builder. Instead of paying a high lease for access to the fiber network it might be possible to reach an agreement where the fiber owner gets access to a service valuable for

him which the builder of the wireless network can deliver at a low cost. It might be difficult to identify such win-win-situations, but considering the potential savings, it is definitely worth the effort to try.

6.1.1 Lease of fiber

If there is no foundation to make the owner of a fiber infrastructure a partner through such a deal presented above, leasing of fiber is another way to make use of available capacity, but the calculations have shown that this is expensive. Within 17 years the cost of leasing exceeds the cost of deploying own fiber, and for link distances shorter than 1000 meters this time period decreases. So leasing fiber over a long time means that all the earnings of using existing fiber end up in the hands of the fiber owner, and nothing is saved for the builder of the backbone.

If deployment of fiber results in so high costs that the builder of the wireless CWN does not have the possibility to finance it, the builder might be forced to accept the high costs of leasing. On the other hand, if deployment of own infrastructure is a possibility, then the builder can try to use the "threat" of deploying its own fiber infrastructure as a mean to get a better deal on the leasing which share the profit of using existing infrastructure more even between the two.

6.2 ADSL2+ and radio

When no fiber infrastructure is available, ADSL2+ and radio are the two cheapest alternatives. As the calculations have shown the cost of an ADSL2+ link is lower than the cost of radio, but since radio can support more APs, the cost per AP is lower for radio calculated over more than three years. However, the assumption of 8 APs connected to each radio (and fiber) trunk is probably optimistic. The case in Appendix A on page 77 has shown that the actual number may be closer to 6, and this makes the cost of ADSL2+ more favorable compared to both radio and fiber.

When the performance of radio is compared to that of ADSL2+, radio is the better technology. The major drawbacks of radio are the limitations on use as a consequence of possible bad propagation conditions for the radio signals, such as no LOS between the radios. In some cases it may not be possible to achieve good enough channel properties for the signals, and radio is therefore not an applicable solution. However, when radio is a possibility it should be chosen in stead of ADSL2+ because:

- The price is close to that of ADSL2+ when evaluated for a period of 3 years, and cheaper for longer depreciation times.
- Radio offers better performance, and scales better than ADSL2+.
- The possibilities for research are very limited when using ADSL2+ because of its low capacity.
- If upgrades should be necessary the calculations show that ADSL2+ may become a very expensive solution since fewer APs are supported by one ADSL2+ link than one radio link.

ADSL2+ should only be used as a temporary solution, maybe as support for one or two APs in an area where more APs are expected to be deployed in a later phase at which time the ADSL2+ link is replaced by radio or fiber. The reason why ADSL2+ should be avoided is its low capacity. If Wi-Fi is used as the access technology, one single AP has the potential to generate more traffic in the uplink than the ADSL2+ link can carry, so ADSL2+ will be insufficient as a backbone when the full potential of the access technology is used. Especially the possibility that VoIP and other services requiring more symmetric capacity will dominate the traffic in a wireless CWN make it very problematic to use an asynchronous technology like ADSL2+ in the backbone.

6.2.1 Upgrade

The calculations have shown that if an upgrade from ADSL2+ to fiber should be necessary and the resulting fiber link only supports two APs this link will be very expensive. For radio the case is very different, as radio shows to be more economical than initial deployment of fiber as long as upgrade to fiber is not needed within the first four years. Radio also offer good possibilities to upgrade from the 155 Mbit/s, assumed to be the initial capacity in the calculations, to capacities of 300 Mbit/s and 600 Mbit/s, and even with such upgrades the deployment of radio is still cheaper than initial deployment of fiber.

6.3 Radio and fiber

Radio is fast to deploy, is relatively cheap and offers good reliability and high capacity. Fiber deployment takes longer time, it costs very much and offers a very high level of reliability and very high capacity. Much the

same is true for leasing of fiber as for fiber deployment except that for leased fiber the long deployment time is avoided.

For most commercial applications the performance of radio will be more than sufficient, and since the cost of radio is considerably lower than the cost of fiber, both deployment and leasing, radio is the recommended choice. Radio is also a flexible solution with several equipment suppliers delivering equipment which is software upgradeable, and in that way allows the buyer to start with a relatively low capacity and just pay for more if it is needed. "You pay as you grow" is a phrase much used in the promotion by amongst others the equipment supplier Nera, and this may be a very important property if it is difficult to get sufficient funding in the start-up phase of a deployment.

The calculations have also shown that if radio should be insufficient after some years, initial deployment of radio is still cheaper than initial deployment of fiber if the upgrade is not needed within the first four years after deployment.

Length of link and cost per meter of fiber

The sensitivity analyses show that the length of the link and the cost per meter of fiber are two of the most important parameters in the calculation of fiber costs. In a city the price per meter of fiber is likely to be at least NOK 700, the value used in the calculations. On the other hand the length of the links may be considerably much shorter than the 1 000 meters used. The Wireless Trondheim case in Appendix A on page 77 has an average link length which is considerably shorter, and in those calculations 400 meters is used as the average distance. Still fiber is not competitive on price with radio. Given a price of NOK 700 per meter of fiber deployment, than a link distance of 130 meters will make the costs of fiber and radio approximately the same if a 10 year depreciation time is used.

If all or much of the cost advantage of radio is eliminated, radio still have the advantage of fast deployment compared to fiber. This may be important enough to make radio the preferred solution, but if the longer time of deploying fiber is acceptable then fiber with its superior performance and long lifetime is the best choice.

Research

The introduction of research makes the problem a little more complicated, as the performance of radio may not be sufficient any more either because of too low capacity and/or too low reliability and availability. If capacity

is the problem radio can still be a solution if the number of APs supported by each radio link is reduced. This will naturally decrease the economical advantage of radio over fiber, but in some cases the difference may be so big that radio is the best solution even with fewer APs connected to each trunk.

It is difficult to foresee the requirements for future research, and this makes fiber with its high reliability, availability and ability to handle very high bit rates more attractive. When fiber is used the best transmission medium available is installed and this should give the most opportunities for research projects of various characters.

6.4 The spreading

When cable can be used in the spreading part of the network at the same or lower costs as radio, then cable should be chosen. This is because a cabled solution (e.g. Ethernet over CAT5, CAT6 or multimode fiber) in most cases will offer better performance than radio. The problem with the spreading in a wireless CWN is that often an AP will be positioned on a location requiring digging if a cable should be deployed between the AP and the trunk termination. This results in high costs of using cable and makes radio a good alternative. Therefore, when no digging is needed use cable, otherwise radio.

When radio is used it will be a good solution to use the same technology for the spreading as is used in the access, since this will offer sufficient capacity at low costs.

Research

The effect of research on the spreading part is much the same as the effect on the trunks. The cheap solutions good enough for commercial application may not be sufficient for research, especially not the radio solution. The only solution good enough may be Gigabit Ethernet over multimode fiber to each of the APs. This will be a very expensive solution if all the AP locations should be wired up like this, and it is therefore recommended to do so only for locations where cabling can be done relatively cheap, i.e. reduce the number of AP locations used for research activity.

The introduction of research has the potential to drive up the expenses very much for both the trunks and the spreading part of the network, so a restriction on which links to use for research purposes can be a good strategy to make the backbone network much cheaper. If all the links in

the backbone is dimensioned for research purposes when not all the links are needed for research, the result will be several links with much better performance than needed, and much of the investments made in expensive equipment will be futile.

Chapter 7

Conclusions and further work

In this thesis different technologies for use in a backbone for a wireless CWN carrying both commercial and research traffic have been evaluated and discussed, and much emphasis has been given to the costs connected to each of the various technologies.

The investigation of the various technologies showed that fiber is the superior one. It has the highest capacity and is more reliable than both xDSL and radio solutions. The major drawbacks of fiber is the high deployment costs and in some cases also the relatively long deployment time. Since it is so expensive to deploy fiber there is much money to save by using fiber infrastructure already deployed, i.e. fiber pairs already in use, dark fiber or microduct tubes. Leasing fiber is an alternative which make use of existing fiber infrastructure, but since the prices for leasing are very high, the calculations have shown that this is an expensive alternative in the long run and all the savings of using existing infrastructure end up with the owner of the infrastructure. Therefore efforts should be made to reach agreements with anyone in possession of any fiber infrastructure to reach agreements which split the profit of using existing infrastructure more even between the infrastructure owner and the leaser, in this case the builder of the wireless CWN.

What seems clear is that research traffic may raise the requirements for capacity and reliability to a level considerably higher than the requirements posed by commercial traffic only. In doing so, the presence of research traffic eliminate the low performing and cheap solutions as alternatives, thus driving up the costs of the backbone network. This is true for both the solutions used for trunks and the solutions used for the spreading.

The sensitivity analyses done in this thesis have shown that various factors affect which is the best choice for the backbone, and especially in

the case of fiber deployment versus lease of fiber the topology chosen and the accompanying characteristics of the trunks are very important factors. With many short links in the trunk part of the network, deployment of own infrastructure is often to prefer since the high fixed rate of leasing fiber will drive up the expenses for this alternative. In the other case, if the trunks are few but long, leasing of fiber will become more attractive since high costs per meter of fiber deployment will make this alternative very costly, while the fixed part of the leasing fee will become less important with fewer and longer links.

As mentioned in section 5.4 on page 59 regarding sources of error, there are several costs connected to the choice of each technology not included in this thesis. To get a more complete picture of the total costs of each solution it could be part of a future work to include also these expenses in the calculations.

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Appendix A

The case - Wireless Trondheim

The background for this thesis is the Wireless Trondheim (WT) project, and as a first phase in this project the city centre of Trondheim should be given wireless coverage. This case gives a suggestion to where the trunk terminations may be located, and which technology to use for each trunk. Costs are calculated for the suggested solution and also for extremities like just radio, just lease of fiber and just deployment of fiber.

A.1 Trunk locations and spreading

For approximately half of the city centre radio planning has been done [61], and the placements of the APs in this part of the city has been used as a basis for deciding where to put the trunk terminations. Most of these trunk locations have already been decided by Wireless Trondheim, and both the radio plan and overview of planned trunk terminations have been supplied by [1]. For the other half of the city centre there has been no radio planning, so in the lack of a plan for the locations of the APs the trunk terminations have been placed near the intersections of an imagined grid covering the area.

Figure A.1 on the next page shows the locations of trunk terminations used in this case. The red circles and the 'A's east of the black dividing line are the trunks supporting APs which have been placed around the city after a radio planning. These trunks are numbered 1 through 17. A circle means that radio or fiber is used for the trunk, while an 'A' means that ADSL2+ is used. The blue squares on the west side of the dividing line are numbered 18 through 26, and are located according to a grid.

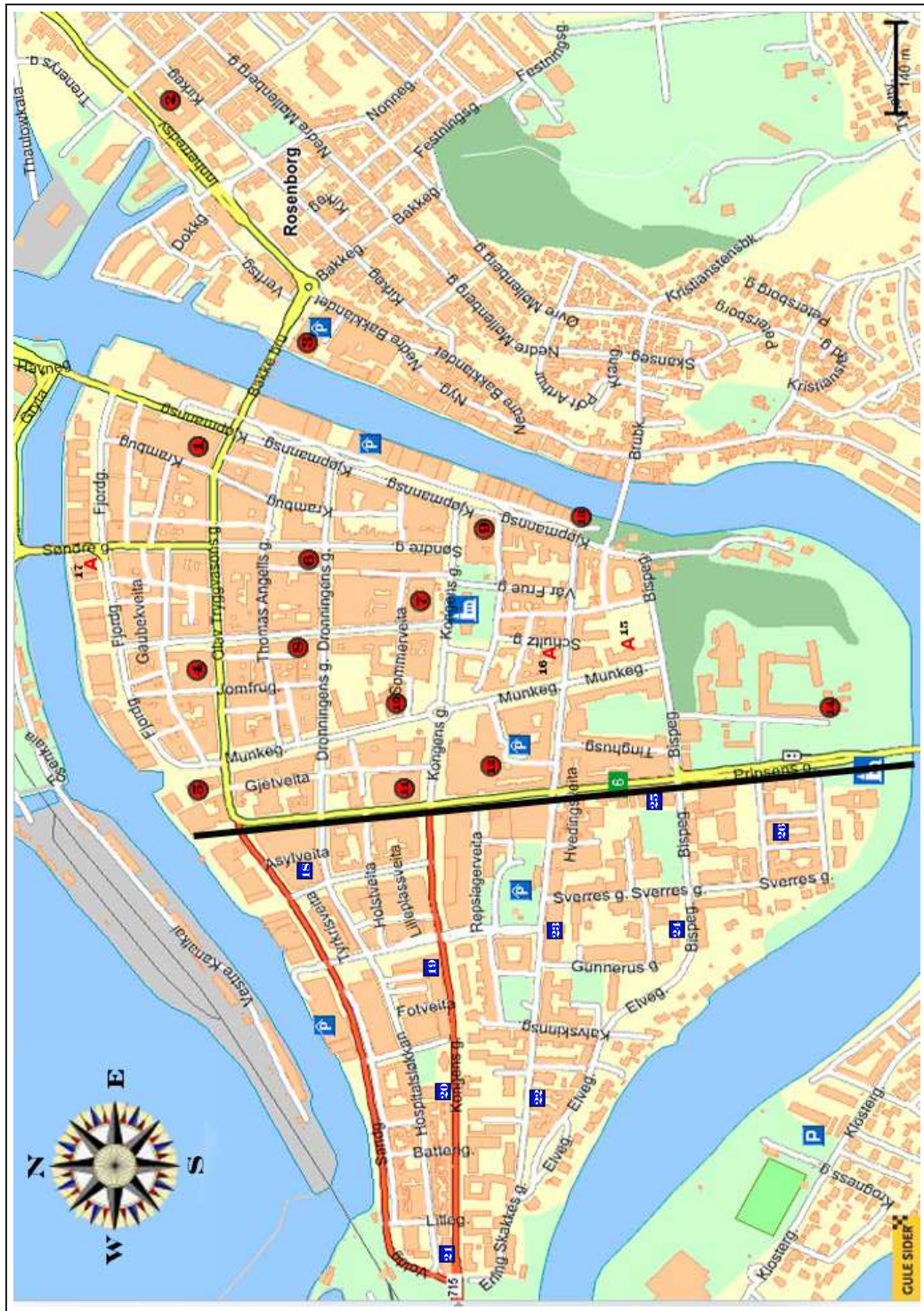


Figure A.1: Overview of the trunk terminations.

A.1.1 APs covered by each trunk

In the calculations it has been assumed that a radio or fiber trunk will cover in average 8 APs, while an ADSL2+ link will support 2 APs. The planning of the locations for the trunk terminations in such a way that all the APs planned for the east side of the city centre are covered showed that it is difficult to cover as many as 8 APs in average from one trunk termination. Table A.1 list how many APs which are intended to be covered by each of the trunk terminations on the east side, and also the number of APs connected to the trunk with cable.

Trunk	Number of APs	Cable
1	13	2
2	6	0
3	4	2
4	9	4
5	4	2
6	6	3
7	6	3
8	2	1
9	4	3
10	6	3
11	3	2
12	7	5
13	4	1
14	3	0
15	1	1
16	1	1
17	1	1
Total	80	34

Table A.1: *Number of APs covered by each of the east side trunk terminations. AP locations are as given in [61]*

From this we get that each ADSL2+ trunk is used to support just 1 AP, and that a radio or fiber trunk in average support ≈ 6 APs. The spreading to APs located at the same building is assumed to be done using cable, while all other APs are reached using radio. The listing above shows that 34 out of 80 or 42,5% of the APs can be reached using cable. Since there is no plan for the APs on the west side of the city centre, it has been assumed in the calculations in this case that each trunk support 6 APs, and that the

spreading to approximately 43% of these is done using cable.

A.1.2 Technology used for the trunks

For trunk 1, 2, 3 and 9 NTNU has fiber available, and fiber is therefore the preferred choice for these locations, and has been chosen by WT to be used for these trunks. There is a fiber pair available for trunk 1, 2 and 9, while it will be necessary to use WDM for trunk 3. Trunk 15,16 and 17 are all ADSL2+ links. These are supporting APs placed in locations where more APs are likely to be added in a later phase, and should therefore be considered as temporary solutions only.

For the remaining trunks there is the choice between radio and fiber, and in most cases both the solutions will probably be possible. The calculations in this thesis have shown that radio is the cheapest alternative when calculated over some years, but it has quite high initial cost compared to lease of fiber. To avoid high future cost and at the same time reduce the initial investments, fiber is assumed to be chosen for the east side trunks supporting 6 APs or more and radio for the rest. On the west side all trunks are assumed to support 6 APs, and it is therefore also assumed that half of them will be fiber trunks and half of them will be radio trunks. This heterogeneity of the backbone network means that different parts of the network will have different properties, and the possibilities for e.g. research will be different at the various locations depending on the technology used for the trunks.

A.2 Calculation

Table A.2 on the next page gives an overview over the different costs of each trunk, both for the east and the west side of the city centre. The '*Spreading with cable*' field gives the number of APs connected to each trunk with cable, and radio is then used for the remaining. The prices used in the calculations are the same as those introduced earlier in the thesis except for the case of leased fiber where the prices are based on the average of price estimates given to WT by BaneTele AS. The prices are:

• Fiber without WDM	NOK 30 000
• Fiber with WDM	NOK 48 000
• Radio deployment cost	NOK 130 000
• Annual license cost	NOK 2 000
• Leased fiber establishment	NOK 30 000

- Monthly rate for leased fiber NOK 4 175
- Monthly rate for ADSL2+ NOK 1 000
- Spreading with cable (100 m) NOK 5 500
- Spreading with radio (Wi-Fi) NOK 12 150

Trunk	Nr. of APs	Spreading with cable	Trunk costs		Spreading costs
			OTC ⁸	ARC ⁸	
1	13	2	NOK 30 000	NOK 0	NOK 144650
2	6	0	NOK 30 000	NOK 0	NOK 72900
3	4	2	NOK 48 000	NOK 0	NOK 35300
4	9	4	NOK 30 000	NOK 50 100	NOK 82750
5	4	2	NOK 130 000	NOK 2 000	NOK 35300
6	6	3	NOK 30 000	NOK 50 100	NOK 52950
7	6	3	NOK 30 000	NOK 50 100	NOK 52950
8	2	1	NOK 130 000	NOK 2 000	NOK 17650
9	4	3	NOK 30 000	NOK 50 100	NOK 28650
10	6	3	NOK 30 000	NOK 50 100	NOK 52950
11	3	2	NOK 130 000	NOK 2 000	NOK 23150
12	7	5	NOK 30 000	NOK 50 100	NOK 51800
13	4	1	NOK 130 000	NOK 2 000	NOK 41950
14	3	0	NOK 130 000	NOK 2 000	NOK 36450
15	1	1	NOK 0	NOK 12 000	NOK 5 500
16	1	1	NOK 0	NOK 12 000	NOK 5 500
17	1	1	NOK 0	NOK 12 000	NOK 5 500
East side total			NOK 938 000	NOK 296 500	NOK 745 900
18	6	2	NOK 30 000	NOK 50 100	NOK 59600
19	6	2	NOK 130 000	NOK 2 000	NOK 59600
20	6	3	NOK 30 000	NOK 50 100	NOK 52950
21	6	3	NOK 130 000	NOK 2 000	NOK 52950
22	6	2	NOK 30 000	NOK 50 100	NOK 59600
23	6	3	NOK 130 000	NOK 2 000	NOK 52950
24	6	3	NOK 30 000	NOK 50 100	NOK 52950
25	6	2	NOK 130 000	NOK 2 000	NOK 59600
26	6	3	NOK 30 000	NOK 50 100	NOK 52950
West side total			NOK 670 000	NOK 258 500	NOK 503 150
Total			NOK 1 608 000	NOK 555 000	NOK 1 249 050

Table A.2: Overview of trunks and spreading in the case

⁸OTC = "One Time Costs" and ARC = "Annual Recurring Costs"

As table A.2 on the preceding page shows, the total investment costs with the solution presented in this case will be **NOK 2 857 050**, and during the first year the payments for leasing and licenses will sum up to **NOK 555 000**. Over time the recurring costs will accumulate, and calculated for different time periods the total costs will be as presented in table A.3.

PV of total costs during the 3 first years:	NOK 4 313 545
PV of total costs during the 5 first years:	NOK 5 132 660
PV of total costs during the 10 first years:	NOK 6 755 138
PV of total costs during the 20 first years:	NOK 8 736 728

Table A.3: *PV of the total costs for the case for various time periods*

A.3 The extremity solutions

The solution for the case combines fiber, radio and ADSL2+ in such a way that the initial costs are kept at a moderate level and at the same time there are trunks supported by fiber and thereby can offer the high reliability and capacity which may be needed by certain areas of research.

In this section the same calculations as before will be done for the extremity solutions, i.e. when either only radio, only lease of fiber or only fiber deployment is used for the trunks. Since fiber is a clear best choice when fiber infrastructure is available, the trunks supported by fiber controlled by NTNU will continue to be so. Also the three ADSL2+ trunks are assumed to be used in all the extremity cases, while the technology used for the remaining 19 trunks will vary. To use ADSL2+ as the only trunk technology is also considered as an extremity, but in this case the trunk locations given in figure A.1 on page 78 will not be applicable, and the number of needed trunks will be assumed to be the number of APs covered by the 19 trunks considered divided by 2, i.e. 50 divided by 2, which gives 25 ADSL2+ trunks.

The costs of the spreading network are assumed to be unaffected by the choice of trunk technology, and will be the same for all the cases. For fiber and radio this will probably be the case, while in the case of only ADSL2+ it is likely that cable can be used more often for the spreading, and the calculations will in this case overestimate the cost of the backbone.

Radio

When only radio is used for the 19 trunks in question the costs will be:

	Trunk costs	
	OTC	ARC
3 × Fiber without WDM	NOK 90 000	NOK 0
Fiber with WDM	NOK 48 000	NOK 0
3 × ADSL2+	NOK 0	NOK 36 000
19 × Radio	NOK 2 470 000	NOK 38 000
Total	NOK 2 608 000	NOK 74 000

The present values of the accumulated costs for different time periods will be:

PV of total costs during the 3 first years:	NOK 4 051 249
PV of total costs during the 5 first years:	NOK 4 160 465
PV of total costs during the 10 first years:	NOK 4 376 795
PV of total costs during the 20 first years:	NOK 4 641 007

Lease of fiber

With lease of fiber as the only alternative for the 19 trunks the costs will be:

	Trunk costs	
	OTC	ARC
3 × Fiber without WDM	NOK 90 000	NOK 0
Fiber with WDM	NOK 48 000	NOK 0
3 × ADSL2+	NOK 0	NOK 36 000
19 × Lease of fiber	NOK 570 000	NOK 951 900
Total	NOK 708 000	NOK 987 900

The present values of the accumulated costs for different time periods will be:

PV of total costs during the 3 first years:	NOK 4 549 612
PV of total costs during the 5 first years:	NOK 6 007 635
PV of total costs during the 10 first years:	NOK 8 895 646
PV of total costs during the 20 first years:	NOK 12 422 877

Deployment of fiber

In the Wireless Trondheim case the link distances are rarely as long as 1 000 meters which is the length used for fiber links previously. In the following calculations an average link length of 400 meters is assumed, and then the costs will be:

	Trunk costs	
	OTC	ARC
3 × Fiber without WDM	NOK 90 000	NOK 0
Fiber with WDM	NOK 48 000	NOK 0
3 × ADSL2+	NOK 0	NOK 36 000
19 × Deployment of fiber	NOK 6 346 000	NOK 0
Total	NOK 6 484 000	NOK 36 000

The present values of the accumulated costs for different time periods will be:

PV of total costs during the 3 first years:	NOK 7 827 525
PV of total costs during the 5 first years:	NOK 7 880 657
PV of total costs during the 10 first years:	NOK 7 985 899
PV of total costs during the 20 first years:	NOK 8 114 435

ADSL2+

Where fiber is available this will still be used, and so will the three ADSL2+ links used in all the other extremity scenarios. If only ADSL2+ is used to cover the rest of the APs, assuming 2 APs per ADSL2+ link, the costs will be:

	Trunk costs	
	OTC	ARC
3 × Fiber without WDM	NOK 90 000	NOK 0
Fiber with WDM	NOK 48 000	NOK 0
25 × ADSL2+	NOK 0	NOK 336 000
Total	NOK 138 000	NOK 336 000

The present values of the accumulated costs for different time periods will be:

PV of total costs during the 3 first years:	NOK 2 268 820
PV of total costs during the 5 first years:	NOK 2 764 716
PV of total costs during the 10 first years:	NOK 3 746 973
PV of total costs during the 20 first years:	NOK 4 946 639

A.3.1 Comparison

There are big difference in the total costs of the various extremities for each of the time periods, and there are big differences in when the costs should be paid. An interesting observation is that ADSL2+ is the cheapest alternative calculated over 3, 5 and 10 years, and with reduced costs also for the spreading it will be even more favorable than these calculations show. So if it were not for the limited performance of ADSL2+, it would have been a very good alternative for use in the backbone for Wireless Trondheim.

Of the three other extremities, radio is the alternative with the lowest present value of the costs for all time periods from 3 - 20 years, but the investments needed to get the network up and working is higher for radio than for leasing of fiber, almost as much as NOK 2 000 000 higher. The initial costs are high for radio but even higher for deployment of fiber which has initial cost of almost NOK 6 500 000, i.e. almost NOK 4 000

000 more than radio. While the ARCs are low for radio and even lower for fiber deployment, this is not the case for leasing fiber. With ARCs of approximately NOK 1 000 000 it is clearly the solution with the highest ARCs. So even though the initial costs of leasing fiber are relatively low, the total costs exceed those of deploying radio within 3 years and those of fiber deployment are exceeded within 10 years.

The low initial capital requirement combined with very high capacities make leasing of fiber a good alternative, but as the calculations show the total costs will get very high with time. Therefore, if it is possible to raise the money needed, fiber deployment will be a better solution. Radio may also be better, but since radio has lower capacity it is more complicated to decide which is the best solution.

Even for a time period as long as 20 years the deployment of fiber costs more than radio, but the PV of the costs is not the only factor which should be considered. Fiber has a much longer life time, so while radio equipment is likely to be outdated or broken after even less than 20 years, fiber is expected to have a lifetime of at least 40 years [42].

Appendix B

The calculations

There are several calculation results presented in this thesis, both as numbers and as the basis for different graphs. This appendix will give a better insight in the number used in the calculations and how the present values (PVs) are calculated.

The present value formula

The formula used for the calculation of the present value is:

$$PV = OTC + RC \times \frac{1 - (1 + r)^{-t}}{r}$$

where

- PV = Present Value
- OTC = One Time Costs, i.e. the initial establishment/deployment costs paid just once
- RC = Recurring Costs, i.e. the cost to be paid each year
- r = the discount rate
- t = the time period for the annuity RC (3, 5 or 10 years)

When the formula is used as it is presented here, it is assumed that the OTC are paid in the beginning of the year while the RC are paid at the end of each year.

B.1 ADSL2+

The input values are:

- Discount rate (r) 7%
- ADSL2+ monthly rate NOK 1 000
- Number of APs connected to one ADSL2+ trunk 2
- Time periods (t) 3, 5 and 10 years

The cost for three years delivery of an ADSL2+ connection is then:

$$PV_{ADSL2+,3years} = 12 \times \text{NOK } 1\,000 \times \frac{1 - (1 + 0,07)^{-3}}{0,07}$$

$$PV_{ADSL2+,3years} = \text{NOK } 31\,492$$

and the cost calculated per AP:

$$PV_{ADSL2+,3years} \text{ per AP} = \text{NOK } 15\,746$$

B.2 Radio

The input values for radio are:

- Discount rate (r) 7%
- Radio deployment cost NOK 130 000
- Annual license cost NOK 2 000
- Number of APs connected to each radio trunk 8
- Time periods (t) 3, 5 and 10 years

The cost for radio with a three year depreciation time is:

$$PV_{Radio,3years} = \text{NOK } 130\,000 + \text{NOK } 2\,000 \times \frac{1 - (1 + 0,07)^{-3}}{0,07}$$

$$PV_{Radio,3years} = \text{NOK } 135\,249$$

and the cost calculated per AP:

$$PV_{Radio,3years} \text{ per AP} = \text{NOK } 16\,906$$

B.3 Fiber

In the case of fiber there are several different scenarios, and the input for the various calculations will be introduced as they are needed.

B.3.1 Fiber available with draw-off point

The needed input variables in this case are:

- Cost of switch NOK 10 000
- Price for 1310 nm GBIC NOK 5 000
- Price for 1550 nm GBIC NOK 20 000
- Cost of one extra channel using WDM and passive MUX NOK 4 000

There are no recurring cost included in the calculation of cost in this case, so the present value is simply the sum of the initial costs. There are two possibilities, i.e. WDM is needed or it is not.

Without WDM:

$$PV_{Fiber_1a} = 2 \times \text{cost of switch} + 2 \times \text{cost of 1310 nm GBIC}$$

$$PV_{Fiber_1a} = 2 \times \text{NOK 10 000} + 2 \times \text{NOK 5 000}$$

$$PV_{Fiber_1a} = \text{NOK 30 000}$$

and the cost calculated per AP:

$$PV_{Fiber_1a} \text{ per AP} = \text{NOK 3 500}$$

With WDM:

$$PV_{Fiber_1b} = 2 \times \text{Passive MUX} + 2 \times \text{cost of 1550 nm GBIC}$$

$$PV_{Fiber_1b} = 2 \times \text{NOK 4 000} + 2 \times \text{NOK 20 000}$$

$$PV_{Fiber_1b} = \text{NOK 48 000}$$

and the cost calculated per AP:

$$PV_{Fiber_1b} \text{ per AP} = \text{NOK 6 000}$$

B.3.2 Fiber available without draw-off point

The additional input parameters needed in this situation are:

- Cost of cutting the fiber NOK 20 000
- Cost of deploying 1 m of fiber cable (fiber included) NOK 700
- Cost of fiber termination (per fiber) NOK 500
- Number of fibers in one cable 8
- Distance from cut to termination 70 m

These parameters give the following cost:

$$\begin{aligned}
 PV_{Fiber_2} &= \text{Cutting} + \text{Distance} \times \text{Fiber deployment} \\
 &\quad + \text{Nr. of fibers} \times \text{Termination} \\
 &\quad + 2 \times \text{cost of switch} + 2 \times \text{cost of 1310 nm GBIC} \\
 PV_{Fiber_2} &= \text{NOK } 20\,000 + 70 \times \text{NOK } 700 \\
 &\quad + 8 \times \text{NOK } 500 \\
 &\quad + 2 \times \text{NOK } 10\,000 + 2 \times \text{NOK } 5\,000
 \end{aligned}$$

$$\begin{aligned}
 PV_{Fiber_2} &= \text{NOK } 103\,000 \\
 &\text{and the cost calculated per AP:} \\
 PV_{Fiber_2} \text{ per AP} &= \text{NOK } 12\,875
 \end{aligned}$$

B.3.3 Microduct tube available

Additional input variables are:

- | | |
|--------------------------------------|---------|
| • Cost of fiber cable (per meter) | NOK 30 |
| • Cost of blowing 1 m of fiber cable | NOK 8 |
| • Number of fibers in one cable | 24 |
| • Length of fiber link | 1 000 m |

The calculations for this case are:

$$\begin{aligned}
 PV_{Fiber_3} &= \text{Length of link} \times (\text{Fiber cable cost} + \text{Blowing cost}) \\
 &\quad + 2 \times \text{Nr. of fibers} \times \text{Termination} \\
 &\quad + 2 \times \text{cost of switch} + 2 \times \text{cost of 1310 nm GBIC} \\
 PV_{Fiber_3} &= 1000 \times (\text{NOK } 30 + \text{NOK } 8) \\
 &\quad + 2 \times 24 \times \text{NOK } 500 \\
 &\quad + 2 \times \text{NOK } 10\,000 + 2 \times \text{NOK } 5\,000
 \end{aligned}$$

$$\begin{aligned}
 PV_{Fiber_3} &= \text{NOK } 92\,000 \\
 &\text{and the cost calculated per AP:} \\
 PV_{Fiber_3} \text{ per AP} &= \text{NOK } 11\,500
 \end{aligned}$$

B.3.4 No fiber available

When no fiber is available there are two possibilities, i.e. to deploy a new fiber infrastructure or lease fiber.

Deployment of fiber

All the parameters needed in the calculations of cost of deploying fiber has already been introduced.

$$\begin{aligned}
 PV_{Fiber_4} &= \text{Length of link} \times \text{Fiber deployment} \\
 &\quad + 2 \times \text{Nr. of fibers} \times \text{Termination} \\
 &\quad + 2 \times \text{cost of switch} + 2 \times \text{cost of 1310 nm GBIC}
 \end{aligned}$$

$$\begin{aligned}
 PV_{Fiber_4} &= 1000 \times \text{NOK } 700 \\
 &\quad + 2 \times 24 \times \text{NOK } 500 \\
 &\quad + 2 \times \text{NOK } 10\,000 + 2 \times \text{NOK } 5\,000
 \end{aligned}$$

$$\begin{aligned}
 PV_{Fiber_4} &= \text{NOK } 754\,000 \\
 &\text{and the cost calculated per AP:}
 \end{aligned}$$

$$PV_{Fiber_4} \text{ per AP} = \text{NOK } 94\,250$$

Lease of fiber

The additional input parameters in this case are:

- Establishment NOK 30 000
- Fixed monthly rate NOK 3 200
- Monthly rate for each commenced 250 m NOK 750

The cost of leasing over a period of three years is then given by:

$$\begin{aligned}
 PV_{Leasing,3years} &= \text{Establishment} + 2 \times \text{cost of switch} + 2 \times \text{cost of 1310 nm GBIC} \\
 &\quad + \text{PV of the recurring costs}
 \end{aligned}$$

$$\begin{aligned}
 PV_{Leasing,3years} &= \text{NOK } 30\,000 + 2 \times \text{NOK } 10\,000 + 2 \times \text{NOK } 5\,000 \\
 &\quad + \left(12 \times \left(\text{NOK } 3\,200 + \left\lceil \frac{1000}{250} \right\rceil \times \text{NOK } 750 \right) \right) \times \frac{1 - (1 + 0,07)^{-3}}{0,07}
 \end{aligned}$$

$$PV_{Leasing,3years} = \text{NOK } 255\,249$$

and the cost calculated per AP:

$$PV_{Leasing,3years} \text{ per AP} = \text{NOK } 31\,906$$