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Radio Planning and Coverage Prediction of Mobile WiMAX in Trondheim

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Problem Description

Mobile WiMAX is expected to be the next generation radio-interface,complementing WLAN and challenging UMTS/HSDPA. Larger cells, better QoS, mobility, and large bandwidth increases the expectations from the users. However, the technology is still very young, and measurements and planning is imminent in order to implement the standard.

Users desire to utilize a high data rate communication fully operationable indoor and outdoor. Thus, Mobile WiMAX has to be planned in order to reach these requirements. The assignment consists of planning topology and base station clusters for coverage of Mobile WiMAX in the populated area of Trondheim, by means of the software tool Astrix.

Assignment given: 16. January 2009
Supervisor: Geir Egil Øien, IET

Abstract

Challenged by the LTE system, Mobile WiMAX is set to be the next generation broadband wireless system. Providing high data rates over large distances gives unlimited possibilities for services provided to the end users. As for all undeveloped systems, Mobile WiMAX has also been exposed to rumors and hypes.

This thesis is based on the work performed in [31], and aims to provide radio planning of a Mobile WiMAX network in the populated areas of Trondheim, Norway. Moreover, preparatory work and suggestions for field testing of the deployed system have been provided. The coverage prediction have been performed by using Astrix 5.0, the radio planning tool of Teleplan. A total of 32 base stations have been suggested to provide ubiquitous coverage of -94 dBm using 92 sectors within the $35.63km^2$ large area. Furthermore, it has been recommended that fixed or nomadic users purchases the si-CPE or CPE PRO for better channel quality and throughput performances at indoor locations.

In the preparatory phase prior to field testing, a python script has been created to perform automated performance testing. The reason for automating the performance measurements has been to increase the test efficiency, and to reduce the possibility of human errors in parameter setting, and file naming.

This thesis will hopefully serve as a guide for future radio planners, where an Astrix user case, measurement scripts, and data processing codes are provided for revision and editing. The work has been performed on the initiative of Wireless Trondheim.

Preface

This thesis has been written as the final part of a master of science program in Electronics Engineering with specialization in Radio Technology and Communications. The program has been carried out at the Department of Electronics and Telecommunications at the NTNU.

During May 2008, I met with Geir Øien to discuss possible project assignments. WiMAX seemed like an interesting technology, and the fact that the assignment involved practical measurements appealed to me. I was thus introduced to Thomas Jelle and Wireless Trondheim, the initiator of the project, and owner of the WiMAX equipment, and decided to work with WiMAX.

During autumn 2008, a fellow student and I had the respective projects of testing indoor capacity, and coverage of pre-mobile WiMAX in Trondheim. Curiosity of the upgraded version of WiMAX, Mobile WiMAX, and the desire to continue working with a 4th generation wireless technology made the choice easy to choose the following thesis of radio planning Mobile WiMAX in Trondheim.

As of today, after I have written written to thesis on the technology, I feel that I have gained a better understanding in advanced wireless technology, the radio planning process and measurement procedures. I truly hope that my newly gained knowledge and experience will be of help for future Mobile WiMAX radio planners, and my future employers.

Jens Wiel Monrad-Hansen
12.06.2009

Acknowledgements

Throughout the process of writing a master thesis, I have had the privilege of meeting many interesting people. All have helped me in the process of forming and executing this report, the last step in finishing my degree. I am truly grateful to have had the opportunity to work with a technology such as Mobile WiMAX. A special thanks have to be given to the following persons:

Geir E. Øien, from the department of electronics and telecommunications, has been my supervisor throughout the project assignment and masters thesis. Mr. Øien have been available and open for discussions, questions, and support in all phases of the two reports performed on Mobile WiMAX.

Thomas Jelle, from Wireless Trondheim, has been my co-supervisor during the project assignment and master thesis. He has been the reason for why I have got the opportunity to work with a 4th generation technology. Mr. Jelle have been answering all question sent in his direction, and been pulling all his strings in order to have the Mobile WiMAX equipment up and running.

Øyvind Rusten and Teleplan for providing me with the radio planning tool, Astrix 5.0. Mr. Rusten have been of great help by installing the software which gave him new experiences for each new installation. Mr. Rusten have also contributed with his experience, and knowledge regarding the tool.

Kristoffer Milligan and NextNet have provided Wireless Trondheim with updated Mobile clients for field testing. Mr. Milligan has also provided me with his experiences on the Alvarion BreezeMAX equipment.

Chriss Greve at Upgrade have been the contact person towards Alvarion, and have answered and forwarded all my questions regarding the Alvarion equipment

Jardar Leira at Uninett have been spending tedious hours trying to get the system up and running. I truly appreciate the effort.

Erika Kvaale, my beloved girlfriend, for her support, understanding, and her parents car. I do not know many girls who gets excited when they find new antennas in the city.

Fellow students at NTNU for being available for discussions, digressions, and making early mornings and late nights a thrill.

Last of all I want to thank my own family for their support and knowing how to calm me down when I am stressed and frustrated.

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Abbreviations

3G 3rd Generation technology

3GPP 3rd Generation Partnership Project

ACK Acknowledgement

ACK-CH Acknowledgement Channel

AU Access Unit

AVU Air Ventilation Unit

AMC Adaptive Modulation and Coding

ARQ Automatic Repeat Request

BDP [Bandwidth Delay Product

BE Best-Effort Service

BER Bit Error Rate

BTC Block Turbo Code

BW Bandwidth

CC Convolutional Code

CCI Co-Channel Interference

CINR Carrier to Interference plus Noise Ratio

CPE Customer Premises Equipment

CQICH Channel Quality Indication Channel

CSI Channel State Information

CSIR Channel State Information at Receiver

CSIT Channel State Information at Transmitter

CTC Convolutional Turbo Code

DFT Discrete Fourier Transform

DoD Department of Defense

ErtPS Extended Real-Time Polling Service

FBSS Fast Base Station Switching

FDD Frequency Division Duplexing

FEC Forward Error Correction

FFT Fast Fourier Transform

FSPL Free Space Path Loss

FTP File Transfer Protocol

FTR Fiber To the Roof

FUSC Full Usage of Sub-Carriers

GPS Global Positioning System

GSM Global System for Mobile communications

HARQ Hybrid Automatic Repeat Request

HDTV High Definition Television

HHO Hard Handover

HSPA High Speed Packet Access

HTTP Hypertext Transfer Protocol

IDU Indoor Unit

IEEE Institute of Electrical and Electronics Engineers

IF Intermediate Frequency

IP Internet Protocol

Iperf Internet Performance Working Group

ISI Intersymbol Interference

LDPC Low Density Parity Check Code

LOS Line Of Sight

LTE 3GPP Long Term Evolution

MAC Medium Access OSI Layer

MCS Modulation and Coding Scheme

MDHO Macro Diversity Handover

MIMO Multiple-Input and Multiple-Output

MPEG Motion Picture Experts Group

MS Mobile Station

NACK Negative Acknowledgement

NLANR/DAST The National Laboratory for Applied Network Research/ Distributed Applications Support Team

NLOS Non Line Of Sight

NPU Network Processing Unit

nrtPS Non-Real-Time Polling Service

NTNU Norwegian University of Science and Technology

ODU Outdoor Unit

OFDM Orthogonal Frequency Division Multiplexing

OFDMA Orthogonal Frequency Division Multiple Access

OSI Open Systems Interconnection Reference Model

PC Personal Computer

PDA Personal Digital Assistant

PHY Physical OSI layer

PIU Power Interface Unit

PLOS Partial Line Of Sight

PSU Power Supply Unit

PUSC Partial Usage of Sub-Carriers

QAM Quadrature Amplitude Modulation

QoS Quality of Service

QPSK Quadrature Phase Shift Keying

RF Radio Frequency

RTG Receive/Transmit Transition Gaps

rtPS Real-Time Polling Service

RTT Round Trip Time

S-OFDMA Scalable-OFDMA

SDR Software-Defined Radio

SINR Signal-to-interference plus noise ratio

SM Spatial Multiplexing

SMTP Simple Mail Transfer Protocol

SNMP Simple Network Management Protocol

SNR Signal-to-Noise Ratio

SSH Secure Shell

SVD Singular Value Decomposition

TCP Transmission Control Protocol

TCP/IP Transmission Control Protocol/Internet Protocol

TDD Time Division Duplexing

TETRA Terrestrial Trunked Radio

TTG Transmit/Receive Transition Gaps

TWS TCP Window Size

UDP User Datagram Protocol

UGS Unsolicited Grant Service

UMTS Universal Mobile Telecommunications System

VoIP Voice over IP

Wi-FI

WLAN Wireless Local Area Network

WiMAX Worldwide Interoperability for Microwave Access

1

Introduction

Wireless technology has proven itself to be a fast evolving technology. From the entry of GSM and WLAN, customers have continuously increased the demand for mobility, services and capacity. Third generation mobile technology and UMTS came as a fresh breath for the mobile industry by supporting higher data rates than GSM, and providing more advanced services such as support for video conferences. As of today, mobile devices are becoming more and more advanced, and supports more demanding applications. Many mobile phones supports advanced applications by the use of WLAN within Wi-Fi hotspots. Outside these cells, the customer have to rely on the UMTS or HSPA technology.

With the prospect of a metropolitan wireless technology supporting data rates of up to 60 Mbps, 4G, the possibilities are unlimited regarding applications to offer the end user. Having such technology incorporated into laptops, PDAs, and mobile phones makes location based information possible. Meaning that users may download real time traffic data for avoiding congested areas during commuting traffic. In emergency purposes, ambulance personnel may upload patient information to prepare the hospital, and fire teams may get building information about the burning building while they are on the road.

For the commercial purpose, video conferences, VoIP, HDTV streaming, music applications, real time surveillance, Internet browsing, and email are some of the possible applications for a metropolitan broadband wireless system.

The Mobile Worldwide Interoperability for Microwave Access (Mobile WiMAX) is a 4G wireless technology with the promise of the mentioned features. Apart from providing high data rates over large distances, Mobile WiMAX supports mobility within and between sectors and base stations of up to 120 km/h. In the initial stage, Mobile WiMAX is intended to complement with WLAN for outdoor access, where users may take the advantage of ubiquitous broadband communication access. By looking at the success of HSDPA and HSUPA today, a well developed Mobile WiMAX network may one day oust WLAN and provide broadband access both outdoor and indoor.

As for the format war over high definition optical discs between Bluray and HD DVD, Mobile WiMAX is not the only 4G wireless technology. As a response to the Mobile WiMAX threat, the 3GPP long-term evolution (LTE) has been developed. LTE is rumored to provide higher data rates than Mobile WiMAX, 100 Mbps DL and 50 Mbps UL over a 20 MHz channel. The 4G war has already began, with some rumors saying that Mobile WiMAX will win it due to a 2 year head start, and other contenders declaring that the LTE is the best and chosen technology. This report is solely focusing on the Mobile WiMAX technology.

1.1 Scope

Radio planning in general is a large and demanding process ranging from the initial process of setting up a business model, deploying the network, and release the services for commercial purposes. In order to limit the scope of this thesis, the main focus has been on the actual radio planning with Astrix 5.0.

Due to problems with the upgrade of the WiMAX equipment, the limitations have been re-defined to comprise radio planning with Astrix, preparatory planning of the measurements, creating an Astrix user case, and provide suggestions to presentation of data, and future work.

1.2 Related Work

This section will provide a brief description of the previous work done in the area of WiMAX. The study has been done to gain better understanding of the technology, standard and to gain some theoretical experience in the area of testing a WiMAX network. Few Mobile WiMAX field tests have been made available, thus pre-mobile WiMAX field trials have been read with inspiration to get hints and tips for planning and testing a WiMAX network.

1.2.1 A field study of the performance of Mobile WiMAX in Wireless Trondheim

The report is a result of a project assignment performed at NTNU in 2008, [34]. The scope was to perform practical performance testing on a pre-mobile WiMAX network in Trondheim city. Wireless Trondheim provided both WiMAX equipment and a base station site at the Gunnerus Library. The transport protocols UDP and TCP were tested both with and without competing traffic created by GenSyn.

The base station was an Alvarion BreezeMAX 2500 operating in the 2.5 GHz frequency band over a 5 MHz channel. A total of 12 locations were tested with both indoor and outdoor performance.

Measured TCP throughput was found to be 6.12 Mbps and UDP throughput 6.0 Mbps, about 70 % of the throughput provided by the system vendor. Synthetic traffic generated by GenSyn showed an earlier decline in throughput at large bandwidths in comparison with the traffic-free measurements.

1.2.2 Mobile WiMAX 802.16e - a study of indoor coverage

Mobile WiMAX 802.16e - a study of indoor coverage is a project assignment performed in 2008 at Wireless Trondheim, [31]. The work was a collaboration with the previous mentioned project assignment, [34], which ended in two reports. One on the system performance/capacity, and the other on the indoor coverage. The scope was to map the indoor performance of pre-mobile WiMAX in a city environment as Trondheim. The reports, [31, 34], have been the motivation for continuing working on Mobile WiMAX, which has resulted in this master thesis.

Propagation, penetration loss and PHY performance has been investigated in the report. The system was as described in the previous subsection operating in the 2.5 GHz frequency band over a 5 MHz channel.

The tests were performed throughout the city of Trondheim with the base station placed at the Gunnerus Library. A total of 5 locations were tested. Each location was tested at different spots both outdoor and indoor to get an average penetration loss through a certain building material.

The tests showed that the propagation in the center of Trondheim followed the COST-231 and the Okumura Hata model for suburban and urban areas. The indoor range of pre-mobile WiMAX was found to be approximately 600 meters in a NLOS environment. Furthermore, the experimental results showed an average 1st wall penetration loss of 9.94 dB. Adaptive transmission power were found to compensate for the penetration loss as long as sufficient power were available.

1.2.3 The Wireless Tram

The Wireless Tram is a master thesis performed on the initiative of Wireless Trondheim by Rein Sigve Karlsen, [19]. Tests on measuring channel quality, and throughput of pre-mobile WiMAX were carried out on the tram in Trondheim, Norway, during 2008.

The tests were performed by using the Alvarion BreezeMAX 2500, operating in the 2.5 GHz frequency band over a 5 MHz channel. The maximum transmitting power of the base station was 30 dBm. Two types of antennas were used during testing, one dual slant polarized antenna with an antenna gain of 16 dBi, and two vertical polarized antennas with an antenna gain of 16.5 dBi. The CPE PRO was used as a subscriber unit with a maximum transmitting power of 19 dBm over an antenna with 8.5 dBi gain.

Tests were performed at the tram with the base station situated at two different locations, the Gunnerus Library and Byåsen Vgs. TCP throughput and link quality was measured at spots along the tram line, and at the tram while moving. The tests showed a TCP maximum throughput of just above 6 Mbps when measuring at a fixed location. The TCP throughput measured in motion did seldom perform better than 1 Mbps.

The impact of 2nd order diversity showed a 14% and 50% improvement of average throughput by separation in polarization and space respectively. Coverage improvements were only measured to a couple of hundred meters.

As a result of testing along the tram line, the following base stations were recommended to provide coverage at the tram: Gunnerus Library, Byåsen Vgs, and the Telenor mast at Storhaug.

Summer internship at Wireless Trondheim

Summer 2008, Rein Sigve Karlsen continued his work on WiMAX at Wireless Trondheim, [18]. The internship consisted in further testing of the coverage of the tram line. The recommendations given in the master thesis, were given in this report too. Furthermore, indoor coverage was tested at 10 different locations. The same system specifications, as previous mentioned, were used with the base station situated at the Gunnerus Library.

Parameters as RSSI, SNR, CPE transmission power and modulation were measured at each location. The report showed good system performance, in form of high modulation and coding rate, at distances up to 1 km away from the base station.

1.2.4 A Field Study of WiMAX Performance

A Field Study of WiMAX Performance is a master thesis written for Telenor R & I by Pål R. Grønsrud, [12]. Tests were carried out in Oslo, Hamar, and Gjøvik, Norway, during 2006 and 2007.

The first test, a fixed WiMAX network was tested throughout the city of Oslo from a base station situated at Fornebu. The Alvarion BreezeMAX 3500 was used as a base station, operating on the 3.5 GHz frequency band with a 3.5 MHz channel. The base station was transmitting with a maximum of 28 dBm over an antenna with a gain of 14 dBi, where only one CPE was used to communicate with the base station. The CPE had a maximum transmitting power of 20 dBm and an antenna gain of 20 dBi.

The tests were performed at 15 different locations throughout the city of Oslo. Quality of the link and throughput performance like UDP, TCP and FTP were tested at each location.

The tests showed good throughput performance of distances up to 2 km away from the base station. A LOS measurement 11.4 km away from the base station did also show good throughput performances. NLOS locations at greater distances than 2 km however, showed poor throughput in the uplink. Furthermore, the maximum measured bit rate was found to be of 76 % of the bit rate given from the system vendor. Overhead and management traffic was given as a possible reason for the decreased capacity.

The second test performed in the master thesis was a deployment test performed on a fixed WiMAX network. The testing was performed in, and around, the city of Gjøvik. The pre-defined area was covered by 10 base stations, with a total of 30 sectors, providing fixed WiMAX access to 850 subscriber units. The system specifications were as mentioned for the previous test.

Performance data like link quality, modulation, and transmission power was gathered every fifth minute for four months. Measurements of RSSI and SNR showed that co-channel interference was present at many locations. More frequency bands, and a more fine tuning of base station parameters were suggested to improve the co-channel interference.

The third, and last, WiMAX test performed in the master thesis was a pre-mobile WiMAX field trial. The tests were performed in the city of Hamar.

One base station with three (3) sectors was used to perform tests from 40 different locations. Each sector was deployed with 2nd and 4th order diversity. The used antennas were the dual slant polarized antennas with 13 dBi gain. The base station was an Alvarion BreezeMAX TDD operating on the 3.5 GHz band with a 5 MHz channel. The maximum transmitting power was set to 34 dBm. The subscriber unit was an si CPE with a maximum transmitting power of 22 dBm over an antenna with 9 dBi gain.

Channel quality and throughput measurements were measured as for all of the other tests performed. 6.2 Mbps were found to be the highest UDP throughput in the uplink and downlink. Furthermore, the highest modulation was observed at a range of up to 1 km away from the base station. Sub-channelization was also concluded to improve the range of the system considerably.

1.3 Readers Guide

Chapter 2 provides a brief background on Wireless Trondheim, the technology in use, and the reason for implementing Mobile WiMAX.

Chapter 3 gives an introduction to the Mobile WiMAX standard, and links the standard with the Alvarion 4MOTION equipment.

Chapter 4 summarizes and compares the most common propagation models for urban areas.

Chapter 5 introduces the TCP/IP model, the most common transport protocols and the Shannon Capacity.

Chapter 6 covers the system available for testing, and its configuration.

Chapter 7 discusses the radio planning methodology and illustrates the predicted radio planning coverage using Astrix 5.0.

Chapter 8 summarizes the preparations done prior to measurements.

Chapter 9 contains a description of testing parameters, and measurement procedures. The chapter also provides a suggestion for presentation of measurement data.

Chapter 10 provides a general discussion of the work performed in this report.

Chapter 11 summarizes and concludes upon the work performed, as well as recommends future work.

Appendices contains additional information on topology and demographics of Trondheim, antenna specifications, an Astrix User Case, possible site candidates, site coverage, and suggested source codes for measurements and data processing.

2

Wireless Trondheim

Wireless Trondheim was initiated as a research and development project at NTNU in 2005. It is today a result of a coalition between NTNU, Trondheim Energi, Adresseavisen, Sparebank 1 Midt-Norge, the municipality of Trondheim, and the county authority of Sør-Trøndelag. The main goal of Wireless Trondheim is to provide Internet access to all the inhabitants in the populated areas of Trondheim city.

The initial project of Wireless Trondheim was to provide Wi-Fi access in the commercial areas of Trondheim city, comprising Solsiden and Midtbyen. The business concept of the project is that the users pay a small fee for a time-limited Internet access. The project has proven itself to be a success, and further expansions has been made.

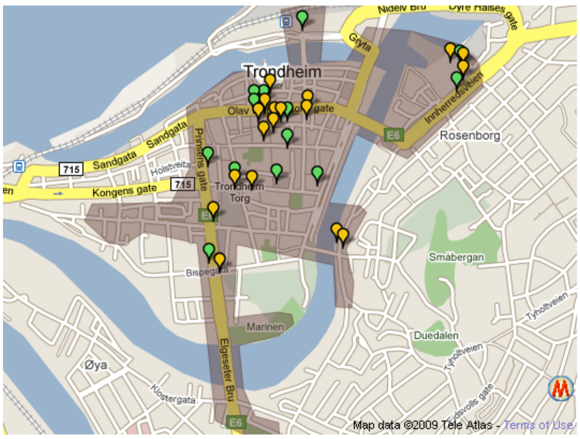


Figure 2.1: Coverage map of offered Wireless Trondheim Wi-Fi access

The current technology is based on the 802.11 standard, where Wi-Fi hotspots are distributed throughout the central areas of Trondheim, see figure 2.1. The Wi-Fi hotspots are basically placed outdoor, thus offering access outdoor. Some hotspots, however, are placed indoor, hence providing indoor Internet access.

The telecommunication is, as known, continuously evolving, and so is Wireless Trondheim. Moreover, the main motivation for implementing a Mobile WiMAX network is to take advantage of high data rates over large ranges. Mobile WiMAX will hopefully prove itself to be cost effective, and thus be the standard to make Trondheim the first city in Norway with ubiquitous Internet access. Mobile WiMAX is not intended to be a direct threat towards Wi-Fi and 3G, but rather co-exist and provide even greater coverage and accessibility to the consumers.

Part I

Theory

3

About Mobile WiMAX

Mobile WiMAX is set to become the next generation of broadband wireless systems. High throughput at large ranges is the main reason for the hype and high expectations around the system. As described in [31], broadband wireless systems are very vulnerable to multipath fading and intersymbol interference (ISI). Orthogonal frequency division multiplexing (OFDM) has thus proven to be the key feature of future wireless systems, such as Mobile WiMAX and LTE, to deal with this problem. The OFDM technology divides the datastreams into several parallel streams. In this way, the transmission will be more robust to multipath fading and, with cyclic prefix, be totally ISI free.

Mobile WiMAX, 802.16e, is based on the amendment of the IEEE 802.16-2004 Air Interface Standard, where the main improvements are due to the support of mobility. Moreover, the WiMAX Forum is a not-for-profit organization consisting of more than 500 members. Its purpose is to create a set of rules, profiles, for system developers to provide interoperability between equipment. Hence WiMAX Forum certified products are able to co-exist in a network. This chapter will provide a brief description of the different features of Mobile WiMAX.

3.1 OFDM

Basic wireless communication theory introduces expressions as absorption, scattering, diffraction, and fading. These effects are all described in [31], and are the reasons for why a wireless channel is characterized as hostile in comparison with wired and optic channels. Moreover, wideband signals often experience intersymbol interference when transmitted over a wireless channel, due to the arrival of several symbols simultaneously.

OFDM (Orthogonal Frequency Division Multiplexing) utilizes a set of orthogonal sub-carriers to form a channel. The wideband information stream is divided into multiple narrowband information streams and transmitted over parallel sub-channels. These sub-channels are created by mapping a subset of the mentioned sub-carriers. The total bandwidth and data rate will remain unchanged since the narrowband signals are sent as parallel streams. The reason for applying OFDM is to increase the symbol length of each sub-stream to be larger than the time delay in the channel, $T_S >> \tau$. By applying a cyclic prefix (CP), the transmission can be totally ISI-free.

Having multiple sub-streams over multiple sub-channels requires many RF-components and filter which will make the system complex and expensive for a high number of sub-channels [31, 20]. Implementing the discrete Fourier transform (DFT) through the fast Fourier transform (FFT) algorithm makes the system more cost effective. FFT enables the possibility of having a channel of up to 2048 sub-carriers. Furthermore, FFT requires circular convolution, which is achieved by introducing a cyclic prefix (CP). The cyclic prefix is a copy of the last bits in the symbol inserted at the beginning of the symbol, see figure 3.1. Another advantage with the CP is, as mentioned, that it completely removes ISI if the prefix is longer than the delay spread, $T_g >> \tau$.

Transmitting redundant bit either requires a larger bandwidth or decreases the data rate. This effect is however barely noticeable since the sub-channels are overlapped in the same manner as for the roll of factor in cosine pulse-shaping [7]. For further explanations on OFDM and cyclic prefix see [31].

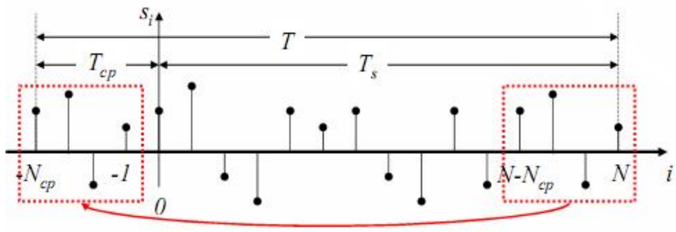


Figure 3.1: Cyclic Prefix [6]

Frequency diversity, see [31, 11], is introduced by interleaving the information bits prior to transmission over the channel. Frequency diversity will facilitate decoding of the information since non-adjacent symbols will be affected if a deep fade is present. Diversity has been further described in [31]. As will be described in subsection 3.1.1, each subchannel consist of a set of sub-carriers. Information are individually coded and modulated per sub-carrier, giving a more effective transmission. The sub-carriers comprising a sub-channel can either be assigned continuously or by PUSC or FUSC

Parameters	*Values*			
System Channel Bandwidth (MHz)	1.25	5	10	20
Sampling Frequency (F_p in MHz)	1.4	5.6	11.2	22.4
FFT Size (N_{FFT})	128	512	1024	2048
Number of Sub-Channels	2	8	16	32
Sub-carrier Frequency Spacing (f)	10.94 kHz			
Symbol Time ($T_b = \frac{1}{f}$)	91.4 μs			
Guard Time ($T_g = \frac{T_b}{8}$)	11.4 μs			
OFDMA Symbol Duration ($T_s = T_b + T_g$)	102.9 μs			
Number of OFDMA Symbols (5 ms Frame)	48			

Table 3.1: OFDMA Scalability Parameters, [7]

to further exploit the advantage of frequency diversity, [7, 20].

3.1.1 OFDMA and S-OFDMA

Scalable OFDMA (S-OFDMA) has its origin in OFDMA (Orthogonal Frequency Division Multiple Access) which introduces multiplexing of multiple users. In other words, each user is assigned to different set of sub-channels depending on the offered service. Thus OFDMA allows the base station to transmit and receive simultaneously from multiple mobile stations. S-OFDMA is an adaptive access technique which assigns different bandwidths to the users by assigning a set of sub-carriers to the sub-channels depending on channel conditions and data requirement. Bandwidth scaling is supported by adjusting the FFT size and keeping the sub-carrier spacing constant at 10 kHz. The benefits of S-OFDMA is to have a flexible bandwidth for the different spectrum allocation and usage models. Table 3.1 consists of sampling frequency, FFT size, and number of sub-channels for the different bandwidths available in Mobile WiMAX. Sub-carrier spacing, symbol time, guard time, OFDMA symbol duration, and number of OFDMA symbols are also listed in the table, 3.1.

Sub-channelization

A sub-channel consists, as mentioned, of a set of sub-carriers. The sub-carriers are divided into three (3) groups [7], data sub-carriers, pilot sub-carriers, and null sub-carriers. Each set of subcarriers are serving different functionalities to the transmission. The data sub-carriers, as the name describes, are the carriers carrying the information data, payload. The pilot subcarriers, synchronizes the transmissions and estimates the channels. As will be described in 3.3 and 3.2.3, estimation and synchronization are two very important features when implementing adaptive coding and modulation (AMC), and time division duplexing (TDD). The null sub-carriers are used as guard band between the different symbols. Apart from increasing the bandwidth, null sub-carriers does not affect the system performance. Figure 3.2 illustrates the symbol structure of the OFDMA.

As beforementioned, PUSC and FUSC describes the sub-carrier allocations. Both PUSC and FUSC chooses the sub-carrier permutations pseudo-randomly to form a sub-channel. The main difference between the permutation modes is that FUSC (Full Usage of Sub-Carriers) chooses all sub-carriers pseudo-randomly, where PUSC (Partial Usage of Sub-Carriers) chooses clusters of adjacent sub-carriers pseudo-randomly.

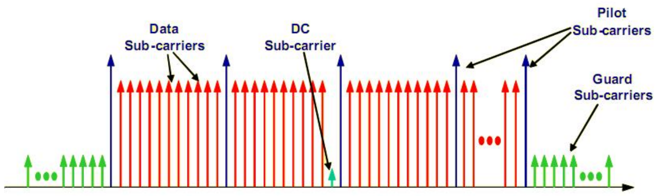


Figure 3.2: OFDMA Sub-Carrier Structure, [7]

3.1.2 OFDM in Alvarion 4MOTION

As described in section 3.1 and [31], OFDM increases the symbol duration. With the introduction of a cyclic prefix, the transmission can be totally ISI-free, hence the system performance in NLOS areas is increased.

OFDMA uses the subchannels to support simultaneous transmission and reception from several mobile stations. Moreover, OFDMA increases the system efficiency.

S-OFDMA, on the other hand, supports bandwidth adaption where the symbol duration is kept constant, and the bandwidth is altered by modifying the FFT-size. According to [29], the subchannel capacity remains the same independent of the channel bandwidth.

The Alvarion 4MOTION system supports all of the mentioned modulation and access techniques. In the sub-carrier permutation, only the PUSC subchannel permutation is supported. Table 3.2 shows the S-OFDMA parameters and the sub-carrier distribution using PUSC. By choosing clusters of sub-carriers randomly throughout the available bandwidth, frequency diversity is exploited. Consequently increasing the system reliability in high-mobility NLOS scenarios. The reason for applying a higher number of pilot and null sub-carriers in the uplink is that mobile stations tend to have less power available, and lower gain.

Parameters		Value
System Channel Bandwidth		5 MHz
Sampling Frequency (F_p)		5.6 MHz
FFT Size (N_{FFT})		512
Sub Carrier Frequency Spacing (f)		10.94 kHz
Useful Symbol Time ($T_b = 1/f$)		91.4 μs
Guard Time ($T_g = T_b/8$)		11.4 μs
OFDMA Symbol Duration ($T_s = T_b + T_g$)		102.9 μs
Frame Duration		5 ms
DL PUSC	Null Sub-carriers	92
	Pilot Sub-carriers	60
	Data Sub-carriers	360
UL PUSC	Null Sub-carriers	104
	Pilot Sub-carriers	136
	Data Sub-carriers	272

Table 3.2: OFDMA Parameters, [29]

3.2 Modulation and Coding

The following section will provide a brief description of the modulation and coding of Mobile WiMAX. Further descriptions can be found in [31].

3.2.1 Modulation

As beforementioned, each sub-carrier is modulated separately. This subsection will list up the modulation types that are optional and mandatory by the WiMAX Forum. In the downlink, QPSK, 16QAM, and 64QAM are all mandatory modulation types. 64QAM are however optional in the uplink.

Table 3.3 shows the minimum sensitivity level for each modulation and coding rate per bandwidth, [15], where the BER is less than 10^{-6}. Table 3.4, however, converts the BER requirement with assumptions to SNR requirements for the MCS, in an AWGN environment, [16]. The relationship between BER and Bit/Symbol energy, E_B/N_0, can be found both mathematical and graphical. For a more in depth description on performance of digital modulations over wireless channels, see [31, 11].

3.2.2 Coding

Channel coding is a way to increase the robustness of a channel by including randomization, interleaving, repetition, and error correction prior to modulation. Forward error correction (FEC) adds redundant bit to the information bits, allowing the receiver to detect and correct errors. The code rate decides how many coded bits that represent the information bit. The supported code

Bandwidth (MHz)	**QPSK**		**16-QAM**		**64-QAM**	
	1/2	**3/4**	**1/2**	**3/4**	**2/3**	**3/4**
1.5	-91	-89	-84	-82	-78	-76
1.75	-90	-87	-83	-81	-77	-75
3	-88	-86	-81	-79	-75	-73
3.5	-87	-85	-80	-78	-74	-72
5	-86	-84	-79	-77	-72	-71
6	-85	-83	-78	-76	-72	70
7	-84	-82	-77	-75	-71	-69
10	-83	-81	-76	-74	-69	-68
12	-82	-80	-75	-73	-69	-67
14	-81	-79	-74	-72	-68	-66
20	-80	-78	-73	-71	-66	-65

Table 3.3: Receiver minimum input sensitivity (dBm), [15]

Modulation	E_b/N_0 **(dB)**	**Coding Rate**	**Receiver SNR (dB)**
QPSK	10.5	1/2	5
		3/4	8
16-QAM	14.5	1/2	10.5
		3/4	14
64-QAM	19.0	1/2	16
		2/3	18
		3/4	20
Assumptions			
Bit error rate (BER):			10^{-6}
Implementation Loss:			5 dB
Noise Figure:			7 dB
Coding:			CC

Table 3.4: Receiver SNR and E_b/N_0 assumptions, [16]

rates of Mobile WiMAX are: 1/2, 2/3, 3/4, and 5/6.

Convolutional Code

Convolutional Coding (CC) is a mandatory error correcting code in the WiMAX standard and profile. CC consists of a shift register and modulo-2 adders, see figure 3.3. Each information bit is passed through all the stages of the shift register, where each codeword is generated as an output of the modulo-2 adders. Figure 3.3 shows a convolutional 1/2 rate encoder with constraint length of seven (7), [15]. The figure shows how a single bit is converted into two bits, X and Y. Graphical ways to gain better understanding of the CC-operations can be found in [22].

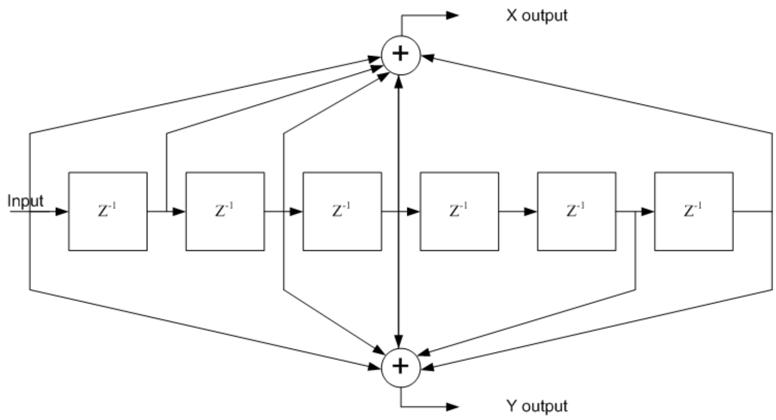


Figure 3.3: Convolutional 1/2 rate encoder [15]

Turbo Codes

Turbo codes are probably the most effective FEC since it approaches the Shannon limit. The Shannon limit is the maximum theoretical transfer rate over a noisy channel. Convolutional turbo code (CTC) enables the support of HARQ, and has proven itself to provide great performance in other broadband wireless systems, [2]. Mobile WiMAX supports CTC with duo-binary turbo encoders. According to [2], duo-binary turbo encoders have the following advantages in comparison with conventional turbo encoders:

- Better robustness of decoder
- Larger minimum distances between codewords
- Less sensitivity to puncturing patterns
- Better convergence

Readers interested in CTC are referred to [2] and [4].

Block Turbo Codes and LDCP Codes

Block turbo codes (BTC), and low density parity check codes (LDPC) are defined in the WiMAX standard as optional. Manufacturers have, according to [2], decided to only implement CTC. Hence BTC and LDPC are not likely to be implemented in WiMAX equipment.

3.2.3 Adaptive Modulation and Coding

Known from basic wireless communication theory, modulation says how a symbol is transmitted over a wireless link, whereas coding increases the reliability of the transmission. Channels do continuously change as transmitter, receiver, and/or environment move relatively to each other. In order to receive a signal correctly, the transmission has to be made as reliable as possible. Unfortunately, reliability comes as a trade-off with throughput. Without adaptive modulation and coding, the system has to transmit at worst-case-scenario in order to provide a reliable transmission. Moreover, AMC adapts modulation and coding to the instantaneous channel state on a per sub-channel basis. In this way the system utilizes water-filling ,[11, 31], in time and space by continuously adapting the modulation and coding. As a consequence, AMC increases the system efficiency.

Mobile WiMAX supports, as mentioned, QPSK, 16QAM, and 64QAM (optional in UL) modulation, Convolutional Coding (CC), Convolutional Turbo Codes (CTC), Block Turbo Codes (BTC), and Low Density Parity Check Code (LDPC). All with various code-rates. As beforementioned, the two latter coding schemes are optional in the Mobile WiMAX profile.

3.2.4 Coding and Modulation in Alvarion 4MOTION

The Alvarion 4MOTION base station supports all of the mentioned modulation methods, whereas CTC is chosen as the coding method due to its high efficient error correction, [29]. Table 3.5 shows an overview of the supported modulation and coding scheme (MCS) for the BreezeMAX 4Motion base station.

The rate adaption is used to continuously adapt the MCS to the current channel conditions, CINR. The chosen rate is thus a result of measured channel condition and QoS requirements. The goal is to maintain the highest possible and reliable throughput. The DL CINR is measured at the mobile client and reported back through the CQICH. The uplink CINR is predicted from the measured noise and interference level and MS received power density, [29]. The received power density is calculated from the path loss, maximum transmitted power, and number of subchannels.

Modulation	Coding Type and Rate
QPSK	CTC 1/2
QPSK	CTC 3/4
16QAM	CTC 1/2
16QAM	CTC 3/4
64QAM	CTC 1/2
64QAM	CTC 2/3
64QAM	CTC 3/4
64QAM	CTC 5/6

Table 3.5: Supported MCS of Alvarion BreezeMAX BS, [29]

3.3 Time Division Duplexing

TDD (Time Division Duplexing) is a multiplexing technique where each channel is given a dedicated time-slot. Being uplink/downlink for one user, or multiple uplink/downlink time-slots for multiple users over the same link. A great advantage with TDD in comparison with FDD (Frequency Division Duplexing) is that TDD supports asymmetric data. Meaning that adjusting the user-uplink/downlink slot-ratio is more feasible than adjusting bandwidths as in FDD. The varying requirements of QoS gives TDD the upper hand against other duplexing technique. Since uplink and downlink utilizes the same channel, reciprocity may be assumed. The transmitter will thus estimate the channel while receiving, and assume that the channel remains the same when transmitting. Advantages does not come alone, and TDD is no exception. Synchronization is the main challenge in TDD. In order to send and receive correctly, both transmitter and receiver has to be accurate synchronized to each other. The synchronization is done in the pilot of each frame. Because of the high importance of receiving the pilot correctly, the sub-carriers are modulated with a low rate and a robust code.

TDD Frame Structure

Figure 3.4 shows the OFDM structure for TDD implementation [7]. Each frame is divided into two sub-frames, downlink sub-frame, and uplink sub-frame. All sub-frames are separated by a TTG (Transmit/Receive Transition Gap) or a RTG (Receive/Transmit Transition Gap). These gaps are guard intervals so that adjacent sub-frames does not interfere with one another. The first symbol of the OFDM symbol is the preamble. The preamble consists of the pilot sub-carriers, and contains synchronization for a reliable transmission.

The FCH (Frame Control Header)follows the preamble and contains information about MAP-lengths, modulation, coding, and sub-channel usage. Furthermore, sub-channel usage and other control information for the uplink and downlink is necessary. The DL-MAP and UL-MAP provides such information to the receiver.

Figure 3.4 shows that each burst may be of different size, depending on CSI and QoS. Bursts utilizing many sub-channels can thus provide high QoS as VoIP, whereas transmissions over a few sub-channels, but many symbols, can deliver QoS as downloading.

Apart from the data transmission, the uplink sub-frame (figure 3.4) consists of ranging, ACK-CH, and CQICH. Ranging is designed for mobile stations (MS) to perform adjustments to time, frequency, and power as well as bandwidth requests. The ACK-CH is to provide HARQ-feedback to the base station. The feedback tells the base station if the MS has received the sent information correctly or not. Fast feedback (CQICH) is a reliable feedback channel to provide CSI (Channel State Information) to the base station.

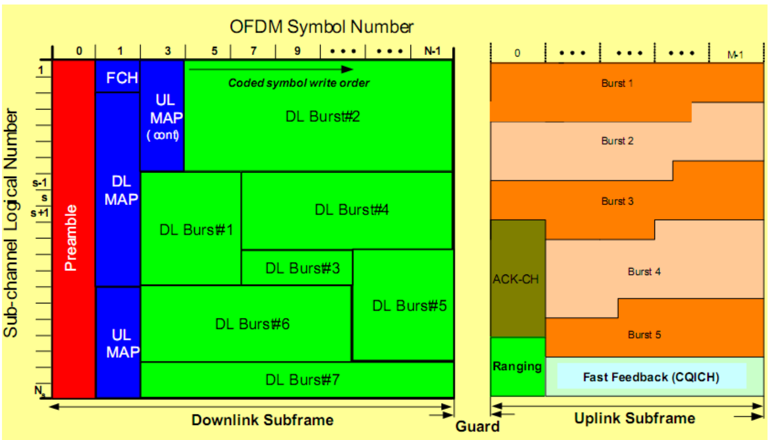


Figure 3.4: WiMAX OFDMA Frame Structure for TDD, [7]

3.3.1 Frame Structure in Alvarion 4MOTION

The frame structure of the Alvarion 4MOTION is, as expected, according to the recommendations from the standard and the WiMAX Forum, see figure 3.4. There are no tolerance for altering the frame structure. The provided bandwidth is adjusted, from the base station, on a per frame basis. Information provided by [29], tells that the UL/DL sub-frame duration is configurable from 12-34 to 21-25 for the UL and DL respectively. Synchronization is, as mentioned, GPS based to keep an accurate synchronization between base stations and mobile clients. The subchannel allocations maximizes the number of subchannels per mobile station to increase the frequency diversity in the DL, whereas the number of subchannels is minimized in the UL. The minimization of subchannels in the UL is to concentrate the power, hence increasing the uplink link budget. Resulting in increased coverage and capacity of the system.

3.4 Hybrid Automatic Repeat Request

HARQ is an improved error control method (originated from ARQ, hybrid-ARQ). As for ARQ, HARQ uses the redundant bits in the codeword to decide if the codeword is received correctly or not. The information is then decoded, and a positive or negative acknowledgement, ACK or NACK respectively, are sent to inform the transmitter about the transmission. If a NACK is sent to the transmitter, the receiver stores the received codeword. The new codeword sent from the transmitter will thus be compared with the previously faulty codeword, which in turn will increase the probability of receiving correctly. The process is repeated a number of times before the connection is disrupted. ARQ, on the other hand, discards faulty codewords. The IEEE 802.16e supports two types of HARQ, type I HARQ and type II HARQ. The Mobile WiMAX profile supports both HARQ types, where type I is mandatory and type II is optional.

Type I HARQ keeps a constant modulation and coding rate for each retransmission. Transmission are repeated until an ACK is received, or the maximum number of retransmissions are sent. Type II HARQ, however, alters the redundant bit so that the probability of decoding the codeword increases. A drawback with Type II HARQ is that it is more complex and requires a larger buffer at the receiver, [19].

3.4.1 HARQ in Alvarion 4MOTION

HARQ is a feature which increases the coverage of a system considerably. Multiple error bursts may result in correctly decoded symbols. As described in the previous section, the Alvarion 4MOTION base station supports both HARQ type I and type II.

3.5 Quality of Service

QoS or Quality of Service describes the type of service delivered to the user. In other words, resource allocation that is required for a given application. Resource allocation depends on the requirement for the given service. For instance VoIP, requires high data rate. Since the human ear is a great decoder of speech, re-sending lost packages is waste of capacity, and will tamper the actual communication between two persons. Downloads from the Internet on the other hand, requires that all data has been received correctly. Bursty traffic is thus acceptable.

Connections are handled by the base station for QoS-control. A unidirectional connection has to be established prior to data transmission for each service. The QoS guarantees for latency, jitter, bandwidth, error rate, and system availability for each connection, [2]. Table 3.6 gives an overview of the supported services, their QoS parameters, and application examples.

The adability of Mobile WiMAX makes it support asymmetric traffic and a wide range of QoS. The WiMAX Forum defines five (5) mandatory Quality of Service categories, [7].

UGS (Unsolicited Grant Service) supports real-time services as voice over IP (VoIP). According to [19], UGS service supports unsolicited transfers of fixed packet sizes. UGS has a maximum sustained rate and latency tolerance, [7].

rtPS (Real-Time Polling Service) supports services as streaming of audio and/or video. The rtPS supports transmission of variable packet sizes.

ErtPS (Extended Real-Time Polling Service) was introduced in the 802.16e amendment, and supports variable bandwidths and packet sizes. Meaning that the bandwidth is decreased when there still is a connection but no transmission. An application utilizing this service is VoIP with activity detection.

nrtPS (Non-Real-Time Polling Service) supports transmissions which tolerate delays, and re-transmissions. FTP is an example of a nrtPS-application.

BE (Best-Effort Service) is supported by applications which has no strict QoS requirement. Data is sent when data is available. Applications such as data transfer, web browsing and e-mail uses BE.

3.6 Mobility and Power Saving

Mobility is the main feature of the 802.16e amendment. With mobility comes many challenging features. Customers require long battery-life and seamless handover between base stations and cells. Power saving management and handover is thus two (2) of the most important features of the 80.216e amendment, and will be further discussed in this chapter. As beforementioned, Mobile WiMAX is not meant to compete with existing technologies, rather complement and co-exist. It is therefore worth mentioning that UNINETT is currently working on the intermedia handover between Wi-Fi and WiMAX (802.11 and 802.16).

Service Flow Designation	QoS Parameters	Examples
UGS	Max sustained rate Max latency tolerance Jitter tolerance	VoIP without silence suppression
rtPS	Min reserved rate Max sustained rate Max latency tolerance Traffic priority	Streaming audio and video, MPEG encoded
nrtPS	Minimum reserved rate Max sustained rate Traffic priority	FTP
BE	Max sustained rate Traffic priority	Web browsing, data transfer
ErtPS	Min reserved rate Max sustained rate Max latency tolerance Jitter tolerance Traffic priority	VoIP with silence suppression

Table 3.6: Supported Service Flows in Mobile WiMAX, [2]

3.6.1 Power Saving

As mentioned, power management is an important feature to increase MS operational lifetime. Mobile WiMAX supports both Idle Mode and Sleep Mode.

Sleep Mode is a controlled time of MS-absence. A mobile station in Sleep Mode is unavailable for both DL and UL traffic. The MS power usage in sleep mode is thus minimized, and the base station resource usage is increased. The period of absence is pre-negotiated with the hosting base station, followed by a listening window. Sleep mode is, in the 802.16e amendment, defined in three (3) classes where only class I is mandatory.

- Class I increases the sleep window exponentially up to a maximum. The class is, according to [16], recommended for BE and nrtPS services, see section 3.5.
- Class II has fixed sleep and listening windows. UGS and rtPS are services which are recommended to use class II sleep mode, [16].
- Class III is recommended for multicast and management. The class has only a one-time sleep window.

During a listen window, the MS updates the information about other base stations in case handoff is required.

Idle Mode enables the MS to receive broadcast DL transmissions while in power saving mode. The MS does not have to register to any base station whenever in Idle Mode. Thus the MS does not take any consideration to handoff between base stations. The MS enters a paging group, which it listens to periodically, and updates in case the MS is outside the given paging group. Idle mode has, according to [2], even greater power savings than the mentioned sleep mode.

3.6.2 Mobility

Mobile WiMAX strive to achieve full mobility for their users. Full mobility is defined as up to 120 kmph mobility with seamless handoff between cells and base stations, [2]. Seamless handoff is, in [2], defined with less than 50 ms latency and 1 % packet loss.

In the 802.16e amendment, [16], handoff is supported in three (3) different ways: Hard Handover (HHO), Fast Base Station Switching (FBSS), and Macro Diversity Handover (MDHO). HHO is the only handoff method which is defined as mandatory in the standard.

HHO is performed by having the MS periodically measuring the link between serving BS and neighboring base stations. The measurement results are reported back to the serving BS, where either the MS or serving BS makes the decision of initiating the HHO. Once a HHO decision is taken, the MS starts synchronizing with the DL-transmissions of the targeting BS. Once synchronization is achieved, the connection with previous BS is interrupted.

FBSS requires that the BS and MS keeps a list of possible BS destinations. The list is referred to as the Active Set. The BS which the MS is connected to is referred to as the Anchor BS in the Active Set. All communication from the BS is directed to the Anchor BS. The MS continuously monitors the signal strengths from all the BS in the active set, and decides whether to change the Anchor BS or not. A change in Anchor BS is done when the MS changes the Anchor BS in the Active Set. The update information is transmitted through the CQICH.

MDHO keeps, as FBSS, a list of all BS within range, here called the diversity set. UL and DL communications are performed with all BS within the diversity set simultaneously. Various receiving diversity techniques are performed at the MS in the DL, see [31] for in depth explanations on different diversity techniques. In the uplink, selection diversity is performed so that the BS with the best reception is used.

3.7 Antenna Features

Advanced antenna features through multiple antennas has several advantages when it comes to reliability, throughput, capacity, coverage, and transmitting power [31]. The popularity of OFDM and OFDMA is because of the support of multiple antennas at the transmitter and the receiver (MIMO), and the mentioned subdivision of a wideband signal into multiple narrowband signals. In MIMO, M_t and M_r are referred to the number of transmitting and receiving antennas respectively. Beamforming, space-time code, and spatial multiplexing are all advanced antenna features supported by the Mobile WiMAX standard.

Beamforming is a collaboration between antenna technology and digital signal processing. The signal phase and amplitude is weighted to direct the main lobe of the antennas in the desired direction. Moreover, beamforming increases the coverage and capacity of the system. Optimum-combining approach weights and combines the received signals so that the SINR (Signal to Interference plus Noise Ratio) is maximized [23]. According to [23], the optimum-combining approach is also referred to as adaptive beamforming. Adaptive beamforming is significantly better than MRC (Maximum Ration Combining). MRC is further described in [31, 11, 23].

Space-Time Coding (STC) is referred to as Matrix A, and exploits both time and space diversity. STC increases the reliability of the system. The Alamouti scheme is supported by the Mobile WiMAX, and does not waste transmission power since two different data-streams are transmitted simultaneously twice. A more in depth description of the Alamouti scheme is provided in [31, 20].

Spatial Multiplexing (SM), Matrix B, multiplexes multiple independent streams over multiple parallel channels. SM may be viewed as having multiple SISO systems sending independent data, see figure 3.5. If all SISO approaches the Shannon limit, then the total system performance exceeds the Shannon limit. SM finds R_H parallel independent channels by using singular value decomposition (SVD) on the channel matrix $\vec{H}$ (the size of $\vec{H}$ is $M_r M_t$). SM requires CSIT (Channel State Information at Transmitter) for precoding, and CSIR (Channel State Information at Receiver) for pulse shaping at the receiver to exploit the parallel independent channels. Worth mentioning is that MSs do often only have one single antenna due to power consumption and available space. Thus Mobile WiMAX supports UL collaborative SM, where multiple users transmit within the same time slot. The MS's are spatially spaced, thus the BS treats the UL as if two independent streams were sent from the same user with two antennas. Readers interested in more in depth explanation of spatial multiplexing are referred to [11].

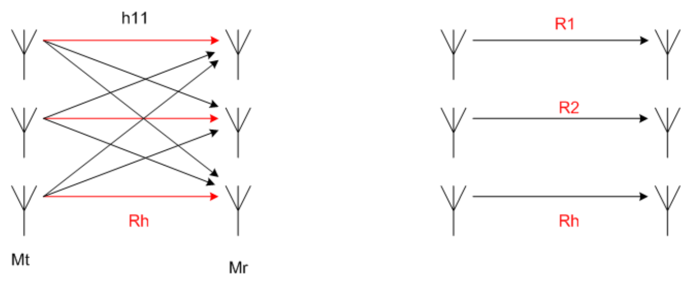


Figure 3.5: Illustration of Spatial Multiplexing

Table 3.7 shows the supported antenna technologies of Mobile WiMAX, [7]. Adaptive MIMO switching (AMS) enables the possibility to switch between the mentioned antenna techniques to adapt to channel conditions. SM improves throughput and capacity, but is not applicable over a poor channel. A poor channel would benefit using STC to increase the reliability and increase the coverage in cell edges.

Link	**Beamforming**	**Space-Time Coding**	**Spatial Multiplexing**
DL	$N_t \geq 2, N_r \geq 1$	$N_t = 2, N_r \geq 1$ Matrix A	$N_t = 2, N_r \geq 2$ Matrix B,vertical encoding
UL	$N_t \geq 1, N_r \geq 2$	N/A	$N_t = 1, N_r \geq 2$ Two-user collaborative SM

Table 3.7: Advanced Antenna Options, [7]

3.7.1 Diversity in Alvarion 4MOTION

Diversity is applied to increase the coverage and capacity of the Mobile WiMAX system. The diversity techniques have been described in this chapter, and more thorough in [31]. According to [29], the Alvarion 4MOTION supports matrix A (STC/the Alamouti scheme) where two information symbols are transmitted twice over two channels. Exploiting both time and space diversity without increasing the bandwidth or power consumption. MRC (Maximal Ratio Combining) is described in [31], and is a receiving diversity method where the signal components arriving at each antenna branch are coherently combined. Meaning that phase and a weighting factor is added to each antenna branch in order to increase the signal reception.

3.8 Fractional Frequency Reuse

Mobile WiMAX supports frequency reuse of one (1), meaning that all cells and base stations can operate with the same frequency band. Cell edges, however, may experience co-channel interference (CCI) if the whole band is used. As beforementioned, MS at the cell edges has poorer signal strength than MS closer to the base station. To improve reliability, users at cell edges utilize just a fraction of the available sub-channels. Thus users at adjacent cell edges can utilize different subsets of the available sub-channels to address the CCI-problem. Figure 3.6 illustrates full usage of bandwidth in the proximity of the base stations, where cell edges uses fractions of the available sub-channels.

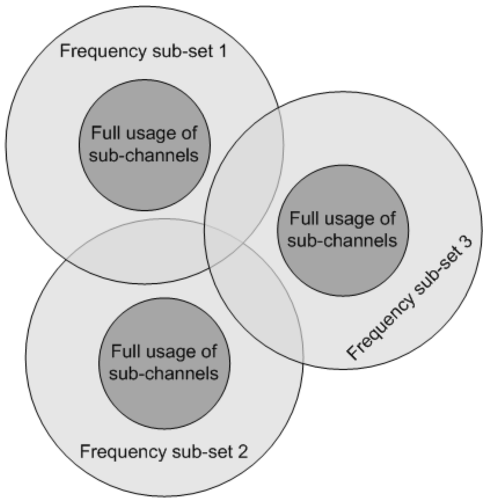


Figure 3.6: Fractional Frequency Reuse

4

Propagation Models

A propagation model is an empirical formulation derived to efficiently calculate and predict radio propagation. There exists many such models, each based on experienced and observed measurements. A model takes in account for effects as attenuation, reflection, diffraction, and scattering. All are mentioned in [31], and are impossible to calculate deterministically.

Propagation models are tailored for specific propagation scenarios, making the propagation statistics as realistic as possible. Propagation in open areas are calculated by using terrain models, whereas metropolitan areas are calculated by using a model which have been developed in a similar scenario. As will be described in appendix A, a city comprises of different environmental classifications, hence different propagation models and parameters can be used for a more accurate prediction of the coverage area. This chapter will describe some of the existing models relevant for this report.

4.1 Free Space Path Loss

The free space path loss (FSPL) is the simplest form of calculating radio propagation. The FSPL model describes an isotropic transmitting antenna in an ideal environment without any objects reflecting, absorbing or obstructing the propagation. Figure 4.1 illustrates how the signal radiates uniformly from a point. The signal strength propagate as a spherical wavefront around the radiating point. Equation 4.1 shows that the received signal strength is proportional with the distance from the radiating source. P_t and P_r are transmitted and received power respectively, whereas G_t, G_r, and λ are antenna gain at transmitter and receiver, and wavelength. The wavefront will become approximately plane at large distances away from the transmitting source. Figure 4.2 shows the FSPL compared with other empirical propagation models. It can bee seen in 4.2 that the FSPL is the most optimistic of the illustrated propagation models.

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \tag{4.1}$$

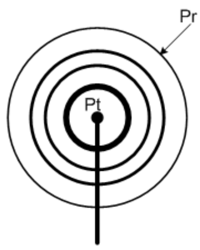


Figure 4.1: Propagation in free space

4.2 Longley-Rice

The Longley-Rice is a propagation model which takes terrain, curvature and climate in account for predicting radio coverage. The model itself is very complex, but there are fortunately many software tools which performs these calculations. Radio Mobile [5] is one of these. In the project assignment for predicting indoor coverage in Trondheim, [31], Radio Mobile was used as the radio planning tool. The model, and software, were found improper for predicting coverage in an urban are like Trondheim.

4.3 Okumura's Model

Okumura's model is one of the most utilized propagation models of today. The empirical model was based on measurement and observations throughout Tokyo. The testing was performed at distances of 1-100 km, frequencies of 150-1500 MHz, and with transmitting antenna heights of 30-100 m [11]. Okumura classified the propagation environment in three (3) classes: urban, suburban, and rural areas. All of the formulations have a basis in the urban formulation. The Okumura Hata model for urban and suburban areas are illustrated in figure 4.2.

$$P_{L,urban}(d) = 69,55 + 26,26log_{10}(f_c) - 13,82log_{10}(h_t) - a(h_r) + (44,9 - 6,55log_{10}(h_t))log_{10}(d) \quad (4.2)$$

$$P_{L,suburban}(d) = P_{L,urban}(d) - 2\left[log_{10}\left(\frac{f_c}{28}\right)\right]^2 - 5,4 \quad (4.3)$$

$$P_{L,rural}(d) = P_{L,urban}(d) - 4,78[log_{10}(f_c)]^2 + 18,33log_{10}(f_c) - K \quad (4.4)$$

$$a(h_r) = (1,1log_{10}(f_c) - 0,7)h_r - (1,56log_{10}(f_c) - 0,8) \quad (4.5)$$

The equations 4.3, 4.4, 4.5, and 4.5 are all in decibel. Variables and values are: carrier frequency (f_c), distance (d), and h_t and h_r, respectively being transmitting and receiving antenna height. The values are given in GHz, km, and m respectively. Equation 4.5 is a correction factor for small to medium sized cities [11]. The variable K, in equation 4.5, is an adaption factor depending on rural terrain and reflection characteristics. The K-factor ranges from 35.94 to 40.97, being countrysides and deserts respectively, [11].

4.4 COST231

The COST231 is another extension of the Okumura Hata model by the European cooperative for scientific and technical research (EURO-COST) [11]. The extension was basically for increasing the frequency range up to 2 GHz. Equation 4.6 are valid for the following parameters: $1.5GHz < f_c < 2GHz$, $30m < h_t < 200m$, $1m < h_r < 10m$, and $1km < d < 20km$.

$$P_{L,urban}(d) = 46.3 + 33.9log_{10}(f_c) - 13.82log_{10}(h_t) - a(h_r) + (44.9 - 6.55log_{10}(h_t))log_{10}(d) + C_M \quad (4.6)$$

4.5 Comparison of Radio Propagation Models

Figure 4.2 compares propagation models mentioned in this chapter. It can be seen from the figure that the free space path loss is the most optimistic model when it comes to range. Unfortunately, such an idealistic environment does not exist. As a result, empirical models have to be used, and both the Okumura Hata and the COST231 are well known propagation models in the wireless communication industry. In [31], the Okumura Hata for urban and suburban areas, and the COST 231, were concluded to be the most appropriate propagation models in an environment like Trondheim. The Longley-Rice model was found to be too optimistic, and Radio Mobile was thus not found to be an adequate radio planning tool in an urban area.

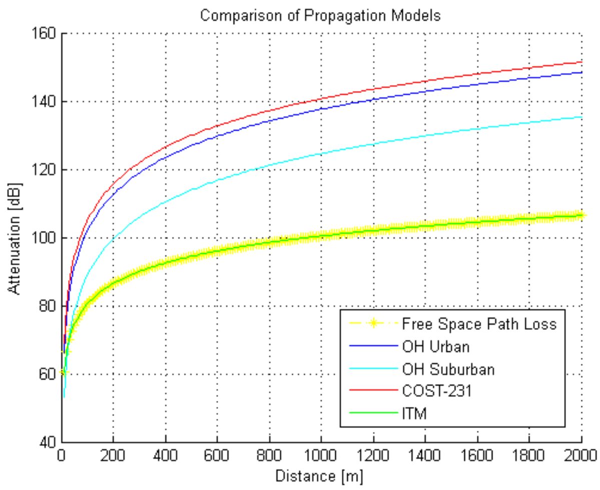


Figure 4.2: Comparison of Propagation Models

5

Data Traffic and Throughput

In the abstract, a wireless network serves one purpose, providing data flow. As mentioned in section 3.5, different services utilizes different protocols to improve the performance and user-experience. Mobile WiMAX is a wireless standard built up by the TCP/IP model. Hence this chapter will provide a brief description of the TCP/IP model, and the two main protocols, implemented in the transport layer, TCP and UDP.

5.1 TCP/IP

The TCP/IP model is a communication protocol named after the two main protocols, the TCP and the IP, the transmission control protocol and the Internet protocol respectively. The TCP/IP model was created by the Department of Defense, hence the model is often referred to as the DoD model. Moreover, the TCP/IP supports Internet applications and transmission of data over networks similar to the Internet. As for the OSI model (Open System Interconnection Reference Model), the TCP/IP model is built up by layers. Where the OSI model is a theoretical model, built up by seven (7) layers, the TCP/IP model describes the actual implementations for Internet-services, comprising a four (4) layer architecture: the process/application layer, the host-to-host layer, the Internet layer, and the network access layer [21].

Common for the two (2) models is that each layer is unknown to the adjacent lower layer. Information and headers received from higher layers is treated as pure data. Furthermore, each layer adds control information, header, to the received data and sends the data one step closer to physical transmission. On the receiving side, however, the process is reversed. Packets are received, headers removed, and information is processed before going to the layer above. This section will provide a brief description of the four

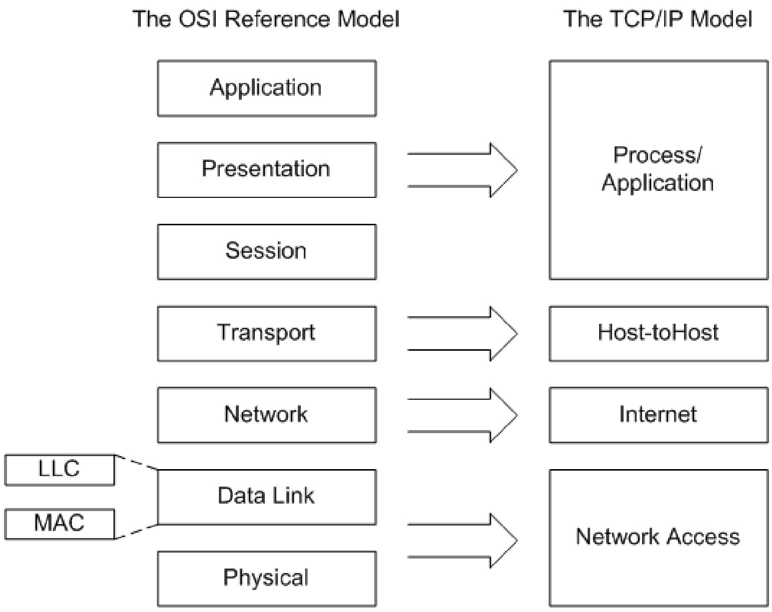


Figure 5.1: The OSI Reference Model, and the TCP/IP Model

layers in the TCP/IP model. Figure 5.1 illustrates, and compares, the OSI model and the TCP/IP model.

The Process/Application Layer is the upper layer in the TCP/IP model. The layer comprises the application layer, presentation layer, and session layer of the OSI model. According to [21], a great number of protocols for node-to-node communications between applications and user-interface are defined here. The layer supports application protocols as HTTP (Hypertext Transfer Protocol), FTP (File Transfer Protocol), and SMTP (Simple Mail Transfer Protocol). Administrative protocols supported by the layer are SNMP (Simple Network Management Protocol), DNS (Domain Name Server), Telnet, and more. Readers interested in descriptions of the protocols in the process/application layer is referred to [21].

The Host-to-Host Layer is directly mapped to the OSI transport layer, and provides end-to-end data transmissions, flow, and error control. The host-to-host layer creates reliable node-to-node communication and ensures error free communication. The most common transport protocols are TCP (Transmission Control Protocol), and UDP (User Datagram Protocol). The two transport protocols are further described in the following two (2) sections. Table 5.1 shows the key features of each protocol, [21].

The Internet Layer provides services as addressing and routing. The Internet layer corresponds to the network layer in the OSI model. The layer is responsible for setting the right destination address and finding a reliable route through multiple networks. The IP (Internet Protocol) is found in this layer. The mentioned layer is one of the keystones in the TCP/IP model,and is often referred to as the network layer.

The Network Access Layer comprises the data link layer and physical layer of the OSI model. The network access layer prepares packets for transmission over a physical medium. The layer is often referred to as the network interface layer and the link layer.

5.2 TCP

TCP (Transmission Control Protocol) is a connection oriented transport protocol, providing reliable transmissions between two applications. Compared with UDP, TCP synchronizes and establishes a connection between two applications prior to transmission. The transmission itself is performed by segmenting and numbering the information blocks so that the receiver easily can put together the intended information block. After transmission, the transmitting host waits for acknowledgement (ACK) in order to know that the sent packets were received correctly. Furthermore, segments or packets in which the transmitter has not received an ACK are re-sent. The TCP is thus a very reliable transport protocol. Examples of multimedia services which uses TCP are file transfer, Internet surfing, and e-mail.

TCP Window Size

The TCP window size (TWC) tells how long the sender will wait for acknowledgement (ACK) before it assumes that the packet is not received and re-sends the packet. In other words, the TWC indicates how many unacknowledged packets can be in transmission before the sender concludes that a packet is lost.

A sliding window size is used as flow control to prevent the transmitter from overflowing the network. The window size is thus updated from the receiving host. Congestion control is a retransmission timer which decides the amount of time the transmitting host will wait for an ACK before it decides that the packet is received incorrectly. The TCP builds up its congestion window by slow start, starting at one TCP packet. The congestion window is then exponentially increased till a give threshold, the slow start threshold. Additional increments are then added until the maximum window size is reached, the TWS. Figure 5.2 shows how TCP and the sliding window works. It can be seen that the window size is increased exponentially before it hits the slow start threshold, and further increases linearly.

The highest throughput performance is maintained when the network is kept busy without any congestion. The bandwidth delay product (BDP) is often a good estimation of the maximum TCP capacity, TCP = BDP, [12]. Equation 5.1 shows that the BDP is a multiplication of the total bandwidth and the transmission delay between the two hosts (measured with ping).

$$BDP = bandwidth * delay \tag{5.1}$$

The maximum available throughput, and maximum allowed delay can be calculated and verified by setting equation 5.1 equal bandwidth and delay respectively. The BDP is thus set equal TWS.

$$\begin{aligned} Bandwidth &= \frac{TWS}{Delay} \\ Delay &= \frac{TWS}{Bandwidth} \end{aligned}$$

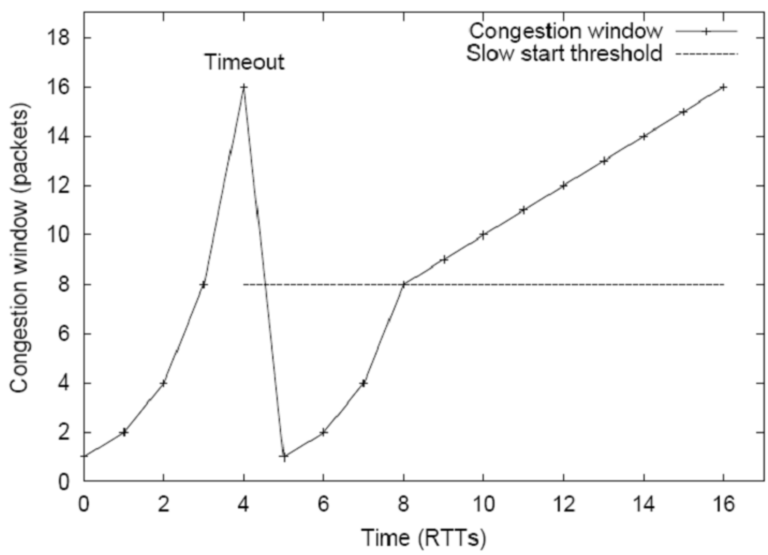


Figure 5.2: TCP congestion window, [34]

5.3 UDP

UDP (User Datagram Protocol) is a connectionless transport protocol used for information which does not require reliable delivery. Hence the UDP does not take up as much bandwidth as the TCP. The UDP is often referred to as an unreliable protocol because it sends and forgets. Meaning that it neither sequences the information nor requires an ACK of safe arrival. Examples of multimedia services appropriate for using UDP are VoIP and streaming.

TCP	**UDP**
Sequenced	Unsequenced
Reliable	Unreliable
Connection-oriented	Connectionless
Virtual circuit	Low overhead
Acknowledgements	No acknowledgement
Windowing flow control	No windowing or flow control

Table 5.1: Key Features of TCP and UDP [21]

5.4 Shannon Capacity

The Shannon capacity is a theoretical limitation of maximum achievable error-free transmission between two peers over a noisy channel. Equation 5.2 shows the Shannon limitation, C, in bits per seconds. The input variables are: the bandwidth, B, and signal to noise ratio, SNR.

$$C = Blog_2(1 + SNR) \tag{5.2}$$

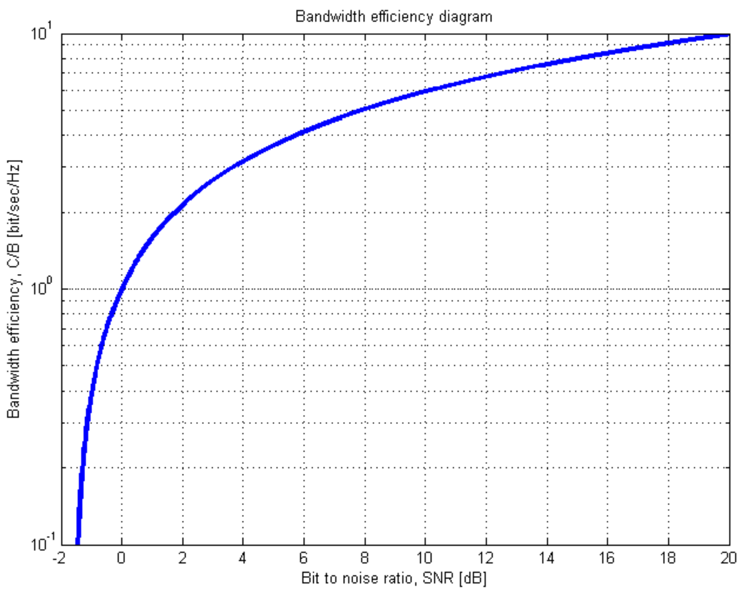


Figure 5.3: Shannon boundary

Figure 5.3 is a bandwidth efficiency diagram, [14], which shows the maximum capacity divided by the available bandwidth. The figure shows the theoretical limitations of a communication system. Meaning that an error-free bit rate, R_b, higher than C is not achievable.

Modulation and Coding	**10 MHz**		**5 MHz**	
	DL [Mbps]	*UL [Mbps]*	*DL [Mbps]*	*UL [Mbps]*
QPSK 1/2	7.0	5.4	3.5	2.6
QPSK 3/4	10.5	8.2	5.2	3.9
16-QAM 1/2	14.8	10.9	7.0	5.2
16-QAM 3/4	21.0	16.3	10.5	7.9
64-QAM 1/2	21.0	16.3	10.5	7.9
64-QAM 2/3	28.0	21.8	14.0	10.5
64-QAM 3/4	31.5	24.5	15.7	11.9
64-QAM 5/6	35.0	27.2	17.5	13.2

Table 5.2: PHY Bit Rate of Alvarion BS

5.5 Data Traffic in Alvarion 4MOTION

Testing of throughput performance is planned to be performed in this report. Actual throughput and throughput promised by the provider tend to differ. Previous work on pre-mobile WiMAX have shown that the experienced throughput is about 76 % of the throughput mentioned in system manuals. The 4MOTION system description, [29], and table 5.2 lists the PHY bit rate per modulation and bandwidth. It has to be emphasized that the bit rate is on the physical layer, including headers, redundancy introduced by coding and the cyclic prefix. Actual throughput, only information bits, will thus be lower.

Figure 5.4 shows the promised bandwidth efficiency for a 5 MHz channel, see table 5.2, versus theoretic bandwidth efficiency and the Shannon capacity. It can be seen from the figure that the promised rates are well within both the Shannon limit, and the theoretic values. It can also be seen from figure 5.4 and table 5.2 that the promised UL rate is lower than the DL rate. A possible explanation is that uplink channels tend to have larger headers in order to provide a reliable transfer of the information bits.

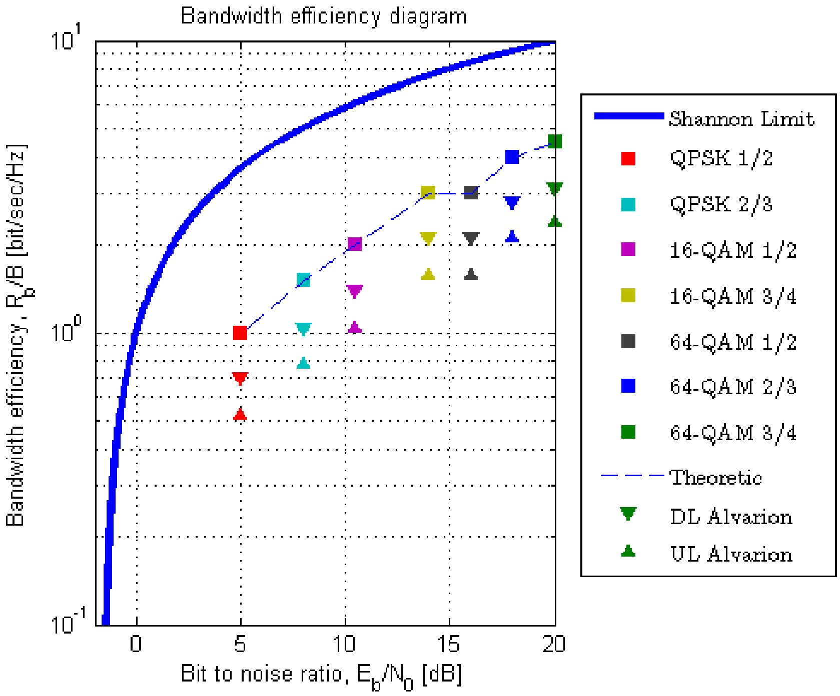


Figure 5.4: PHY bit rate versus Shannon capacity

6

System Description

Wireless Trondheim and UNINETT are, since 2008, proud co-owners of an Alvarion BreezeMAX base station and mobile stations. Alvarion is, according to [1], one of the main providers of WiMAX and broadband network solutions, and an active member of the WiMAX Forum. Furthermore, the Alvarion equipment is WiMAX Forum certified, a certification which guaranties for fully interoperability with other WiMAX Forum certified products.

The equipment delivered in mid 2008 was pre-mobile, but is now set to be upgraded to fully Mobile WiMAX, and ready for testing.

This chapter will provide information on the Alvarion BreezeMAX equipment at disposal for this project. Worth noticing is that the 4Motion product line of Alvarion delivers full promise of Mobile WiMAX, [1], hence the Mobile WiMAX equipment is referred to as Alvarion 4MOTION.

6.1 Alvarion BreezeMAX 4Motion BS Components

The Alvarion BreezeMAX is a modular base station comprising chassis, air ventilation, power supply, power interface, access unit, network processing unit, outdoor units, and external antennas. The mentioned components will be described in the following subsections. Figure 6.1 and 6.2 shows the chassis and the base station architecture respectively.

Air Ventilation Unit

The AVU (Air Ventilation Unit) consists of ten (10) fans for constant airflow and cooling of the BS equipment.

Power Supply Unit

The PSU (Power Supply Unit) supplies -48 VDC to the BS equipment.

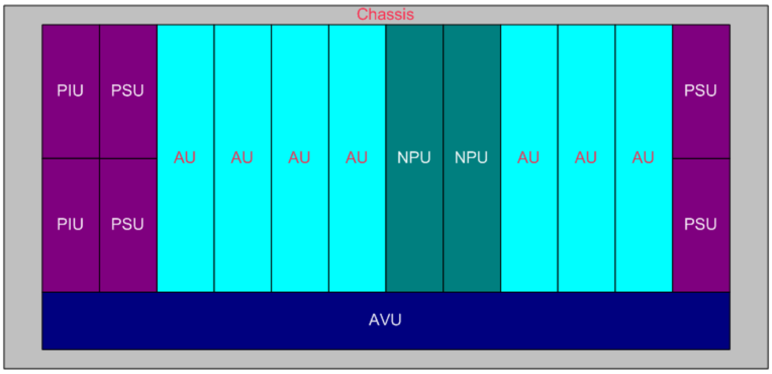


Figure 6.1: The modular base station of Alvarion BreezeMAX

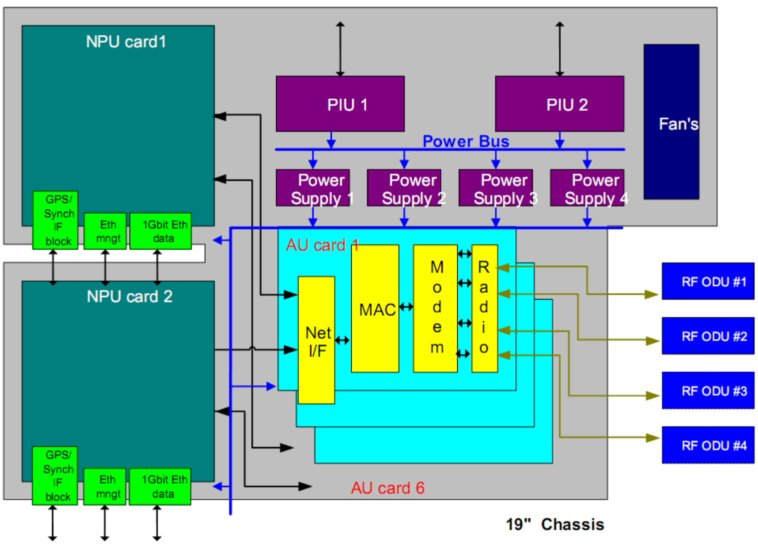


Figure 6.2: Base station architecture, [29]

Power Interface Unit

The PIU (Power Interface Unit) is the interface between the PSUs and the DC source of the BS. The main purpose of the PIU is to filter and stabilize the input power. Over-voltage, short circuits, and peak pulses are handled by the PIU. The PIU also provides signal quality and noise level indications for power control and rate adaption, [29].

Access Unit

The AU (Access Unit) is the radio components of the base station. The implementation of the Mobile WiMAX functionality is done here. The functionalities are, according to [29, 28], OFDMA, diversity, flexible channel BW and FFT, channel coding, HARQ, rate adaption, IF connectivity to ODU, scheduling, frame/burst building, power saving, handover management, and power control. The AU is built as a software-defined radio (SDR), where the software implements the functionality of the radio. SDR upgrades are only applied to the software, not hardware, a cost-effective solution in a rapidly evolving market. The AU is connected with the NPU inside the BS chassis and has the possibility of operating up to four (4) channels.

Network Processing Unit

The NPU (Network Processing Unit) is the main controller of the base station. All traffic from and to the backbone is processed here. The NPU decides what kind of data is transmitted or, in some cases, terminated. According to [29], the main functions of the NPU is management of traffic to and from the backbone, inter-connect base stations, VLAN- and QOS-tagging, control and diagnostics of the other base station components, synchronization, and management.

Global Positioning System

A GPS (Global Positioning System) is used to synchronize the frames sent to and from the base station. As mentioned in [31], accurate frame synchronization is imminent in a TDD system to distinguish channels and users from one another. Each base station, however, is equipped with an internal clock for packet synchronization, but GPS synchronization with four (4) satellites, or more, is more accurate for synchronizing multiple base stations.

Outdoor Unit

The ODU (Outdoor Unit) is a high-power, multi-carrier radio connected in the immediate proximity of the external antenna. The ODU consists of a low-noise amplifier to provide high power and low noise.

Antennas

The WiMAX base station is equipped with two vertical polarized antennas, and one dual-slant cross polarized antennas. Hence the base station can exploit 2nd order diversity.

The vertical polarized antennas operate with 16.5 dBi gain, 3dB azimuth beamwidth of 60 degrees, and elevation beamwidth of 7 degrees,[24]. Figure 6.3 shows the vertical polarized antenna pattern implemented in Astrix 5.0.

The duals-slant antennas have 10 dBi gain, 65 degrees 3dB beamwidth, and 8 degrees of elevation beamwidth, [25]. The specifications, and patterns of the antennas are given in appendix C. Table 6.1 lists up the mentioned antenna specifications.

	Vertical	*Dual-slant*
Gain [dBi]	16.5	10
3dB Azimuth	60 °	65 °
Elevation	7 °	8 °

Table 6.1: Antenna specifications

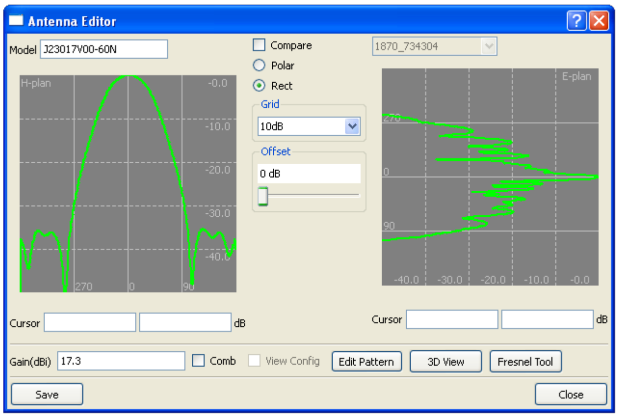


Figure 6.3: Antenna plot generated in ASTRIX 5.0

6.2 Customer Premises Equipment

The customer premises equipment (CPE) are self installing clients for use at the customers premises. The clients of Alvarion are: CPE PRO, si CPE, and a PC-card. Neither the CPE PRO nor the si CPE have been updated to fully Mobile WiMAX, nor have updated production manuals been made available. The gains of the antennas are however the same, hence only gain and transmission power is included for the two clients.

6.2.1 PC-Card

The PCMCIA-card (Personal Computer Memory Card International Association) is a fully mobile network adapter for Mobile WiMAX access. The card has two fold-out antennas, to exploit receiving diversity. The card uses no transmitting diversity, meaning that it is only transmitting from one of the available antennas. On the receiving side however, MRC is used by coherently combining the reception at the two antennas. Table 6.2 gives an overview of the specifications of the PC-card. It can be seen that the antenna supports all specified modulation and coding rates in the downlink, but only the mandatory modulation and coding rates in the uplink. Table 6.3 shows the required receiving sensitivities per modulation and coding rate.

PC-Card Specifications	
Tx-diversity	Single antenna
Rx-diversity	Two antennas (MRC)
Gain	2 dBi
FFT-size	512 and 1024
Bandwidth	5, 7, 8.75 or 10 MHz
DL rate	$<$ 20 Mbps
UL rate	$<$ 7 Mbps
Tx power	23 dBm (max)
Modulation and Coding	
Downlink	QPSK 1/2 CTC & CC
	QPSK 3/4 CTC & CC
	16-QAM 1/2 CTC & CC
	16-QAM 3/4 CTC & CC
	64-QAM 1/2 CTC & CC
	64-QAM 2/3 CTC & CC
	64-QAM 3/4 CTC & CC
	64-QAM 5/6 CTC & CC
Uplink	QPSK 1/2 CTC & CC
	QPSK 3/4 CTC & CC
	16-QAM 1/2 CTC & CC
	16-QAM 3/4 CTC & CC

Table 6.2: PC-Card Specifications, [30]

Modulation and Coding rate	**Receive Sensitivity**
QPSK 1/2 CTC	-93 dBm
16-QAM 3/4 CTC	-83 dBm
64-QAM 3/4 CTC	-78 dBm

Table 6.3: Receiving Sensitivity, [30]

6.2.2 si CPE

The self install CPE is intended for indoor installations and easy nomadic installations. The si CPE includes modem, radio, and data processing and management components. The unit has six (6) internal antennas mounted on top, providing 360 °coverage. The receiving diversity is selection combining, meaning that the strongest antenna branch is used for reception. Further information on selection combining diversity and the si CPE can be found in [31]. Table 6.4 lists up gain and transmission power of the si CPE.

si CPE Specifications	
Gain	7 dBi
Tx Power	24 dBm

Table 6.4: si CPE Specifications, [27]

6.2.3 CPE-PRO

The CPE-PRO is a high gain customer equipment with an antenna mounted outdoor, hence the CPE PRO is characterized as fixed. The CPE-PRO comprises an outdoor unit and an indoor unit. The outdoor unit (ODU) is a high gain flat antenna and concludes modem, radio, and data processing and management components, [26]. Table 6.5 lists the antenna gain and the maximum power of the CPE-PRO. The indoor unit (IDU) provides power and control signals to the ODU. There are three different IDUs: Data Connection IDU, Networking Gateway IDU, and Voice Gateway IDU. None will be further discussed here.

CPE-PRO Specifications	
Gain	14 dBi
Tx Power	19 dBm (max)

Table 6.5: CPE-PRO Specifications, [27]

Part II

Radio Planning and Measurements

7

Radio Planning

Providing ubiquitous coverage in a predefined area is the main purpose of setting up a wireless communication network. Knowledge about wireless communication theory, technology standard, equipment together with topology and demographics are important prerequisites. Furthermore, knowledge and experience with the radio planning tool is also important. In [31], a description of wireless communication theory linked with Mobile WiMAX, and the pre-mobile WiMAX equipment of Wireless Trondheim was provided. The 802.16e technology and the Mobile WiMAX equipment has been described in the previous chapters. Whereas, topology and demographics has been mentioned in appendix A. The reason for studying topology and demographics is to define the desired area to cover with Mobile WiMAX.

From an operators point of view, ubiquitous coverage provided by minimum number of base stations is desirable, making the system more cost efficient. Furthermore, a data rate threshold has to be taken in consideration in order to provide the desired QoS. Quality of Service requires, as mentioned, a given throughput. In urban areas, wireless communication systems are often capacity limited rather than range limited. Increasing the number of base station in an area where it is expected to be capacity limited is thus a countermeasure which has to be taken in consideration. Øya and NTNU are such areas which are expected to be capacity limited.

7.1 The radio planning process

Building a Mobile WiMAX network demands a thorough radio planning process in order to deliver great services while keeping the business aspect intact, minimum input - maximum output. The white paper "Don't Even Think You Can Go Without Some Accurate and Professional Radio & Microwave Network Planning!", [35], has derived a seven (7) step life cycle for setting up a broadband wireless network. All ranging from the initial phase of creating the business case and allocation of the budget, to the planning and design of the network, followed by the final stages where the actual network is built, tested, and optimized.

Important features on the way of planning a broadband wireless network is to create a good business case, and a reliable budget. Furthermore, a reliable and robust access solution and backhaul is imminent to provide high quality services to the users. The network planning alone serves one purpose, to satisfy the coverage and capacity requirements in order to deliver the promised services.

Preliminary planning may be viewed as a "get to know the equipment" phase. A thorough market analysis sets up the customer requirements, and implements the results in the business case. The next phase is thus to make the system deliver such services, and to know its features and limitations. A thorough analysis of coverage, capacity, and antenna configurations on a preliminary network increases the quality of the following radio planning process.

Moreover, by knowing the system performance, radio propagation models may be tuned and tailored to fit the deployed scenario. Along with detailed topographical data and propagation models, radio planning tools can estimate and predict the desired coverage to optimize the network in terms of resource allocation.

Unfortunately, base stations can not be deployed wherever the radio planner desires. Sites have to be analyzed and viewed to see if they fit the requirements of being a base station sites. The site survey phase requires information regarding obstructions in the surroundings, the physical environment, and installation requirements. Hence multiple site candidates have to be considered before one is chosen.

Furthermore, with a set of site candidates, tailored propagation models, topographical data, and a radio planning software, coverage prediction can be performed according to the requirements in the business model. When radio planning, considerations have to be taken regarding signal strength, data rate, interference, frequency reuse, estimated customer traffic, capacity, and handover.

As previously mentioned, an important part of the radio planning process is the backhaul network. Without any backhaul, base stations would neither be able to communicate with one another nor exchange information to clients outside the network. Backhaul networks do often consist of cable, fiber, and microwave radio links. The latter requires approximately the same radio planning process as mentioned. Where LOS scenarios is a requirement, meaning that the two end points need visual contact, and the first Fresnell zone free of obstacles, see [31].

Prior to deployment and testing of the network, site negotiation has to be performed. In order to be able to locate the equipment at a site, the vendor have to consider if co-location with other operators, or if constructing an individual base station site is the most feasible. When deploying a large network, backup sites are necessary since it is not common that all pre-planned sites will be available due to capacity limitations or other restrictions of the desired site.

7.2 Site Planning

The first step in radio planning is to have a clear idea of which area to cover. Appendix A gives a brief overview of the demographics of Trondheim, and concludes upon that the central parts of the city were to be covered. Site planning is another important part of the radio planning process. Mobile WiMAX has, as beforementioned in section 3.8, a reuse factor of one (1). Interfering cells results in decreasing number of used sub-channels thus reduced throughput in the edges of the cells, see figure 3.6. As a result, large buildings with large cells does not necessarily be the best option if the area is capacity limited.

Another challenge is that all buildings within the predefined area are not necessarily available for being a base station site. Neither is it possible to raise a 15 meter high mast wherever it is found suitable. Criterias does thus have to be defined in order to make the radio planning as realistic as possible. The following main criterias has been defined in this report: availability, backhaul, and environmental dominance.

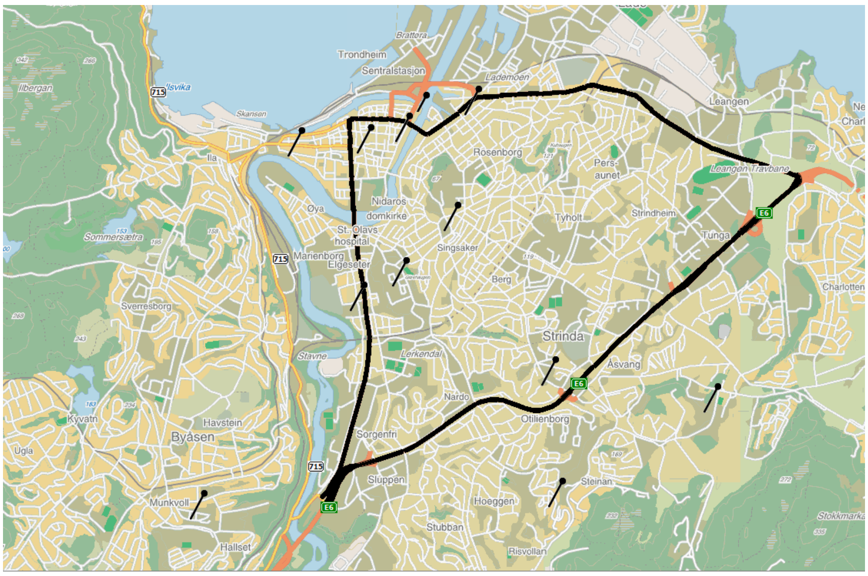


Figure 7.1: Planned and existing fiber network in Trondheim city (marked in black).

Availability has been defined as public and commercial buildings owned by the municipality of Trondheim, as well as already existing base station sites for GSM and UMTS. Existing base station sites has the advantage of being prepared for the given purpose. These sites contains elementary components as 48 VDC and backup power. Co-location with Telenor and/or NetCom is therefore beneficial.

Backhaul has been defined as the possibility of providing backhaul to the base station site through either fiber or radio link. Figure 7.1 shows the position of planned and existing fiber network available for Wireless Trondheim. Sites in the immediate proximity of fiber, is easily connected to the backhaul. The black pins indicates buildings with fiber connections, these sites are available for providing backhaul to Wireless Trondheim. Furthermore, setting up a radio link is however a possible solution for sites where fiber is not available. Line of Sight (LOS), and free first Fresnel zone, see [31], is thus required between the connected sites. As a requirement, one of the sites has to be connected to the backhaul. As a last resort, when co-locating equipment with an existing operator, rental of fiber access is often provided. Rental of fiber network is unfortunately often an expensive solution, and should be avoided.

Environmental dominance has the benefit of illuminating an area from above. The range, and interference, can be adjusted by mechanically tilting the antennas. Communication masts and high buildings are preferred, but as mentioned, not a requirement.

The previous work performed by Rein S. Karlsen [18, 19], masters thesis and summer internship report respectively, has been taken as a basis for the radio planning. Both [18] and [19] contains recommendations for providing WiMAX access to the tram, and along the tram line, see figure 7.2. These recommended sites, see figure 7.4, along with Olavskvartalet and NTNU, will form the starting points of the chosen base station sites.

Positions of base station sites have been a company secret for many years. Requests of such type of information has thus been rejected. An article from NRK-brennpunkt [13] however, says that the network providers have been instructed to keep an updated database of such information available for the public. As of today, no such database exists. According to an article from www.digi.no [17], Post and Teletilsynet is currently working on a map application with the possibility for the public to search and find mobile antennas in Norway. Since tender deadline for creating the application is due the 25th of June 2009. The application alone is not expected to be finished before the end of 2009. Possible base station sites have thus been found through observations. Appendix E contains a table with possible base

Figure 7.2: Covered tram line in [19, 18]

station site. These sites are presented with their name, geographical position, and antenna height above ground.

7.3 Co-Location

Instead of constructing a base station site, where space, power, heat, and backhaul are essential features to consider, co-location with other telecommunication operators is a probably a more feasible solution. By co-location, the operator rents access to the infrastructure of a main operator, for instance Telenor or NetCom. According to Jara, `http://www.jara.no`, the infrastructure service provider of Telenor, power, backup, and space for equipment and antennas are promised to the operator if an agreement have been reached. The main operators, Telenor and NetCom, are obliged to provide co-location, meaning that an agreement depends solely on economy the operator, and capacity of the site.

In the specification from Jara, 230/400 VAC, 48 VDC, backup, and cooling is provided to all locations available for co-location. The operator can rent space for equipment with the minimum size of 60x30x25 where the height is increased with 25 cm. Rental of antenna space comprises mounting and cables to the antenna from the base station equipment. Furthermore, it is possible to provide own network access for backhaul to the equipment, or rent capacity on the existing network.

7.4 Radio Planning Tool

A radio planning tool implements statistical propagation models to facilitate estimation of coverage. There exists several tools to predict radio propagation and coverage. Astrix, ICS telecom nG, and Radio Mobile are some of many. The latter is a freeware suitable in open areas.

Effectively using the available software is a demanding task. Concentration and experience are key features for making the predictions as accurate and efficient as possible. Continuously comparing the prediction with real time measurement increases the accuracy of the software. Astrix has, for instance, a measurement logging tool. The measurements are thus implemented in the software, where a correction layer adjusts the predicted coverage data, resulting in an improved and more accurate coverage prediction.

Apart from having the software, high resolution terrain data which is up to date is imminent. Additional layers like clutters with building heights makes the tool more accurate than a clutter only describing the ground occupancy. A building height layer provides reflection, scattering and absorption from actual buildings, and not from statistical buildings which would be the case in a ground occupancy layer.

7.4.1 Astrix 5.0

Astrix 5.0 is a radio planning tool by Teleplan Globe [3] designed for planning and implementation of radio networks. Figure 7.3 is a print screen of Astrix 5.0. Propagation models and antenna patterns are adjustable for the operator to adapt the software to the particular network. Previous versions of the software were specially tailored for planning GSM 900/GSM 1800, and TETRA. The latest release, 5.0, have implemented WiMAX, whereas Teleplan Globe is continuously improving the software and preparing for future LTE-systems. An Astrix User Case has been created in appendix D to provide a basic user guide for future radio planners.

Base Station parameters

In the case of radio planning Mobile WiMAX for Wireless Trondheim, the base station parameters are set as a default according to table 7.1. The antenna pattern have been plotted according to the data provided from the supplier, see appendix C. Figure 6.3 shows the antenna pattern of the vertical polarized antenna, plotted in Astrix. Appendix C contains the antenna specifications of the available antennas. Each base station has been set default with six (6) sectors, separated by 60 degrees. Experience shows that three (3) sectors are sufficient for covering a 360 degree angle. Tuning of each sector is possible to adapt to the base station location.

Single and combined coverage prediction is performed with a resolution

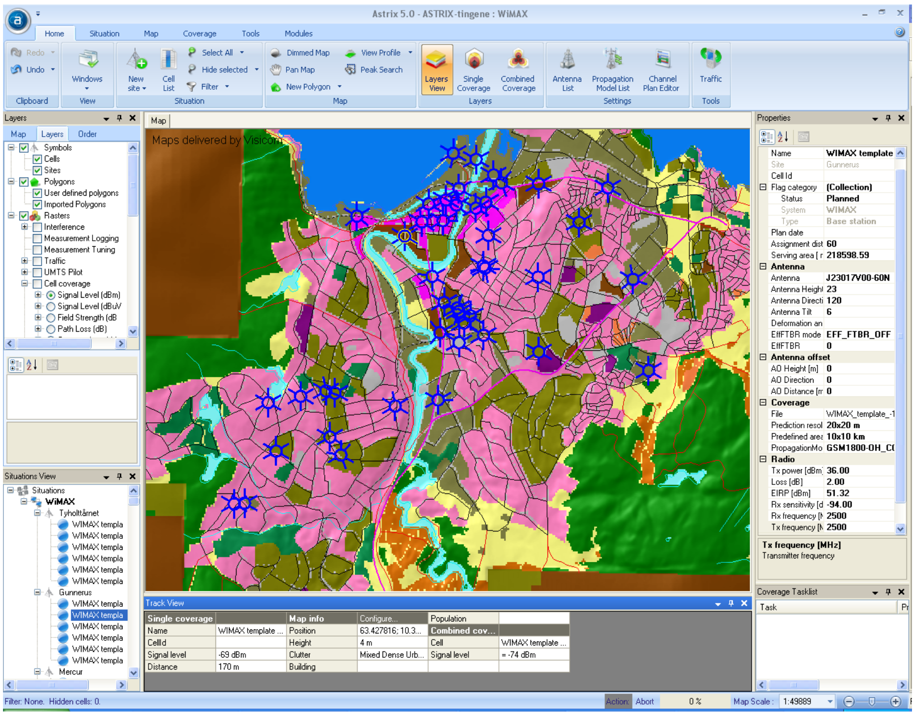


Figure 7.3: Print screen of Astrix 5.0

Parameter	Value
Tx Power	36 dBm
Loss	2 dB
Antenna Gain	16.5 dB
Rx Sensitivity	-94 dBm
Frequency	2500 MHz

Table 7.1: Base Station Parameters

of 20 meters. A higher resolution will only slow the system down, and not improve the prediction, because of the available resolution of the terrain.

7.5 Coverage-prediction

Choosing the base station sites have been performed according to the site criterias mentioned in section 7.2. Appendix E provides information about possible base station sites. These sites have been found through observations throughout the city of Trondheim. Information about position and height above ground can be found in the mentioned appendix. Further descriptions about the chosen sites are found in the following sections. Appendix F provides information about chosen sectors, and coverage map for each of the sites described in the following sections.

7.5.1 Recommended sites from [19, 18]

The recommended sites from Rein S. Karlsen, for covering the tram along the tram line are given in this section. A more thorough description is given in [18, 19].

Gunnerus is a library positioned at Øya. The site has fiber to the roof (FTR), and has been used for providing coverage to the tram [19, 18] and for indoor coverage testing [34, 31]. In the purpose of [18], Gunnerus is supposed to have one sector with 240° azimuth and no tilt, and a second sector within 70° and 100° azimuth with some mechanical down-tilt.

Låve Hoem is a barn where its locations are rented by either Telenor or NetCom, [18]. A radio link is recommended from Byåsen VGS for backhaul, [18]. A sector pointing with an azimuth of 350° and one with 240° with 0° and 10° respectively are recommended in [18].

Byåsen VGS is a school with fiber access. The school was used for testing in [19]. Two sectors are recommended from this site for covering the tram line. The sectors are 300° and 40°, both with 0° tilt.

Telenor Storhaug is a communication mast where co-locating the equipment should be possible. A radio link with Byåsen VGS will provide backhaul for the site. One sector is recommended to provide coverage along the tram line.

NetCom Kyvatn is a communication mast close to Kyvatnet. The site has been recommended in [18] as a possible substitute for Telenor Storhaug.

Figure 7.4 shows the covered area with the recommended sites from [19, 18]. Deviations from the figures in the mentioned reports can be explained from usage of transmitting antenna, propagation model, and radio planning tool. In [18] and [19], the ICS telecom nG and Radio Mobile were used respectively. The radio planning tool used in this report is the Astrix 5.0 from Teleplan. The masters thesis "The wireless tram" ,[19], used the Okumura-Hata model for sub-urban areas with a close to realistic antenna pattern at the transmitter. Moreover, the summer internship report, [18], used Radio Mobile, which only implements the Longley-Rice model, with an Yagi-udi antenna at the transmitter. The results are however quite similar in this report, with the ICS telecom and the Radio Mobile being a bit more optimistic than Astrix 5.0.

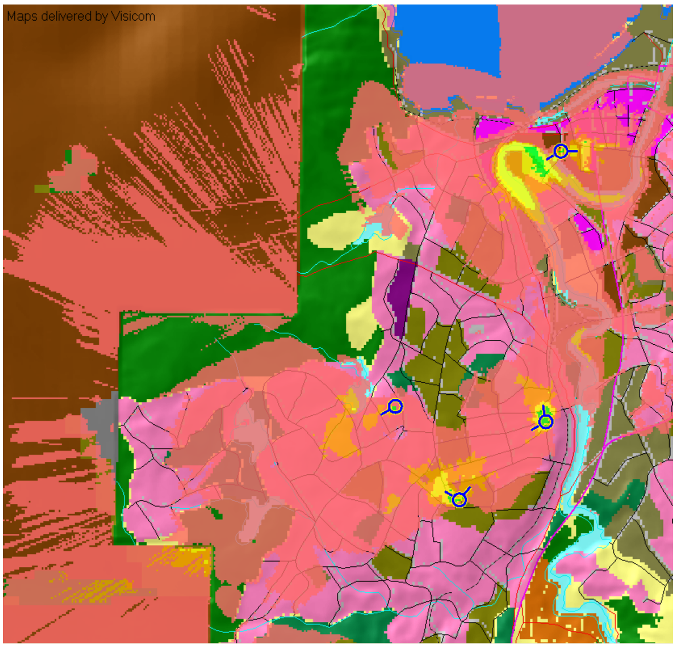


Figure 7.4: Coverage with recommended BS sites in [19, 18]

7.5.2 Midtbyen

Midtbyen is a 2.686km^2 large area located in the central area of Trondheim. The area is a dense urban area with commercial buildings and shops. As beforementioned, Midtbyen is expected to be capacity limited, hence the base station density is higher here than other areas throughout Trondheim. According to the radio planning performed using Astrix, six (6) base stations and 15 sectors is expected to be sufficient for covering Midtbyen, Piren and Ila. Appendix F lists up the recommended sites in the pre-planning phase with number of sectors, and a figure of provided coverage from the given site.

Figure 7.5 shows the predicted Mobile WiMAX coverage in Midtbyen.

Gunnerus Library is one of the recommended base station sites mentioned in the previous subsection. Two sectors are recommended for covering Midtbyen, where an additional sector is recommended for improved capacity performance at Øya. The site is already provided with fiber to the roof, thus backhaul is accessible. The Gunnerus Library has been tested for capacity and range in [34] and [31]. The recommended sectors from the Gunnerus Library are given in table F.1, where figure F.1 shows the coverage from the site with the recommended sectors.

Felleskjøpet Kornmottak is a grain silo which is dominant within its area. Two sectors are recommended from this site, see table F.2, for providing coverage at Ila. Backhaul is expected to be provided through a radio link from the Gunnerus Library. Since the site is already providing mobile communication coverage, power and backup should be available through co-location at Felleskjøpet Kornmottak.

Prinsen Hotell is a hotel in the center of Midtbyen. The site is chosen to provide coverage, with three (3) sectors, to the commercial areas of Trondheim. Backhaul to Prinsen Hotell is feasible through fiber since the hotel is located in the near proximity of a fiber network, see figure 7.1. The site is already used for radio-communication, thus elementary components such as power and backup should be available through co-location.

Mercursenteret is a shopping center with a communication mast on top. The site is thus providing good coverage to the commercial areas of Midtbyen. In table F.4, three sectors are recommended to provide coverage to the eastern part of Midtbyen. Backhaul is expected through an existing radio link provided by Wireless Trondheim, and power is assumed to be available through co-location.

Olavskvartalet is another shopping center in Trondheim. The site is chosen to provide access to the northern part of Midtbyen, as well as Solsiden and the lower part of Møllenberg. Backhaul and power is expected to be available at this site since it already has fiber to the roof, and is an existing base station for mobile telephony.

Pirsenteret is an office building and a college of higher education. Pirsenteret is located in an industrial area, thus only one sector is suggested in table F.6 to provide coverage here. Backhaul is expected to be provided through fiber or a radio link from Olavskvartalet.

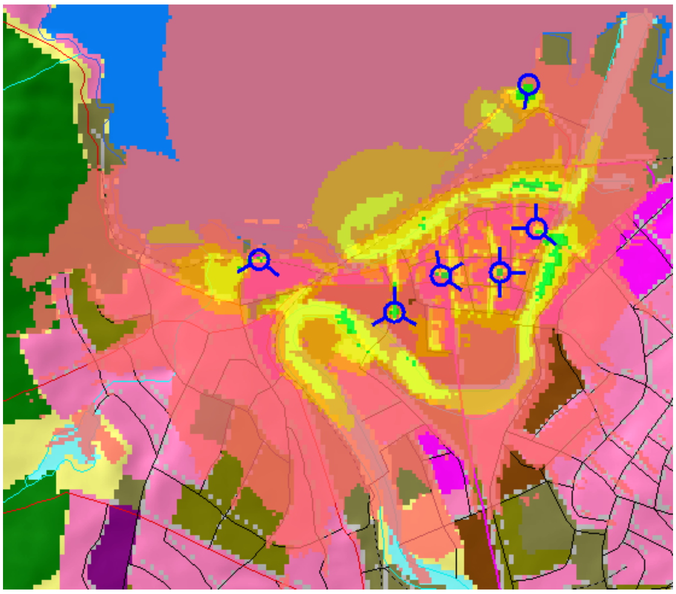


Figure 7.5: Predicted coverage in Midtbyen

7.5.3 Møllenberg and Tyholt

The area Møllenberg and Tyholt, does also include Singsaker, Bakklandet, Persaunet and Buran. The area is $5.818 km^2$ large, and is classified as a suburban area, with residential houses. The area is covered by having five (5) base station sites with 15 sectors in the area, and by using four sectors from neighboring areas, two from Midtbyen and two from Lade.

Figure 7.6 shows the predicted coverage between Singsaker, Solsiden, Leangen and Tyholt.

Industrial Building is as the name indicates, an industrial building. The building is situated in the close proximity of Solsiden, in which its coffee-houses and shopping center is frequently visited. The building holds offices and a food store. Two (2) sectors have been recommended from this site. One directed at Solsiden, and another to provide coverage to the lower part of Møllenberg. An additional sector is listed in table F.7, and planned for in figure F.7. The reason for adding the additional sector is to improve the coverage of Møllenberg. Furthermore, backhaul is accessible since the building is situated along the E6, and is already provided with fiber. Power and basic base station components are also already installed, hence co-location should be possible.

Tomasskolen is a Christian school which is already hosting mobile telephony equipment. The site is a small shed located beside the green area at Festningen. Although the building is not dominant in the area, the open landscape and hilly background makes it a good site for Mobile WiMAX. Three sectors are recommended in table F.8 to provide coverage to the upper part of Møllenberg and up to Tyholt, see figure F.8. Basic elementary components are available for hosting a Mobile WiMAX base station. Backhaul however, could be a problem since the site may not be available through radio link.

Singsaker Skole is a primary school located at Singsaker. The school is already hosting communication equipment, and fiber should be accessible to this site. The environment around the building consists of residential houses. Table F.9 recommends four (4) sectors to cover Singsaker,down to Bakklandet, and up to Tyholt. The area covered by the fourth sector, 340°, is already partly covered by Tomasskolen. Colocation is expected to be possible at Singsaker Skole. The predicted coverage from Singsaker Skole can be seen in figure F.9.

Tyholttårnet is a communication tower situated at the highest point in the central part of Trondheim. Being a communication tower makes Tyholtårnet the ideal site for Mobile WiMAX. Three (3) sectors have been recommended to provide coverage to Tyholt, see table F.10. Backhaul to Tyholttårnet should be available through a radio link from the NTNU Gløshaugen Campus. Being a communication tower, colocation is expected to be possible. Figure F.10 shows the expected coverage prediction from Tyholttårnet.

Persaunet is a suburban residential area. At Persaunet lies an old military camp, which has been converted into a residential area. A communication tower is located in this old military camp, thus co-location is expected to be possible. The location of the tower makes it suitable to provide backhaul through fiber to the site. Three (3) sectors have been recommended in table F.11 to provide coverage to Persaunet up to Tyholt, and down to KBS and Leangen, see figure F.11.

Additional sectors have been added to provide coverage to the mentioned area. Two sectors have been added from Midtbyen to provide coverage to Solsiden and Bakklandet. The used sites are Olavskvartalet and Mercursenteret. The remaining two (2) sectors have been added to provide coverage to Buran. The used sites are Laugesand Helse- og Velferdssenter and Toyota Material Handling AS. A description of the two latter sites will be given in subsequent sections.

7.5.4 Øya and NTNU Gløshaugen Campus

The area characterized as Øya and NTNU Gløshaugen is expected to be covered by 17 sectors provided by six (6) base stations within the area, and

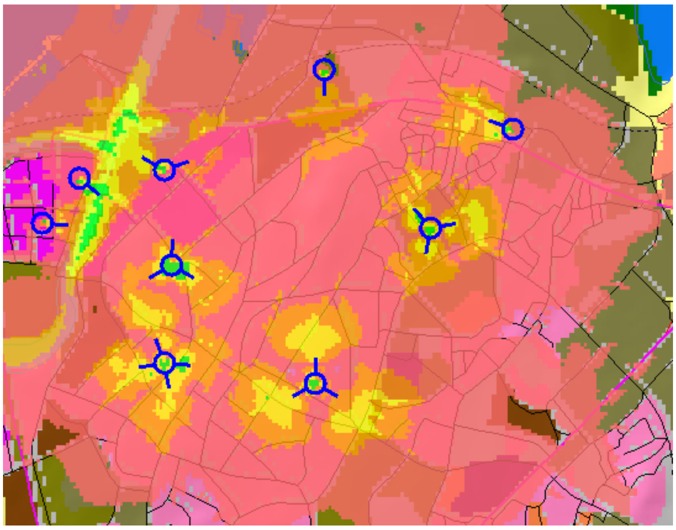


Figure 7.6: Predicted coverage of Møllenberg and Tyholt

one outside. Øya is a flat suburban residential area, and Gløshaugen is a hilly urban area. Tempe, which is also a suburban area with industrial buildings, is also covered in this session. The area Øya and NTNU Gløshaugen campus is measured to be $3.342km^2$. Backhaul is expected to be available at the whole campus.

As beforementioned, NTNU Gløshaugen campus is another area which is characterized as capacity limited, hence the high base station density. Under follows a description of the chosen base station sites. Figure 7.7 shows the predicted coverage in the area ranging from Øya, via NTNU Gløshaugen, to Nardo and Tempe.

St. Olavs Hospital is the district general hospital of Sør-Trøndelag. The chosen building for providing Mobile WiMAX coverage is the most dominant building within the area. Furthermore, the building is already providing GSM and UMTS coverage, hence power and backup should be available through co-location. Backhaul through fiber or a radio link is also expected to be available here. The hospital is set up with three (3) sectors, see figure F.12 and table F.12. One to provide Samfundet and the green area Marinen, and the two (2) others to provide Øya and the lower part of Sverresborg.

Elektrotaket is a building in the north-western edge of the NTNU Gløshaugen campus. Apart from being in the edge of the campus, Elektrobygget is also located on the top of a hill, dominant over the surroundings in the west. Thus good coverage at the campus and the recreational areas are provided by two sectors, whereas one sector provides coverage to the surroundings, see figure F.16 and table F.17 for predicted coverage and recommended sectors respectively.

Sentralbygg N and S are situated in the center of NTNU Gløshaugen Campus. The buildings are dominant within the areas, and are chosen to illuminate the whole campus with four (4) sectors, two from each building. Table F.13 and table F.14 lists up the recommended sectors. Figure F.13 shows the predicted coverage from the two sites, with the recommended sectors.

Realfagsbygget is a building situated in the eastern part of the NTNU Gløshaugen campus. Table F.15 shows the recommended sectors from the mentioned site. One sector provides coverage to the residential area east of Gløshaugen, and the other two provides the campus with additional capacity. Figure F.14 shows the predicted coverage from Realfagsbygget.

Siemens is an office building situated in the industrial area of Sorgenfri. The building is the most dominant in the area, and is used as a base station by mobile telephony operators. Co-location is hence been expected to be possible. It can be seen in table F.16 that it has been recommended three (3) sectors to provide Mobile WiMAX coverage in the area surrounding the building. One sector is set to cover the residential area east of the building, where the two other sectors are to cover the areas north and south of the building. Figure F.15 shows the predicted coverage. Furthermore, backhaul is expected to be provided through fiber or a radio link from NTNU Gløshaugen Campus.

Additional sector is provided by the Gunnerus Library to give additional coverage to Øya.

7.5.5 Lade

Lade is an industrial part of Trondheim with residential areas. The area is of $4.621km^2$, relatively flat with some curvature. Three (3) base stations are planned to provide coverage to the area with additional coverage from two base stations, respectively one from Møllenberg and Tyholt, and one from Charlottenberg and Steinan. Figure 7.8 shows the predicted coverage with 11 sectors. The uncovered area is woodland, hence setting up an extra base station for coverage to this area has been concluded to be unprofitable.

Harry Borhens vei 9 is a building situated in a mixed urban area in the outer (north) part of Lade. The building is by far the most dominant in the area. That the building is filled with antennas at the roof proofs that it is ideal as a Mobile WiMAX base station site. Backhaul through a radio link from Tyholttårnet, or other solutions is a problem which

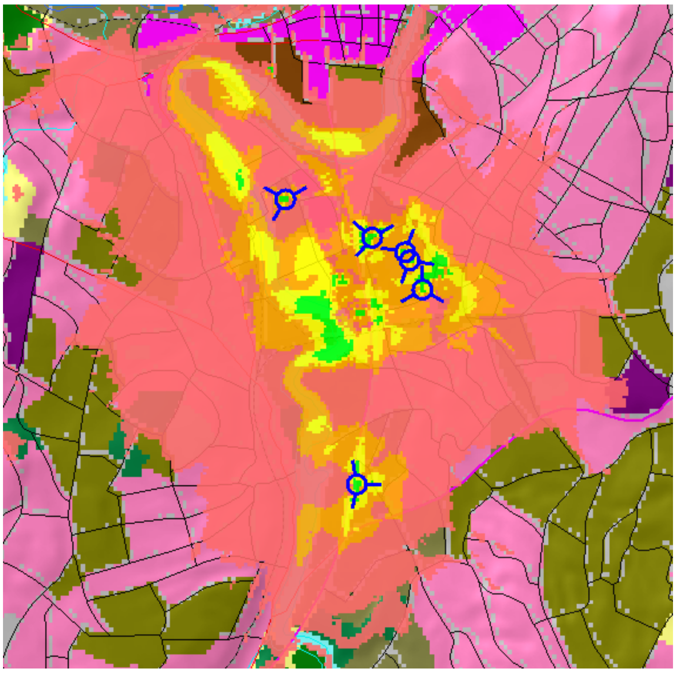


Figure 7.7: Predicted coverage of Øya and NTNU Gløshaugen Campus

has to be addressed. Table F.25 shows the recommended sectors to provide coverage to the northern part of Lade, whereas figure F.24 shows the predicted coverage.

Laugesand Helse- og Velferdssenter is a health care center situated in an urban environment. Several communication antennas has been observed at this building, which is dominant in the area. Backhaul and power should be provided since the building is situated close to the E6, and is already used by communication operators. Table F.24 lists up the recommended sectors from Laugesand Helse- of Velferdssenter. One sector is planned to give coverage to the industrial area around the harbour, where the two other sectors are to provide coverage to the southern part of Lade, see figure F.23. One of the antennas are also planned to provide additional coverage to Møllenberg and Buran.

Toyota Material Handling Norway AS is an industrial building situated in an industrial area. The building is an existing base station for mobile telephony, and is supposed to provide coverage to two shopping centers, KBS and City Lade, see figure F.25. Table F.26 lists up the recommended sectors from Toyota Material Handling Norway AS.

Additional sectors are recommended to provide coverage at Lade. One sector from the Industrial Building at Solsiden will provide coverage to Svartlamoen. Moreover, a sector from Travbaneveien 4 is set to provide coverage to the eastern part of Lade.

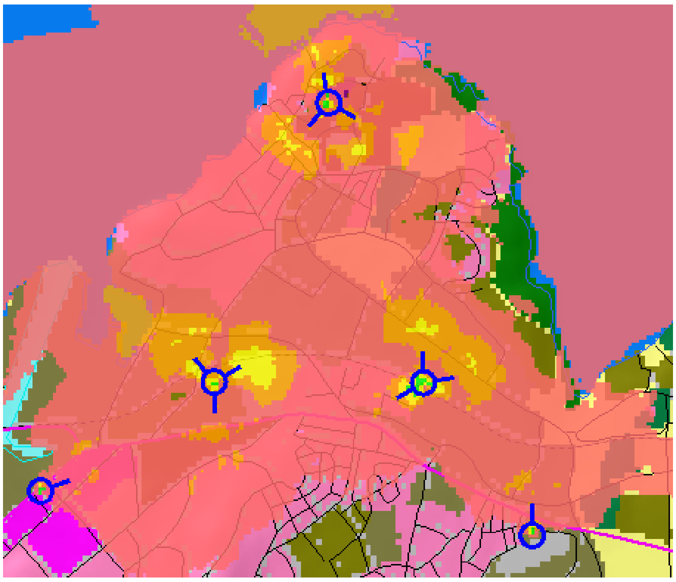


Figure 7.8: Predicted coverage of Lade

7.5.6 Charlottenlund and Steinan

Charlottenlund and Steinan comprises the eastern part of Trondheim. The area is mainly a hilly residential area. Seven (7) base station sites have been recommended to provide coverage to the defined area of $10.177km^2$. The base stations provides a total of 23 sectors. Figure 7.9 shows the predicted coverage in the given area.

Travbaneveien 4 is a communication mast situated in the close proximity of Leangen Travbane. The site is recommended with two sectors. One to provide additional coverage to Lade, and the other to cover the area between Leangen and Charlottenlund. Figure F.27 shows the predicted coverage from Travbaneveien 4, using the recommended sectors given in table F.28. Backhaul through fiber, and co-location is expected to be the most feasible solution at Travbaneveien 4 since the site is an existing base station for mobile communication.

Felleskjøpet Tunga is a department store situated at Leangen. The building is dominant within its area, and its surrounding is mostly industrial. Furthermore, the site is already providing UMTS and GMS coverage, hence co-location is expected to be possible. Three sectors have been recommended in table F.27. One sector is set to provide additional coverage to Tyholt, another to provide coverage up to Charlottenlund, and the third to provide the area between Leangen and Moholt with Mobile WiMAX. Figure F.26 shows the predicted coverage from Felleskjøpet Tunga.

Midtre Tunhøgda 2 is an apartment building situated at the top of Charlottenlund. The building is already providing mobile telephony coverage to Charlottenlund. Hence power and backup is already available at the site through co-location. Backhaul however, is assumed to be available through fiber, or a radio link from Felleskjøpet Tunga. The site has been set with three sectors to provide Charlottenlund with Mobile WiMAX access. Table F.29 shows the recommended sectors from the mentioned site, where figure F.28 shows the predicted coverage.

Granåsen Gård is a communication mast situated at the top of a hill. The site is, as mentioned, providing mobile telephony coverage, thus power and backup is expected to be accessible through co-location. Furthermore, it should be possible to provide backhaul through radio link from Tyholttårnet or Midtre Tunhøgda 2. In table F.30, the site is recommended with three sectors. One to complement with the sector from Midtre Tunhøgda 2, one to provide access at Dragvoll, and the last to provide coverage in the direction of Moholt. Figure F.29 shows the predicted coverage using the sectors listed in the mentioned table.

Loholt Sør is a farm located on a the top of a hill, looking down at the residential areas of Steinan and Risvollan. The farm is equipped with mobile telephony equipment, thus power and backup is expected to be accessible. Furthermore, it is assumed that backhaul is feasible through fiber from Dragvoll. Figure F.30 shows the predicted coverage with the sectors recommended in table F.31. Each sector provides coverage in the direction of Dragvoll, Moholt and Steinan respectively.

Brøsetveien 186B is an industrial building at Moholt. The building located in an industrial area and is expected to provide coverage to Moholt Studentby, and the surrounding residential areas. Power and backup is expected to be available through co-locating the equipment with existing communication operators at the site. Moreover backhaul through fiber or a radio link from Moholt Studentby is expected to be accessible. Table F.32 shows the recommended sectors from Brøsetveien 186B, where figure F.31 shows the predicted coverage.

Nardosenteret is a shopping center situated in a residential area in the outskirt of central Trondheim. The site is already hosting communication equipment, thus power and backup should be accessible through co-location. Furthermore, backhaul through fiber is expected to be available since the center is located close to Omkjøringsveien. Table F.33 lists up the recommended sectors with figure F.32 showing the predicted coverage from Nardosenteret.

Additional sectors from Realfagsbygget is recommended to provide coverage to the lower part of Nardo.

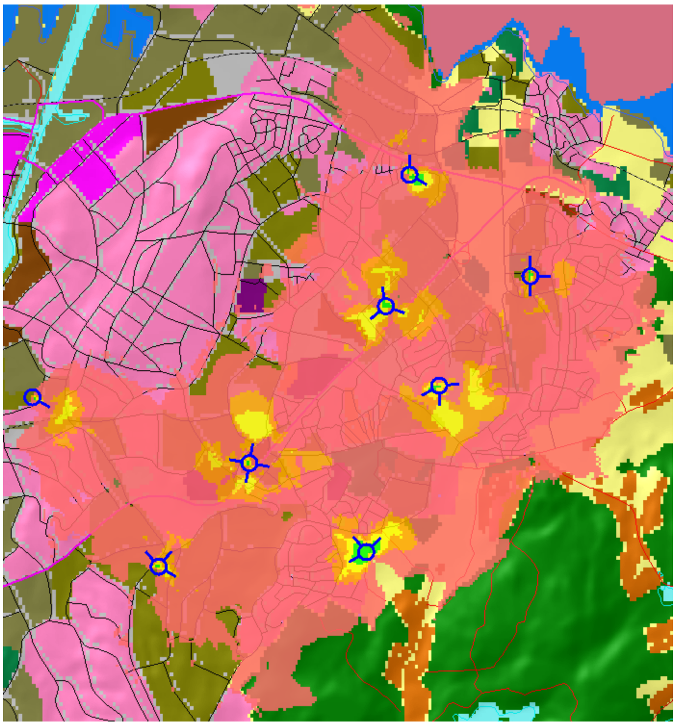


Figure 7.9: Predicted coverage of Charlottenlund and Steinan

7.5.7 Byåsen

Byåsen is a hilly urban residential area of $7.895km^2$. Coverage of the tram, [19, 18], has been performed in this area. The recommended base station sites from the mentioned reports have thus been used as a basis for additional coverage of the area. A total of five (5) base stations have been recommended to provide coverage in the mentioned area. Additional sectors from Felleskjøpet Kornmottak, Gunnerus Library, and St. Olav hospital have been used to provide coverage to the lower part of Byåsen. In figure 7.10 it can be seen how the 18 sectors covers the defined area.

Hoem Gård is a farm situated in the residential area of Munkvoll. Other communication operators have used one of the barns as a base station site. In [18] and [19], Hoem Gård was recommended as a Mobile

WiMAX site for coverage of the tram line. Co-location with existing communication operators solves the power and backup case, whereas [19] recommends a radio link from Byåsen Vgs to provide backhaul to the site. Table F.18 shows the recommended sectors from Hoem Gård, where figure F.17 shows the predicted coverage.

Byåsen Vgs is an upper secondary school. The school has been recommended and tested in [18, 19] to provide coverage to the tram line. The same sectors with one additional have been recommended in table F.19 to provide Mobile WiMAX access to the surroundings of the school. Two of the sectors are recommended to go along the tram line, whereas the third is recommended to provide coverage in the direction of Selsbakk. Figure F.18 shows the predicted coverage from Byåsen Vgs.

NetCom Kyvatn is a communication mast situated in an open area. The site has, in [18], been recommended as a possible substitute to Telenor Storhaug. NetCom Kyvatn is predicted to provide coverage to the upper part of the tram line, Havstein, and in the direction of Byåsen Vgs, see figure F.20. Table F.21 lists up the recommended sectors from NetCom Kyvatn.

Havsteinekra Helse- og Velferdssenter is a health center situated in a residential area at Havstein. The building is already contributing to mobile telephony coverage, and is thus well suited as a Mobile WiMAX base station. Table F.22 recommends four sectors at this site to provide the surroundings with Mobile WiMAX coverage. Furthermore, Backhaul is expected to be achievable through radio link.

Sverresborg alle 13 is a museum at Sverresborg. The site is located at the top of a hill, with residential surroundings. Sverresborg alle 13 is already providing mobile telephony coverage, hence co-locating the Mobile WiMAX equipment should be feasible. Getting backhaul to the location is however a problem which has to be addressed. The site is recommended to provide coverage to the surroundings by using three sectors, see figure F.22 and table F.23.

Additional sectors has been set to provide coverage of Byåsen is received from Felleskjøpet Kornmottak, Gunnerus Library, and St. Olav hospital. Each providing the area with one sector.

7.5.8 Trondheim

The coverage prediction performed using Astrix shows that satisfactory signal performance is achieved by having 92 sectors from 32 base stations

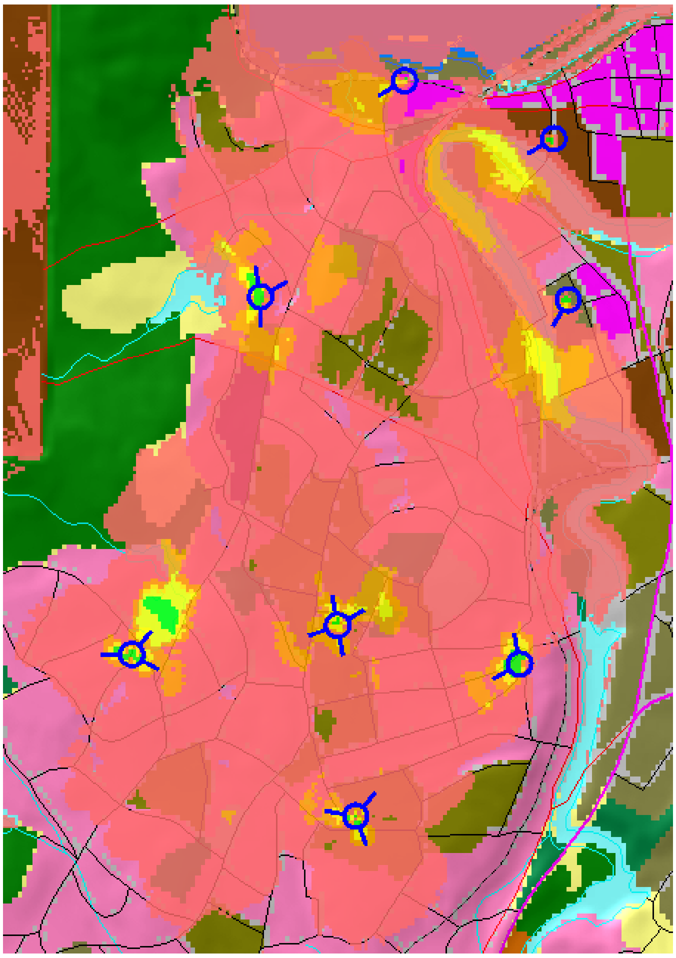


Figure 7.10: Predicted coverage of Byåsen

throughout the $35.630km^2$ large area. Worth mentioning is that some areas are assumed to be capacity limited, hence the base station density have been increased within these areas. From figure 7.11, which shows the predicted Mobile WiMAX coverage, it can be seen some spots which does not have predicted Mobile WiMAX coverage. These spots have a predicted signal reception level lower than -95 dBm, meaning that that the signal level might be lower than required. Furthermore, its worth emphasizing that the coverage prediction in this section have been performed without any real life measurements. Meaning that the data has not been made available for testing if the prediction is close to a real life scenario.

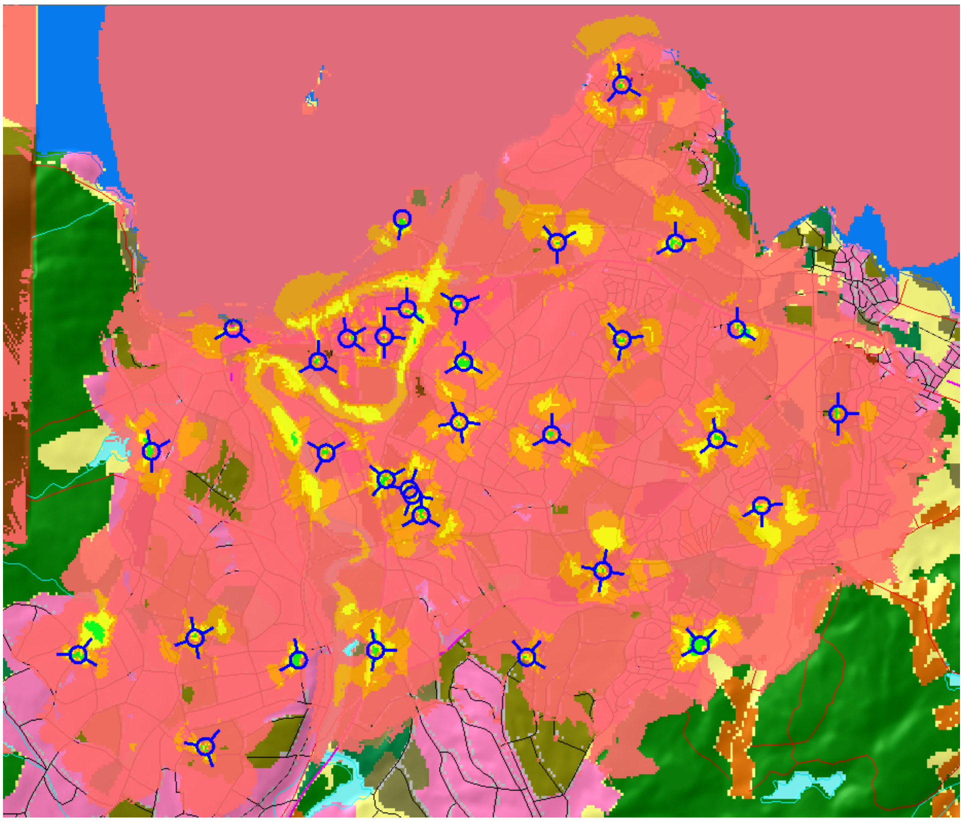


Figure 7.11: Predicted coverage of Trondheim using Astrix 5.0

At Sverresborg and Lade, a relatively large area stands without any Mobile WiMAX coverage. These areas are forests, hence the coverage-request is assumed to be non-existing. The system is also left out with intentional backup in power and sectors. The maximum transmitted power is set to 30 dBm, a number used when configuring the transmitting power level in [19, 18, 34, 31], where 36 dBm is the maximum power available. Furthermore, experiences from the pre-mobile test set in [31] showed that three sectors provides 360 degree coverage. An average of 2.9 sectors per base station shows that an additional sector is available for capacity increment, or coverage, in most base station sites.

8

Preparations

Apart from the radio planning described in chapter 7, an automated test bench has been constructed to make the testing more time efficient and to reduce the probability of human errors. Python has been used as the programming language. The physical performance measurements are to be retrieved directly from the PCMCIA-card, whereas throughput measurements are performed by using Iperf, [9]. Furthermore, a Matlab code has been written to read and process the retrieved data.

8.1 Physical Performance

The physical performance of the system tells something about the quality of the channel. Information such as signal strengths, used modulation and coding rate, CPE transmission power, and sub-channel usage are important physical performance data. In the pre-mobile test set in [31], such information were collected from the CPE. Although the PCMCIA provides such information in the GUI (Graphical user interface), Alvarion has not provided any information on how to use a command line interface in order to collect such information. Not having the system up and running has not made it possible to find such information. The PCMCIA card however has a log-window where such information is expected to be stored.

8.2 Throughput Performance

The throughput performance measures the average rate of successful delivered bits over a given time period. The throughput tests are intended to be performed with Iperf, a TCP and UDP bandwidth measurement tool developed by NLANR/DAST, [9]. Iperf allows the user to set various TCP and

UDP parameters, and reports bandwidth, delay jitter, and number of lost datagrams. The software is a command line tool, but does also come as a Java-based GUI-tool, Jperf. Being a command line tool makes it feasible to write Python scripts for running the throughput measurements.

The throughput performance measurements in this report are based on the previous work described in [34], where the TCP and UDP were measured over pre-mobile WiMAX. The two protocols have been described in section 5.2 and 5.3. TCP performance tests comprises three (3) tests with various window-size, 32kB, 56kB, and 64kB respectively. The buffer length is set to 56kB for all of the measurements. Furthermore, the UDP performance tests comprises eight (8) measurements with various bandwidths. The window-size and buffer-size are 64kB and 1kb respectively for all of the tested bandwidths. The bandwidths are: 2Mbps, 4Mbps, 4.5Mbps, 5.5Mbps, 6.5Mbps, 7Mbps, 7.5Mbps, and 8Mbps. The reason for choosing many bandwidths is to find the optimal bandwidth for error-free transmission. Too high bandwidth will result in overload, and lost packages.

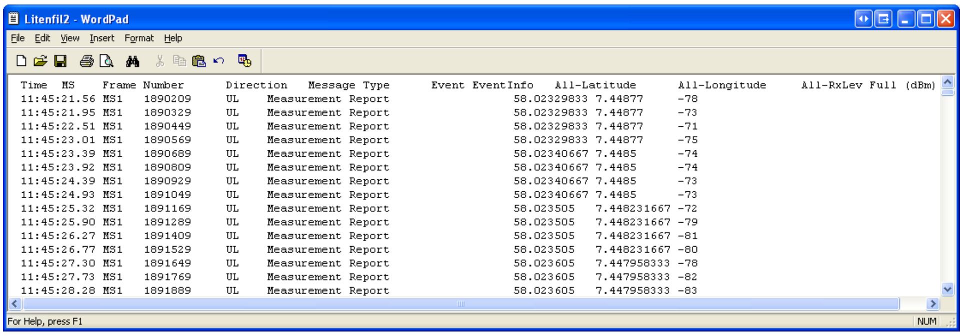
Python has been used to create the automated process. The source code and explanations of the python scripts can be found in appendix G.

8.3 Data processing

After a set of different locations have been measured, the data processing phase starts. Measured data is stored both on the client computer and the server. In the preparation of measurements, the server has been set with an FTP server, in order to be able to collect data on the server remotely. The data processing has been set to be using the mathematical tool Matlab. A Matlab code has been written in order to present the measured locations in the same manner. It is however, expected that the code will be in need of some editing, since it has not been tested on the Mobile WiMAX system. The source code of the Matlab scripts can be found in appendix H, and is available for revision, editing and as a help for future work on Mobile WiMAX.

8.4 Measurement logging

Astrix 5.0 has, as beforementioned, a measurement logging tool and a measurement tuning tool to implement the real-life measurements into the radio planning software. The input data consists of data like time, link direction, latitude and longitude, and signal strength. The input data uses the tab (white space) as delimiter between each column. Figure 8.1 shows a screen shot of an example of the .FMT input file provided by Teleplan.



Time	MS	Frame Number	Direction	Message Type	Event	EventInfo	All-Latitude	All-Longitude	All-RxLev Full (dBm)
11:45:21.56	MS1	1890209	UL	Measurement Report			58.02329833	7.44877	-78
11:45:21.95	MS1	1890329	UL	Measurement Report			58.02329833	7.44877	-73
11:45:22.51	MS1	1890449	UL	Measurement Report			58.02329833	7.44877	-71
11:45:23.01	MS1	1890569	UL	Measurement Report			58.02329833	7.44877	-75
11:45:23.39	MS1	1890689	UL	Measurement Report			58.02340667	7.4485	-74
11:45:23.92	MS1	1890809	UL	Measurement Report			58.02340667	7.4485	-74
11:45:24.39	MS1	1890929	UL	Measurement Report			58.02340667	7.4485	-73
11:45:24.93	MS1	1891049	UL	Measurement Report			58.02340667	7.4485	-73
11:45:25.32	MS1	1891169	UL	Measurement Report			58.023505	7.448231667	-72
11:45:25.90	MS1	1891289	UL	Measurement Report			58.023505	7.448231667	-79
11:45:26.27	MS1	1891409	UL	Measurement Report			58.023505	7.448231667	-81
11:45:26.77	MS1	1891529	UL	Measurement Report			58.023505	7.448231667	-80
11:45:27.30	MS1	1891649	UL	Measurement Report			58.023605	7.447958333	-78
11:45:27.73	MS1	1891769	UL	Measurement Report			58.023605	7.447958333	-82
11:45:28.28	MS1	1891889	UL	Measurement Report			58.023605	7.447958333	-83

Figure 8.1: .FMT example file for importing measured data into Astrix 5.0

9

Measurements

The following chapter was intended to give a thorough description of the measurements performed on Mobile WiMAX throughout Trondheim. Unfortunately, the upgrade from pre-mobile WiMAX to Mobile WiMAX did not go as foreseen. In our case, the system did not work properly. As a result, testing on a Mobile WiMAX network has not been performed in this report. The purpose of this chapter will thus be to provide information on how it is assumed that the measurement procedure and data processing would be performed. Hopefully, this chapter, and report, will be of great help and guidance for future Mobile WiMAX radio planners.

9.1 Measurement parameters

The following section will provide information regarding the measurement parameters of a Mobile WiMAX network.

Physical performance

RSSI (Received Signal Strength Indication) shows the amount of signal energy at the receiving antenna. The value is presented in dBm.

SNR (Signal to Noise Ratio) shows the measured signal energy relative to noises and interference at the receiving antenna. The SNR is commonly presented in dBm.

Subchannels shows the amount of subchannels allocated to the given transmission. The number of allocated subchannels is dependent on the quality of the channel.

Tx Rate shows the output power delivered to the antenna. The power is dependent on the signal quality, where the Tx power strives to achieve an optimal quality of the channel.

9.2 Measurement Procedure

As described in chapter 6, one base station and three (3) antennas have been made available for testing in this report. Having two (2) vertical antennas and one dual slant antenna, makes the system available for testing no diversity and 2nd order diversity.

As for the initial stage of radio planning, a reference site has to be set up for thorough testing, preliminary testing. In this report, Olavskvartalet was decided to be the candidate for such testing. Figure F.5 shows the predicted coverage with the recommended sectors given in table F.5. Testing of range, attenuation, key features, diversity and antenna configuration are all features which should be explored.

The exploration of range and attenuation contributes to improved propagation models, where parameters can be adjusted in the radio planning tool in order to increase quality of the radio planning. Key features are referred to as the throughput, modulation, and coding. These features tells the system planner something about the performance of the system as well as how the network should be deployed in order to provide the promised services. Furthermore, diversity and antenna configuration can increase range, reliability, and performance of the system. By exploring diversity and antenna configurations, the system planner may adapt each base station to each scenario to increase the system efficiency.

To facilitate the process, a Python-script has been created. The script requires Iperf installed at both hosts, the server at the base station side, and the client behind the CPE or PCMCIA. Moreover a telnet server has to be set at the server side for configuration of the Iperf server.

Figure 9.1 illustrates the probable Mobile WiMAX test set. The client side comprises a computer and the CPE or PCMCIA card. The base station site however, comprises the components mentioned in chapter 6. It is important to notice that the switch is needed between the server and the base station to provide the information with VLAN tags. Backhaul however, is not necessary for the test purpose with one base station.

In all testing, including the preliminary testing from Olavskvartalet, it is recommended to have a similar test bench as provided in appendix G. A description of the Python scripts are also given in the appendix G. As beforementioned, an automatic generated test bench removes the possibility of human errors in configuration and naming of parameters and files.

9.2.1 Preliminary testing

As beforementioned, the preliminary testing serves the purpose of getting to know the system, and how it works. Theory says among other things that dual slant antennas performs better than vertical polarized antennas in dense NLOS-scenarios. Such theory has to be set out in practice. A

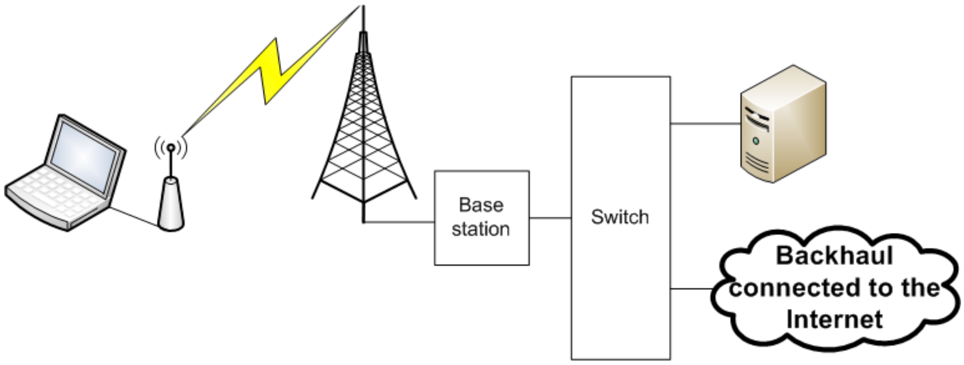


Figure 9.1: Mobile WiMAX test set, [31]

thorough preliminary testing will enlighten the radio planner, making the radio planning process and the network more efficient.

Appendix G contains a description of the Python-scripts written for testing of the Mobile WiMAX base station. It is recommended that the preliminary test locations are spread throughout the coverage area to exploit the performance in LOS, PLOS, and NLOS scenarios. Furthermore, range, and width have to be mapped. As can be seen in figure F.5, the river is predicted to be a great conductor for the signal energy.

During preliminary testing, a comparison between theoretical, promised, and experienced throughput on a per modulation and coding rate basis should be performed, as well as maximum and minimum throughput. The maximum and minimum are found when the system is using the highest and lowest modulation and coding rate respectively. The mentioned parameters should be performed for each diversity and antenna configuration.

9.2.2 Field Trial

When the preliminary testing has given satisfactory knowledge about the system performance and behavior, the field trial may begin. In the case of this report, the base station were to be positioned at several base station sites for testing of coverage, range, and capacity with the recommended sectors provided from the radio planning process. The methodology follows the same pattern as for preliminary testing of one given diversity and antenna configuration. Worth mentioning is that signal energy may rebuild on a hill although the signal have been lost further down, giving spots without coverage (shadowing).

9.3 Presentation and processing of data

As mentioned earlier, the automated test bench written in Python generates three (3) TCP sub-tests with various window sizes, and eight (8) UPD sub-tests of variable bandwidths. The information is as described in appendix G stored at both the server and client computer. For processing of data, all the information have to be located at the same computer, for example the client computer.

The ways of presenting the measured data are many, the following sub-section will provide some suggestions. Table 9.1 shows a suggested table with parameters for each measured location. In the throughput measurements, a relative comparison with maximum observed throughput at the preliminary site is recommended for increased knowledge of the location.

Location-Name

Longitude					
Latitude					
Distance from BS [m]					
Elevation [m]					
Tx-Power [dBm]					
Subchannel					
BDP					
		max	**avg**	**min**	**Relative**
UDP [Mbps]	UL				
	DL				
TCP [Mbps]	UL				
	DL				

Table 9.1: Example-table for presentation of data at each location

9.3.1 Physical Performance

Physical performance data comprises signal strength, subchannels, Tx power, and modulation and coding.

Propagation is measured in signal strengths throughout the measured area. RSSI and SNR are parameters which are dependent on distance from the transmitting source. A comparison with the UL and DL signal strengths versus distance makes the data comparable with the used propagation models. Experiences from [31] shows that different propagation environments approaches different propagation models, thus no scenario is alike.

RSSI vs. SNR Where RSSI measures the amount of signal energy received at the antenna, SNR measures operational conditions of the system where interference and noise is taken in consideration. Equation 9.1 shows the relationship between RSSI, noise (N), and interference (I) measured in decibel. In an ideal environment, where only noise is present, a linear relation between the RSSI and SNR would be expected. A presentation of the RSSI versus SNR would thus show the amount of co-channel interference present at the receiving side. In the case presented in this report, a linear distribution is expected due to the absence of multiple base stations, and interfering sources.

$$SNR = RSSI - N - I \tag{9.1}$$

\# **UL channels vs. UL SNR** indicates how the system adapts to different propagation channels. The system may for instance decrease the number of allocated subchannels to increase the range.

Modulation and coding is continuously adapted to the channel quality. A comparison between experienced modulation and coding threshold versus system vendor specification may be found interesting.

9.3.2 Throughput

In terms of deciding what type of QoS to offer the consumers, throughput has to be explored. As previously mentioned, throughput performance is dependent on channel conditions, modulation and coding rate.

TCP in the uplink and downlink direction versus UL and DL SNR respectively shows what kind of throughput one can expect at each signal level, giving a threshold for the further planning of coverage. TCP throughput versus distance, on the other hand, gives an indication of maximum range for promising a given threshold.

UDP versus the signal strengths in the dedicated directions shows, as for TCP, coverage thresholds for a given throughput. The same relationship in distance is achieved the UDP throughput versus distance. Furthermore, additional UDP information is provided in Iperf, thus table 9.2 is a possible suggestion for presentation of jitter and packet loss.

Speed and mobility is another important feature of Mobile WiMAX. Exploration of data rates versus speed is thus important to reveal.

Location-Name

Bandwidth	Throughput			Jitter			Packet Loss		
	max	avg	min	max	avg	min	max	avg	min
2 MHz									
4 MHz									
4.5 MHz									
5.5 MHz									
6.5 MHz									
7 MHz									
7.5 MHz									
8 MHz									

Table 9.2: Example-table for presentation of UDP throughput measurements

Part III

Discussion and Conclusion

10

Discussion

The following chapter will provide a general discussion on the work performed throughout this report.

10.1 Radio Planning

The radio planning performed in this report has been more of a pre-planning stage of a total radio planning scenario. The area has been restricted to comprise the dense populated areas of Trondheim. Moreover, base station site requirements have been defined, and a total of 83 possible sites have been observed throughout the pre-defined area.

As previously mentioned, the Mobile WiMAX is set to complement and co-exist with WLAN. Hence, the radio planning have been performed to provide ubiquitous outdoor coverage with a minimum of -94 dBm. The threshold is set as the minimum received signal strength required by the Alvarion PCMCIA-card.

A total of 32 base stations using 92 sectors have been found to provide ubiquitous outdoor coverage to customers using the mentioned PCMCIA-card. During the radio planning, the main goal has not been to provide coverage from a minimum of base stations and sectors, but considerations towards assumed capacity limited areas has also been taken in account for. The base station density has thus been increased in the areas which has been classified as capacity limited. In this report, where the pre-defined area is of $35.63km^2$, the base station density was found to be 1.113 km^2 per base station. The characterization of a capacity limited area have been due to high population density and/or high expectation of high end users. Midtbyen and NTNU Gløshaugen Campus are such areas. It can bee seen in table 10.1 that the two mentioned areas have an average base station density

Name	Area [km^2]	# base stations	BS density [km^2/BS]
Midtbyen	2.686	6	0.448
Øya and NTNU Gløshaugen campus	3.342	6	0.557
Lade	4.621	3	1.54
Charlottenlund and Steinan	10.177	7	1.454
Byåsen	7.895	5	1.579
Møllenberg	5.818	5	1.164
Trondheim	*35.630*	*32*	*1.113*

Table 10.1: Base station density per region

of 0.5 km^2 per base station where the average of the range limited areas have been found to be of approximately 1.4 km^2 per base station.

Experience gained from previous work, [31], shows that the propagation models do not provide an exact image of the coverage. In Astrix 5.0, the measurement logging tool have the ability to import measured data to adjust and improve the radio planning image. Density clutters, reflection constants, and penetration loss can all be tailored to fit the deployed scenario. A correction layer is then added after importion of the measured data. How the data is to be formatted has been described in this report.

In terms of coverage, the base stations have been set to transmit at a maximum of 30 dBm. Thus a 6 dB back off from the maximum of 36 dBm has been introduced. Should the measurements reveal that the predicted coverage is not achieved, 6dB transmission power may be added to each base station for increased range. Furthermore, signal strengths as low as -94 dB will not provide high throughput for the end users. Using the si CPE or the CPE PRO, which has higher antenna gains than the PCMCIA-card, will provide a better channel, resulting in a higher modulation and coding rate. As known, higher and modulation coding provides higher throughput. The si CPE and CPE PRO are thus recommended for an increased throughput for fixed and nomadic users.

10.2 Testing

As previously mentioned, testing has unfortunately not been performed in this report. However preparation have been made to automate the testing process. A python script has been constructed to perform UDP and TCP throughput tests, and ping measurements between the client and the base station. The reason for automating the measurement process is to remove human errors and to make the measurements more time efficient.

Although the scripts have been created for Mobile WiMAX measurements, testing have unfortunately only been performed over an Ethernet connection between two remote hosts. The scripts are enclosed in the appendix, and are available for revision and editing. Some adjustments are probably required for the scripts to work properly since it has not been tested in a Mobile WiMAX scenario.

On the processing side, a matlab code has been created to perform the processing of the measured data. As beforementioned, testing on Mobile WiMAX measurements has not been performed due to failure of the equipment upgrade. As for the Python script, the matlab code will provide suggestions for how the measured data can be processed and presented.

10.3 Further Comments

Due to lack of measurements, the radio planning has not been performed as expected. This report will hopefully provide some insight and recommendations for Mobile WiMAX radio planners. Apart from giving an introduction to the Mobile WiMAX standard, and equipment, this report does also contain a user guide for radio planning with Astrix 5.0.

10.4 Problems Encountered

When working with new technology and system, surprises and problems tend to appear. The work with Mobile WiMAX has been no exception. Underneath follows a list of problems encountered in the process of radio planning a Mobile WiMAX network in Trondheim for Wireless Trondheim.

Base Station Equipment was to be upgraded from pre-mobile WiMAX to Mobile WiMAX. Old NPU was substituted with an upgraded NPU, and Jardar Leira became the designated upgragder for the base station equipment. Software files were provided from Alvarion and Upgrade, but unfortunately, the upgrade did not go as seamless as expected. The upgraded NPU with its software did neither communicate nor connect with the outdoor units or the GPS. Jardar Leira performed some tedious error search on the base station equipment. His first discovery was finding that the first upgrade file was corrupt, and later discovering that a probable firmware upgrade was missing. At the time of writing, Alvarion has been performing remote support on the base station equipment, but the system is still not working.

Clients were also to be upgraded. Unfortunately, the upgrade was not available from the supplier. NextNet however, offered to lend some of their clients out to Wireless Trondheim. The self installer CPE was unfortunately broken, and had to be changed. Since the base station did not work, the drawback had no influence on testing.

Astrix 5.0 is a new release with the promise of supporting WiMAX systems. A propagation model tailored for WiMAX was promised by Teleplan in January, but was unfortunately never released. The software also supports implementation of measured data for creating a correction layer. The correction layer should make the radio planning even more accurate. Due to lack of measurements, the correction layer was never added to the coverage prediction of Astrix.

11

Conclusion and Future Work

The following chapter will conclude upon the work performed in this thesis, and recommend some future work in the area of Mobile WiMAX deployment in Wireless Trondheim.

11.1 Conclusion

This report is based on the work performed in [31] and [34], where a connection between Mobile WiMAX theory and basic wireless theory were drawn, and field trials on pre-mobile WiMAX were performed for uncovering indoor coverage and performance in a city like Trondheim.

The report consist of three (3) parts, where part one sums up some of the features of the Mobile WiMAX standard, and draws a connection between the standard and the Alvarion BreezeMAX equipment available for testing. Part two consists of the actual radio planning with the preparations performed prior to testing. Measurements were unfortunately not performed in this report due to problems with the upgrade of the base station from pre-mobile WiMAX to Mobile WiMAX. Suggestions on how to perform and process the measurements has thus been provided. The work performed in this report will hopefully be of great help for future radio planners in the sense of setting up and performing coverage and performance tests on a Mobile WiMAX network, and/or other wireless networks. The third part of this report sums up and concludes upon the work performed in this report.

The 802.16e Standard - and some of it key features has been discussed, and linked with the equipment provided by Alvarion. A comparison of the standard, and basic wireless communication theory has been provided in [31].

Radio Planning - The radio planning process has been performed by defining site criterias, and by finding suitable site candidates through observations. A total of 83 base stations have been found throughout the populated areas of Trondheim. Furthermore, the radio planning tool Astrix 5.0 have been used for coverage prediction in the pre-defined area of $35.63 km^2$. A total of 92 sectors from 32 base stations have been predicted to provide ubiquitous outdoor coverage with a PCMCIA-card at the client side, giving an average base station density of 1.113 km^2 per base station.

Base stations providing coverage to capacity limited areas have been recommended to serve an area of approximately 0.5 km^2 where the base stations in a range limited area is recommended to serve an area of approximately 1.4 km^2. Furthermore, for customers interested in indoor coverage, a client upgrade to the si CPE or the CPE PRO have been suggested because of the higher antenna gain, and increased throughput.

The COST-231 has been used as propagation model in the radio planning tool since the promised WiMAX propagation model has not been made available from Teleplan. In [31], the COST-231 was found to provide the best coverage prediction in a propagation environment as Trondheim city. Moreover, an Astrix user case has been created in appendix D to provide a brief introduction to the use of the radio planning tool for future Astrix 5.0 radio planners.

Preparations - In terms of performing error free and time efficient coverage and performance tests, a test bench has been created using Python. The Python scripts includes measurements of delay using ping, and a total eight (8) UDP and TCP performance tests at the server and the client side using various bandwidths and window sizes. The script has been tested to work over an Ethernet connection, but it is however assumed that some changes have to be applied to the Python script since it has not been tested on a Mobile WiMAX network.

Measurements - Due to problems with the upgrade of the base station, measurements has not been performed in this report. However, ideas and suggestions on how to process and present the data have been given for future radio planners to revise and edit.

It is recommended for future work on Mobile WiMAX in Trondheim to set up a small network for performing deployment analysis, using multiple base stations and clients. Coverage, capacity, co-channel interference, and mobility would thus be parameters available for testing. A smaller network would also be feasible to manage and work with, giving a thorough system analysis.

11.2 Future Work

Coverage is a much needed topic to address. No measurements have been performed in this report to verify and improve the radio planning. By importing the measured data into the measurement logging tool of Astrix, the radio planning prediction is expected to be improved and more accurate.

Capacity performance tests with the promised QoS parameters is important for addressing the limitations of the system. When the system limitations are found, the radio planner will have a better basis in providing better capacity to the limited areas.

Backhaul has been considered, but not planned in this report. Due to lack of building clutter in Astrix 5.0, radio link predictions have not been performed. A thorough planning of the backhaul network have to be performed in order to make the system ready for deployment. A base station site is in need of having access to backhaul in order to communicate with other base stations and networks.

Mobility is the main upgrade in the 802.16e amendment. How the base stations are to address mobility between sectors, base stations and operators is thus important for the system to compete with existing wireless technologies such as UMTS, and the future LTE.

Intermedia handover between Mobile WiMAX and Wi-Fi. As mentioned in this report, Mobile WiMAX is expected to complement and co-exist with Wi-Fi. In order to have seamless handover between the two technologies, intermedia handover have to be investigated thoroughly.

Co-channel interference arises when setting up multiple base stations in a region. Frequency reuse, and configuration of the base stations is thus important to study for optimal performance of the network.

Negotiations of co-location of the base station equipment, or for providing necessary space and components for a site, is imminent in order to place the base station equipment at the desired location. Having a secondary location for positioning the base station equipment is probably necessary since some sites may not be accessible do to capacity limitations, or restrictions.

Detailed radio planning with considerations to co-channel interference, transmission power, antenna tilt, polarization, and beamwidths should be performed as the last instance before the network is available for the commercial market.

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Part IV

Appendix

A

Topology and Demography of Trondheim

Trondheim is a city and a municipality in Norway. The municipality is the third (3rd) most populated municipality, and the fourth (4th) largest urban area in Norway, [33]. The city is situated at 63.4 degrees north, where the river Nidelven meets Trondheimsfjorden. The climate is predominantly maritime with gusty weather conditions.

Figure A.1: Clutter raster of Trondheim city, [3]

Trondheim is often referred to as the technological capital of Norway since NTNU, SINTEF, UNINETT, and many other technological companies are situated here. As a result, Trondheim consists of many high-end users, making the city well suited for employing and testing new wireless technologies such as Mobile WiMAX.

As most metropolitan areas, Trondheim has a densely populated city center with decreasing population density further away from the city core. Characterizations of the metropolitan areas are divided into the common five (5) categories. Figure A.1 shows how the different areas are characterized in the radio planning tool Astrix 5.0, [3]. Underneath follows a description of the five area classifications. Table A.1 provides the color-mapping of the clutter layer in figure A.1.

Dense urban areas are found in the city center. Commercial buildings and multi dwelling homes provides a hostile propagation environment with many reflections and multipaths. Dense urban areas are marked in brown (commercial buildings), see figure A.1.

Urban areas consists of more sparsely separated multi dwelling buildings with lower building heights. The radio propagation is approximately equal with a dense urban area. Figure A.1 marks the urban areas in light brown, which symbolizes multi dwelling buildings.

Suburban areas have lower building density, where buildings are single dwelling homes. The propagation environment is better due to the more open areas. Single dwelling homes are marked with pink in figure A.1.

Rural areas are in the outskirt of a city. The areas consists of widely separated single dwelling homes.

Open space consists of open areas as parks, forests, green belts, and lakes. Open space is colored yellow and green in A.1.

It can be seen that propagation statistics changes within the city limits. Furthermore, another interesting feature to map is the demographics. Demographics tells us, among other factors, something about population density. Population density is important for a radio planner in order to decide where the radio planning is to be performed, and if the system is expected to be capacity limited or range limited within certain areas.

Table A.2 provide statistics gathered from [33]. As mentioned, Trondheim is the third (3rd) most populated area in Norway with its 165 191 inhabitants, as of 1st of January 2008. The effective population of Trondheim is about 190 191, where approximately 25 000 are unregistered students living in Trondheim.

It can be seen from table A.2 that the average population density is 482.7 inhabitants per km^2. Table A.2 and figure A.2 shows that the main population, 96 %, live in the built up areas. Moreover, table B.1 shows

Color	Definition
	Open areas
	Forest
	Sea
	Inland Water
	Residential Area
	Urban Area
	Dense Urban Area
	Block of Buildings
	Industrial Area
	Villages
	Open Areas in Urban Area
	Parks in Urban Area
	Airport
	Dense Residential Area
	Mixed Dense Urban Area

Table A.1: Clutter-color definition in Astrix 5.0

settlement divided per the four (4) regions in Trondheim, see figure B.1, whereas figure A.2 shows the actual distribution of the inhabitants.

Figure A.2 shows that the main population is settled in the city center and the immediate proximity. The implementation of Mobile WiMAX will thus be restricted to the high populated areas, and with the possibility of expansion.

Area	342.2 km^2
Population	165 191
Youth (0-15 years old)	19.7 %
16 - 80 years old	80.3 %
$>$ 80 years old	3.9 %
Students	25 000
Population per km^2	482.7
Population in built-up-areas	96 %

Table A.2: Statistics of Trondheim municipality, [33]

Coverage and Capacity

Mobility and wide range of services increases the requirements to coverage and capacity. Building heights, density, material, and terrain do all affect the link budget and has to be considered during radio planning.

Mobility increases the requirement of ubiquitous coverage where mobile users may traverse through areas with low or no population. Fixed systems

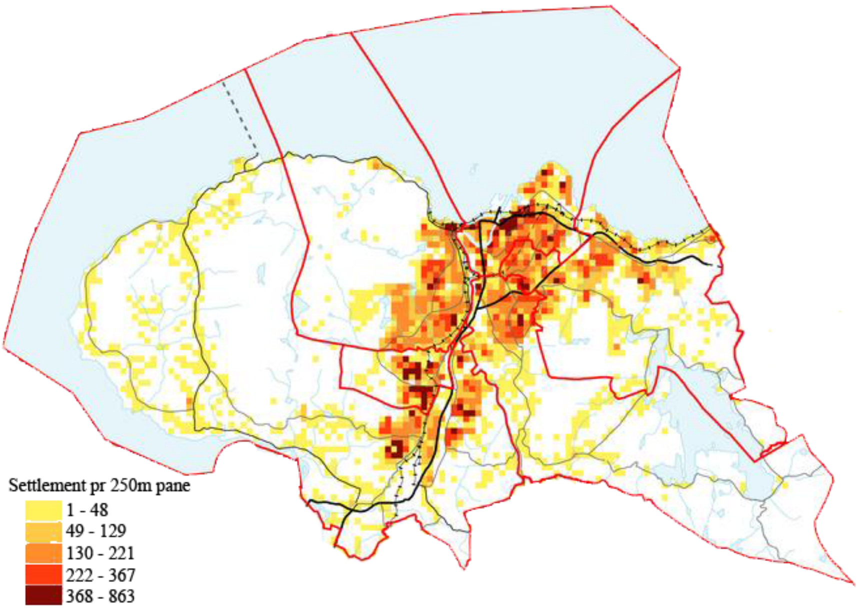


Figure A.2: Settlement in Trondheim, [33]

does thus not have the same requirement when it comes to coverage of open areas since fixed and/or nomadic equipment often require access to power.

Moreover, coverage and capacity does, unfortunately, not come hand in hand, and dense areas tend to be capacity limited rather than range limited. Hence another consideration is that business hours often require more capacity in central areas due to the commuter traffic. A population increment of 15 % is a common value for many metropolitan areas because of the commuting traffic, [8].

The service demand from users span from web-browsing to video conferences. Users are often divided into three (3) categories.

Professional Users requires services for both business and personal usage. The most common services are: e-mail, VoIP, voice conference, video conference, and download.

High-end Consumers uses the services for personal usage. Video streaming, Internet, gaming, and e-mail are the most common services demanded for this type of users. Trondheim is, as beforementioned, referred to as the technological capital of Norway, and have many high-end consumers. Thus, suitable for testing market penetration with new technologies.

Casual Users are persons with periodic usage of mainly web-browsing.

B

Regions of Trondheim muncipality

Region	**Age**			**Total**	**Size** km^2	**Density** $1/km^2$
	0-15	**16-79**	**80+**			
Midtbyen	8 396	34 538	2 033	44 967	54.8	820.6
Østbyen	8 051	32 996	1 660	42 707	74.3	574.8
Lerkendal	9 295	35 472	1 836	46 603	77.5	601.3
Heimdal	6 825	23 052	867	30 744	137.6	223.4
Unregistered	12	158	-	170		
Trondheim	32 579	126 216	6 396	165 191	342.2	482.7

Table B.1: Settlement per region, [33]

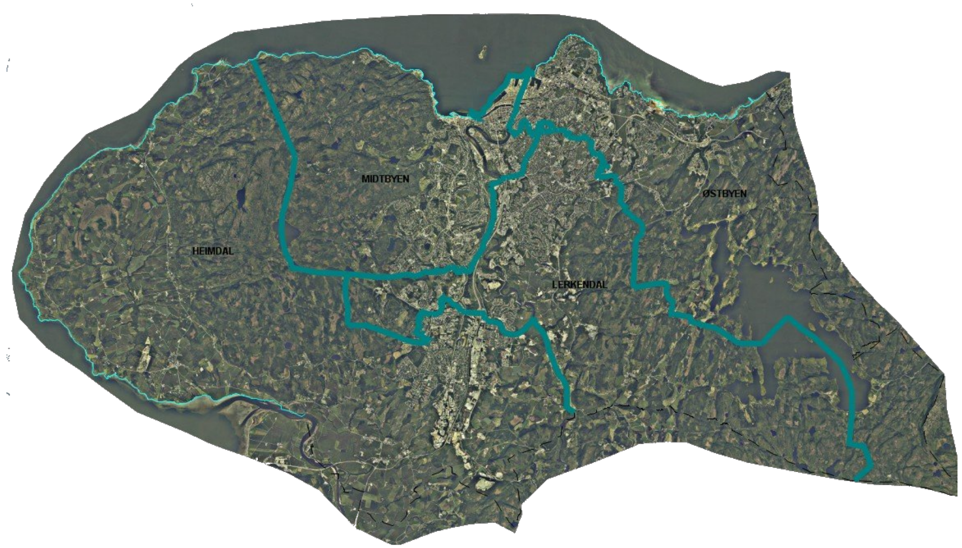
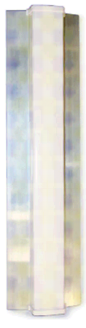


Figure B.1: The four (4) regions of Trondheim muncipality

C

Antenna Specifications

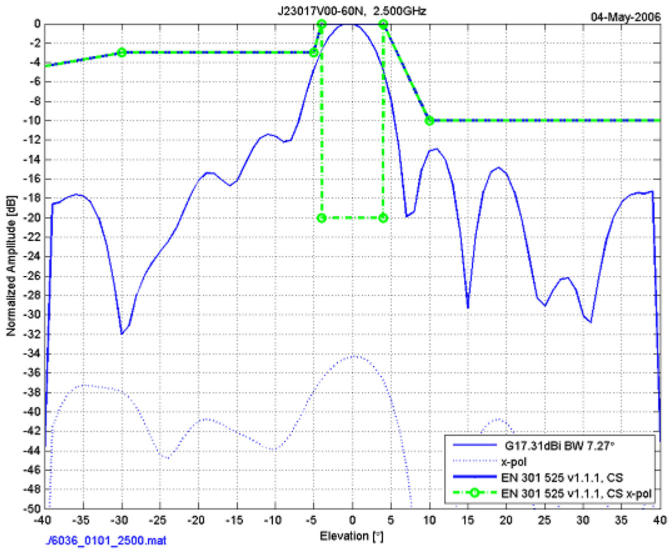
BASE STATION ANTENNA, [24]
2.3 - 2.7 GHz 60°VERTICAL
P.N 723208



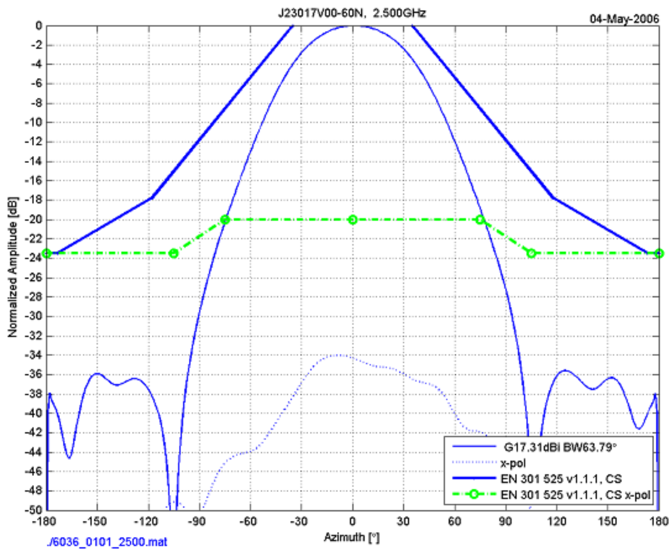
REGULATORY COMPLIANCE	ESTI EN 301 525 V.1.1.1 (2000-06) CS RoHS Compliance
ELECTRICAL	
FREQUENCY RANGE	2.3 - 2.7 GHz
GAIN	16.5 dBi (min)
VSWR	1.9:1 (max)
3 dB ASIMUTH BEAMWIDTH	60°(typ)
POLARIZATION	Vertical
ELEVATION BEAMWIDTH	7°(typ)
SIDELOBES LEVEL	ESTI EN 301 525 V.1.1.1 (2000-06) CS
ELEVATION NULL FILL	Down to -25°
CROSS POLARIZATION	ESTI EN 301 525 V.1.1.1 (2000-06) CS
F/B RATIO	ESTI EN 301 525 V.1.1.1 (2000-06) CS
INPUT IMPEDANCE	50 (ohm)
INPUT POWER	20W (max)
LIGHTNING PROTECTION	DC Grounded
MECHANICAL	
DIMENSIONS (LxWxD)	1093 x 213 x 124 mm (Nom)
WEIGHT	5.0 Kg (max)
CONNECTOR	N-TYPE Female
RADOME	ASA White
BASE PLATE	Aluminum with chemical conversion coating
Pole mounting hardware	Tilt Mounting Kit for 2" to 4.5" Dia pole
ENVIRONMENTAL	
TEMP. CYCLING	-40°C to +70°C
VIBRATION	ETSI 300 019-2-4 E2.2.2(2003) E4. 1E
SHOCK MECHANICAL	ETSI 300 019-2-4 E2.2.2(2003) E4. 1E
HUMIDITY	95% Condensation, (IEC 60068)
WATER TIGHTNESS	IP-67
SOLAR RADIATION	IEC 68-2-5, MIL-STD-810
FLAMMABILITY	UL 94 Class HB
SALT SPRAY	ETSI 300 019-2-4
ICE AND SNOW	25mm at 7Kn/m^3
WIND SPEED SURVIVAL OPERATION	 220 Km/h 160 Km/h

ANTENNA PATTERNS

Elevation Pattern
Frequency 2.5GHz



Azimuth Pattern
Frequency 2.5GHz

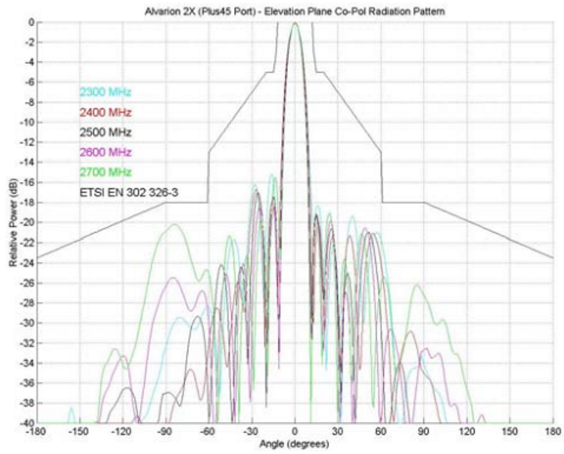


BASE STATION ANTENNA, [25]
2.3 - 2.7 GHz Dual Slant Sector 65°
P.N 300640

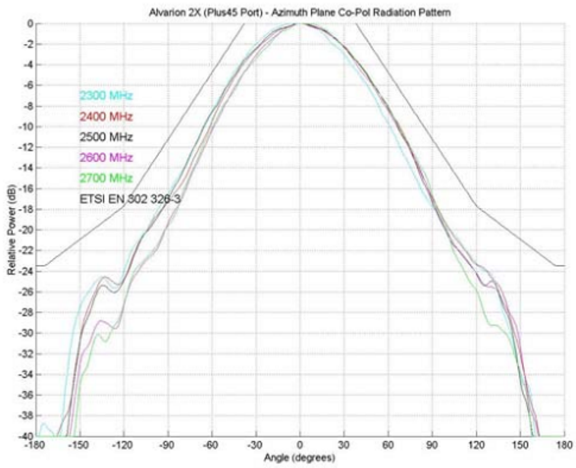
REGULATORY COMPLIANCE	ETSI EN 302 326-3 V1.2.1 class CS RoHS Compliance
ELECTRICAL	
FREQUENCY RANGE	2.3 - 2.7 GHz
GAIN	16.0dBi $\pm$ 0.5 dB
VSWR	1.5:1
3 dB AZIMUTH BEAMWIDTH	65° $\pm$ 45°
POLARIZATION	Dual Slant $\pm$45°
ELEVATION BEAMWIDTH	8° $\pm$ 2°
INTERPORT ISOLATION	<25dB
CROSS POLARIZATION	-15dB
F/B RATIO	>28dB
INPUT IMPEDANCE	50 (ohm)
INPUT POWER	50W (max)
LIGHTNING PROTECTION	DC Grounded
MECHANICAL	
DIMENSION (LxWxD)	711 x 171 x 90 mm
WEIGHT	2.6 Kg
CONNECTOR	2 x N-Type Female
RADOME	Gray UV resistant PVC
Pole mounting hardware	Fully adjustable pipe mount with 0-15°down tilt
ENVIRONMENTAL	
TEMP.CYCLING	MIL-STD-810F. Method 503.4 -40°C to +65°C
VIBRATION	MIL-STD-810E. Method 514.4, Procedure 1-3.3
SHOCK MECHANICAL	MIL-STD-810F. Method 516.5
HUMIDITY	95% Condensation
WATER TIGHTNESS	IP-65
SOLAR RADIATION	MIL-STD-810F. Method 505.3
FLAMMABILITY	UL 94 Class HB
SALT SPRAY	48 hours continuous salt spray at 35°C MIL-STD-810E, Procedure I, Aggravated Screening and/or ASTM B 117-94
ICE AND SNOW	25mm Radial
WIND SPEED: SURVIVAL OPERATION	 220 Km/h 160 Km/h

ANTENNA PATTERNS

Elevation Pattern
Frequency 2.xGHz



Azimuth Pattern
Frequency 2.xGHz



D

Astrix User Case, a brief introduction

Astrix 5.0 [3] is a radio planning tool designed by Teleplan Globe. The software is designed for frequency planning, coverage prediction, interference calculation, radio link planning, and network design. Supported layers are, according to [10]:

- Ground heights
- Morphology
- Ortho photo
- Building heights
- 3D vector of building foot-prints and heights
- Demographic data

Supported propagation models are:

- COST-231
- Multiple Knife Edge
- Walfish Ikegami

The available terrain model provided by Teleplan Globe has a resolution of 20 meters in the urban areas of the largest cities of Norway. In Trondheim, the area is restricted to the populated areas, see figure A.2. Moreover, the resolution outside the mentioned area is 100 meters. Another restriction worth mentioning is that building heights are not included in the delivered package from Teleplan, meaning that propagation predictions are based on

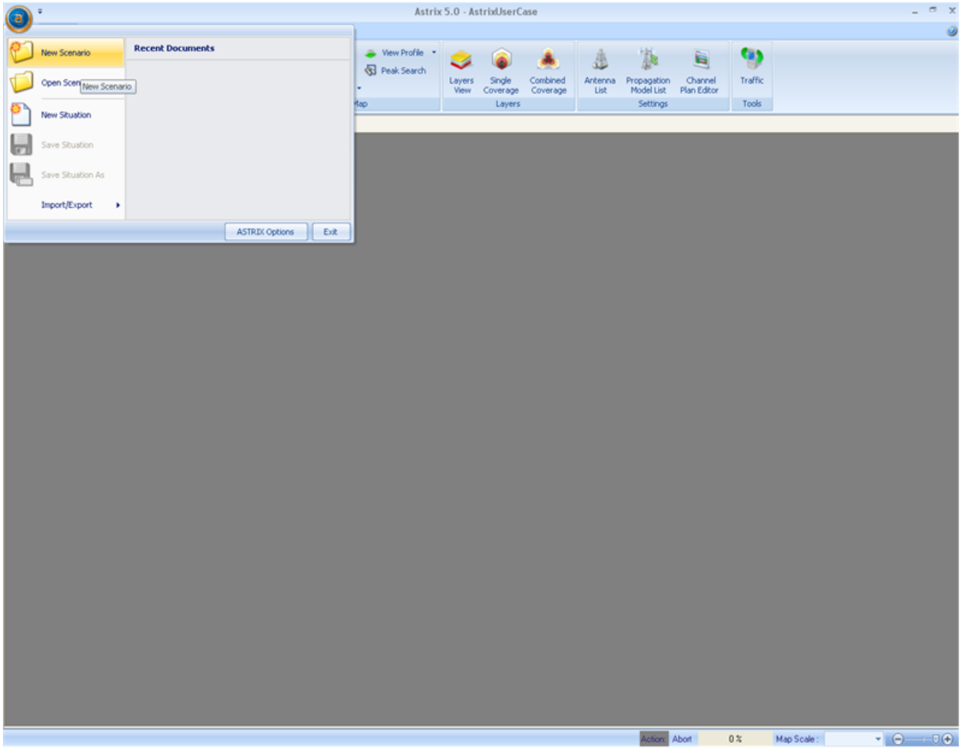


Figure D.1:

ground occupancy, and not the actual propagation environment. The statistics is however adjustable.

The following chapter is meant as an introductional guide for usage of Astrix 5.0. Teleplan has approved for the guide to be written and published in this thesis.

D.1 Getting started

In the initial stage, Astrix uses scenarios and situation. A scenario may be viewed as the main project, and include many situations. A scenario is created by executing Astrix 5.0, pressing the Astrix button -> New Scenario, see figure D.1. Importion of terrain data is executed in Map -> Open Map. In a normal installation, the maps are found in C:\Documents and Settings\All Users\Maria Files\Map\Templates. The map provided by Teleplan is called "TPStd.m5map".

Default in the map, is the city of Oslo, zooming out is performed by using the "Map Scale" in the bottom right corner of the window, or by pushing the Ctrl button and scrolling with the mouse wheel. Panning the map is performed through Map -> Pan Map. This gives the possibility of panning once. Holding the Ctrl button while pushing the Pan Map button enables multiple pan. Trondheim is thus within the reach through pan and zoom.

Furthermore, a new situation is created through the Astrix button -> New Situation. The situation can be named by "Save Situation As". A PDF help file is available by clicking on the question mark in the upper right corner of the Astrix window, see figure D.1.

D.1.1 Astrix Options

The Astrix Options sets default parameters for the deployed network. Flags, templates, and coordinate system is all set here. The option is found in Astrix button -> ASTRIX Options.

Flags

Base stations are often characterized as candidate, planned, operative, rejected, and tested. Having all base stations plotted in the system, makes the tool look messy, and is quite inefficient. Flags is thus a feature to set on each site in order to filter base stations and cells, making the tool clearer and increasing the efficiency of the radio planning process. The number of flags the system planner wants to use is individual. Recommended is to add an area-flag, where all base stations and cells within the same area carries the same flag. If there exists several radio planners using the same scenario, a system planner flag may be an easy way for each system planner to find its own base stations and cells. Figure D.2 shows the ASTRIX Options menu, and the flag-window.

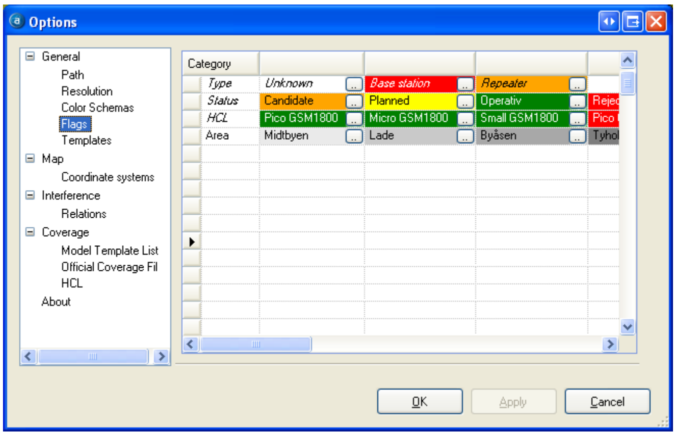


Figure D.2: ASTRIX Options for setting flags

Templates

Further in the process, while still having the ASTRIX Options window open, site and cell templates can be created. The site templates may be viewed as the base station parameter, and the cells as its sectors. The number of sectors and cells depends on the antenna patterns. For configuration of the antenna pattern, see section D.1.2. Creating sites are done by right-click -> Site -> Add Template. The site template may then be named. Cells are created in the same manner. Antenna parameters such as pattern, height, direction, and tilt are all set for each cell. Moreover, the parameters are editable when deployed in the scenario. For prediction of coverage, resolution, predefined area and propagation models are all set here. A prediction resolution higher than the resolution of the map is accessible, but not feasible. The desired propagation model is chosen from a drop down list. Radio parameters such as transmitting power, loss, sensitivity and frequency are also set for each cell. Figure D.3 shows the Template menu for editing the mentioned parameters.

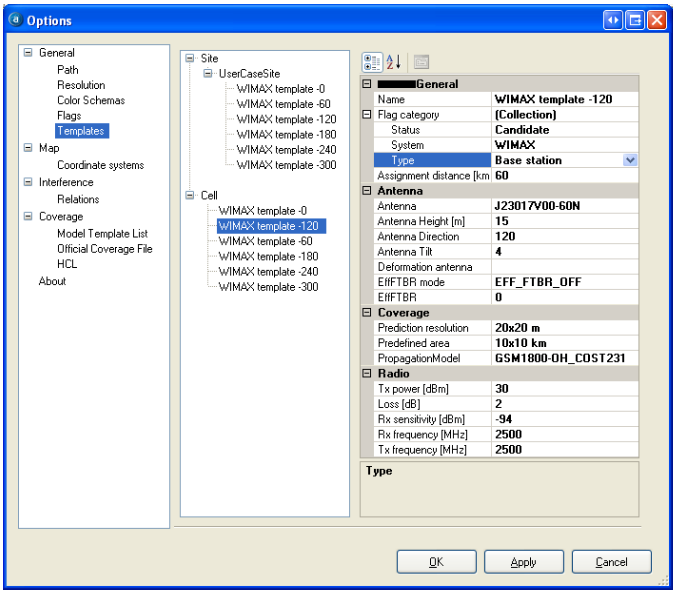


Figure D.3: Configuration of site and cell templates

Coordinate System

Coordinate systems are, as known, found in many different formats. Astrix 5.0 supports a total of six (6) different coordinate systems. The advantage of choosing between coordinate systems is for system adaption towards other systems such as a GPS or Google Earth. The coordinate systems are found in the Astrix Options under Map -> Coordinate systems.

D.1.2 Adding Antennas

In order to perform a realistic as possible radio planning, the antenna pattern has to be as close as possible to the employed antennas. Astrix 5.0 contains a list of 66 predefined antenna patterns. If the desired pattern is not found, a new antenna pattern is easily added if the system manufacturer has provided such information. Home -> Antenna List shows a list of the predefined antennas and the editor window, see figure D.4.

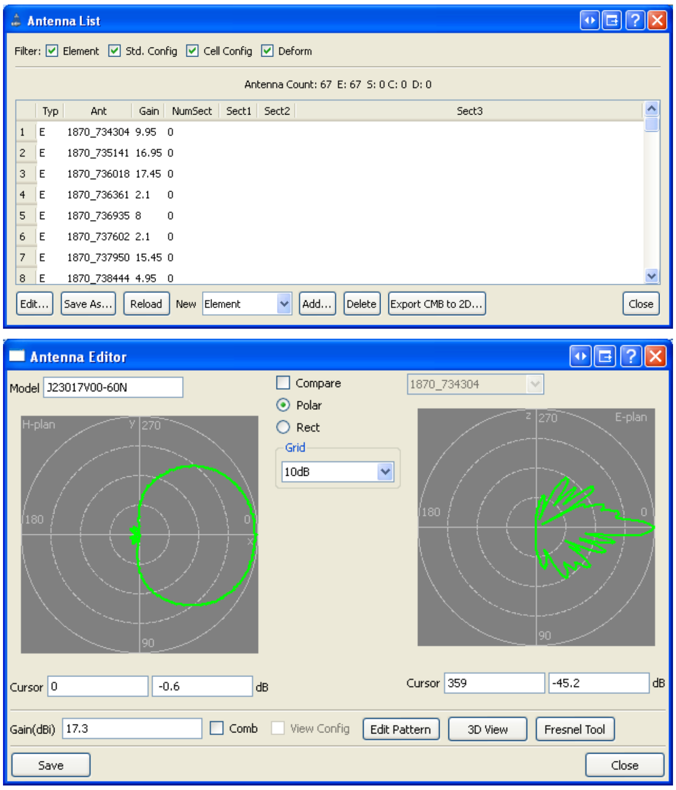


Figure D.4: List and configuration of predefined antennas

To create an antenna file, the setup has to be known. Figure D.5 shows an example file for importing an antenna element. Worth noticing is that the delimiter is tab. Furthermore, values are set for every degree increment from 0°up to 360°respectively for the horizontal and the vertical plane. When the file has been stored in the directory C:\AstrixFile\ant\element, Astrix has to be restarted before the antenna is found in the antenna list.

D.2 System Deployment

Setting up templates, system parameters, and antenna configurations is a great step towards the actual deployment of the system. The next step is

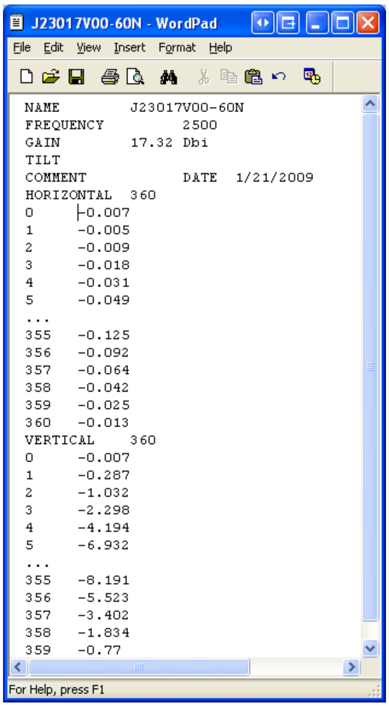


Figure D.5: Example file for importing antenna element

thus to position and direct the base stations and cells. Before positioning the sites, windows should be placed for adjustments of the deployed sites. The subsequent section provides a brief description and suggestions of window-views in Astrix 5.0.

D.2.1 Window-views

Astrix 5.0 is a module based software with dockable windows. The different windows are found in Home -> Windows, see figure D.6. As can be seen from the figure, a total of nine (9) windows are available. The recommended windows when radio planning are:

- Track view
- Layers view
- Coverage Tasklist
- Situation Tree
- Properties

As mentioned, the windows are dockable, meaning that the windows can be embedded into the total software window. Figure D.7 shows how the

Figure D.6: Dockable windows alternatives

properties window is docked into the upper part of the right frame in the window.

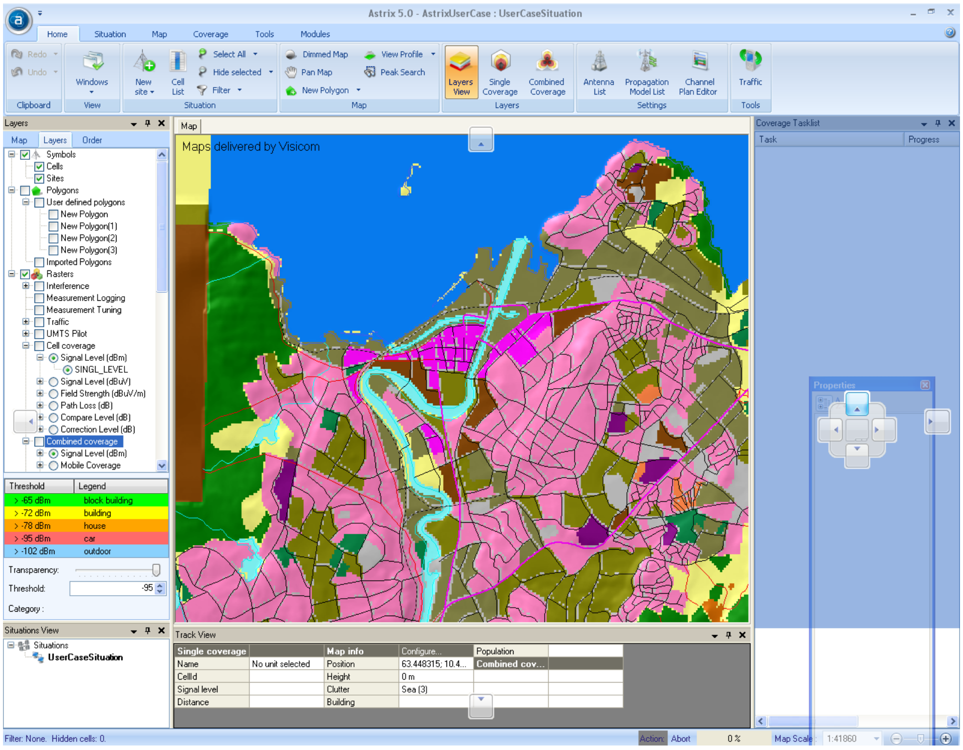


Figure D.7: Docking of the properties window

Adding sites and cells

Site and cells are easily added, by right-click -> New Site, wherever it is desired to position the given site. The site and its cells are then available in the drop down menu, under the given situation, in the Situation View window. By marking the new site in the Situation View window, renaming, flagging, and entering the position is possible in the Properties Window. The same counts for each cell, where properties of each marked cell is viewed and editable. Common parameters are possible to edit by marking several cells and/or sites. Figure D.8 shows the recommended outline of the dockable windows, and how the properties of a marked cell is editable.

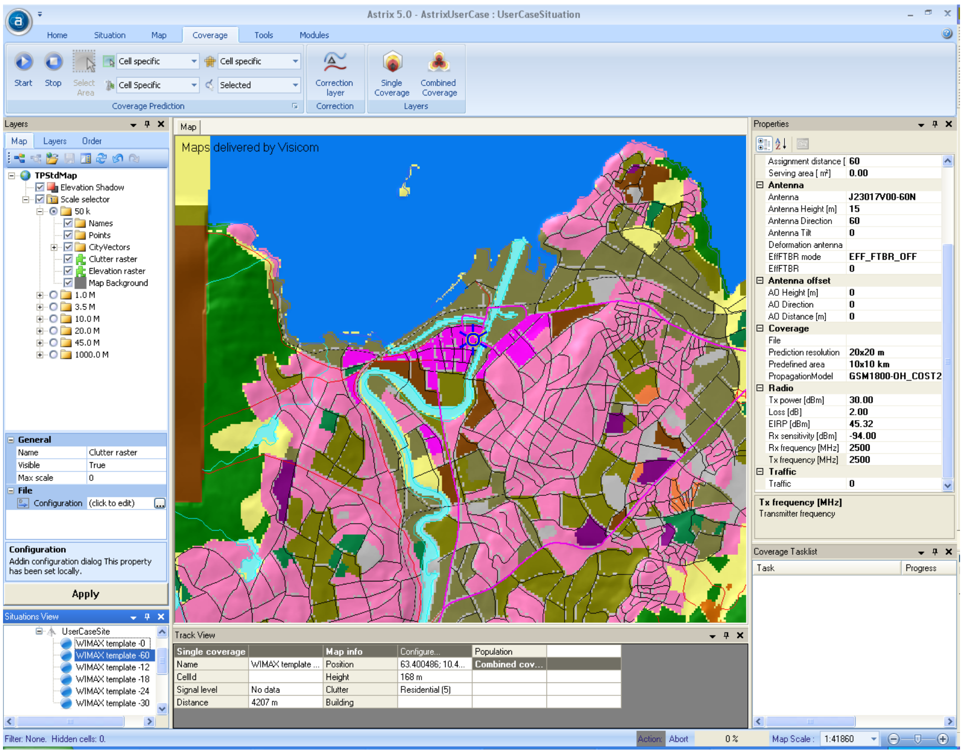


Figure D.8: View of the docked windows, and how a cell is editable

D.3 Coverage Prediction

Coverage prediction can be calculated in two ways, the single coverage, and combined coverage. Single coverage is for predicting coverage from one sector, where combined coverage predicts the total coverage from multiple cells and base stations. The coverage prediction is found by pressing the Coverage tab, see figure D.9. The options presented for coverage is propagation model, size of area to predict coverage, coverage resolution, and number of cells. If no adjustments is performed, then the software calculates with the default values set in the Astrix Options. By pressing the highlighted button, Coverage Prediction, in figure D.9, an additional window appears. The window allows the user to set the height of the receiving client, and the other parameters just mentioned. It is recommended to use this window for coverage prediction.

Furthermore, when calculating, the process may be followed in the Coverage Tasklist window. Without this window, the user will not know if the software is calculating, or when the calculation has finished.

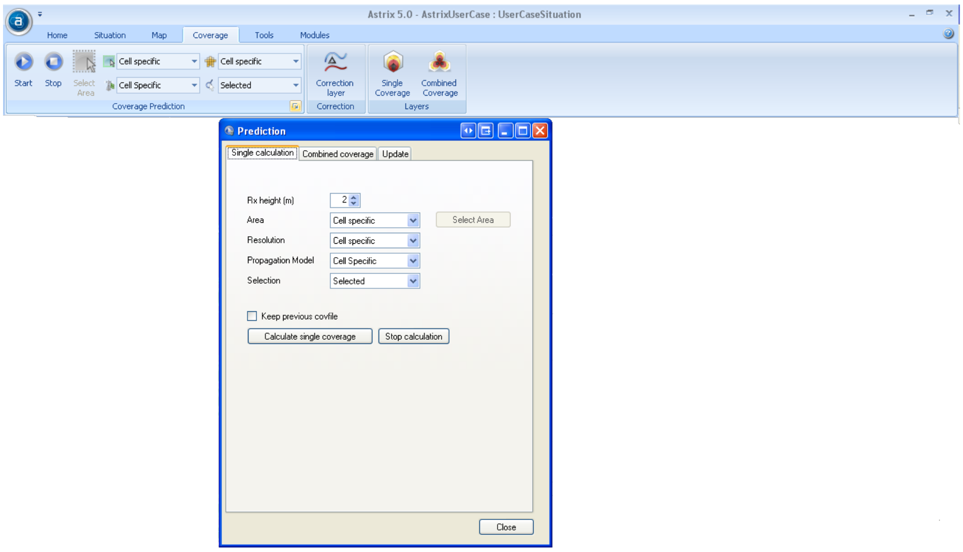


Figure D.9: Options in the Coverage menu

Combined coverage, however, is recommended to be calculated through the Coverage Prediction button, highlighted in figure D.9, and the Combined coverage tab. The reason for recommending this way is that the combined coverage can be saved in several files, making it possible to have several combined coverages. When a single coverage calculation is performed, the combined coverage prediction is updated to the active combined coverage calculation, which is set in the Prediction window. Having only one combined coverage file makes it difficult to follow when many calculations are being performed. Figure D.10 shows the Prediction window for combined coverage. The combined coverage taskbar is displayed in the bottom of the Astrix window, next to the Map Scale. Figure D.11 shows the predicted combined coverage from three sectors.

A handy feature in Astrix, is the transparency mode. Highlighting the cell coverage or combined coverage in the Layers window -> Layers, gives the opportunity to make the coverage prediction transparent, see figure D.11.

It has to be stressed that the Cell coverage or Combined coverage have to be checked in the Layers window -> Layers for single and combined coverage to be viewed respectively. Another way is to see if the Single Coverage or Combined Coverage are highlighted in the Coverage tab.

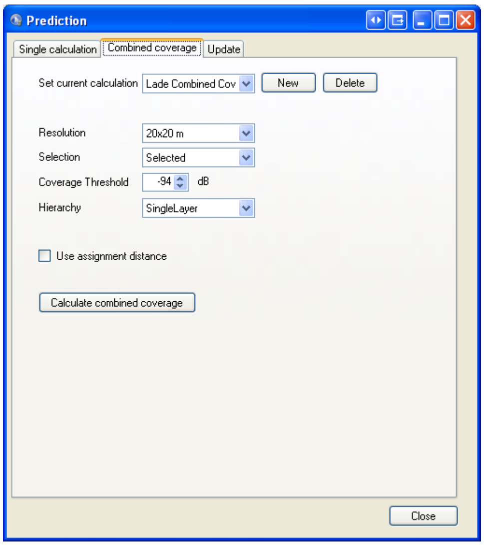


Figure D.10: Combined coverage calculation

D.3.1 Tracking

Tracking is a useful feature for checking the signal strength throughout the predicted area. Highlighting the desired antenna, and moving the cursor around on the map gives combined signal strength and signal strength from the selected cell along with other information such as distance from base station, clutter type, and position of the cursor. Figure D.11 shows predicted coverage at a point 222 meters away from the base station. It can be seen from the figure that single coverage from the selected cell is 6dB lower than the combined coverage.

D.4 Logging and tuning tool

The logging and tuning tool enables the possibility to implement measurements from field trials. The idea behind the logging and tuning tool is to add a correction layer to improve the coverage prediction. Figure D.12 shows how the measurement data has to be formatted in order to have Astrix reading the data. The delimiter for separating columns is the tab.

D.5 Backup

Backup is always a necessity. The files which are important to have backup on are the ones located in the Scenario folder. The default directory for this folder is C:\AstrixFiles\Scenarios. The folder contains the created situations, and all logs regarding coverage prediction.

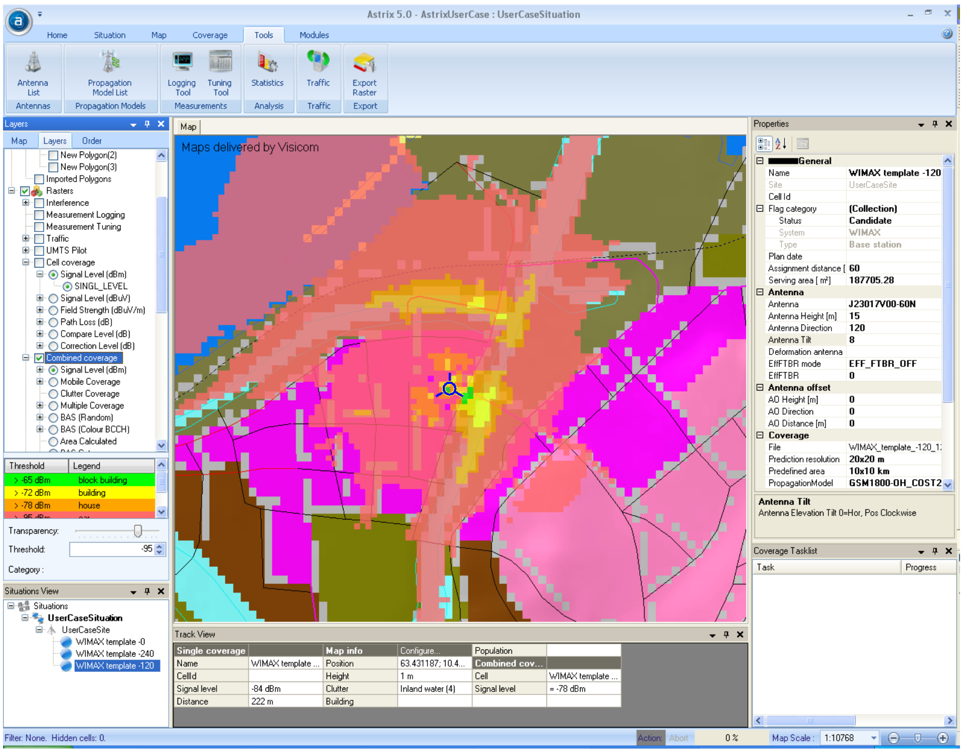
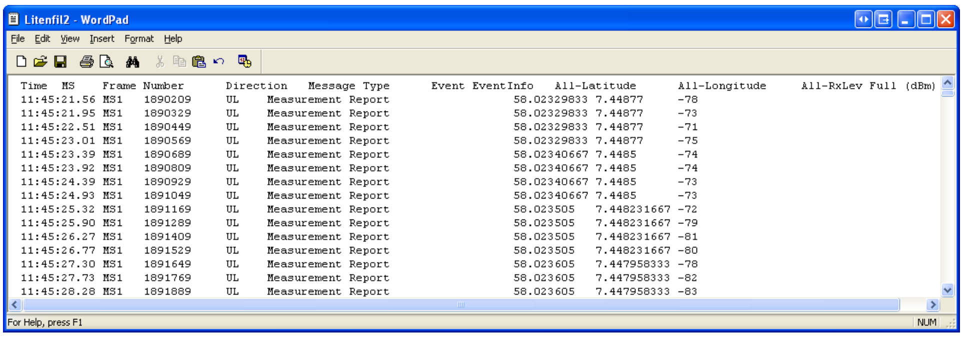


Figure D.11: Combined coverage, and track view



Time	MS	Frame Number	Direction	Message Type	Event	EventInfo	All-Latitude	All-Longitude	All-RxLev Full (dBm)
11:45:21.56	MS1	1890209	UL	Measurement Report			58.02329833	7.44877	-78
11:45:21.95	MS1	1890329	UL	Measurement Report			58.02329833	7.44877	-73
11:45:22.51	MS1	1890449	UL	Measurement Report			58.02329833	7.44877	-71
11:45:23.01	MS1	1890569	UL	Measurement Report			58.02329833	7.44877	-75
11:45:23.39	MS1	1890689	UL	Measurement Report			58.02340667	7.4485	-74
11:45:23.92	MS1	1890809	UL	Measurement Report			58.02340667	7.4485	-74
11:45:24.39	MS1	1890929	UL	Measurement Report			58.02340667	7.4485	-73
11:45:24.93	MS1	1891049	UL	Measurement Report			58.02340667	7.4485	-73
11:45:25.32	MS1	1891169	UL	Measurement Report			58.023505	7.448231667	-72
11:45:25.90	MS1	1891289	UL	Measurement Report			58.023505	7.448231667	-79
11:45:26.27	MS1	1891409	UL	Measurement Report			58.023505	7.448231667	-81
11:45:26.77	MS1	1891529	UL	Measurement Report			58.023505	7.448231667	-80
11:45:27.30	MS1	1891649	UL	Measurement Report			58.023605	7.447958333	-78
11:45:27.73	MS1	1891769	UL	Measurement Report			58.023605	7.447958333	-82
11:45:28.28	MS1	1891889	UL	Measurement Report			58.023605	7.447958333	-83

Figure D.12: Format example of measurement data

E

Site Candidates

The following appendix contains tables of all the possible base station sites found through observations throughout the central parts of Trondheim. A total of 83 possible base station sites have been found throughout the city of Trondheim. The following tables will hopefully be of help for future radio planners. Figure E.1 shows an overview of the possible base station sites observed throughout the pre-defined area. As previously mentioned, Telenor have been instructed to publish a database with the positions of all their base stations and antennas in Norway. The list will probably be made available in the end of 2009.

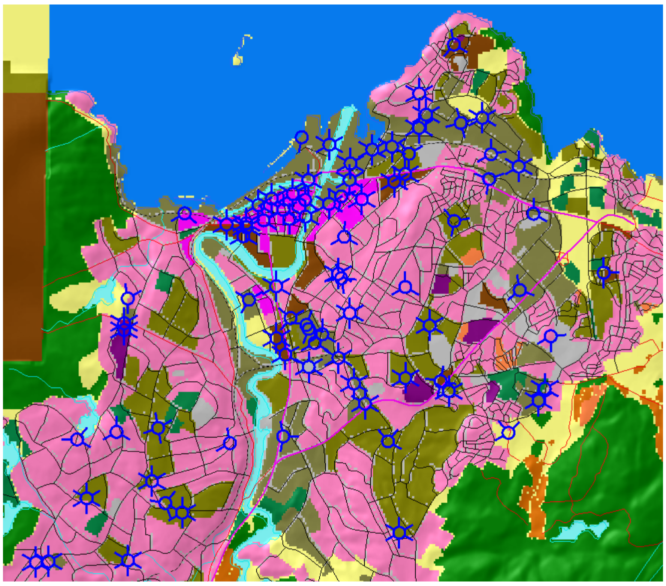


Figure E.1: Overview of the possible base station sites observed in Trondheim

E.1 Midtbyen

Gunnerus Library	
Latitude	63.428991°
Longitude	10.385808°
Height above ground	23m
More	Erling Skakkes gate 47C
Felleskjøpet Kornmottak	
Latitude	63.431912°
Longitude	10.369068°
Height above ground	16m
More	Nedre Ila 58
Mercursenteret	
Latitude	63.431203°
Longitude	10.398902°
Height above ground	22m
More	Kongens Gate 8
Prinsen Hotell	
Latitude	63.431020°
Longitude	10.391578°
Height above ground	21m
More	Beddingen 1
Olavskvartalet	
Latitude	63.433634°
Longitude	10.403415°
Height above ground	18m
More	Kjøpmannsgata 48
Pirsenteret	
Latitude	63.441611°
Longitude	10.402432°
Height above ground	14m
More	Havnegata 9
Sør-Trøndelag Politidistrikt	
Latitude	63.436152°
Longitude	10.404331°
Height above ground	17m
More	Gryta 4

– Continued on next page

Table E.1 – continued from previous page

Hotel Chesterfield	
Latitude	63.434399°
Longitude	10.399889°
Height above ground	18m
More	Søndre gate 26
Prinsens gate 61	
Latitude	63.433793°
Longitude	10.393898°
Height above ground	19m
More	Appartments
Taubåtkompaniet	
Latitude	63.440675°
Longitude	10.410330°
Height above ground	14m
More	Pir II 13A
Kongensgate 60	
Latitude	63.430660°
Longitude	10.386658°
Height above ground	14m
More	Office building
Kongensgate 86	
Latitude	63.430491°
Longitude	10.380997°
Height above ground	13m
More	Apartments
Skatteetaten	
Latitude	63.430134°
Longitude	10.382687°
Height above ground	19m
More	Kongensgate 87
Sandgata 2	
Latitude	63.432973°
Longitude	10.390082°
Height above ground	16m
More	Appartments
Kjøpmannsgata 41	
Latitude	63.431484°
Longitude	10.403523°
Height above ground	9m
More	Gas station

– Continued on next page

Table E.1 – continued from previous page

Nordre Gate 12	
Latitude	63.432369°
Longitude	10.397216°
Height above ground	5
More	Office building

Table E.1: Overview of possible base station sites in Midtbyen

E.2 Møllenberg and Tyholt

Industrial building	
Latitude	63.434069°
Longitude	10.413691°
Height above ground	16m
More	Inherredsveien 7
Tomasskolen	
Latitude	63.428928°
Longitude	10.414566°
Height above ground	3m
More	Festningsgata 2
Singsaker skole	
Latitude	63.423634°
Longitude	10.413706°
Height above ground	14m
More	Jonsvannsveien 2
Tyholttårnet	
Latitude	63.422523°
Longitude	10.431961°
Height above ground	30 - 70m
More	Otto Nielsens vei 4
Persaunet	
Latitude	63.430933°
Longitude	10.445917°
Height above ground	19m
More	Persaunet 4

– Continued on next page

Table E.2 – continued from previous page

NAV	
Latitude	63.436160°
Longitude	10.416091°
Height above ground	14m
More	Bassengbakken 1
Singsaker Studenterhjem	
Latitude	63.424194°
Longitude	10.412805°
Height above ground	8m
More	Roberts gate 1
Innherredsveien 82A	
Latitude	63.436918°
Longitude	10.431924°
Height above ground	11m
More	Appartments at Buran
KBS kjøpesenter	
Latitude	63.436291°
Longitude	10.455877°
Height above ground	14m
More	Owesens gate 29-31
Inherredsveien 8-10	
Latitude	63.433133°
Longitude	10.410231°
Height above ground	15m
More	Shops and appartments
Eberg Idrettsanlegg	
Latitude	63.417601°
Longitude	10.438907°
Height above ground	12m
More	Sigurd Jorsalfars veg 31
Wessels Gate 19	
Latitude	63.433701°
Longitude	10.419566°
Height above ground	21m
More	Apparments at Møllenberg
Berg Skole	
Latitude	63.419191°
Longitude	10.416142°
Height above ground	11m
More	Bergbakken 17

– Continued on next page

Table E.2 – continued from previous page

Frostaveien 11-13	
Latitude	63.435936°
Longitude	10.428833°
Height above ground	14m
More	Appartments

Table E.2: Overview of possible base station sites at Møllenberg and Tyholt

E.3 Øya and NTNU Gløshaugen Campus

St. Olvas Hospital	
Latitude	63.420900°
Longitude	10.387409°
Height above ground	25m
More	Olav Kyrres gate 17
Sentralbygg N	
Latitude	63.417679°
Longitude	10.403785°
Height above ground	28m
More	Alfred Getzvei 1
Sentralbygg S	
Latitude	63.417174°
Longitude	10.404409°
Height above ground	28m
More	Alfred Getzvei 3
Realfagsbygget	
Latitude	63.415385°
Longitude	10.406144°
Height above ground	14m
More	Høgskoleringen 5
Siemensbygget	
Latitude	63.403461°
Longitude	10.397176°
Height above ground	18m
More	Bratsbergvegen 5

– Continued on next page

Table E.3 – continued from previous page

Elektrobygget	
Latitude	63.418562°
Longitude	10.399269°
Height above ground	13m
More	O.S. Bragstads plass 2
Kommunebygget	
Latitude	63.413893°
Longitude	10.397786°
Height above ground	32m
More	Holtermannsveien 1
Lerkendal	
Latitude	63.412327°
Longitude	10.404445 °
Height above ground	15m
More	Klæbuveien 125
Bergbygget	
Latitude	63.416484°
Longitude	10.408309°
Height above ground	12m
More	Høgskoleringen 6
Petter's Pizza	
Latitude	63.413476°
Longitude	10.412901°
Height above ground	3m
More	Dybdahls vei 5
Samfundet	
Latitude	63.422606°
Longitude	10.395127°
Height above ground	13m
More	Elgsetergata 1
Uninett	
Latitude	63.41598°
Longitude	10.395240°
Height above ground	15m
More	Abels gate 5

Table E.3: Overview of possible base station sites at Øya and NTNU Gløshaugen Campus

E.4 Lade

Laugsand Helse- og Velferdssenter	
Latitude	63.439509°
Longitude	10.433048°
Height above ground	15m
More	Thomas Von Westens gate 34
Harry Borthens vei 9	
Latitude	63.453432°
Longitude	10.445831°
Height above ground	26m
More	Apartments
Toyota Material Handling Norway AS	
Latitude	63.439467°
Longitude	10.456408°
Height above ground	11m
More	Haakon VIIs gate 23c
Kjeldsberg	
Latitude	63.438274°
Longitude	10.416343°
Height above ground	9m
More	Beddingen 8
Jarleveien 1	
Latitude	63.444482°
Longitude	10.437918°
Height above ground	11m
More	Appartments at Lade
City Lade kjøpesenter	
Latitude	63.443435°
Longitude	10.447791°
Height above ground	12m
More	Haakon VII's gate 9
Dorahallen	
Latitude	63.440046°
Longitude	10.422522°
Height above ground	13m
More	Maskinist gata 1

– Continued on next page

Table E.4 – continued from previous page

Ladeveien 11	
Latitude	63.442807°
Longitude	10.435886°
Height above ground	13m
More	Industrial building
Lade Skole	
Latitude	63.447170°
Longitude	10.435931°
Height above ground	8m
More	Ladehammerveien 45
Ringnes E.C. Dahls Bryggeri	
Latitude	63.440424°
Longitude	10.428170°
Height above ground	16m
More	Brewery
Haakon VII's gate 4	
Latitude	63.444080°
Longitude	10.453944°
Height above ground	17m
More	Sports center
Haakon VII's gate 27B	
Latitude	63.437878°
Longitude	10.464315°
Height above ground	12m
More	Industrial building

Table E.4: Overview of possible base station sites at Lade

E.5 Charlottenlund and Steinan

Landbrukssenteret Tunga	
Latitude	63.422122°
Longitude	10.464610°
Height above ground	18m
More	Bromstadveien 57

– Continued on next page

Table E.5 – continued from previous page

Travbaneveien 4	
Latitude	63.431860°
Longitude	10.468533°
Height above ground	12m
More	Communication mast
Midtre Tunhøgda 2	
Latitude	63.424343°
Longitude	10.488540°
Height above ground	11m
More	Apartments
Granåsen Gård	
Latitude	63.416244°
Longitude	10.473457°
Height above ground	12m
More	Communication mast
Loholt Søndre	
Latitude	63.403914°
Longitude	10.461388°
Height above ground	4m
More	Kleiaveien 2
Brøsetveien 186B	
Latitude	63.410501°
Longitude	10.442047°
Height above ground	19m
More	
Nardosenteret	
Latitude	63.402831°
Longitude	10.427031°
Height above ground	7m
More	Hans Baucks vei 1
Moholt student home	
Latitude	63.410906°
Longitude	10.431991°
Height above ground	11m
More	Moholt alle
Dragvoll	
Latitude	63.408023°
Longitude	10.469990°
Height above ground	14m
More	Universitetssenteret Dragvoll

– Continued on next page

Table E.5 – continued from previous page

Loholt alle 90	
Latitude	63.409553°
Longitude	10.471740°
Height above ground	6m
More	TEV Dragvoll
Risvollan Senter	
Latitude	63.391172°
Longitude	10.430259°
Height above ground	4m
More	Ingeborg Aas veg 2
Nardoveien 16B	
Latitude	63.407639°
Longitude	10.420482°
Height above ground	12m
More	Office building
Nardoveien 6	
Latitude	63.410209°
Longitude	10.417344°
Height above ground	14
More	Sector Alarm
Coop Mega	
Latitude	63.409225°
Longitude	10.444379°
Height above ground	14m
More	Vegamot 4

Table E.5: Overview of possible base station sites at Charlottenlund and Steinan

E.6 Byåsen

Hoem Gård	
Latitude	63.402598°
Longitude	10.381958°
Height above ground	2m
More	Hoemshøgda 2

– Continued on next page

Table E.6 – continued from previous page

Byåsen vgs	
Latitude	63.394986°
Longitude	10.364138°
Height above ground	12m
More	Selsbakkvegen 34
Telenor Storhaugen	
Latitude	63.404028°
Longitude	10.349630°
Height above ground	12m
More	(behind) Freidigstien 14
NetCom Kyvatnet	
Latitude	63.403065°
Longitude	10.338412°
Height above ground	12m
More	Kyvannsvegen 12
Havsteinekra Helse- og Velferdssenter	
Latitude	63.404532°
Longitude	10.361500°
Height above ground	12m
More	Havsteinekra 9
Sverresborg alle 13	
Latitude	63.421050°
Longitude	10.356535°
Height above ground	6m
More	Sverresborg Museum
Sportshuset Byåsen	
Latitude	63.387371°
Longitude	10.326647°
Height above ground	6m
More	Nils Uhlin Hansens veg 14
Åsheim Barneskole	
Latitude	63.350484°
Longitude	10.342992°
Height above ground	5m
More	Myrstadveien 1
Dalgård Skole	
Latitude	63.395549°
Longitude	10.341124°
Height above ground	4m
More	Dalgårdstien 7

– Continued on next page

Table E.6 – continued from previous page

Stavsetsenter	
Latitude	63.387495°
Longitude	10.330214°
Height above ground	5m
More	Enromveien 1
Munkvoll Stasjon	
Latitude	63.397737°
Longitude	10.359748°
Height above ground	2m
More	Skjermveien 89
Bunnpris Rydningen	
Latitude	63.387641°
Longitude	10.352910°
Height above ground	4m
More	Rydningen 1
Selsbakkvegen 1	
Latitude	63.393713°
Longitude	10.368350°
Height above ground	14m
More	Appartments
Byåsen Butikksenter	
Latitude	63.417893°
Longitude	10.351786°
Height above ground	6m
More	Fjellseterveien 1
Gamle Osloveien 2c	
Latitude	63.417027°
Longitude	10.352850°
Height above ground	12m
More	Apartments

Table E.6: Overview of possible base station sites at Byåsen

F

Site-Coverage

The pre-planning stage is set to be the recommended base station sites prior to testing. The recommended sites and sectors are thus the ones that seems like the most effective sites before measurements are performed, and the correction layer added.

F.1 Midtbyen

Gunnerus Library

The Gunnerus library is a scientific library, and is the most dominant building within its area. The building has already fiber to the roof, and is providing radio link to one of the Wireless Trondheim Wi-Fi hotspots. The building has been used for WiMAX testing in [18, 19, 31, 34], and is one of the recommended sites for covering the tram line, see [18, 19]. Figure F.1 shows the coverage map when selecting three sectors according to table F.1.

Gunnerus Library		
Sector	*Azimuth*	*Tilt*
1	0°	4°
2	120°	4°
3	240°	0°

Table F.1: Recommended sectors from Gunnerus Library

Felleskjøpet Kornmottak

Felleskjøpet Kornmottak is a grain silo located in the suburban area of Trondheim, see figure F.2. The building is dominant in the area, and is already

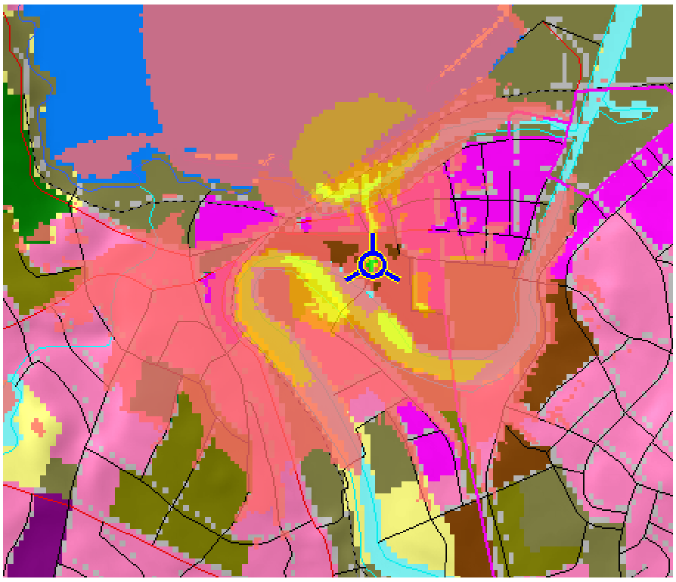


Figure F.1: Coverage from site: Gunnerus Library

an existing base station for mobile telephony. Co-locating the equipment with other operators should thus be possible. Table F.2 lists up the recommended sectors for this site. Providing backhaul to the site can either be done through fiber or radio link from the Gunnerus library.

Felleskjøpet Kornmottak		
Sectors	*Azimuth*	*Tilt*
1	130°	1°
2	240°	2°

Table F.2: Recommended sectors from Felleskjøpet Kornmottak

Prinsen Hotell

Prinsen Hotel is an hotel situated in the city center, along the E6. The building is dominant in its are, and is already used for communication services, thus co-locating the equipment is possible. Since the building is along the E6, fiber and backhaul is accessible. Figure F.3 shows the coverage diagram of the sectors given in table F.3.

Mercursenteret

Mercursenteret is a shopping center situated in the heart of the most dense area in Trondheim. The building has an antenna mast on the top, making it ideal for Mobile WiMAX. Co-locating the equipment is possible, as well as

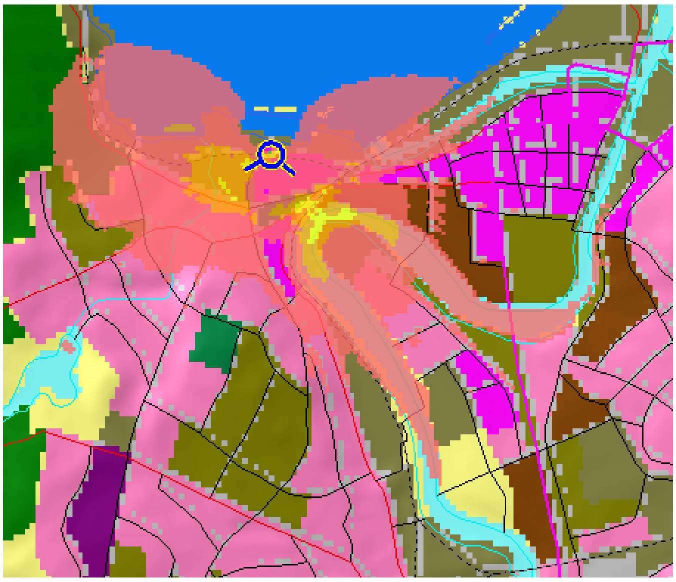


Figure F.2: Coverage from site: Felleskjøpet Kornmottak

Figure F.3: Coverage from site: Prinsen Hotell

Prinsen Hotell		
Sector	*Azimuth*	*Tilt*
1	60°	6°
2	125°	6°
3	350°	6°

Table F.3: Recommended sectors from Prinsen Hotell backhaul access with an existing Wireless Trondheim radio link. Figure F.4 shows the coverage from this site with the recommendations in table F.4.

Figure F.4: Coverage from site: Mercursenteret

Mercursenteret		
Sector	*Azimuth*	*Tilt*
1	0°	6°
2	95°	6°
3	180°	6°

Table F.4: Recommended sectors from Mercursenteret

Olavskvartalet

Olavskvartalet is a shopping center, concert hall and hotel. The building is the most dominant building in the area, and is situated close to the Nidelven, see figure F.5. Backhaul through fiber is already provided to the site. The building is already an existing base station for mobile telephony, thus the elementary power components should be available through co-locating the equipment with existing operators. Table F.5 lists up the recommended sectors for this site.

Pirsenteret

Pirsenteret houses many companies and the Norwegian school of management, BI. The building is, as can be seen from figure F.6, situated at the

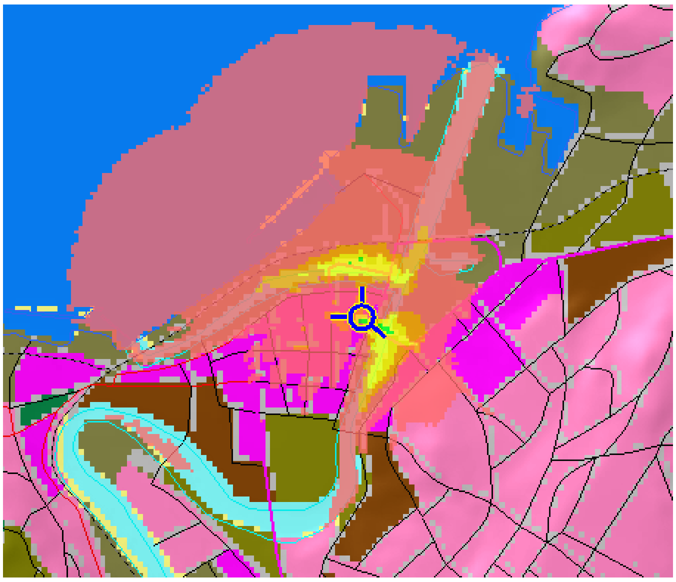


Figure F.5: Coverage from site: Olavskvartalet

Olavskvartalet		
Sector	*Azimuth*	*Tilt*
1	0°	6°
2	130°	6°
3	270°	6°

Table F.5: Recommended sectors from Olavskvartalet harbour. Table F.6 shows the recommended sector from this site. Backhaul is expected to be provided through fiber or a radio link.

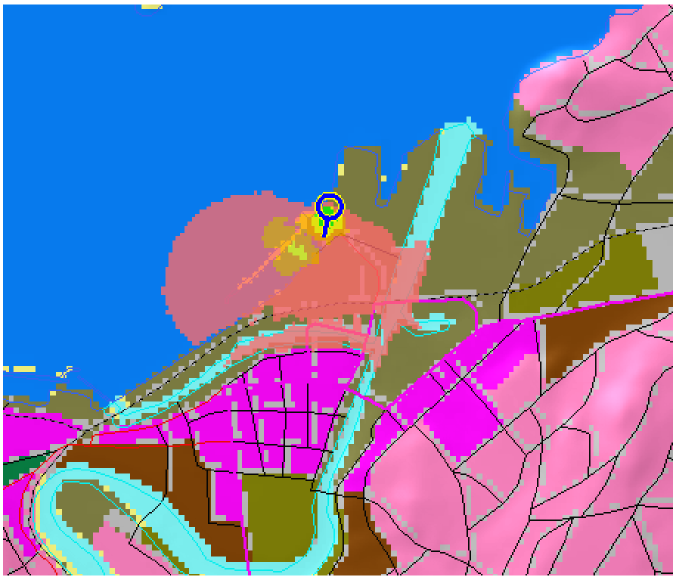


Figure F.6: Coverage from site: Pirsenteret

Pirsenteret		
Sector	*Azimuth*	*Tilt*
1	190°	8°

Table F.6: Recommended sectors from Pirsenteret

F.2 Møllenberg and Tyholt

Industrial Building

The industrial building is situated close to Solsiden, and is already connected to fiber backhaul. The building has been chosen due to availability rather than environmental dominance. Figure F.7 shows the coverage from the sectors recommended in table F.7.

Tomasskolen

Tomasskolen is a Christian school situated at the top of Møllenberg. The location for placing the antennas is a small shed with existing communication antennas, where co-locating with existing operators should be possible. Although the building itself is not very high, the immediate surroundings are parks and open areas. Getting backhaul to the location however is probably

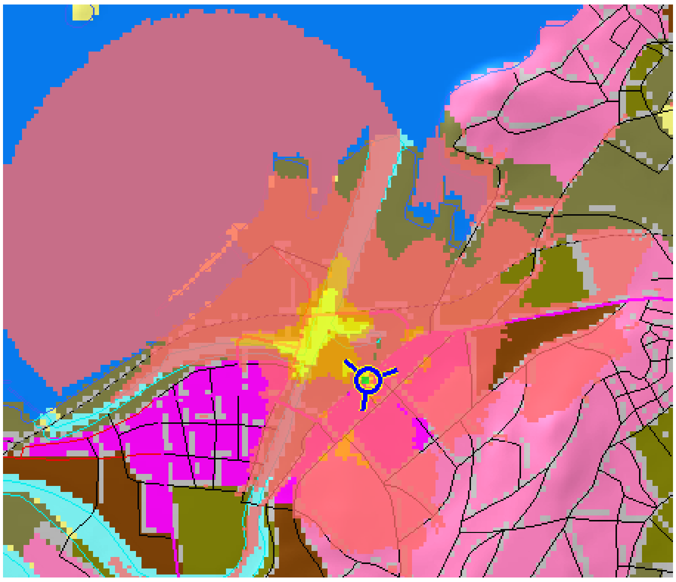


Figure F.7: Coverage from site: Industrial Building

Industrial Building		
Sector	*Azimuth*	*Tilt*
1	70°	0°
2	190°	0°
3	300°	4°

Table F.7: Recommended sectors from Industrial Building the main challenge of choosing this site. Furthermore, figure F.8 shows the coverage from the site with the recommended sectors provided in table F.8. The antenna height of sector 1 is set to five (5) meters, since the antennas has to be set up at the rooftop to provide coverage to the lower part of Møllenberg.

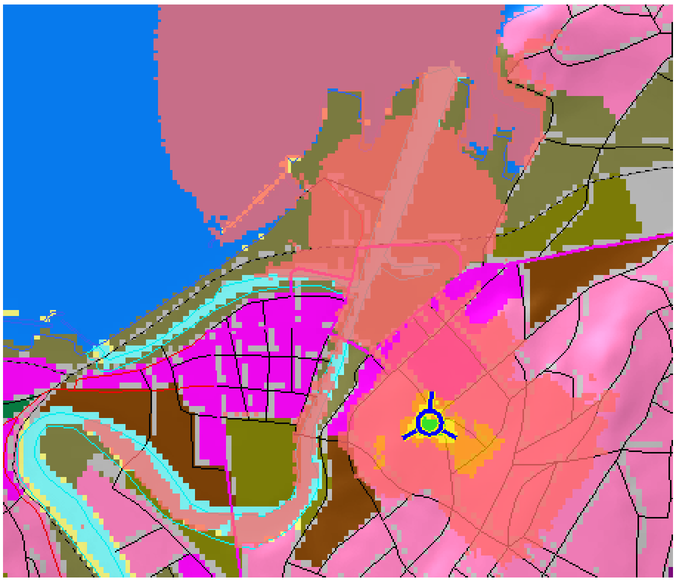


Figure F.8: Coverage from site: Tomasskolen

Tomasskolen		
Sector	*Azimuth*	*Tilt*
1	3°	2°
2	120°	-2°
3	240°	0°

Table F.8: Recommended sectors from Tomasskolen

Singsaker Skole

Singsaker Skole is a primary school situated in a populated area. The school is an existing base station for mobile communication, thus co-locating the equipment should be possible. Figure F.9 shows the coverage with the recommended sectors given in table F.9. Fiber is already available at Singsaker Studenterhjem, thus backhaul should be accessible.

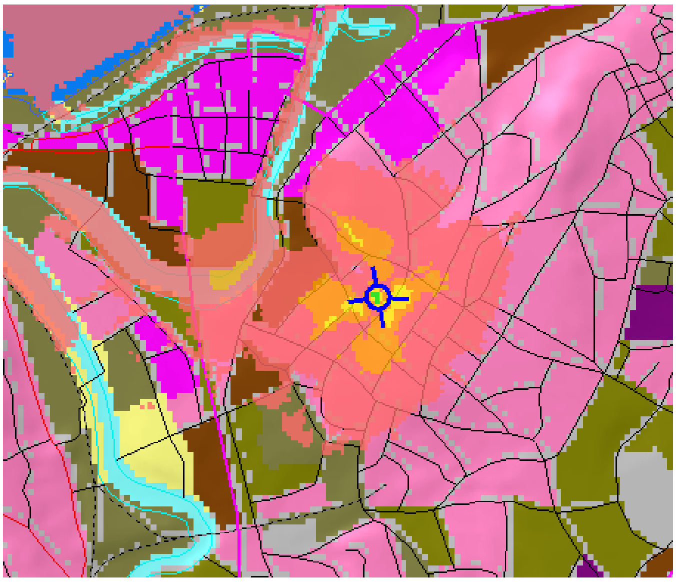


Figure F.9: Coverage from site: Singsaker Skole

Singsaker		
Sector	*Azimuth*	*Tilt*
1	95°	0°
2	170°	0°
3	260°	6°
4	340°	1°

Table F.9: Recommended sectors from Singsaker Skole

Tyholttårnet

Tyholttårnet is a communication tower situated at the top of Trondheim. The height of the tower makes it ideal for making a large footprint. As a consequence, capacity constraints has to be taken in consideration. The tower has other communication equipment, thus co-location is possible. Figure F.10 shows the predicted coverage with the recommended sectors from table F.10. Backhaul is expected to be provided through a radio link from NTNU Gløshaugen Campus.

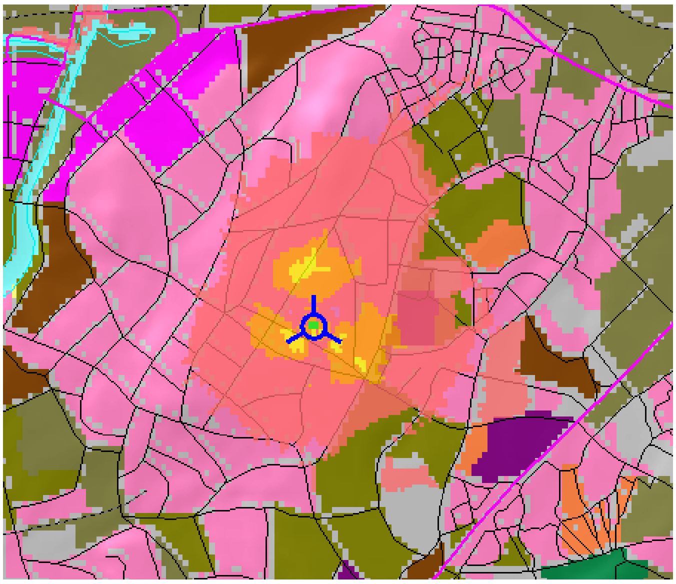


Figure F.10: Coverage from site: Tyholttårnet

Tyholttårnet		
Sector	*Azimuth*	*Tilt*
1	0°	6°
2	120°	6°
3	240°	6°

Table F.10: Recommended sectors from Tyholttårnet

Persaunet

Persaunet is an old military camp which has been converted to a residential area. In the center of this area, rises an old tower with many antennas attached. The tower is dominant in the area, and is a possible base station site for Mobile WiMAX. Figure F.11 shows the predicted coverage with the sectors recommended in table F.11. Co-location at the site should be possible. Backhaul however, is a problem which has to be addressed.

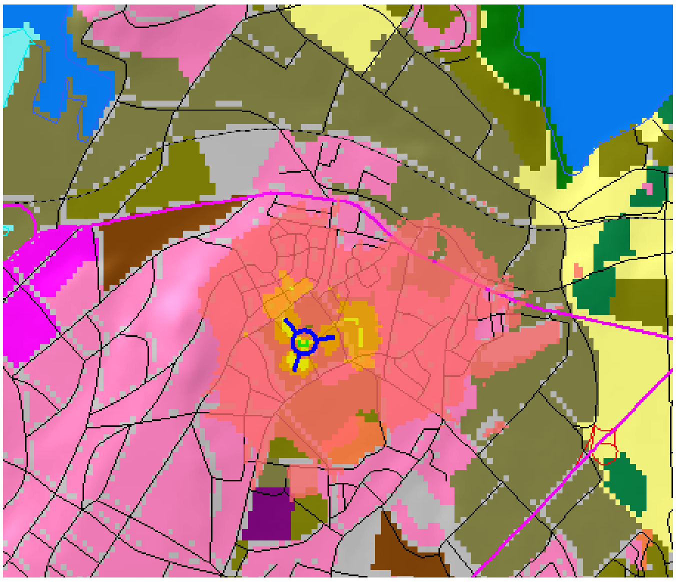


Figure F.11: Coverage from site: Persaunet

Persaunet		
Sector	*Azimuth*	*Tilt*
1	80°	6°
2	190°	4°
3	320°	6°

Table F.11: Recommended sectors from Persaunet

F.3 Øya and NTNU Gløshaugen Campus

St. Olavs Hospital

St. Olavs Hospital is a hospital situated at Øya. One of the main buildings is, as of today, used as a base station for mobile communications. The building is the most dominant in its area, thus well suited as a Mobile WiMAX site. Figure F.12 shows the predicted coverage with the recommended sectors given in table F.12. Co-location, and backhaul, at St. Olavs Hospital is expected to be available.

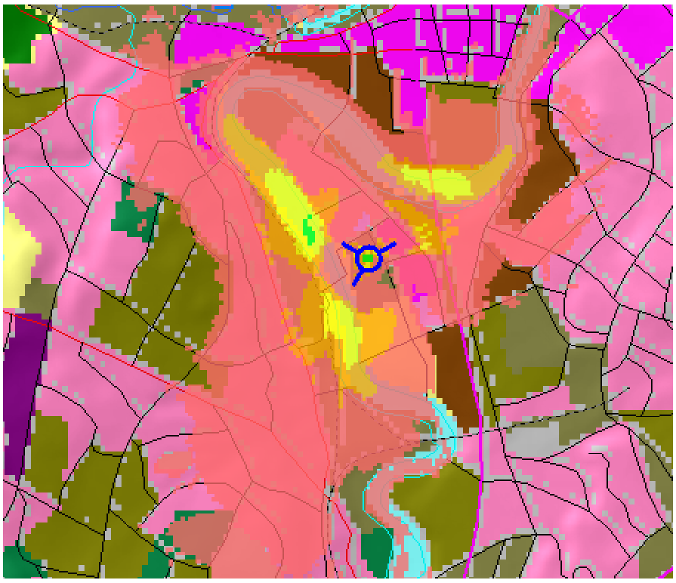


Figure F.12: Coverage from site:

St. Olav Hospital		
Sector	*Azimuth*	*Tilt*
1	60°	4°
2	210°	1°
3	300°	2°

Table F.12: Recommended sectors from St. Olav Hospital

Sentralbygg N and S

The buildings Sentralbygg N and Sentralbygg S are the two most dominant buildings in the center of NTNU Gløshaugen campus. The buildings are situated close by each other, thus only two sectors have been planned from each site. Backhaul is available all over the campus, thus should not be a problem. The Gløshaugen campus is assumed to be capacity limited, thus further base station sites have to be planned although the two buildings is providing sufficient coverage, see figure F.13. Recommended sectors are given in table F.13 and F.14, respectively being Sentralbygg N and Sentralbygg S.

Figure F.13: Coverage from site: Sentralbygg N and Sentralbygg S

Sentralbygg N		
Sector	*Azimuth*	*Tilt*
1	20°	8°
2	280°	8°

Table F.13: Recommended sectors from Sentralbygg N

Sentralbygg S		
Sector	*Azimuth*	*Tilt*
1	100°	8°
2	200°	8°

Table F.14: Recommended sectors from Sentralbygg S

Realfagsbygget

Realfagsbygget is a part of NTNU Gløshaugen campus. Having a base station site here would provide coverage to the campus, and the area in the direction of Tyholt and Lerkendal. Figure F.14 shows the predicted coverage with sectors according to table F.15. The site is already hosting several communication antennas, thus co-location should be possible. Backhaul through fiber is already provided to Realfagsbygget.

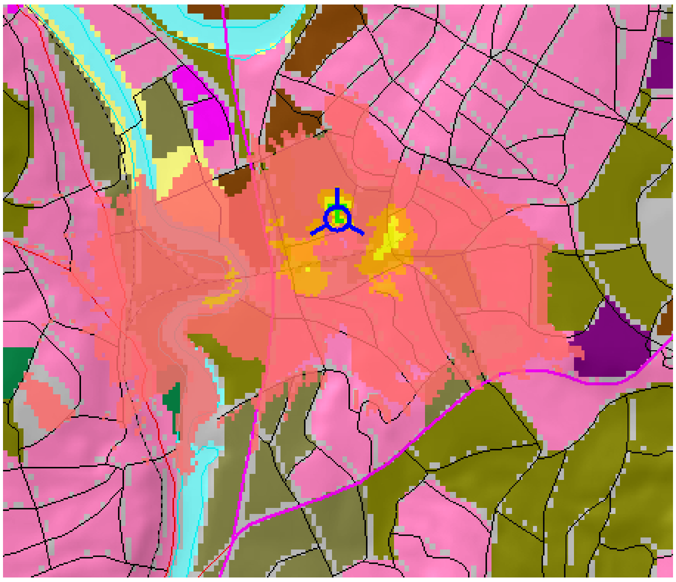


Figure F.14: Coverage from site: Realfagsbygget

Realfagsbygget		
Sector	*Azimuth*	*Tilt*
1	0°	6°
2	120°	0°
3	240°	4°

Table F.15: Recommended sectors from Realfagsbygget

Siemens

The Siemens building is the most dominant building in the area of Tempe. It is already hosting several communication antennas. Co-locating the Mobile WiMAX at the Siemens building should thus be possible. Figure F.15 shows the coverage from this site with the recommended sectors given in table F.16. Backhaul is expected to be available since the site is located nearby the E6.

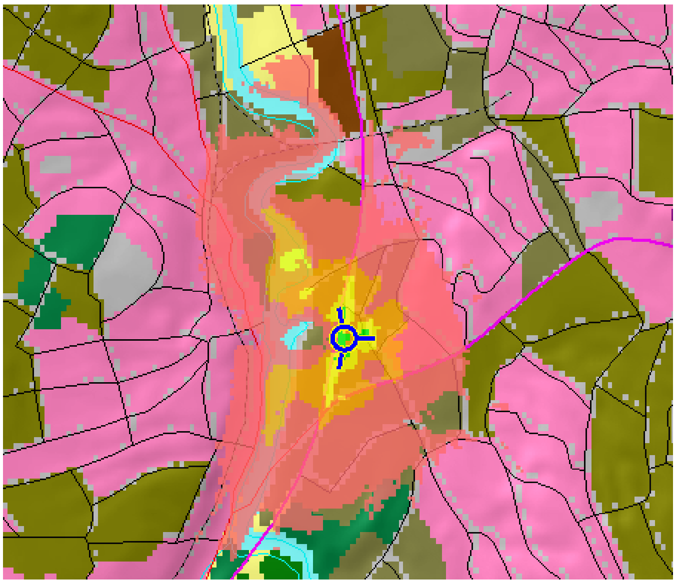


Figure F.15: Coverage from site: Siemens

Siemens		
Sector	*Azimuth*	*Tilt*
1	80°	2°
2	190°	6°
3	350°	6°

Table F.16: Recommended sectors from Siemens

Elektrobygget

Elektrobygget is the building situated in the north-west of NTNU Gløshaugen. Located in the outer part of the campus, Elektrobygget will provide good coverage to the campus, and the are below. Furthermore, backhaul is expected to be available through fiber. Figure F.16 shows the predicted coverage with the recommended sectors given in table F.17.

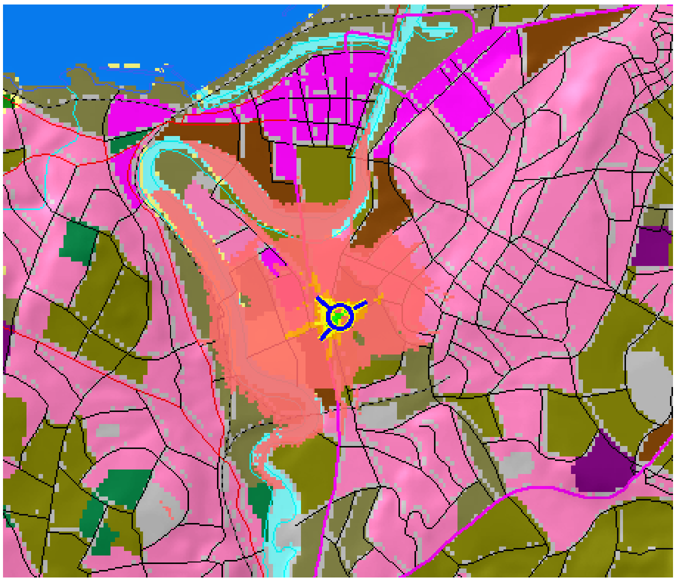


Figure F.16: Coverage from site: Elektrobygget

Elektrobygget		
Sector	*Azimuth*	*Tilt*
1	60°	6°
2	220°	8°
3	310°	8°

Table F.17: Recommended sectors from Elektrobygget

F.4 Byåsen

Hoem Gård

Hoem Gård is a farm in which one of the barns is used for hosting communication equipments. The barn is situated along the tram line, and is one of the recommended base station sites from [19, 18]. Co-locating the equipment should be possible with a radio link from Byåsen Vgs to provide backhaul, [18]. Figure F.17 show the predicted coverage from Hoem Gård. Recommended sectors are listed in table F.18.

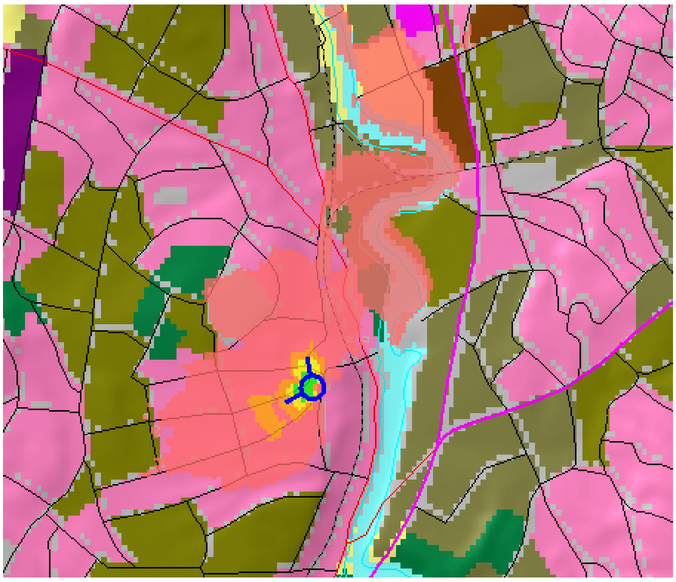


Figure F.17: Coverage from site: Hoem Gård

Hoem Gård		
Sector	*Azimuth*	*Tilt*
1	350°	0°
2	240°	-4°

Table F.18: Recommended sectors from Hoem Gård

Byåsen Vgs

Byåsen Vgs is an upper secondary school. The school has been used for testing in [19, 18], and has been recommended as a base station site for coverage of the tram line. The school has fiber, but 48 VDC and power backup is necessary to make the site a base station, [19]. Figure F.18 shows the predicted coverage with the sectors recommended in table F.19.

Telenor Storhaug

Telenor Storhaug is communication mast located in the suburban area of Storhaug. Although the mast is owned by Telenor, [19], co-location at this site should be possible. The site is recommended as a base station in [19, 18]. Figure F.19 shows the predicted coverage with the recommended sites given

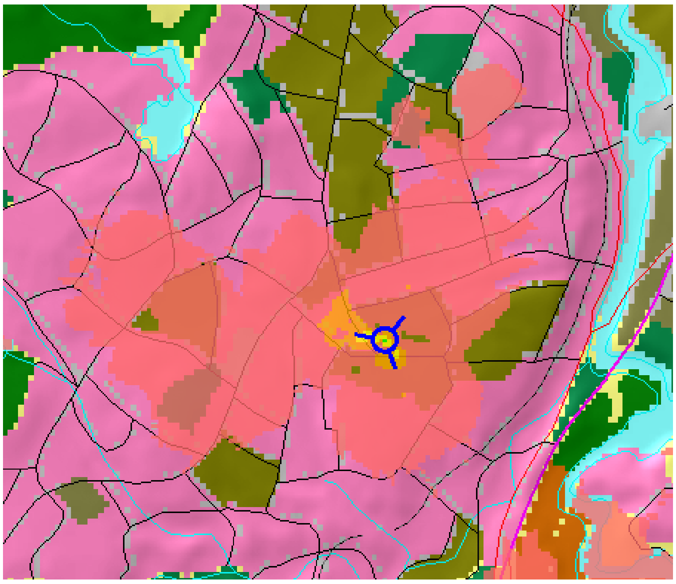


Figure F.18: Coverage from site: Byåsen Vgs

Byåsen Vgs		
Sector	*Azimuth*	*Tilt*
1	40°	0°
2	160°	4°
3	280°	0°

Table F.19: Recommended sectors from Byåsen Vgs in table F.20. Backhaul is expected to be provided through a radio link from Byåsen vgs.

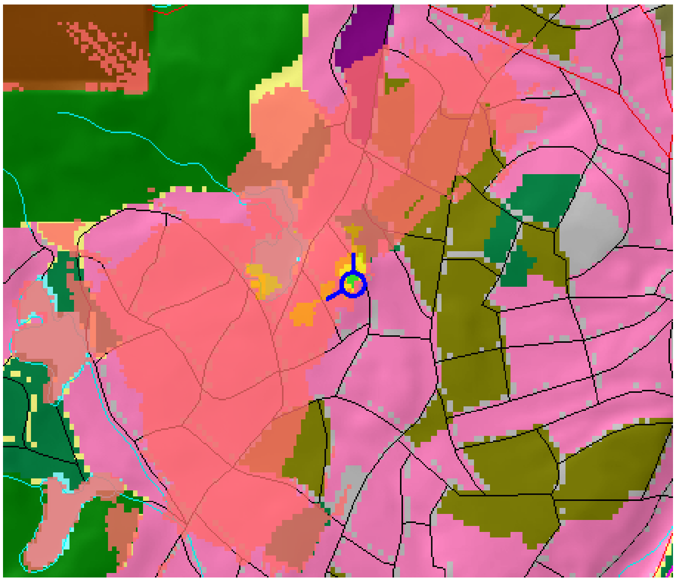


Figure F.19: Coverage from site: Telenor Storhaug

Telenor Storhaug		
Sector	*Azimuth*	*Tilt*
1	0°	8°
2	240°	4°

Table F.20: Recommended sectors from Telenor Storhaug

NetCom Kyvatn

NetCom Kyvatn is a communication mast located close to Kyvatn in an open terrain. The site has been recommended as a possible substitute to Telenor Storhaug for coverage of the upper part of the tram line. A possible problem with choosing NetCom Kyvatn as a base station is the access of backhaul. A radio link to NetCom Kyvatn seems challenging, and is a problem which has to be considered. Figure F.20 shows the predicted coverage from NetCom Kyvatn with the recommended sectors given in table F.21.

Havsteinekra

Havsteinekra is a health center at Havstein. The center is already an existing base station for mobile communication, thus power and backup should be available through co-location. Figure F.21 shows the predicted coverage with

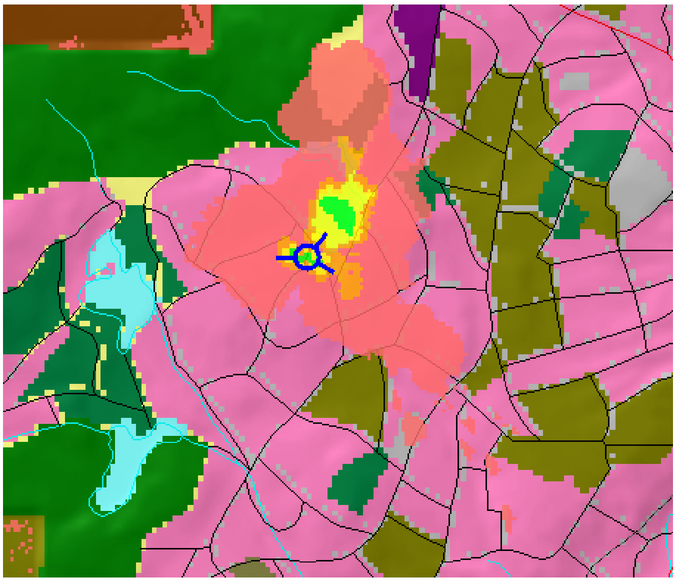


Figure F.20: Coverage from site: NetCom Kyvatn

NetCom Kyvatn		
Sector	*Azimuth*	*Tilt*
1	40°	2°
2	120°	4°
3	270°	4°

Table F.21: Recommended sectors from NetCom Kyvatn the recommended sectors given in table F.22. Backhaul should be possible through radio link at Havsteinekra.

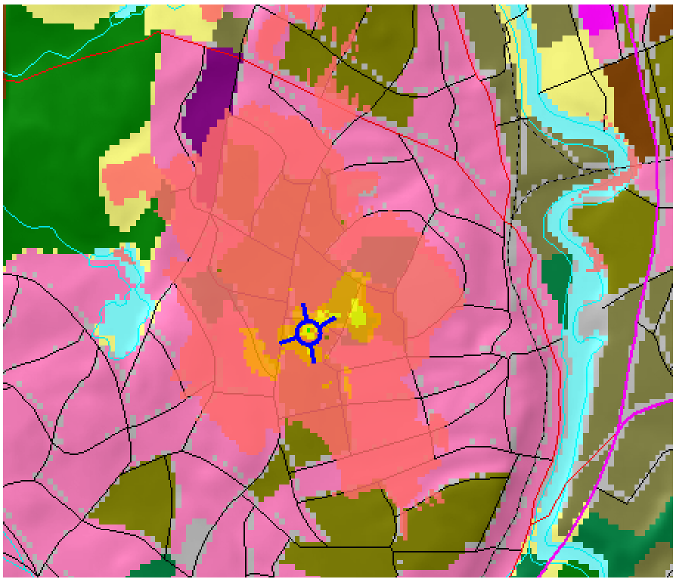


Figure F.21: Coverage from site: Havsteinekra

Havsteinekra Helse- og Velferdssenter		
Sector	*Azimuth*	*Tilt*
1	60°	4°
2	170°	4°
3	250°	0°
4	350°	2°

Table F.22: Recommended sectors from Havsteinekra

Sverresborg alle 13

Sverresborg alle 13 is a museum located at the top of Sverresborg. The area is mainly residential, but with some open landscape and forests. Sverresborg alle 13 is already contributing to mobile telephony coverage, and is thus well suited to work as a base station site for Mobile WiMAX. Figure F.22 shows the predicted coverage with the recommended sectors given in table F.23.

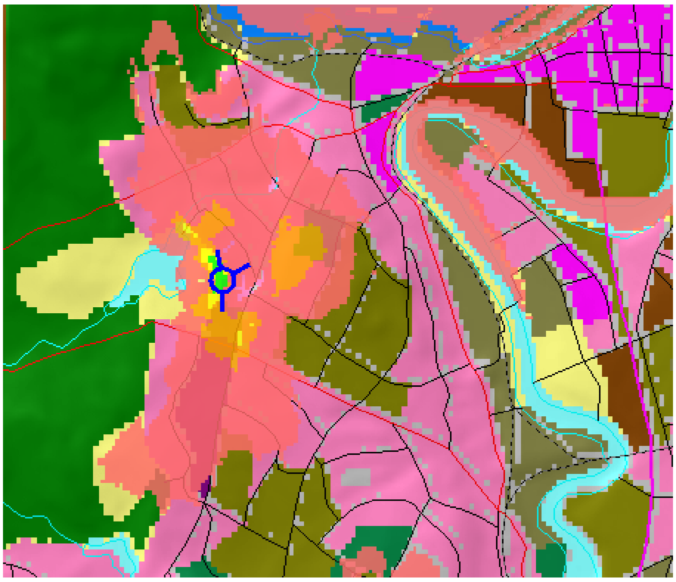


Figure F.22: Coverage from site: Sverresborg alle 13

Sverresborg alle 13		
Sector	*Azimuth*	*Tilt*
1	60°	2°
2	180°	2°
3	350°	6°

Table F.23: Recommended sectors from Sverresborg alle 13

F.5 Lade

Laugesand Helse- og Velferdssenter

Laugesand Helse- og Velferdssenter is a health center situated in a suburban area. The center is dominant in its area, and is an existing site for communication equipment. Backhaul to the center should be possible through fiber. Figure F.23 shows the predicted coverage with the recommended sectors given in table F.24.

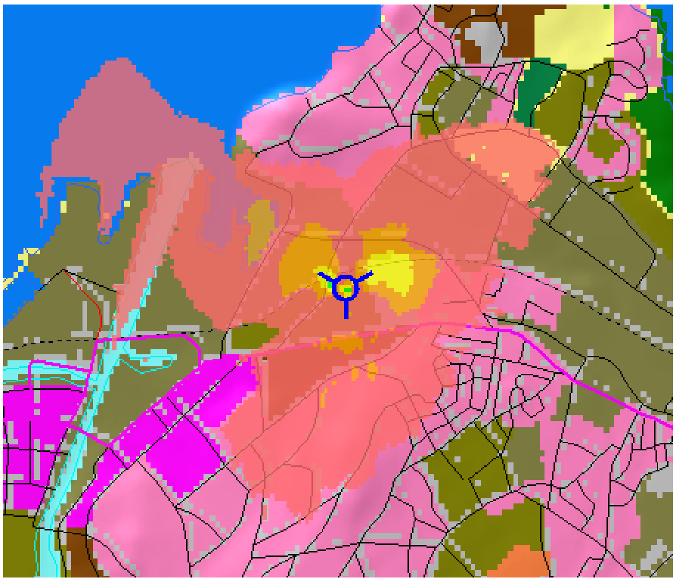


Figure F.23: Coverage from site: Laugesand Helse- og Velferdssenter

Laugesand Helse- og Velferdssenter		
Sector	*Azimuth*	*Tilt*
1	60°	4°
2	180°	0°
3	300°	6°

Table F.24: Recommended sectors from Laugesand Helse- og Velferdssenter

Harry Borhens vei 9

Harry Borhens vei 9 is a dominant building located in the northern part of Lade. The building hosts several communication antennas. Table F.25 lists up the recommended sectors from the site. It can be seen in figure F.24 that the building will provide coverage to the main part of Lade. Co-location should be possible at this site, a radio link from Olavskvartalet have to be considered for backhaul.

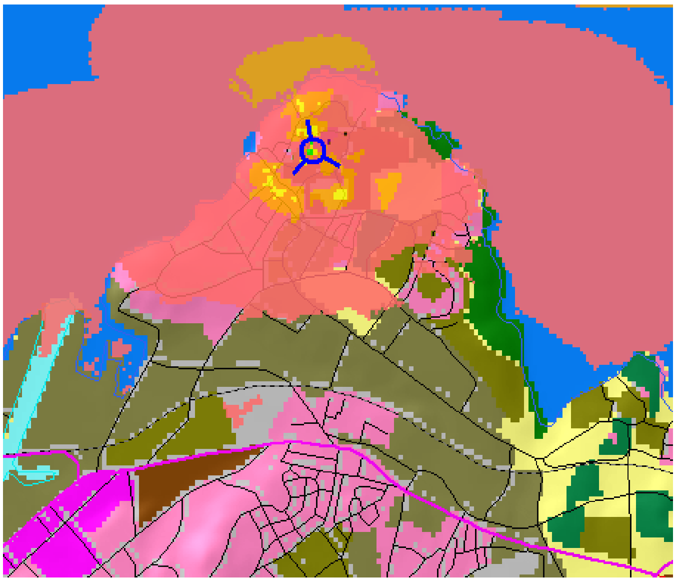


Figure F.24: Coverage from site: Harry Borhens vei 9

Harry Borhens vei 9		
Sector	*Azimuth*	*Tilt*
1	120°	6°
2	220°	4°
3	350°	10°

Table F.25: Recommended sectors from Harry Borhens vei 9

Toyota Material Handling Norway AS

Toyota Material Handling Norway AS is an department store situated in the industrial part of Lade. The building is an existing base station for mobile communication, thus co-location should be possible. Figure F.25 shows the coverage provided from the site with the recommended sectors listed in table F.26. Backhaul is expected to be available through fiber.

F.6 Charlottenlund and Steinan

Felleskjøpet Tunga

Felleskjøpet Tunga is a storehouse situated in the outskirt of Trondheim city in a suburban area. The building is dominant in its area, and is an existing

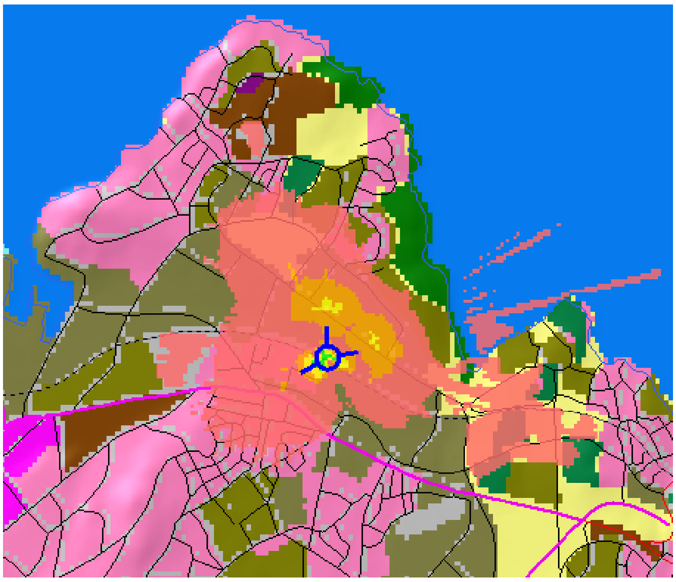


Figure F.25: Coverage from site: Toyota Material Handling Norway AS

Toyota Material Handling AS		
Sector	*Azimuth*	*Tilt*
1	0°	0°
2	80°	0°
3	240°	4°

Table F.26: Recommended sectors from Toyota Material Handling AS base station for communication equipment. Co-locating the Mobile WiMAX equipment should thus be possible. Since the building is located close to Omkjøringsveien, backhaul is expected to be available through fiber. Figure F.26 shows the predicted coverage with the recommended sectors given in table F.27.

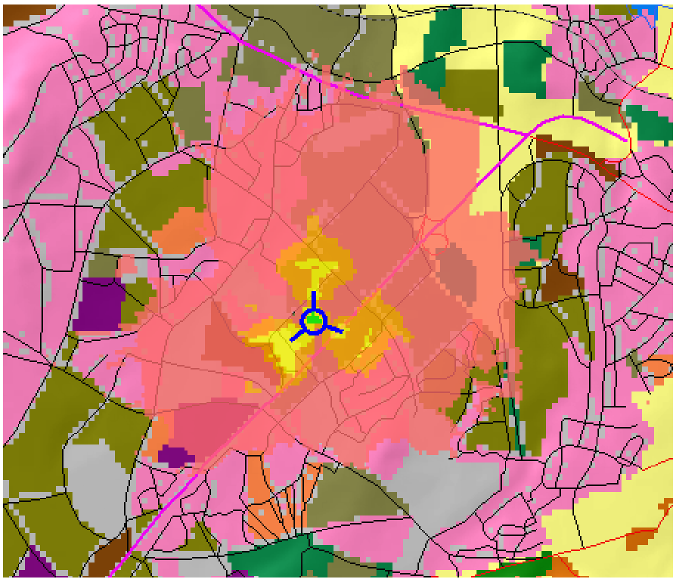


Figure F.26: Coverage from site: Felleskjøpet Tunga

Felleskjøpet Tunga		
Sector	*Azimuth*	*Tilt*
1	110°	1°
2	230°	4°
3	350°	6°

Table F.27: Recommended sectors from Felleskjøpet Tunga

Travbaneveien 4

Travbaneveien 4 is a communication mast providing coverage to the industrial area of Lade and Leangen. The site does already have power and backup available. Furthermore, backhaul is expected to be accessible. Figure F.27 shows the predicted coverage from Travbaneveien 4 with the sectors recommended in F.28.

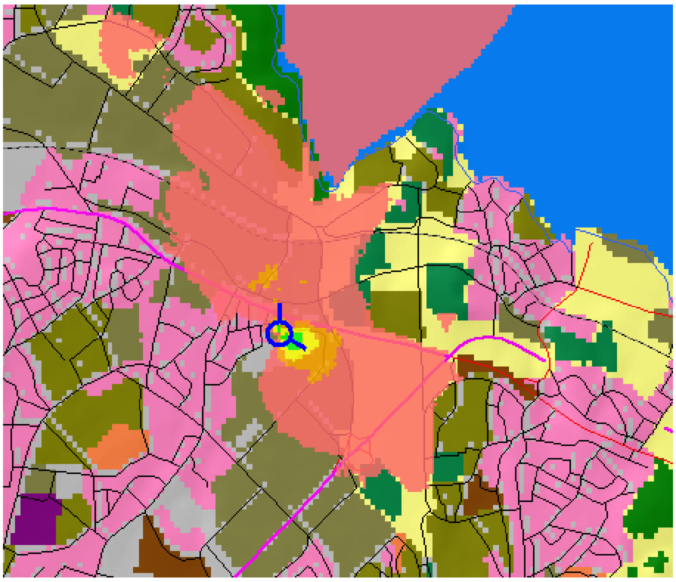


Figure F.27: Coverage from site: Travbaneveien 4

Travbaneveien		
Sector	*Azimuth*	*Tilt*
1	°0	0°
2	°120	4°

Table F.28: Recommended sectors from Travbaneveien 4

Midtre Tunhøgda 2

Midtre Tunhøgda is an apartment building located at Charlottenlund. The site is already providing mobile telephony to the area. Hence power is expected to be available at the site. Backhaul on the other hand, is assumed to be provided through fiber or radio link from Felleskjøpet Tunga. Figure F.28 shows the coverage from Midtre Tunhøgda 2 with the recommended sectors given in table F.29.

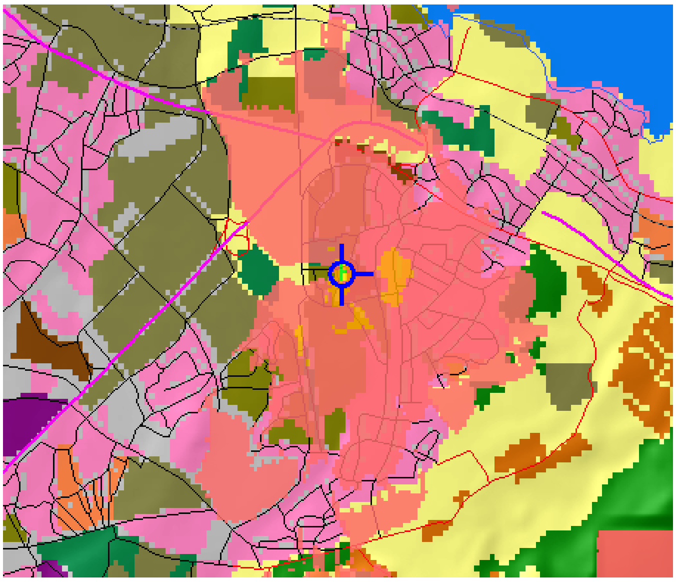


Figure F.28: Coverage from site: Midtre Tunhøgda 2

Midtre Tunhøgda 2		
Sector	*Azimuth*	*Tilt*
1	0°	0°
2	90°	0°
3	180°	0°

Table F.29: Recommended sectors from Midtre Tunhøgda 2

Granåsen Gård

Granåsen Gård is a farm located at the top of a hill. The site has a communication mast to provide coverage throughout the surrounding suburban residential areas. Figure F.29 shows the predicted coverage with the recommended sectors given in F.30. Backhaul is expected to be available through radio link, whereas power through co-location.

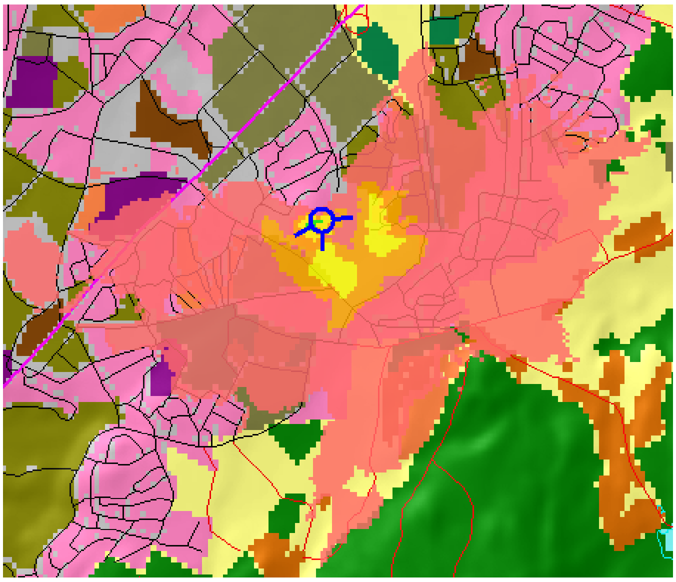


Figure F.29: Coverage from site: Granåsen Gård

Granåsen Gård		
Sector	*Azimuth*	*Tilt*
1	85°	4°
2	180°	2°
3	240°	0°

Table F.30: Recommended sectors from Granåsen Gård

Loholt Sør

Loholt Sør is a farm where one of the barns is equipped with communication equipment. The farm is located at the top of a hill, looking down at the surrounding suburban areas. Backhaul to the farm is expected to be provided through fiber from Dragvoll. Table F.31 shows that the site has been planned with three sectors. One to provide coverage in the direction of Dragvoll, and the other sectors in the directions of Steinan and Moholt respectively. Figure F.30 shows the predicted coverage with the sectors recommended in table F.31.

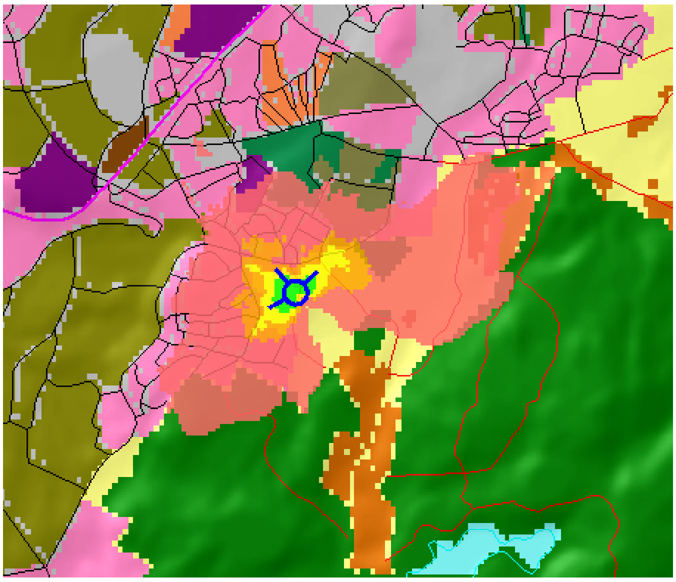


Figure F.30: Coverage from site: Loholt Sør

Loholt Sør		
Sector	*Azimuth*	*Tilt*
1	45°	2°
2	240°	1°
3	320°	0°

Table F.31: Recommended sectors from Loholt Sør

Brøsetveien 186B

Brøsetveien 186B is an office building located in an industrial area. The building is an existing base station site for mobile communication, thus co-locating the Mobile WiMAX equipment should be possible. Backhaul is expected to be provided through fiber. Brøsetveien is set to provide Mobile

WiMAX access to the suburban areas around the site with four sectors. The sectors can be found in table F.32, and the predicted coverage from the four sectors can be found in figure F.31. The sectors are set to provide coverage in the directions of Dragvoll, Steinan, Nardo, and Tyholt respectively.

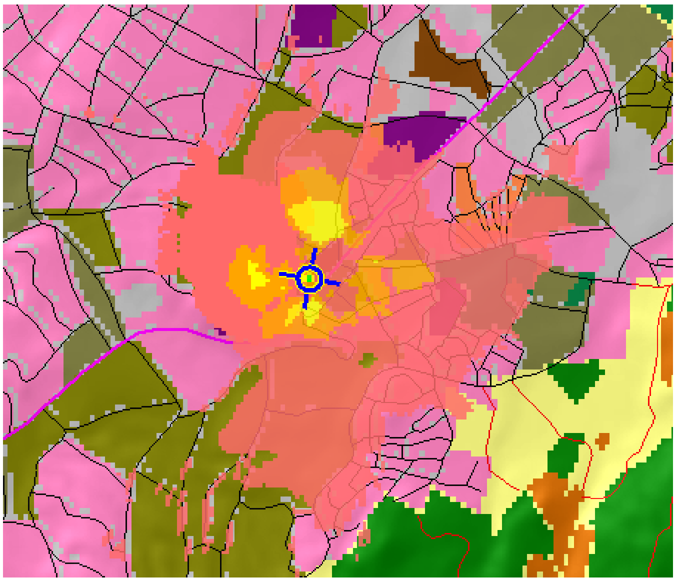


Figure F.31: Coverage from site: Brøsetveien 186B

Brøsetveien 186B		
Sector	*Azimuth*	*Tilt*
1	10°	4°
2	100°	0°
3	190°	2°
4	280°	4°

Table F.32: Recommended sectors from Brøsetveien 186B

Nardosenteret

Nardosenteret is a shopping center situated in a residential area in the outskirt of central Trondheim. Furthermore, the shopping center is already hosting communication equipment, thus power and backup should be accessible through co-locating the Mobile WiMAX equipment with existing operators. Fiber is assumed to be available to provide backup since the shopping center is located nearby Omkjøringsveien, see figure 7.1. Figure F.32 shows the predicted coverage from Nardosenteret using the three recommended sectors given in table F.33.

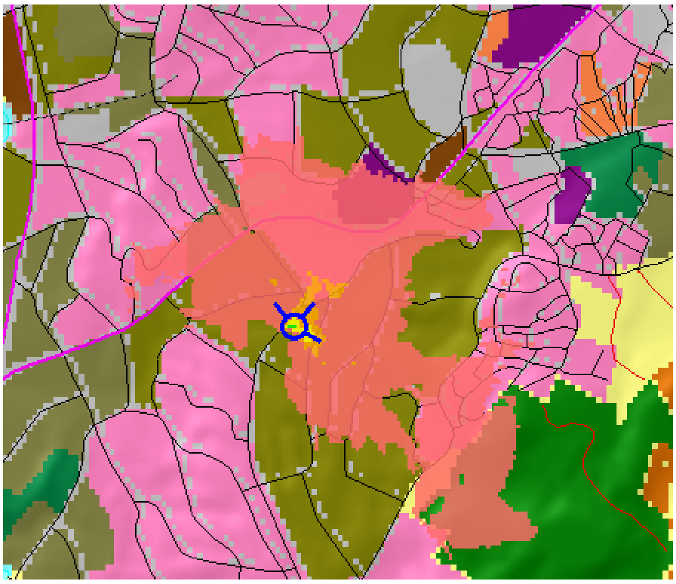


Figure F.32: Coverage from site: Nardosenteret

Nardosenteret		
Sector	*Azimuth*	*Tilt*
1	40°	-2°
2	120°	-2°
3	320°	-2°

Table F.33: Recommended sectors from Nardosenteret

G

Source code (Python)

This appendix contains a description of the Python scripts created during preparations prior to the intended measurements. The reports [12, 19, 32] have been studied and used as a basis for constructing the scripts provided in this appendix. A description of the files comprising the Python scripts are given here, the scripts themselves are enclosed in the end of this appendix, available for revision and editing for future radio planners. The output files are described in the subsequent subsection.

G.1 Description of the Python-files

test.py is the main controller of the Python script, and is the only file to be executed when measuring. The file is "pre-programmed" with IP, user-name and password for connection to the computer at the server side. The root directory have been set to C:\WiMAX_Measurements, meaning that the directory has to exist at both the server and client side prior to execution of test.py. On the server side, another subfolder SERVER has to be created on beforehand. When executed, the script asks for location name, distance to base station, and description of the location. The location name is used to generate a new folder where all files from the current location are stored. TCPdir and UDPdir are directories created within the location folder for storage of TCP and UDP measurements respectively. test.py calls for ping information from ping.py, and starts selected TCP and UDP measurements with MeasureThroughput.py and TelnetConnect.py. Figure G.1 shows the relations between the different files.

ping.py sends a ping command to the remote node, and stores all information in PingInfo_[location]_[time].txt, at the client computer. A total of four (4) packages are sent.

MeasureThroughput.py is used as a controller for creating a telnet connection, set, start and stop the Iperf at the server and the client side.

TelnetConnect.py connects to the server using telnet. Through telneting to the server, Iperf can be set, started and stopped from the client computer. As for setting all parameters at the server side, TelnetConnect.py sets, starts and stops the Iperf at the client side as well. All after instructions from MeasureThroughput.py and test.py. All measurements are written to files at both the client and server.

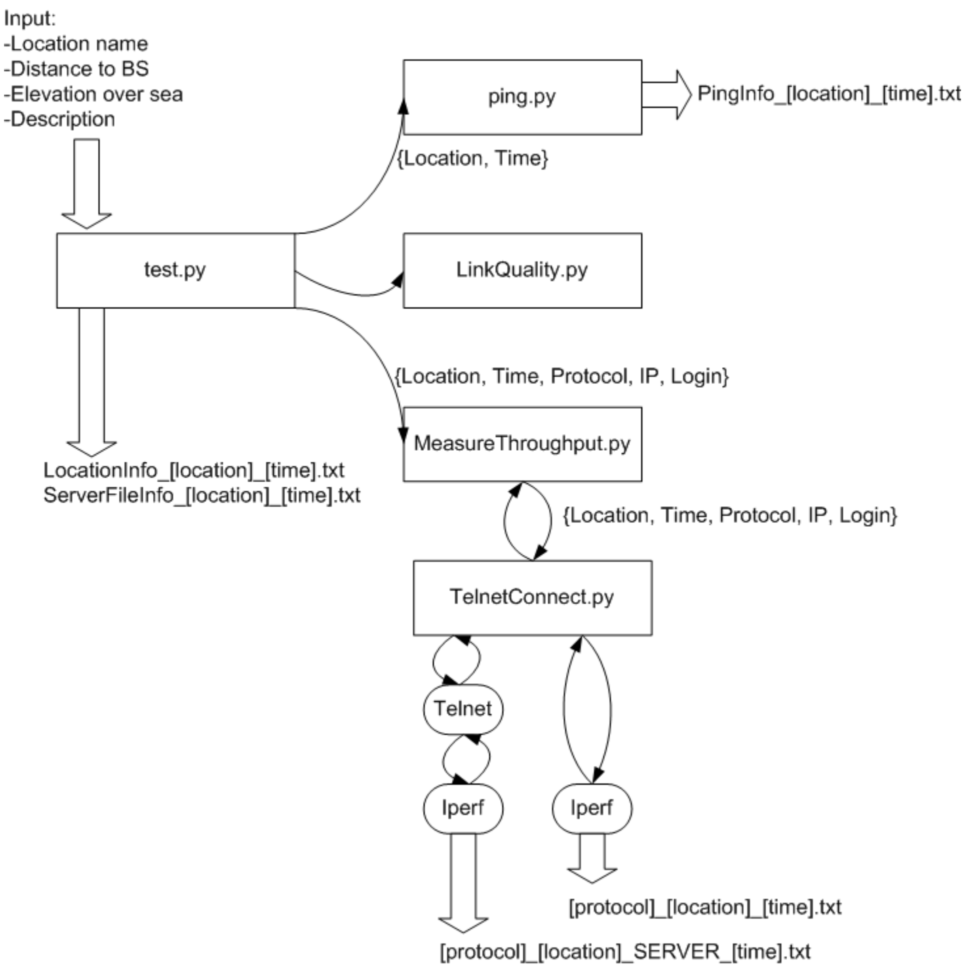


Figure G.1: The scripts performing the measurements

G.1.1 Output files (.txt)

The following subsection describes the contents of the output files generated when running the Python scripts.

LocationInfo_[location]_[time].txt contains name of location, distance to BS, receiver elevation, names of the different measurements received at the client side. The file is stored in in the pre-defined folder: C:\WiMAX_Measurements\[location].

ServerFileInfo_[location]_[time].txt contains the names of all the files generated using Iperf at the server side. The file is stored in the pre-defined folder named C:\WiMAX_Measurements\[location] at the client computer.

PingInfo_[location]_[time].txt contains all information received when using a ping command to a remote node. The file is stored at the client computer, C:\WiMAX_Measurements\[location].

[protocol]_[location]_[time].txt contains information about the transfer and bandwidth for each test set retrieved at the client side. The files are stored at C:\WiMAX_Measurements\[location]\[protocol].

[protocol]_[location]_SERVER_[time].txt is a throughput file, containing transfer and bandwidth data. One file represent one test set at the server side. UDP measurements has additional jitter delay and information about lost packages. The files are stored in the pre-defined folder C:\WiMAX_Measurements\SERVER at the computer on the server side.

G.1.2 Test.py

```
#!/usr/bin/python
# -*- coding: iso-8859-15 -*-

import os
import telnetlib
import time
from time import localtime, strftime
import sys
import TelnetConnect
import MeasureThroughput
import ping
import LinkQuality
#from time import localtime, strftime

SERVER = "xxx.xxx.xxx.xxx"
USER = "XXXXX" #username at server
PASSWORD = "XXXXXXX" #password at server
TIME = strftime("%H%M%S", localtime())
```

```
ROOT_DIR = "C:\\WiMAX_Measurements"

## Input data, Location, Distance, and Elevation
location = raw_input("Location(name): ")
distanceToBS = raw_input("Distance to BS [km]: ")
elevationOverSea = raw_input("Elevation Over Sea Level [m]: ")
SiteDescription = raw_input("Description of the Site: ")
LOCATION_DIR = location

## Makes directory and TCP Folder
ProtocolDir = "TCPdir"
## Makes tcpTest directory in the given LOCATION_DIR folder...
(Client PC)
if not os.path.isdir(ROOT_DIR +"/" +LOCATION_DIR):
    os.mkdir(ROOT_DIR +"/" +LOCATION_DIR +"/")
if not os.path.isdir(ROOT_DIR +"/" +LOCATION_DIR +"/" ...
+ProtocolDir):
    os.mkdir(ROOT_DIR +"/" +LOCATION_DIR +"/" +ProtocolDir ...
+"/")

## Write information about location to file and file-names
infoFile = open(ROOT_DIR +"/" +LOCATION_DIR +"\\" ...
+"LocationInfo_" +location +"_" +TIME +".txt", "wb")
infoFile.write("Location: " +location +"\n")
#infoFile.write("Date: " +DATE +"\n")
infoFile.write("Time: " +TIME +"\n")
infoFile.write("Distance To BS [km]: " +distanceToBS +"\n")
infoFile.write("Elevation Above Sea-level [m]: " ...
+elevationOverSea +"\n")
##infoFile.write("Description of the site: " ...
+SiteDescription +"\n")
##infoFile.close()

## Write information about file names at server
infoSERVERfile = open(ROOT_DIR +"/" +LOCATION_DIR ...
+"\\" +"ServerFileInfo_" +location +"_" +TIME +".txt", "wb")

## Pinging client host
TIME = strftime("%H%M%S", localtime())
infoFile.write("File-name PING: " +"PingInfo_" ...
+LOCATION_DIR +"_" +TIME +".txt" +"\n")
# make list of hosts to ping
hostLi = [SERVER]
q = ping.Queue.Queue()
```

```
for host in hostLi:
    """Create and start all necessary threads, ...
passing results
    back via thread safe Queue instance.
    """
    ping.Pinger(host,q).start()
i = len(hostLi)
while i > 0:
    """Loop ends when all responses to dispatched ...
pings arrive"""
    ping.showResponse(q.get(), LOCATION_DIR, TIME)
    i -= 1

##LinkQuality measurements
#LinkMeasurements = LinkQuality.LinkQualityDisplay...
(LOCATION_DIR)

## Starting TCP measurements
TIME = strftime("%H%M%S", localtime())
THROUGHPUT = MeasureThroughput.ThroughputMeasurement...
(TIME, LOCATION_DIR, ProtocolDir, SERVER, USER, PASSWORD)
PARAM = "-w32K"
clientPARAM = "-P1 -i1 -p5001 -w32K -l56K -fm -t30"
THROUGHPUT.TCPthroughput(PARAM, clientPARAM)
infoFile.write("File-name WS=32K: " +"TCPdir_" ...
+LOCATION_DIR +"_" +TIME +".txt" +"\n")
infoSERVERfile.write("File-name WS=32K: " +"TCPdir_" ...
+LOCATION_DIR +"_SERVER_" +TIME +".txt" +"\n")

TIME = strftime("%H%M%S", localtime())
THROUGHPUT = MeasureThroughput.ThroughputMeasurement...
(TIME, LOCATION_DIR, ProtocolDir, SERVER, USER, PASSWORD)
PARAM = "-w56K"
clientPARAMw56K = "-P1 -i1 -p5001 -w56K -l56K -fm -t30"
THROUGHPUT.TCPthroughput(PARAM, clientPARAMw56K)
infoFile.write("File-name WS=56K: " +"TCPdir_" ...
+LOCATION_DIR +"_" +TIME +".txt" +"\n")
infoSERVERfile.write("File-name WS=56K: " +"TCPdir_" ...
+LOCATION_DIR +"_SERVER_" +TIME +".txt" +"\n")

TIME = strftime("%H%M%S", localtime())
THROUGHPUT = MeasureThroughput.ThroughputMeasurement...
(TIME, LOCATION_DIR, ProtocolDir, SERVER, USER, PASSWORD)
PARAM = "-w64K"
```

```
clientPARAMw64K = "-P1 -i1 -p5001 -w64K -l56K -fm -t30"
THROUGHPUT.TCPthroughput(PARAM, clientPARAMw64K)
infoFile.write("File-name WS=64K: " +"TCPdir_" ...
+LOCATION_DIR +"_" +TIME +".txt" +"\n")
infoSERVERfile.write("File-name WS=64K: " +"TCPdir_" ...
+LOCATION_DIR +"_SERVER_" +TIME +".txt" +"\n")

## UDP throughput
ProtocolDir="UDPdir"
## Makes a udpTest directory in the given LOCATION_DIR ...
folder (Client PC)
if not os.path.isdir(ROOT_DIR +"/" +LOCATION_DIR):
    os.mkdir(ROOT_DIR +"/" +LOCATION_DIR +"/")
if not os.path.isdir(ROOT_DIR +"/" +LOCATION_DIR +"/" ...
+ProtocolDir):
    os.mkdir(ROOT_DIR +"/" +LOCATION_DIR +"/" ...
+ProtocolDir +"/")

# Starting UDP Throughput measurements
TIME = strftime("%H%M%S", localtime())
THROUGHPUT = MeasureThroughput.ThroughputMeasurement...
(TIME, LOCATION_DIR, ProtocolDir, SERVER, USER, PASSWORD)
PARAM = "BW-2M"
clientPARAMudp = "-u -P1 -i1 -p5001 -w64K -l1k -fm ...
-b2M -t30 -T1"
THROUGHPUT.TCPthroughput(PARAM, clientPARAMudp)
infoFile.write("File-name UDP BW=2M: " +"UDPdir_" ...
+LOCATION_DIR +"_" +TIME +".txt" +"\n")
infoSERVERfile.write("File-name UDP BW=2M: " +"UDPdir_" ...
+LOCATION_DIR +"_SERVER_" +TIME +".txt" +"\n")

TIME = strftime("%H%M%S", localtime())
THROUGHPUT = MeasureThroughput.ThroughputMeasurement...
(TIME, LOCATION_DIR, ProtocolDir, SERVER, USER, PASSWORD)
PARAM = "BW-4M"
clientPARAMudp = "-u -P1 -i1 -p5001 -w64K -l1k -fm ...
-b4M -t30 -T1 "
THROUGHPUT.TCPthroughput(PARAM, clientPARAMudp)
infoFile.write("File-name UDP BW=4M: " +"UDPdir_" ...
+LOCATION_DIR +"_" +TIME +".txt" +"\n")
infoSERVERfile.write("File-name UDP BW=4m: " +"UDPdir_" ...
+LOCATION_DIR +"_SERVER_" +TIME +".txt" +"\n")

TIME = strftime("%H%M%S", localtime())
```

```
THROUGHPUT = MeasureThroughput.ThroughputMeasurement...
(TIME, LOCATION_DIR, ProtocolDir, SERVER, USER, PASSWORD)
PARAM = "BW-4.5M"
clientPARAMudp = "-u -P1 -i1 -p5001 -w64K -l1k -fm ...
-b4.5M -t30 -T1 "
THROUGHPUT.TCPthroughput(PARAM, clientPARAMudp)
infoFile.write("File-name UDP BW=4.5M: " +"UDPdir_" ...
+LOCATION_DIR +"_" +TIME +".txt" +"\n")
infoSERVERfile.write("File-name UDP BW=4.5M: " +"UDPdir_" ...
+LOCATION_DIR +"_SERVER_" +TIME +".txt" +"\n")

TIME = strftime("%H%M%S", localtime())
THROUGHPUT = MeasureThroughput.ThroughputMeasurement...
(TIME, LOCATION_DIR, ProtocolDir, SERVER, USER, PASSWORD)
PARAM = "BW-5.5M"
clientPARAMudp = "-u -P1 -i1 -p5001 -w64K -l1k -fm ...
-b5.5M -t30 -T1 "
THROUGHPUT.TCPthroughput(PARAM, clientPARAMudp)
infoFile.write("File-name UDP BW=5.5M: " +"UDPdir_" ...
+LOCATION_DIR +"_" +TIME +".txt" +"\n")
infoSERVERfile.write("File-name UDP BW=5.5M: " +"UDPdir_" ...
+LOCATION_DIR +"_SERVER_" +TIME +".txt" +"\n")

TIME = strftime("%H%M%S", localtime())
THROUGHPUT = MeasureThroughput.ThroughputMeasurement...
(TIME, LOCATION_DIR, ProtocolDir, SERVER, USER, PASSWORD)
PARAM = "BW-6.5M"
clientPARAMudp = "-u -P1 -i1 -p5001 -w64K -l1k -fm ...
-b6.5M -t30 -T1 "
THROUGHPUT.TCPthroughput(PARAM, clientPARAMudp)
infoFile.write("File-name UDP BW=6.5M: " +"UDPdir_" ...
+LOCATION_DIR +"_" +TIME +".txt" +"\n")
infoSERVERfile.write("File-name UDP BW=6.5M: " +"UDPdir_" ...
+LOCATION_DIR +"_SERVER_" +TIME +".txt" +"\n")

TIME = strftime("%H%M%S", localtime())
THROUGHPUT = MeasureThroughput.ThroughputMeasurement...
(TIME, LOCATION_DIR, ProtocolDir, SERVER, USER, PASSWORD)
PARAM = "BW-7M"
clientPARAMudp = "-u -P1 -i1 -p5001 -w64K -l1k -fm ...
-b7M -t30 -T1 "
THROUGHPUT.TCPthroughput(PARAM, clientPARAMudp)
infoFile.write("File-name UDP BW=7M: " +"UDPdir_" ...
+LOCATION_DIR +"_" +TIME +".txt" +"\n")
```

```
infoSERVERfile.write("File-name UDP BW=7M: " +"UDPdir_" ...
+LOCATION_DIR +"_SERVER_" +TIME +".txt" +"\n")

TIME = strftime("%H%M%S", localtime())
THROUGHPUT = MeasureThroughput.ThroughputMeasurement...
(TIME, LOCATION_DIR, ProtocolDir, SERVER, USER, PASSWORD)
PARAM = "BW-7.5M"
clientPARAMudp = "-u -P1 -i1 -p5001 -w64K -l1k -fm ...
-b7.5M -t30 -T1 "
THROUGHPUT.TCPthroughput(PARAM, clientPARAMudp)
infoFile.write("File-name UDP BW=7.5M: " +"UDPdir_" ...
+LOCATION_DIR +"_" +TIME +".txt" +"\n")
infoSERVERfile.write("File-name UDP BW=7.5M: " +"UDPdir_" ...
+LOCATION_DIR +"_SERVER_" +TIME +".txt" +"\n")

TIME = strftime("%H%M%S", localtime())
THROUGHPUT = MeasureThroughput.ThroughputMeasurement...
(TIME, LOCATION_DIR, ProtocolDir, SERVER, USER, PASSWORD)
PARAM = "BW-8M"
clientPARAMudp = "-u -P1 -i1 -p5001 -w64K -l1k -fm ...
-b8M -t30 -T1 "
THROUGHPUT.TCPthroughput(PARAM, clientPARAMudp)
infoFile.write("File-name UDP BW=8M: " +"UDPdir_" ...
+LOCATION_DIR +"_" +TIME +".txt" +"\n")
infoSERVERfile.write("File-name UDP BW=8M: " +"UDPdir_" ...
+LOCATION_DIR +"_SERVER_" +TIME +".txt" +"\n")

infoFile.write("Description of the site: " +SiteDescription ...
+"\n")
infoFile.close()
infoSERVERfile.close()
```

G.1.3 ping.py

```
import threading
import os
import Queue
import time

## Edited after retrieval from http://mail.python.org/...
pipermail/python-list/2003-January/179514.html
## 20.04.2009

ROOT_DIR = "C:\\WiMAX_Measurements"
```

```
def showResponse(args, LOCATION_DIR, TIME):
    """Pretty prints passed tuple to stdout
    @param args: ip, stdoutLi, threadName
    @param LOCATION_DIR: location directory
    @param TIME: time of measurement
    """
    LOCATION_DIR = LOCATION_DIR
    location = LOCATION_DIR
    TIME = TIME
    ip, stdoutLi, threadName = args
    print '%s \t\t\t\t\t%s\n' % (ip, threadName)
    pingFile = open(ROOT_DIR +"/" +LOCATION_DIR +"\\" ...
+"PingInfo_" +location +"_" +TIME +".txt", "wb")
    for line in stdoutLi:
        line = line.strip()
        if not line: continue
        print '\t' + line
        pingFile.write(line +"\n")

    pingFile.close()

class Pinger(threading.Thread):
#class Pinger():

    def __init__(self, host, queue):
        threading.Thread.__init__(self)
        self.__host = host
        self.__queue = queue
        self.setDaemon(1)

    def run(self):
        pingCmd = "ping -n 4 -w 1000 " + self.__host
        childStdout = os.popen(pingCmd)
        result = (self.__host, childStdout.readlines(), ...
self.getName())
        childStdout.close()
        self.__queue.put(result)
```

G.1.4 MeasureThroughput.py

```
#!/usr/bin/python
```

```
# -*- coding: iso-8859-15 -*-

import os
import TelnetConnect

class ThroughputMeasurement:
    """ Class that runs the TelnetConnect and its methods
    @ivar TIME: When the measurements started
    @ivar LOCATION_DIR: Name of the measured spot
    @ivar ProtocolDir: Creates directory depending on ...
protocol; TCP vs. UDP
    @ivar SERVER: server IP
    @ivar USER: username for Telnet
    @ivar PASSWORD: password for connecting with Telnet
    @ivar PARAM: Parameters for the Iperf Server
    @ivar clientPARAM: Parameters for the Iperf client
    """

    def __init__(self, TIME, LOCATION_DIR, ProtocolDir, ...
SERVER, USER, PASSWORD):
        """ Class that runs the TelnetConnect and its methods
        @param TIME: When the measurements started
        @param LOCATION_DIR: Name of the measured spot
        @param ProtocolDir: Creates directory depending on ...
protocol; TCP vs. UDP
        @param SERVER: server IP
        @param USER: username for Telnet
        @param PASSWORD: password for connecting with Telnet
        """
        self.TIME = TIME
        self.LOCATION_DIR = LOCATION_DIR
        self.ProtocolDir = ProtocolDir
        self.SERVER = SERVER
        self.USER = USER
        self.PASSWORD = PASSWORD

    def TCPthroughput(self, PARAM, clientPARAM):
        """ Runs TelnetConnect
        @param PARAM: Parameters for the Iperf Server
        @param clientPARAM: Parameters for the Iperf client
        """
        self.PARAM = clientPARAM
        self.clientPARAM = clientPARAM
        ConnectTELNET = TelnetConnect.TelnetConnection
```

```
(self.TIME, self.LOCATION_DIR, self.ProtocolDir, self.SERVER...
, self.USER, self.PASSWORD)

        try:
            ConnectTELNET.login()
        except:
            print "Failed to connect using Telnet"

        try:
            ConnectTELNET.startIperfSERVER(self.PARAM)
        except:
            print "The server did not start"

        try:
            ConnectTELNET.startIperfCLIENT(self.clientPARAM)
        except:
            print "Something went wrong with the Iperf Client"

        try:
            ConnectTELNET.stopIperfSERVER()
        except:
            print "Could not break connection"
```

G.1.5 LinkQuality.py

```
#!/usr/bin/python
# -*- coding: iso-8859-15 -*-

import os
import telnetlib
import sys
import datetime
import string
import time
from time import localtime, strftime

class LinkQualityDisplay:
    def __init__(self, LOCATION_DIR):
        """ Class to perform tests of link quality
        @param LOCATION_DIR: location
        """
        LOCATION_DIR = LOCATION_DIR
        TIME = strftime("%H%M%S", localtime())
        IP_CPE = "192.168.254.251"
```

```
        PASSWORD = "installer"
        ESC = chr(27)
        ITERATE = 60 #1200
        ROOT_DIR = "C:\\WiMAX_Measurements"

        # Open file for writing
        outfile = open(ROOT_DIR +"/" +LOCATION_DIR +"\\" ...
+"LinkQuality_" +LOCATION_DIR +TIME +".txt","wb")
        #outfile = open("LinkQuality_" +TIME +".txt","wb")

        # Create a new telnet connection to the CPE
        telnet = telnetlib.Telnet(IP_CPE)

        # Authenticate the connection
        telnet.read_until("Enter the password: ")
        telnet.write(PASSWORD + "\r\n")
        telnet.read_until("Enter your choice > ")
        telnet.write("7\r\n")
        telnet.read_until("Enter your choice > ")
        print "Starting the link quality display...\r\n"

        # Start the link quality display
        telnet.write("1\r\n")
        telnet.read_until("Started. Press ESC to stop...")

        # Loop while fetching one line at the time
        for i in range(1, ITERATE + 1):
            LINK_DATA = telnet.read_until("\n")
            CUR_TIME = strftime("%H:%M:%S", localtime())
            outfile.write(CUR_TIME + " " + LINK_DATA)
            print CUR_TIME + " " + LINK_DATA ,
        else:
            # Clean up and exit
            telnet.write(ESC)
            telnet.write("9\r\n")
            telnet.close()
            outfile.close()
```

G.1.6 TelnetConnect.py

```
#!/usr/bin/python
# -*- coding: iso-8859-15 -*-

import os
```

```
import telnetlib
import time
import sys
from time import localtime, strftime

ROOT_DIR = "C:\\WiMAX_Measurements"

class TelnetConnection:
    """ Class connects to telnet, and starts and stops Iperf
    @ivar TIME: When the measurements started
    @ivar LOCATION_DIR: Name of the measured spot
    @ivar ProtocolDir: Creates directory depending on ...
protocol; TCP vs. UDP
    @ivar SERVER: server IP
    @ivar USER: username for Telnet
    @ivar PASSWORD: password for connecting with Telnet
    """

    def __init__(self, TIME, LOCATION_DIR, ProtocolDir, ..
SERVER, USER, PASSWORD):
        """ Class that starts and stops Iperf
        @param TIME: When the measurements started
        @param LOCATION_DIR: Name of the measured spot
        @param ProtocolDir: Creates directory depending on ...
protocol; TCP vs. UDP
        @param SERVER: server IP
        @param USER: username for Telnet
        @param PASSWORD: password for connecting with Telnet
        """
        self.TIME = TIME
        self.LOCATION_DIR = LOCATION_DIR
        self.ProtocolDir = ProtocolDir
        self.SERVER = SERVER
        self.USER = USER
        self.PASSWORD = PASSWORD

    def login(self):
        """ Uses Telnet for login """
        ## Create telnet connection to the server
        self.telnet = telnetlib.Telnet(self.SERVER)
        #Authenticate
        self.telnet.read_until("Login username: ")
        self.telnet.write(self.USER +"\r\n")
        self.telnet.read_until("Login password: ")
```

```
        self.telnet.write(self.PASSWORD +"\r\n")
        self.telnet.read_until("Domain name: ")
        self.telnet.write("\r\n")
        print "CONNECTED WITH TELNET"

    def startIperfSERVER(self,clientPARAM):
        """ Starts the Iperf server
        @param clientPARAM: Iperf server parameter
        """
        self.PARAM = clientPARAM
        # Output directory
        serveroutputdir = "C:\\WiMAX_Measurements" +"/Server/"
        # Generates Server output file
        serverlistingFile = self.ProtocolDir +"_" ...
+self.LOCATION_DIR +"_SERVER_" +self.TIME +".txt"
        #Starting and setting parameters for the Iperf Server
        self.telnet.read_until("C:\\> ",5)
        self.telnet.write("cd Program Files/iperf-2.0.2/bin"...
+"\r\n")
        self.telnet.read_until(">")
        self.telnet.write("iperf -s " +self.PARAM + " > " ...
+ serveroutputdir + "\\" +serverlistingFile +"\r\n")
        print "Iperf server is set"
        # Wait 3 seconds for server to start
        time.sleep(3)

    def stopIperfSERVER(self):
        """ Stops the iPerf server and closes the telnet ...
connection """
        self.telnet.read_until(">")
        self.telnet.write("iperf -s -R" +"\r\n")
        self.telnet.read_until(">")
        self.telnet.write("exit" +"\r\n")
        self.telnet.close()
        print "The server has stopped, and the telnet ...
connection is broken"

    def startIperfCLIENT(self, clientPARAM):
        """ Starts the Iperf client
        @param clientPARAM: Parameters to be set at the ...
client side
        """
        self.clientPARAM = clientPARAM
        # making a output file
```

```
        listingfile = self.ProtocolDir +"_" ...
+self.LOCATION_DIR +"_" +self.TIME +".txt"
        outputdir = "C:\\WiMAX_Measurements" + "/" + ...
self.LOCATION_DIR + "/" + self.ProtocolDir + "/"
        # Finding Iperf
        try:
            os.chdir("C:\\Program Files\\iperf-2.0.2\\bin")
        except:
            print "FEIL os.chdir"
        #Starts the Iperf client
        os.system("iperf -c " + self.SERVER + " " +...
self.clientPARAM +" > "+outputdir +"\\" +listingfile +"\r\n")
        print "The Iperf client has started"
```

H

Source code (Matlab)

The following appendix contains descriptions of the matlab files suggested for processing the measurement data found by using the python script in appendix G. The files are enclosed in the subsequent sections for future radio planners to revise and edit. Figure H.1 shows the output to screen when running read.m.

H.1 Description of the Matlab-files

read.m is the executable matlab file for processing the measured data. The LocationInfo and ServerFileInfo files are imported for location of data. Worth emphasizing is that the whole file-name, including the .txt, have to be typed when prompted for the file-names. The read.m file outputs distance to base station, elevation, and ping results. Furthermore, tcptreatment.m, tcpSERVERtreatment.m, udptreatment.m, and udpSERVERtreatment.m are all executed when running read.m.

tcptreatment.m is executed from the read.m. The tcptreatment.m finds the max, min, and average TCP values as well as plots the throughput with time for each TCP window-size.

tcpSERVERtreatment.m treats the TCP measurements at gathered at the Iperf server. Max, min, and average TCP values are calculated, and the TCP throughput is drawn with respect to time for each TCP window-size.

udptreatment.m treats the UDP measurements for each bandwidth. UDP throughput per time is plotted, and max, min, and average UDP values are calculated for each bandwidth measurement.

udpSERVERtreatment.m serves the same purpose for the server measurements as the udptreatment.m for the client measurements. In addition, max, min, and average jitter is being calculated.

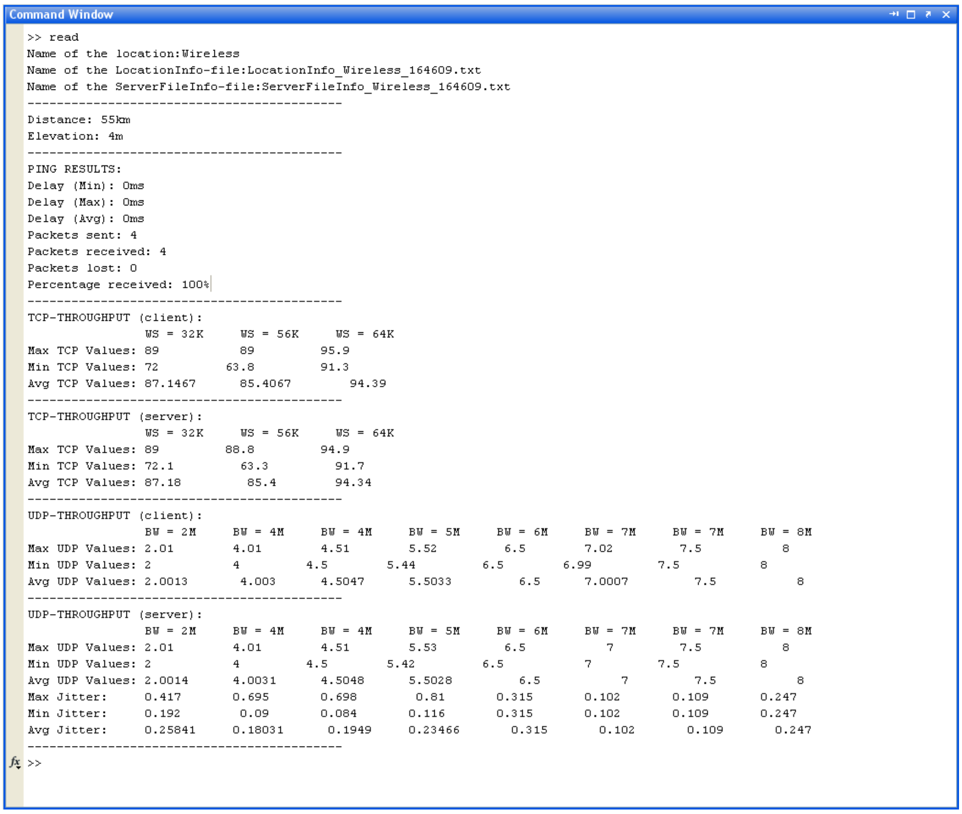


Figure H.1: Matlab output measured between to nodes over Ethernet

H.1.1 read.m

```
LOCATION = input('Name of the location:', 's');
LocationInfo = input('Name of the LocationInfo-file:', 's');
ServerFileInfo = input('Name of the ServerFileInfo-file:',...
 's');

% The measurement files have to be located in the ...
C:\WiMAX_Measurements\ folder. Server files are copied ...
into the subfolder named location-name

ROOT_DIR = 'C:\WiMAX_Measurements\';
BRACKET = '\';

fidL = fopen(['',ROOT_DIR, '',LOCATION,'',BRACKET,'',...
```

```
LocationInfo]);
junkI = fgets(fidL);
junkI = fgets(fidL);
K = textscan(fidL, '%s %f', 2, 'delimiter', ':');
fid = textscan(fidL, '%*s %s', 12, 'delimiter', ':');
fclose(fidL);
Distance = K{2}(1);
Elevation = K{2}(2);
fid = fid{1};
fidarray = fid(2:12);

fidS = fopen(['',ROOT_DIR, '',LOCATION,'',BRACKET,'',...
ServerFileInfo]);
fidSERVER = textscan(fidS, '%*s %s', 'delimiter', ':');
fclose(fidS);
fidarrayS = fidSERVER{1};

PingInfo = fid(1);
PingInfo =PingInfo{1};
fidP = fopen(['',ROOT_DIR, '',LOCATION,'',BRACKET,'',...
PingInfo]);
JunkI = fgets(fidP);
JunkI = fgets(fidP);
JunkI = fgets(fidP);
JunkI = fgets(fidP);
JunkI = fgets(fidP);
JunkI = fgets(fidP);
K1 = textscan(fidP, '%*s %d %*s %d %*s %d %*s', 1, ...
'delimiter', '=');
JunkI = fgets(fidP);
JunkI = fgets(fidP);
K2 = textscan(fidP, '%*s %d %*s %d %*s %d %*s', ...
'delimiter', '=');
fclose(fidP);
PacketsSent = K1{1};
PacketsReceived = K1{2};
PacketsLost = K1{3};
MinTime = K2{1};
MaxTime = K2{2};
AvgTime = K2{3};

disp('--------------------------------------------')
disp(['Distance: ', num2str(Distance), 'km'])
disp(['Elevation: ', num2str(Elevation), 'm'])
```

```
disp('-----------------------------------------')
disp('PING RESULTS:')
disp(['Delay (Min): ', num2str(MinTime), 'ms'])
disp(['Delay (Max): ', num2str(MaxTime), 'ms'])
disp(['Delay (Avg): ', num2str(AvgTime), 'ms'])
disp(['Packets sent: ', num2str(PacketsSent)])
disp(['Packets received: ', num2str(PacketsReceived)])
disp(['Packets lost: ', num2str(PacketsLost)])
disp(['Percentage received: ', num2str(PacketsReceived*100/...
PacketsSent), '%'])
disp('-----------------------------------------')

[TCPtransfer, TCPbandwidth] = tcptreatment(fidarray, LOCATION);
[TCP_SERVER_transfer, TCP_SERVER_bandwidth] = ...
tcpSERVERtreatment(fidarrayS, LOCATION);
[UDPtransfer, UDPbandwidth] = udptreatment(fidarray, LOCATION);
[UDP_SERVER_transfer, UDP_SERVER_bandwidth, ...
UDP_SERVER_jitter] = udpSERVERtreatment(fidarrayS, LOCATION);
```

H.1.2 tcptreatment.m

```
function [TCPTransfer, TCPBandwidth] = tcptreatment(fidarray...
, LOCATION)

ROOT_DIR = 'C:\WiMAX_Measurements\';
BRACKET = '\';
TCP_DIR = 'TCPdir\';
Window = ['TCP plots, client side, Window size: 32K';...
'TCP plots, client side, Window size: 56K'; 'TCP plots, ...
client side, Window size: 64K'];

for i=1:3 %size(fid,1);
    fid = fopen(['',ROOT_DIR, '',LOCATION,'',BRACKET,...
    '',TCP_DIR,'',fidarray{i}]);
    junk1 = fgets(fid);
    junk2 = fgets(fid);
    junk3 = fgets(fid);
    junk4 = fgets(fid);
    junk5 = fgets(fid);
    % [ID]  Interval    Transfer    Bandwidth
    C = textscan(fid,'%21c %f %s %f %s');
    fclose(fid);
    TCPTransfer(:,i) = C{2};
    TCPBandwidth(:,i) = C{4};
```

```
    figure(1)
    subplot(3,1,i)
    plot(TCPBandwidth(1:size(TCPBandwidth,1)-1,i), '-*')
    % sett like akser for alle subplotene!!!
    title(Window(i,:))

    %finner max, min og avg throughput
    MaxTCP_Values (i) = max(TCPBandwidth(1:size(TCPBandwidth...
    ,1)-1,i));
    MinTCP_Values (i) = min(TCPBandwidth(1:size(TCPBandwidth...
    ,1)-1,i));
    AvgTCP_Values (i) = sum(TCPBandwidth(1:size(TCPBandwidth...
    ,1)-1,i))/(size(TCPBandwidth,1)-1);
end

disp('TCP-THROUGHPUT (client):')
disp(['                ', 'WS = 32K     ', 'WS = 56K     ',...
 'WS = 64K'])
disp(['Max TCP Values: ', num2str(MaxTCP_Values)])
disp(['Min TCP Values: ', num2str(MinTCP_Values)])
disp(['Avg TCP Values: ', num2str(AvgTCP_Values)])
disp('------------------------------------------')
```

H.1.3 tcpSERVERtreatment.m

```
function [TCPserverTransfer, TCPserverBandwidth] =...
 tcpSERVERtreatment(fidarrayS, LOCATION)

ROOT_DIR = 'C:\WiMAX_Measurements\';
BRACKET = '\';
SERVER_DIR = 'SERVER\';

Window = ['TCP plots, server side, Window size: 32K';...
'TCP plots, server side, Window size: 56K'; 'TCP plots,...
 server side, Window size: 64K'];

for i=1:3 %size(fid,1);
    fid = fopen(['',ROOT_DIR, '', LOCATION, '', BRACKET, '',...
     SERVER_DIR,'', fidarrayS{i}]);
    junk1 = fgets(fid);
    junk2 = fgets(fid);
    junk3 = fgets(fid);
    junk4 = fgets(fid);
    junk5 = fgets(fid);
```

```
    % [ID]  Interval    Transfer    Bandwidth
    C = textscan(fid,'%21c %f %s %f %s');
    fclose(fid);
    TCPserverTransfer(:,i) = C{2};
    TCPserverBandwidth(:,i) = C{4};
    figure(3)
    subplot(3,1,i)
    plot(TCPserverBandwidth(1:size(TCPserverBandwidth,1)...
    -1,i), '-*')
    % sett like akser for alle subplotene!!!
    title(Window(i,:))

    %finner max, min og avg throughput
    MaxTCP_serverValues (i) = max(TCPserverBandwidth(1:size(...
    TCPserverBandwidth,1)-1,i));
    MinTCP_serverValues (i) = min(TCPserverBandwidth(1:size(...
    TCPserverBandwidth,1)-1,i));
    AvgTCP_serverValues (i) = sum(TCPserverBandwidth(1:size(...
    TCPserverBandwidth,1)-1,i))/(size(TCPserverBandwidth,1)-1);
end

disp('TCP-THROUGHPUT (server):')
disp(['                ', 'WS = 32K     ', 'WS = 56K     ',...
 'WS = 64K'])
disp(['Max TCP Values: ', num2str(MaxTCP_serverValues)])
disp(['Min TCP Values: ', num2str(MinTCP_serverValues)])
disp(['Avg TCP Values: ', num2str(AvgTCP_serverValues)])
disp('-----------------------------------------')
```

H.1.4 udptreatment.m

```
function [UDPTransfer, UDPBandwidth] = udptreatment(...
fidarray, LOCATION)

ROOT_DIR = 'C:\WiMAX_Measurements\';
BRACKET = '\';
UDP_DIR = 'UDPdir\';
BW = ['UDP plots, client side, Bandwidth: 2M';...
'UDP plots, client side, Bandwidth: 4M';'UDP plots,...
 client side, Bandwidth: 4M';'UDP plots, client ...
 side, Bandwidth: 5M';'UDP plots, client side, ...
 Bandwidth: 6M';'UDP plots, client side, Bandwidth:...
  7M';'UDP plots, client side, Bandwidth: 7M';...
  'UDP plots, client side, Bandwidth: 8M'];
```

```
for i=4:size(fidarray,1);
    fid = fopen(['',ROOT_DIR, '',LOCATION,'',...
    BRACKET,'',UDP_DIR,'',fidarray{i}]);
    junk1 = fgets(fid);
    junk2 = fgets(fid);
    junk3 = fgets(fid);
    junk4 = fgets(fid);
    junk5 = fgets(fid);
    junk6 = fgets(fid);
    % [ID]  Interval    Transfer    Bandwidth
    C = textscan(fid,'%21c %f %s %f %s');
    fclose(fid);
    k=i-3;
    UDPTransfer(:,k) = C{2};
    UDPBandwidth(:,k) = C{4};
    figure(2)
    subplot(size(fidarray,1)-3,1,k)
    plot(UDPBandwidth(1:size(UDPBandwidth,1)-1,k),'-*')
    title(BW(k,:))

    % sett like akser for alle subplotene!!!

    %finner max, min og avg throughput
    MaxUDP_Values (k) = max(UDPBandwidth(1:size(...
    UDPBandwidth,1)-1,k));
    MinUDP_Values (k) = min(UDPBandwidth(1:size(...
    UDPBandwidth,1)-1,k));
    AvgUDP_Values (k) = sum(UDPBandwidth(1:size(...
    UDPBandwidth,1)-1,k))/(size(UDPBandwidth,1)-1);
end

disp('UDP-THROUGHPUT (client):')
disp(['                 ', 'BW = 2M     ', 'BW = 4M...
     ', 'BW = 4M     ', 'BW = 5M     ', 'BW = 6M  ...
   ', 'BW = 7M     ', 'BW = 7M     ', 'BW = 8M     '])
disp(['Max UDP Values: ', num2str(MaxUDP_Values)])
disp(['Min UDP Values: ', num2str(MinUDP_Values)])
disp(['Avg UDP Values: ', num2str(AvgUDP_Values)])
disp('------------------------------------------')
```

H.1.5 udpSERVERtreatment.m

```
function [UDPserverTransfer, UDPserverBandwidth,...
```

```
 UDPserverJitter] = udpSERVERtreatment(fidarrayS, LOCATION)

ROOT_DIR = 'C:\WiMAX_Measurements\';
BRACKET = '\';
SERVER_DIR = 'SERVER\';
BW = ['UDP plots, client side, Bandwidth: 2M';'UDP plots,...
 client side, Bandwidth: 4M';'UDP plots, client side, ...
 Bandwidth: 4M';'UDP plots, client side, Bandwidth: 5M';'UDP...
 plots, client side, Bandwidth: 6M';'UDP plots, client side...
 , Bandwidth: 7M';'UDP plots, client side, Bandwidth: 7M';...
 'UDP plots, client side, Bandwidth: 8M'];

for i=4:size(fidarrayS,1) %size(fid,1);
    fid = fopen(['',ROOT_DIR, '', LOCATION, '', BRACKET,...
     '', SERVER_DIR,'', fidarrayS{i}]);
    junk1 = fgets(fid);
    junk2 = fgets(fid);
    junk3 = fgets(fid);
    junk4 = fgets(fid);
    junk5 = fgets(fid);
    junk6 = fgets(fid);
    % [ID]  Interval    Transfer    Bandwidth Jitter ...
    Lost/Total Datagrams
    C = textscan(fid,'%21c %f %s %f %s %f %s %s %f %4c',30);
    fclose(fid);
    k=i-3;
    UDPserverTransfer(:,k) = C{2};
    UDPserverBandwidth(:,k) = C{4};
    UDPserverJitter(:,k) = C{6};
    figure(4)
    subplot(size(fidarrayS,1)-3,1,k)
    plot(UDPserverBandwidth(:,k), '-*')
    title(BW(k,:))
    % sett like akser for alle subplotene!!!

    %finner max, min og avg throughput
    MaxUDP_serverValues (k) = max(UDPserverBandwidth(1:size(...
    UDPserverBandwidth,1)-1,k));
    MinUDP_serverValues (k) = min(UDPserverBandwidth(1:size(...
    UDPserverBandwidth,1)-1,k));
    AvgUDP_serverValues (k) = sum(UDPserverBandwidth(1:size(...
    UDPserverBandwidth,1)-1,k))/(size(UDPserverBandwidth,1)-1);
    MaxUDP_jitter (k) = max(UDPserverJitter(1:size(...
    UDPserverJitter,1)-1,k));
```

```
    MinUDP_jitter (k) = min(UDPserverJitter(1:size(...
    UDPserverJitter,1)-1,k));
    AvgUDP_jitter (k) = sum(UDPserverJitter(1:size(...
    UDPserverJitter,1)-1,k))/(size(UDPserverJitter,1)-1);
end

disp('UDP-THROUGHPUT (server):')
disp(['                ', 'BW = 2M     ', 'BW = 4M     ',...
 'BW = 4M     ', 'BW = 5M     ', 'BW = 6M     ', ...
 'BW = 7M     ', 'BW = 7M     ', 'BW = 8M     '])
disp(['Max UDP Values: ', num2str(MaxUDP_serverValues)])
disp(['Min UDP Values: ', num2str(MinUDP_serverValues)])
disp(['Avg UDP Values: ', num2str(AvgUDP_serverValues)])
disp(['Max Jitter:     ', num2str(MaxUDP_jitter)])
disp(['Min Jitter:     ', num2str(MinUDP_jitter)])
disp(['Avg Jitter:     ', num2str(AvgUDP_jitter)])
disp('-------------------------------------------')
```