UNIVERSITY OF OSLO
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A Field Study of WiMAX Performance

Master Thesis

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Abstract

WiMAX is a wireless access system that offers fixed, nomadic, portable and soon mobile wireless broadband connectivity. Much hype is spread about system performance and loads of contrary statements are observed. This thesis aims at discovering the real life performance of WiMAX, and will concentrate on both the fixed and mobile WiMAX profiles. Scientific research methods are used to study performance in a fixed WiMAX field trial, a fixed WiMAX deployment and a pre-mobile WiMAX field trial. The performance study is focused on throughput and coverage, where the affecting underlying parameters and relations among them are analyzed. All the measurement results and analyses are presented, and a detailed overview of the two profiles fixed- and mobile WiMAX is given.

WiMAX performance showed to be close to the vendor specifications and the theoretical limits under perfect conditions, but deviated significant in imperfect scenarios, which is the normal case. Maximum throughput obtained was 76% compared to the theoretical limitations, where factors as protocol overhead caused the deviations. Typical imperfect scenarios may be at long distances, without clear sight to the base station in a possible overloaded cell with radio interference. Throughput and coverage was therefore found to be dependent variables in that they rely on underlying independent parameters and the relations between them. For instance, both throughput and coverage depends on the attribute received signal strength, which again depends on the sight capabilities. Analytical expressions and models were derived based on measured field data when determining and modelling WiMAX performance under imperfect conditions. Specific derived expressions determine throughput performance and path loss models determine the expected coverage. An analytical expression that reveals co-channel interference is derived together with a range of expressions that model the gain in performance for different attributes when various diversity orders are used.

To satisfy all the hype and expectations about WiMAX performance, deployment conditions must be perfect with line of sight at longer distances, no co-channel interference and most of the various optional system parameters must be optimal. Because WiMAX performance depends on a range of varying factors, analytical expressions and models should be used to determine the real life performance.

List of Publications

This thesis resulted in three conference papers:

1. Grøndalen,O., Grønsund,P.,Breivik,T., Engelstad.P, “Fixed WiMAX Field Trial Measurements and Analyses”, Mobile Summit 2007, Budapest (Hungary), July 1-5, 2007

2. Grønsund,P., Grøndalen,O., Breivik,T., Engelstad.P, “Fixed WiMAX Field Trial Measurements and the derivation of a Path Loss Model”, Mosharaka International Conference on Communication Systems and Circuits (M-CSC 2007), Amman, May 21, 2007

3. Grønsund,P., Engelstad,P., Johnsen,T., Skeie,T, ”The Physical Performance and Path Loss in a Fixed WiMAX Deployment”, International Wireless Communications and Mobile Computing Conference (*IWCMC*) 2007, Honolulu (Hawaii), August 12-16, 2007

Preface

This master thesis (60 credits) is the final part of a master degree at the faculty of Informatics at the University of Oslo.

In early 2006, I met Tor Skeie at Simula Research Laboratory to whom I presented my ideas about topics for a master thesis. Tor Skeie was enthusiastic and showed great interests in the topics, which was streaming of video over WiMAX with IPv6. These topics were not his main area of research at the moment, but he introduced me to a person of great interests in these topics.

This person was Paal Engelstad at Telenor R&I. Tor Skeie and Paal Engelstad discussed my requests and found them to be interesting and relevant. Half a year before the master thesis work should start out, Paal contacted me. We became known and discussed the future of a master thesis. Two months later, with his enthusiastic and directly nature, Paal invited me to participate in a preliminary WiMAX filed trial that was about to be performed at Telenor R&I. I participated, and this master thesis had a perfect kick off. Paal further introduced me to a range of people at Telenor R&I, where I enjoyed staying and got the opportunity to have a summer internship. I did analysis of the preliminary measurements, programming of automated measurement scripts and studied WiMAX. I'm grateful for these opportunities.

At the end of the summer 2006, all focus was on the master thesis. Telenor R&I gave me the ability to participate in a more extensive WiMAX field trial. I became highly engaged in WiMAX with focus on performance. This study has been comprehensive, where I have obtained great knowledge on different technologies with specialization in WiMAX. In this environment with focus on research together with motivating and teaching scientists, I have improved my skills in research processes and built up a basis for a hopefully future career within research activities. Nextn€et as, with the first WiMAX deployment in Norway, gave me the possibility to study their deployment and to participate in a pre-mobile WiMAX field trial. The topic of this thesis became a WiMAX performance study in real life.

Acknowledgements

During this thesis I have been involved in many activities with many people, thus my acknowledgements to people that have contributed and supported me are many. First of all I want to thank my supervisors and advisers Paal Engelstad and Tor Skeie for having belief in me and giving me the opportunity to write this thesis in the maybe best possible research environments at Telenor R&I and Simula Research Laboratory. Both have contributed to this thesis with ideas, thesis reviewing and writing of conference papers. Paal Engelstad has been more than a technical supervisor to me, where he has given me advices, been open for all possible discussions and spent much time on me. I had never imagined such a supervisor. I'm thankful to my supervisors.

I have cooperated with many people at Telenor R&I. Especially I want to thank Ole Grøndalen and Tor Breivik for their contributions, Thomas Haslestad for his support and all the scientists at Telenor R&I for their frankness. Thanks to all the people at NextNet as for the support and opportunity to analyze their WiMAX system and participating in a pre-mobile WiMAX field trial.

Finally I want to thank my beautiful and smart girlfriend Tuva, my parents Eirik and Lillian, twin brother Tor and little sister Vera, for all the support and love they give me.

Acronyms

3GPP	3G Partnership Project
AAS	Adaptive Antenna System also Advanced Antenna System
ACK	Acknowledge
AMC	Adaptive Modulation and Coding
ARQ	Automatic Repeat reQuest
ASN	Access Service Network
ASP	Application Service Provider
BE	Best Effort
BER	Burst Error Rate
CC	Chase Combining (also Convolutional Code)
CCI	Co-Channel Interference
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CINR	Carrier to Interference + Noise Ratio
CP	Cyclic Prefix
CPE	Customer Premises Equipment
CQI	Channel Quality Indicator
CSN	Connectivity Service Network
CTC	Convolutional Turbo Code
DL	Downlink
DVB	Digital Video Broadcast
DVB-RCS	Digital Video Broadcast - Return Channel via Satellite
ErtPS	Extended Real-Time Polling Service
ETSI	European Telecommunications Standards Institute
FBSS	Fast Base Station Switching
FCH	Frame Control Header
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
FTP	File Transfer Protocol
FUSC	Fully Used Sub-Carrier
HARQ	Hybrid Automatic Repeat reQuest
HHO	Hard Hand-Off
HiperMAN	High Performance Metropolitan Area Network
HO	Hand-Off or Hand Over
HTTP	Hyper Text Transfer Protocol
IETF	Internet Engineering Task Force
IFFT	Inverse Fast Fourier Transform
IM	Instant Messaging
IP	Internet Protocol
ISI	Inter-Symbol Interference
L2	Layer 2
LOS	Line of Sight
MAC	Media Access Control
MAN	Metropolitan Area Network
MAP	Media Access Protocol
MBS	Multicast and Broadcast Service
MDHO	Macro Diversity Hand Over
MIMO	Multiple Input Multiple Output

MMS	Multimedia Message Service
MPLS	Multi-Protocol Label Switching
MS	Mobile Station
NACK	Not Acknowledge
NAP	Network Access Provider
NLOS	Non Line-of-Sight
NRM	Network Reference Model
nrtPS	Non-Real-Time Polling Service
NSP	Network Service Provider
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
PER	Packet Error Rate
PUSC	Partially Used Sub-Carrier
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RR	Round Robin (Scheduler)
rtPS	Real-Time Polling Service
SDMA	Space (or Spatial) Division (or Diversity) Multiple Access
SHO	Soft Hand-Off
SIMO	Single Input Multiple Output
SINR	Signal to Interference + Noise Ratio
SLA	Service Level Agreement
SM	Spatial Multiplexing
SNIR	Signal to Noise + Interference Ratio
SNR	Signal to Noise Ratio
S-OFDMA	Scalable Orthogonal Frequency Division Multiple Access
SS	Subscriber Station
STC	Space Time Coding
SU	Subscriber Unit
TCP	Transmission Control Protocol
TDD	Time Division Duplex
UDP	User Datagram Protocol
UE	User Equipment
UGS	Unsolicited Grant Service
UL	Uplink
UMTS	Universal Mobile Telephone System
VoIP	Voice over Internet Protocol
VPN	Virtual Private Network
WiFi	Wireless Fidelity
WiBro	Wireless Broadband (Service)
WiMAX	Worldwide Interoperability for Microwave Access

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1 Introduction

1.1 Motivation and Goals

WiMAX (Worldwide Interoperability for Microwave Access) provides fixed, nomadic, portable and soon mobile wireless broadband connectivity without the need for direct line of sight with a base station. Wide coverage and great capacities are promised. Cell radius of three to ten kilometres with capacities of up to 40 Mbps per channel is specified [1]. The technology is expected to be incorporated in laptops, PDA's and gradually in smart and mobile phones. A great pool of applications may be offered, where VoIP, IPTV, Instant Messaging, Video streaming and web surfing is emphasized. A future potential clearly exists where deployments of the technology around the world is ongoing and underway. We will present a well arranged tutorial of fixed- and the upcoming mobile WiMAX profiles.

Performance as promised by the standardizing organization, considering throughput, coverage and Quality of Service (QoS) are great and also rumoured to be hyped. WiMAX is an immature system and equipment has recently reached the marked. There exists scarce information about how the system performs in real life, though much hype of great performance is observed, and WiMAX is often abused by other parties. In this thesis, we investigate the WiMAX system with main considerations on performance.

3G systems [2] provide network functionality with a packet switched core in addition to the circuit switched core. Mobility is built into these systems, where a migration towards broadband IP connectivity is emerging. WiMAX has been designed to provide wireless broadband access, where IP is fully supported from day one. Support for mobility is a future functionality in the WiMAX system, which will be important for market penetration when chipsets reaches mobile devices as laptops and cellular phones. Thus the 3G and WiMAX systems are closing each other, where broadband IP-connectivity and mobility are common attributes for a future mobile broadband IP network. 3G is maturing and WiMAX is coming into the mobile world, where both systems continually seek to improve performance. WiMAX market acceptance as a competitor to 3G systems depends among other factors a lot on performance.

Fixed WiMAX is a promising wireless access system, which is well suited for rural areas and areas in general with lack of infrastructure. Low cost deployment of a system with great performance and wide coverage is attractive, where expensive cable investments are saved. A future profile of WiMAX will add mobility and become a mobile wireless broadband access system called mobile WiMAX, which is planned to be incorporated in laptops, PDAs and cellular phones. Both profiles will offer the quadruple play which represents broadband internet access, television and telephone service with wireless service provisions.

WiMAX is under development, and will support mobility in the coming release. It is therefore interesting to gain a deep understanding of the fixed system, which builds the foundation for the mobile WiMAX platform. The physical layer in the mobile profile has been improved. Performance is enhanced and complexity is added. Standardization of the network architecture is needed to support mobility in an all-IP system as WiMAX. Advanced features have been added to different parts of the system. A goal of this thesis is to gain a deep understanding of both the fixed and the mobile profiles of WiMAX, and present them in a well arranged presentation.

The main goal of this thesis is to perform reliable performance tests in order to conclude upon WiMAX performance. Both the fixed and mobile WiMAX profiles will be considered. The goal is further subdivided into two as illustrated in Fig. 1, and described as follows:

The first goal is to conclude upon fixed WiMAX performance. The conclusion is based on data from two scientific research methods. One experimental research method was used where we sat up a fixed WiMAX field trial over which measurements were performed. A second empirical research method was used where we analysed a real life WiMAX deployment.

The second goal is to investigate how the future mobile WiMAX system will perform. We used an experimental research method for achieving this goal. The method was to set up a field trial with a pre-mobile WiMAX system over which we performed measurements.

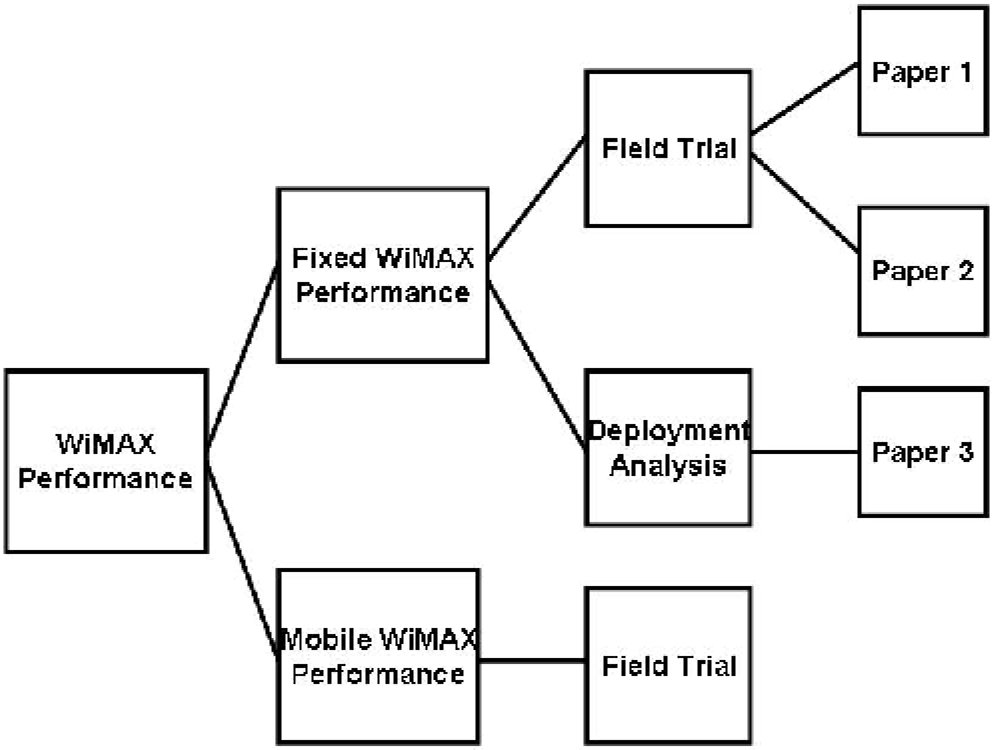


Fig. 1 Main Goals of Thesis

Equipment for Fixed WiMAX reached the marked in early 2006 and was used for performance testing. An extensive test bed was setup, where we measured a range of important performance parameters for the radio link quality, throughput and coverage. Strengths and weaknesses in the system was pointed out and discussed, where iterative measurements were performed and the system was configured to behave optimal. We derived analytical expressions for throughput performance and a path loss model based on the measurements performed.

Our field trial performance measurements were satisfactory in that a conclusion could be drawn on performance with one subscriber present in the system, but it would be interesting to analyse the system performance with many subscribers. As a real life fixed WiMAX deployment had expanded with a great amount of subscribers and base stations, we decided to analyze the deployment in early 2007. The physical parameters were extracted from all the present subscribers, over which we performed extensive analysis of the system performance. Signal propagation and co-channel interference was analysed. We derived an accurate path loss model with great confidence due to the large amount of measurements obtained.

A mobile WiMAX profile adds mobility to WiMAX and is expected to be on the market in 2007. The mobile WiMAX profile is hyped and told to surpass other wireless access systems with a combination of broadband and mobility, but little or no information exists about performance in real life. As a pre-mobile WiMAX system was available in February 2007, we sat up a field trial over which we performed measurements for throughput and physical performance at a range of random locations. The system was delivered with 4th order diversity, thus measurements was executed and analyzed on the performance of different orders of diversity. We derived analytical expressions for the performance gain achieved when adding orders of diversity.

With hands on experience and analyzed results from a fixed WiMAX- field trial, a real life fixed WiMAX deployment and a pre-mobile WiMAX field trial, we will draw a conclusion that uncovers all the hype, abuse and expectations about WiMAX performance.

1.2 Problem Statement

Little or no published information is presented about WiMAX performance based on real life measurements. WiMAX is victim of great expectations, rumoured to be hyped and often abused. This thesis seeks to uncover the WiMAX performance in real life. The problem statement is simply stated as:

> *How does WiMAX perform in real life according to the theoretical limitations given by the standard specifications.*

The WiMAX standard constitutes the two profiles fixed- and mobile WiMAX, which are based on the IEEE 802.16d [3] and IEEE 802.16e [4] specifications of the IEEE 802.16 standard [3] respectively. The fixed WiMAX profile will be the main focus in this thesis as certified equipment for this profile became available in mid 2006, over which we performed extensive field trial measurements in addition to a deployment analysis. The mobile WiMAX profile will be certified in mid 2007, but as a pre-mobile WiMAX system became available in early 2007 this will also be considered with extensive measurements over a field trial setup. The problem statement therefore considers both profiles, where the fixed WiMAX performance will be concluded upon with great confidence and the mobile WiMAX profile performance will be a study of what the future mobile profile will bring to WiMAX.

In real life is meant that WiMAX systems are set up in real life field trails, and will be used for performance testing. Real life also suit to the analysis performed over a WiMAX certified system deployment, which operates as it is in real life. The systems tested are as delivered by a specific vendor.

Performance is defined as *"A major factor in determining the overall productivity of a system, performance is primarily tied to availability, throughput and response time"* [5]. A range of different system characteristics can be considered to determine the overall productivity of a WiMAX system. To place a limitation on this study, the performance of WiMAX was limited to throughput and coverage at different distances under various conditions and sight capabilities. Throughput and coverage are tightly related to the link quality and conditions. By link quality we mean physical parameters such as received signal strength, signal to noise ratio, transmitted power, modulation rate and multipath effects. By conditions we mean distance, interfering objects and sight capabilities. All these parameters and the relation between them will be studied. WiMAX is a complex system, thus it will be important to relate the measured performance attributes to the WiMAX system characteristics when analyzing.

From the definition of throughput, "*The amount of actual user data (payload) transmitted per second without the overhead of protocol information such as start and stop bits, TCP/IP overhead, HTTP headers, and such.*" [6], it can be seen that throughput is the user data transmitted and not the physical bitrate, thus a negative variance should be estimated. Another deviation from the standard is the system implementation from a specific vendor, which should be evaluated according to the standard specification.

The theoretical limitations for throughput and coverage given by the standard specifications are the calculated maximum quantity that could possibly be achieved in a given scenario with specific conditions and system parameters. For instance there might be perfect sight capabilities where the highest modulation rate is used, such that the theoretical limitations specify a maximum throughput of 12.71 Mbps in a 3.5 MHz channel. The coverage would, in this scenario, have theoretical limitations specified to the free space loss in the 3.5 GHz band with the actual system parameters. It should be considered that management traffic and different layers in the communications stack introduces overhead to the throughput compared to the physical bitrate.

1.3 Research Methods

This thesis utilized two scientific research methods, which was an experimental research method and an empirical research method. *"The two research methods are often contrasted, but an essential difference is that in an experiment, the different 'trials' are strictly manipulated so that an inference can be made as to causation of the observed change that results. This contrasts with the empirical method of aggregating naturally occurring data."* [7]. Aggregating naturally occurring data refers to the empirical research method.

Experimental research methods were further used in two occasions in this thesis. Field trials for performance measurements and analysis over two different WiMAX systems, one fixed and one pre-mobile, delivered by a specific vendor were set up at different locations. The main features of the experiments were to set up field trials, with a manipulated set of initial parameters and perform measurements in various topological environments and under different conditions. The resulted data and analysis based on the experiments were used to derive analytical models and conclude upon WiMAX performance in real life.

Empirical research is defined as *"any research that bases its findings on direct or indirect observation as its test of reality"* [8]. This thesis will utilize an empirical research method for analysis performed over parameters extracted from a fixed WiMAX system deployment in reality. *"An empirical method is generally taken to mean the collection of data on which to base a theory or derive a conclusion in science"* [7]. This thesis will employ an empirical method where analytical models and conclusions will be based on data collected from the fixed WiMAX deployment.

"The scientific process is iterative. At any stage it is possible that some consideration will lead the scientist to repeat an earlier part of the process." [9] This is often the case when performing measurements over real life field trials, where for instance misconfigured system parameters may cause abnormal system behaviour. This may cause the measurements to be repeated. The experimental measurements was therefore analysed and iterated before the actual experimental measurements were performed. The iterative processing of experiments lead to construction of problem statements and assured higher quality of the results obtained.

When using a scientific method, it is important to make available all data and the methodology used so it is available for careful scrutiny by other scientists, thereby allowing other researchers the opportunity to verify results by attempting to reproduce them. A scientific research method is understood to follow a structural process, but the steps order may vary dependent on the subject of research and other factors. The experimental and empirical research methods used in the fixed and pre-mobile WiMAX field trials and fixed WiMAX deployment are quite similar and illustrated in Fig. 2.

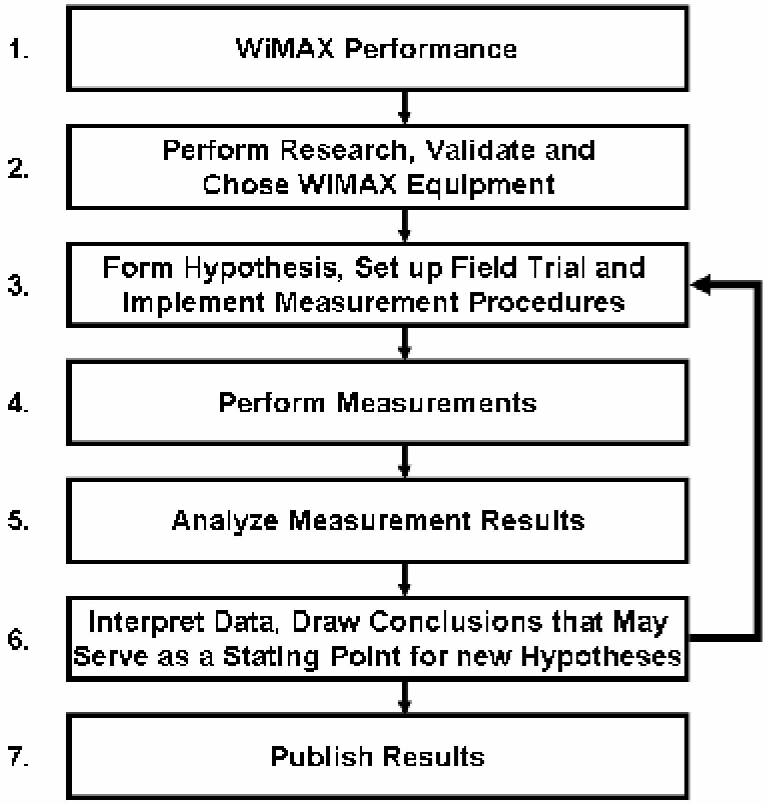


Fig. 2 Steps followed in the Scientific Research Methods

The topic and question for the research is defined in step 1, which will be fixed and mobile WiMAX performance in the respective researches performed.

In step 2, research is performed on the system where documentation, background and relevant information are investigated. It is common to distinguish independent and dependent variables in scientific research, where the performance variables throughput and coverage are dependent in that their values depend on a range of other variables in our case. Both throughput and coverage depends on the other variables or attributes that may be distance and sight capabilities between sender and receiver, received signal strength, signal to noise ratio, modulation technique, order of diversity and other parameters as time of year and weather conditions. Most of these variables are important for analysis, where relationships among them may have huge impact on performance. For instance the relation signal strength versus signal to noise ratio reveals interference that reduces the throughput performance. Based on a developed specification, we evaluated and confirmed equipment to be used for testing from various vendors. The equipment should support the needed functionality to perform the required experiments.

In step 3, we form the hypothesis. A scientific method requires that one can test a scientific hypothesis. *"A hypothesis consists either of a suggested explanation for a phenomenon or of a reasoned proposal suggesting a possible correlation between multiple phenomena"* [10]. The hypotheses in this thesis are based on the vendor specification of the equipment used in the field trial and deployment analyses, where for instance a claim that the system provides a throughput of 9.6 Mbps under ideal conditions. This may be the main hypothesis for the throughput variable. Another specification is that throughput is different under certain conditions with a specific modulation rate, which also will be a hypothesis. There are also relations between phenomena, for instance that the system will have lower throughput performance when the sight capabilities are weak. The different scientific methods for studies performed in this thesis will have different hypotheses, and there may be several hypotheses for each. With well formed the hypothesis, the field trial is setup. We install the equipment, decide upon which measurements to perform at which locations, design the procedure and implement automated measurement procedures.

The measurements are then performed in step 4, before they are analyzed in step 5. As the WiMAX performance is dependent on many attributes, the definition of analysis is seen as *"the abstract separation of a whole into its constituent parts in order to study the parts and their relations"* [11]. Analyses involves the displaying of graphs and tables, investigation of relationships among attributes and other phenomena, mathematic involving calculus and theory of limits and the use of relevant work and theories.

The data is interpreted in step 6, where mathematical models and expressions are derived before conclusions are drawn. The conclusion may serve as a starting point for a new hypothesis. A failure in the experiment to produce interesting results may lead to reconstruction of the method, hypothesis, field trial setup or measurement procedure. An iterative cycle inherent in this step-by-step methodology therefore goes from point step 3 to step 6, and back to step 3 again.

The final step 7 is to publish the results in both this thesis and in paper format for scientific conferences.

1.4 Main Contributions of Thesis

The main contribution and objective of this thesis is to determine the performance of WiMAX through real life experiments with field trials and deployment analysis. Especially performance regarding throughput, coverage and link quality will be measured and analyzed. Both fixed WiMAX and a pre-mobile WiMAX are measured and analyzed.

A second contribution is a well arranged and detailed presentation of background on WiMAX, where both the fixed and mobile profiles are presented. This presentation aims as a tutorial for students and other parties interested in learning about WiMAX.

This thesis resulted in four conference papers as illustrated in Fig. 1. Two papers are based on the measurement results from the fixed WiMAX field trial and a third paper is based on the fixed WiMAX deployment analysis. The contributions of the papers may be described as follows:

Paper 1, “Fixed WiMAX Field Trial Measurements and Analyses”, contributes with the presentation and analysis of fixed WiMAX field trial measurements. We derive two analytical expressions for UDP bitrate, one as a function of distance and a second as a function of received signal strength. Signal propagation is analysed and compared against well known propagation models.

Paper 2, “Fixed WiMAX Field Trial Measurements and the derivation of a Path Loss Model”, contributes with the presentation of fixed WiMAX field trial measurements and the derivation of a path loss model based on non line of sight conditions. We also derive a model for calculating received signal strength as a function of signal strength.

Paper 3, ”The Physical Performance and Path Loss in a Fixed WiMAX Deployment”, contributes with analysis of measurement results from a fixed WiMAX deployment with 850 subscribers. Based on these measurements a path loss model is derived, which is of great confidence due to the large amount of measurements. Co-channel interference is revealed.

The conference papers are based on this thesis, thus the contents of this thesis has the same contributions. These contributions are found in this thesis as described in Fig. 1. Since this thesis contains the fundament for the papers, additional background work has leaded to other contributions. One contribution is the implementation of automated measurement scripts, which have been of great importance for use when performing measurements over the field trials in an accurate and efficient manner. Secondly, much time has been spent on research to achieve maximum system performance, which is as close to the vendor specification and physical system limits as possible. This thesis aims at uncovering difficulties for deployment of a WiMAX system, where solutions to problems and system tuning are given and solved before a WiMAX system can be deployed and field trials can be performed.

As little or no presented material existed about real life WiMAX performance previous to this thesis, it will hopefully be of great importance to students, operators, service providers and other instances involved in WiMAX.

1.5 Outline of Thesis

This thesis is arranged in a way that all the chapters may be read as standalone chapters, but all chapters are recommended to be read consecutively for a throughout study. Fig. 3 illustrates the organization of the rest of this thesis together with the scope, contributions, scientific method used and published papers specific for each chapter. The problem statement in Fig. 3 is illustrated as a read thread throughout this thesis.

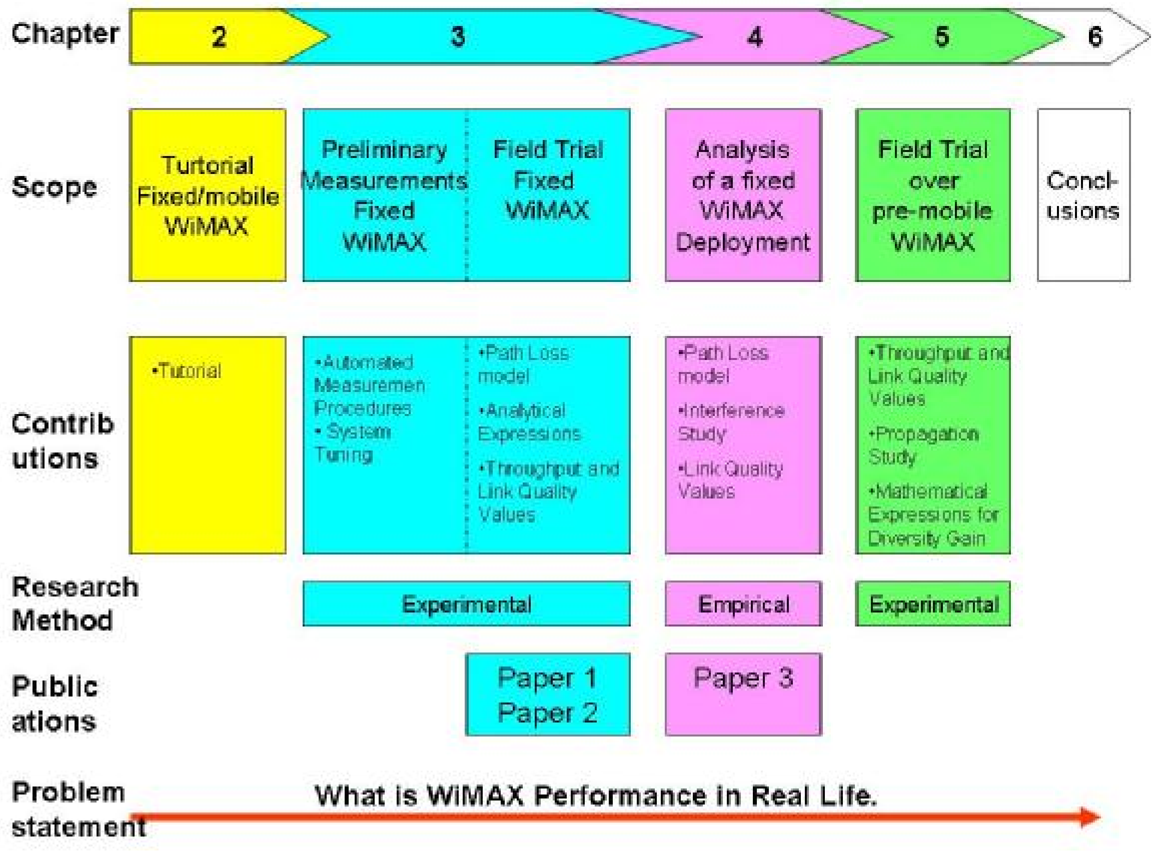


Fig. 3 Chapters, Scope, Contributions, Publications and Problem Statement.

The organization of this thesis is as follows:

Chapter 2 presents background on WiMAX. The two main profiles of WiMAX, that is the fixed- and mobile profile will be described in detail. This chapter act as a background chapter in the thesis context, but is constructed to be used as a tutorial.

Chapter 3: Equipment for fixed WiMAX reached the marked in early 2006 and later became WiMAX certified. This chapter presents extensive measurements and analysis based on the fixed WiMAX field trial measurements. Discussion is given on system tuning to obtain maximum performance. Physical and throughput performance is analyzed. A path loss model and mathematical expressions for system performance is derived.

Chapter 4: We performed a fixed WiMAX field trial in the previous chapter, which concluded upon performance with one subscriber present in the system. In this chapter, we present the study and analysis of fixed WiMAX deployment that have increased largely, with focus on physical performance. A path loss model with enhanced confidence is derived based on a great amount of measurement points and co-channel interference is revealed.

Chapter 5: Mobile WiMAX is approaching the market and the expectations about system performance are huge, but little or no information exists about performance in real life. This chapter presents field trial measurements over a pre-mobile WiMAX system that was setup in February 2007. Important measurements together are performed and extensive analysis is given on system performance. The system uses 4th order diversity, thus we measured the performance with different diversity orders, the analysis is presented and analytical expressions are derived.

Chapter 6 concludes upon WiMAX performance.

Some appendixes are attached to this thesis. They are listed and described shortly in the following subsection.

1.5.1 Appendixes

Appendix A describes the measurement locations and lists the raw results from the WiMAX field trial measurements in Chapter 3.

Appendix B gives the results and location description for the preliminary field trail measurements.

Appendix C lists the raw results from the WiMAX Deployment Analysis and frequency planning data.

Appendix D lists the results from the pre-mobile WiMAX field trail measurements.

Appendix E contains source code for the automated measurement procedures implemented.

Appendix F contains the three conference papers based on work in this thesis.

2 Background on WiMAX

2.1 Introduction

WiMAX is a certification mark for products that pass conformity and operability test for the IEEE 802.16 standard [3]. It is a technology enabling the delivery of last mile wireless broadband access (BWA) as an alternative to cable and DSL. It is a point-to-multipoint (PMP) architecture, which resemble our traditional mobile telephone system, though it differs in specification and properties. Mainly WiMAX defines an all-IP architecture, which supports high throughput over long distances. Two layers in the OSI-stack are defined by WiMAX, which are the Physical (PHY) and the Medium Access Control (MAC) layer. These will be described in later sections.

By arguing that WiMAX is all-IP, is meant that a common IP network core is used, where the circuit core network is absent in favour of the IP packet network. Overhead and complexity is reduced by deploying a single protocol. The fact that WiMAX is all IP makes it extremely attractive in that it is well suited for IP-services like among others VoIP, IPTV, streaming applications and Internet surfing. Services already available at the internet will be available for use over WiMAX. This is realized since IP works outside and inside the access network.

WiMAX is based on the IEEE 802.16 standard. Features that are mandatory in 802.16 are mandatory in WiMAX, and optional features in IEEE 802.16 may be optional, mandatory or not included. WiMAX is therefore a subset of the IEEE 802.16 standard as illustrated in Fig. 4.

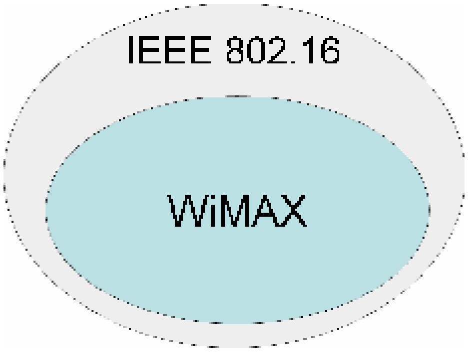


Fig. 4 WiMAX a subset of IEEE 802.16

The main part of the WiMAX is the compatibility and interoperability of WiMAX products, which is provided by WiMAX Forum [1], an organization of leading operators, communications-, components- and equipment companies. WiMAX systems implemented by various vendors with different equipment will interoperate. The common platform will drive down costs and enhance performance, thus the market will adopt the technology faster and more widely. A parallel can be drawn to the success of WiFi, a Wireless Local Area Network (WLAN) system, specified by the WiFi Alliance [12] based on the standard 802.11b/g [13, 14].

The IEEE 802.16 Air Interface Specification contains options for a number of physical layers for different frequency bands and region-by-region frequency regulatory rules. In order to achieve interoperability, WiMAX has undertaken the development of System Profiles specifying which options to utilize. Testing Specifications are developed to verify these specific profiles, and

Certification Labs are used to permit vendors to prove that their equipment meets these profiles and interoperates. WiMAX Forum arranges meetings called plugfests, where vendors meets for validating and verifying interoperability with other vendors equipment [15].

Two system profiles are defined. Fixed WiMAX was first specified and later mobile WiMAX which adds mobility to WiMAX. These profiles are based on the specifications IEEE 802.16d and IEEE 802.16e respectively. An overview will be given for both system profiles.

The initial version of the IEEE 802.16 specification was aimed at the frequencies between 10 and 66 GHz, but the functionality possible in these frequencies is limited when considering the requirement for Non Line of Sight (NLOS) and mobility. Line of Sight (LOS) is a must at these higher frequencies and the multipath effects may be omitted. The IEEE 802.16 Working Group is now focusing on the sub 11 GHz frequency ranges, where NLOS is a requirement. At higher frequencies there is less interference and wider bandwidths are available, which is suitable for point to point (PtP) LOS backhaul connections between base stations and mesh networking.

WiMAX specifies layers in the IEEE 802 reference model as illustrated in Fig. 5, which contains the lower two layers in the OSI reference model. WiMAX specifies the Medium Access Control (MAC) and Physical (PHY) layers. This reflects the all-IP structure of WiMAX, where the network layer (e.g. IP-layer) is above the IEEE 802 reference model.

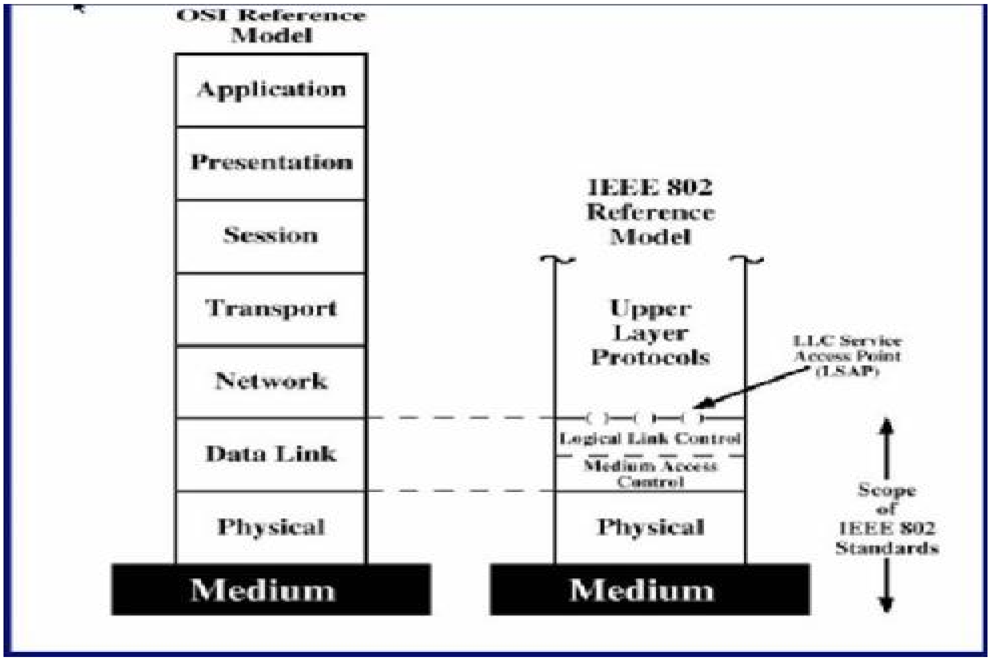


Fig. 5 OSI and IEEE 802 reference models

Quality of Service (QoS) is extensively supported in WiMAX, where a range of different classes is provided to differentiate packets by levels of prioritizing. QoS can be guaranteed in the WiMAX access network. Further QoS is also supported throughout the network, where VLAN tagging and Differentiated Services may be used.

Security is also well supported through encryption and authentication.

The following two sections present tutorials for both fixed- and mobile WiMAX, where the MAC and PHY layers will be presented for each.

2.2 Fixed WiMAX

The fixed WiMAX profile, based on the IEEE 802.16d specification, is mainly targeted for fixed wireless access, but may also support nomadic and portable access.

Fragmentation and packing is used at both the MAC and PHY layers. A variable length Protocol Data Unit (PDU) is used at the MAC layer. A PDU is the data exchanged between peer entities of the same protocol layer (Fig. 6). Multiple MAC PDUs may be concatenated into a single burst at the physical layer to save overhead and increase throughput. Similarly, multiple Service Data Units (SDU) from the same network service, may be concatenated into a single MAC PDU. A SDU is the data unit exchanged between two adjacent protocol layers. Thus overhead is saved by both the MAC and PHY layer. TCP/IP is the Transmission Control Protocol (TCP) on top of the Internet Protocol (IP), which is a group of protocols that specify how computers communicate over the Internet. All computers on the Internet need TCP/IP software.

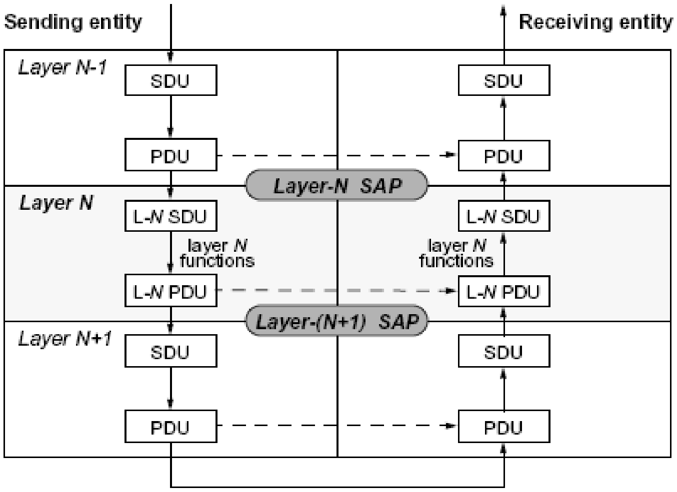


Fig. 6 PDU and SDU in the protocol stack [16]

The following two subsections present the MAC and PHY layers for fixed WiMAX.

2.2.1 PHY Layer

The physical layer is the bottom layer in the OSI and IEEE 802 reference models, hence also in the TCP/IP stack. PDUs arriving from the MAC-layer are processed for transmission on the physical channel. The most important parameters for fixed WiMAX are listed in Table 1, and discussed in the following subsections.

Table 1 Parameters for fixed WiMAX (802.16-2004)

	Fixed WiMAX (IEEE 802.16d)
Multiplexing	OFDM

FFT size	256
Duplexing mode	TDD, FDD, HFDD
Modulation	BPSK, QPSK, QAM16, QAM64
Channel bandwidth	3.5, 7, 10 MHz
Frequency	2 GHz – 11 GHz

2.2.1.1 Multiplexing

In telecommunications, multiplexing is the combining of two or more information channels onto a common transmission medium [17].

Orthogonal Frequency Division Multiplexing (OFDM) splits the broad carrier-frequencies into multiple sub-carriers that each uses its own frequency as illustrated in Fig. 7. Each sub-carrier can then carry different parts of a frame simultaneously. Input data stream is divided into several parallel sub-streams of reduced data rate, each modulated and transmitted on a separate orthogonal sub-carrier. This is a FDM scheme where all the sub-carriers are orthogonal to each other with no overlap to avoid interference. Increased bandwidth and data capacity is achieved. Since the data rate of each sub-stream is reduced, the symbol duration is increased. This improves the robustness of OFDM to delay spread [1]. Since the information is transmitted at a lower rate, the effects of fading and intersymbol interference are mitigated.

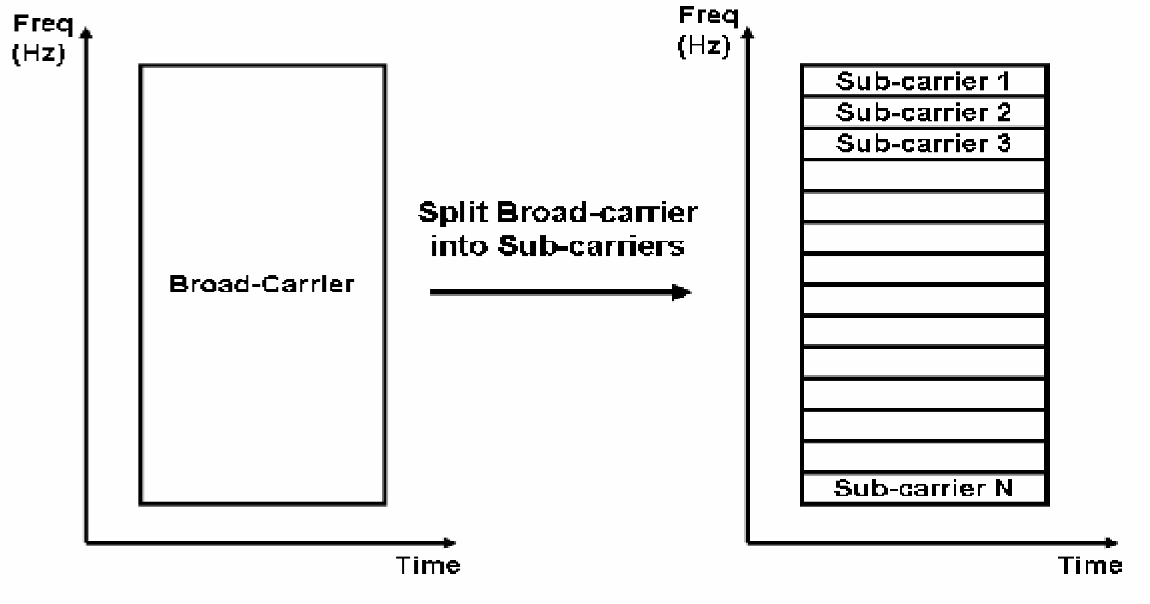


Fig. 7 OFDM - Splitting Broad Channel into Sub-channels

Compared to a single carrier system, the data rate on each of the channels equals the original rate divided by the number of carriers used. Interference between the different carriers is nearly eliminated [18]. OFDM-based systems are used to overcome the Non Line Of Sight (NLOS) propagation.

2.2.1.2 Frame Structure

The OFDM PHY layer maps into a logical structure that represents a frame, with FFT-symbols on the horizontal axis and sub-carriers on the vertical as illustrated in Fig. 8.

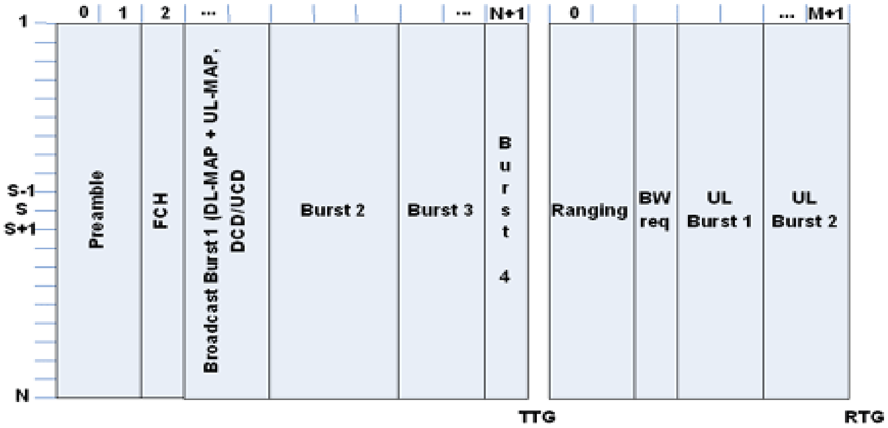


Fig. 8 OFDM Frame Structure [3]

FFT symbols can be put together into a burst as viewed from the MAC layer. Each burst is scheduled for use by a subscriber, where the frame can be viewed as a one-dimensional structure in that all the sub-carriers for an FFT instance are being allocated to the same burst. From there on, bursts are being concatenated by contiguous FFT instances.

In Fig. 8, Burst 1 is allocated for broadcast and goes to all the subscribers. This burst contains downlink and uplink Media Access Protocol (MAP) messages, which contain the outline for the current downlink and uplink OFDM frame. The bursts 2, 3 and 4 are sent to the subscribers 2, 3 and 4 respectively. The Preamble frame is used for synchronization between Subscriber Stations and the Base Station.

Downlink (DL) is the left part of Fig. 8, and uplink (UL) is the right part. Both the DL-MAP and UL-MAP are located in the broadcast Burst 1 in the downlink part of the frame. The FCH (Frame Control Header) burst provides information for the frame configuration such as MAP message length, coding scheme and usable sub-channels.

TTG is a gap introduced to let the BS switch from transmit to the receive mode, and RTG vice verca.

Multipath interference caused by signal reflections from different obstacles is common in wireless systems, causing various versions of the same signal to arrive at the antenna at different times. These multiple signals can interfere with each other when arriving out of order. This is called Inter Symbol Interference (ISI), which is often coped with by implementing a time domain equalizer (channel filter) that multiplies the received signal with the estimated channel response. In WiMAX, ISI is effectively mitigated by a Cyclic Prefix (CP) appended to the end of the data payload in a block as illustrated in Fig. 9. The criterion for this is that the CP duration is longer than the channel delay spread. The CP is a repetition of the first data samples of the block. Some overhead to the bandwidth efficiency is caused by the CP, but is considered as significant to system performance.

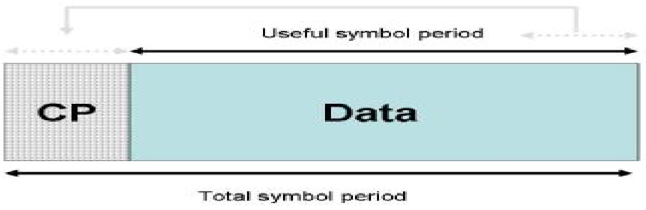


Fig. 9 Cyclic Prefix

The OFDM symbol is made up of sub-carriers of three different types, where the amount of sub-carriers determines which FFT size used as illustrated in Fig. 10. The different types of sub-carriers are:

1. **Data sub-carriers** for data transmission
2. **Pilot sub-carriers** for estimation and synchronization purposes
3. **Null sub-carriers** for no transmission, which is used for guard bands and DC carriers

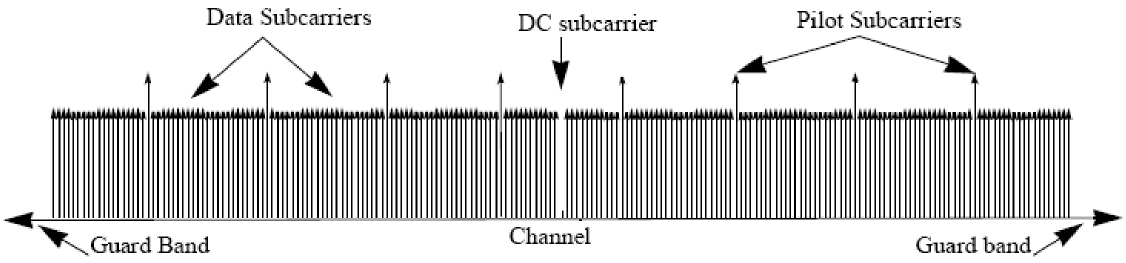


Figure 196—OFDM frequency description

Fig. 10 OFDM Frequency Description [4]

2.2.1.3 Duplexing

A duplex communication system is a system composed of two connected parties or devices which can communicate with one another in both directions [19]. A duplexing technique is needed to allow communication between two parties in both directions.

In the fixed WiMAX system one can use one of the two duplexing techniques offered by the specification, Time Division Duplexing (TDD) or Frequency Division Duplexing (FDD). TDD allocates different timeslots for uplink and downlink, FDD allocates different Frequencies for uplink and downlink. This is illustrated in Fig. 11.

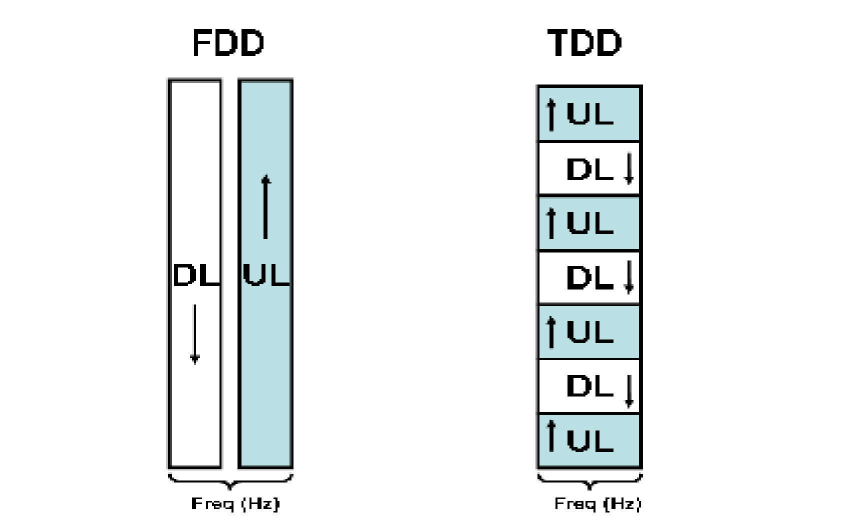


Fig. 11 FDD and TDD

TDD requires more synchronization than FDD, but is more flexible in that asymmetric downlink (DL) and uplink (UL) traffic is supported. A typical scenario would be that DL traffic is much greater than UL traffic. Thus the UL bandwidth would be idle during periods where the DL bandwidth is full. Since TDD support asymmetric DL and UL traffic, this scenario would be solved by allocating different time-slots for DL and UL. For FDD, DL and UL always have fixed bandwidths. TDD also has the advantage that it only requires one channel, whereas two channels are required in FDD.

There is also support HFDD (half-duplex FDD), which is very similar to TDD. An HFDD device transmits and receives at different times like a TDD device. The difference is that it also uses different frequencies for transmit and receive to communicate with an FDD Base Station. As a result, HFDD Subscriber Units offer only half the throughput capacity of a full duplex FDD Subscriber Unit.

2.2.1.4 Adaptive Modulation

Modulation is the process by which a carrier wave is able to carry the message or digital signal (series of ones and zeroes). Four different modulation techniques (Table 1) are used in an adaptive manner, dependent on the link characteristics. BPSK is used when the link quality is weak. A typical BPSK scenario would be at long distances from the BS and under NLOS conditions. QAM 64 is the modulation technique that offers highest data rates, but the link quality must be appropriate. LOS situations at a close distances to the BS are typical scenarios where QAM 64 would be used. The simple physics is that higher order modulations allow us to encode more bits per symbol.

2.2.1.5 Support for different Bandwidths

The system offers different channel bandwidth alternatives, among 3.5, 7 and 10 MHz for fixed WiMAX. The bandwidth that is being used must be determined at system setup. Alternative channel bandwidths is a great advantage for operators when for instance restrictions may be set by the regulators, or competitive spectrum bidding restricts the amount of bandwidth to available for use. With the higher bandwidth alternatives one can achieve great throughput for bandwidth demanding applications.

2.2.2 MAC Layer

The Media Access Control (MAC) sub-layer determines who is allowed to access the physical medium at given times, thus controlling the underlying medium. Packets arriving from the Logical Link Control (LLC) sub-layer are adapted for the physical medium. The MAC acts as an interface between the LLC and PHY. Various responsibilities are given to the MAC layer based on the characteristics of the PHY.

Security is considered at this layer through encryption. Reliability is provided through providing retransmission of lost and erroneous packets, which is important to be handled by the wireless system due to more unreliable physical medium than in fixed networks. The technique used is Automatic Repeat Request (ARQ), which automatically detect errors in packets and request retransmissions at the MAC-layer. Problems with TCP-retransmissions that cause lowered bandwidth may then be spared. Fragmentation and packing is performed.

Who should access the channel is implemented through a multiple access method. Another important topic at this layer is the handling of Quality of Service (QoS). These topics are further discussed below.

2.2.2.1 Point to MultiPoint (PMP) and Multiple Access

WiMAX Medium Access Control (MAC) layer is connection oriented and uses Time Division Multiplex (TDM) for the downlink and a Time Division Multiple Access (TDMA) scheme in the uplink. This reflects the PMP architecture. In TDM, multiple signals can be carried on a single frequency by allocating different timeslots for each receiver. TDMA is similar where each user is assigned one timeslot for transmission on the frequency. TDM in the downlink and TDMA in the uplink are illustrated in Fig. 12.

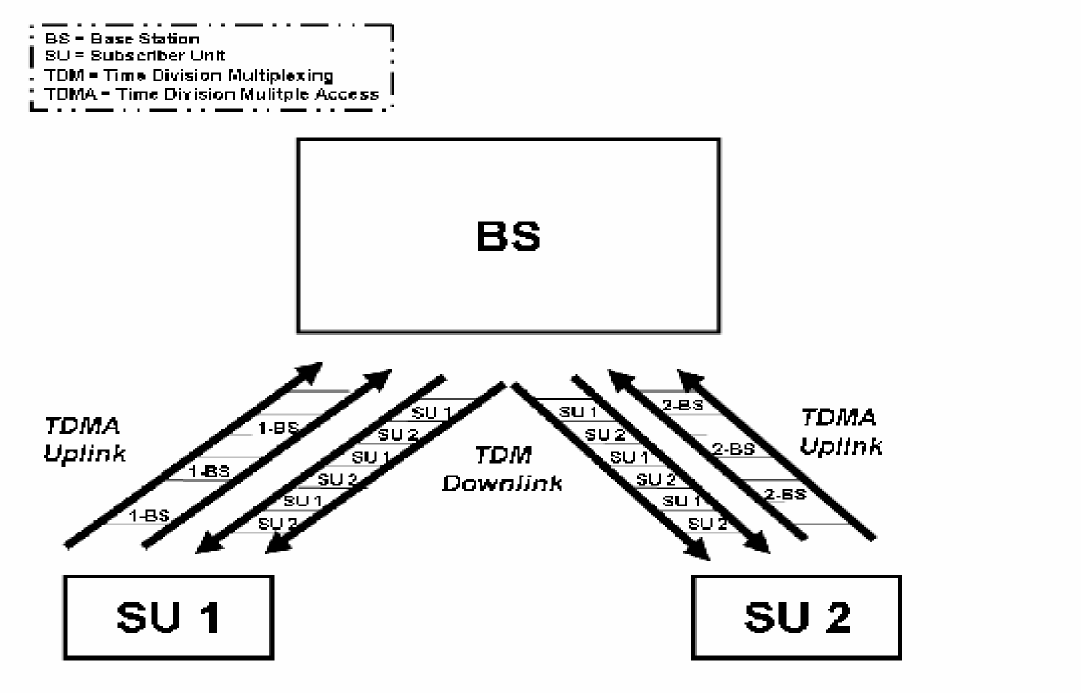


Fig. 12 TDMA in uplink and TDM in downlink

A more precise definition of the multiple access method used is Demand Assignment Multiple Access TDMA (DAMA-TDMA), since time-slots are only allocated when the Subscriber Unit (SU) wants to transmit packets. Traditional TDMA has allocated time-slots without regard to data being transmitted or not. DAMA-TDMA is therefore more efficient in that the bandwidth is only used by the active SUs.

2.2.2.2 Quality of Service (QoS)

The TDM/TDMA access technique assures a collision free data access to the channel which offers a Grant/Request protocol. A polling-based MAC is used, that is more reliable and deterministic than the contention-based MAC used by for instance IEEE 802.11b/g [13, 14]. Differentiated service levels and QoS can thus be quaranteed. A 16-bit Connection ID (CID) is used to identify a connection that can be either a Management or a Transport connection. Additional connections may also be reserved for other purposes like DL broadcast.

The transport connections are unidirectional, where different QoS classes may be used for uplink and downlink traffic. The concept of service flows is used to define unidirectional transport of packets, where each service flow is provided a particular QoS. Each admitted service flow is mapped to a CID. A Service Flow is identified by a 32-bit SFID when inactive. An active Service Flow is thus mapped one-to-one with a connection. Fig. 13 illustrates a Service Data Unit (SDU) arriving from the above layer to the Classifier. The classifier maps the SDU to a Service Flow that when active becomes a Transport Connection identified by the mapping {SDU,CID}.

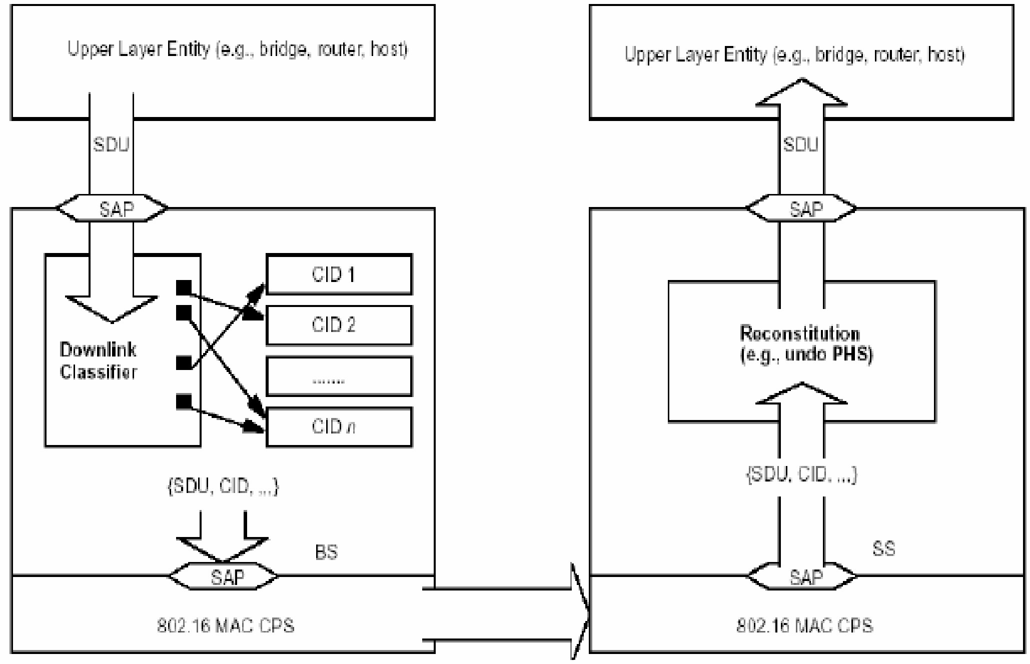


Fig. 13 The Convergence Sublayer, Classification and CID mapping (BS to SS) [3]

A scheduler is located in each base station at the MAC layer. Each {SDU,CID} mapping is given a QoS class. Four QoS classes, as described in Table 2, are defined for WiMAX. These are listed with their respective specifications, their suitable applications and how they are similar to QoS in ATM.

Table 2 QoS Classes and Suitable Applications

QoS Service	QoS Specifications	Suitable Applications	ATM similarities
Unsolicited Grant (UGS)	Maximum Sustained Rate Maximum Latency Tolerance Jitter Tolerance	VoIP	CBR
Real Time Polling (rtPS)	Minimum Reserved Rate Maximum Sustained Rate Maximum Latency Tolerance	Streaming Audio and Video	RT-VBR
Non-Real-Time Polling (nrtPS)	Minimum Reserved Rate Maximum Sustained Rate Traffic Policy	File Transfer Protocol (FTP)	NRT-VBR
Best Effort (BE)	Maximum Sustained Rate Traffic Priority	Data Transfer, Web, Browsing.	UBR

2.3 Mobile WiMAX

The IEEE 802.16e specification adds to the IEEE 802.16 standard the needed functionality to support mobility. As Fixed WiMAX is based on the IEEE 802.16d specification, mobile WiMAX is based on the IEEE 802.16e specification [20].

Mobile WiMAX uses Orthogonal Frequency Division Multiple Access (OFDMA) in the air interface for improved performance in mobile multi-path non-line of sight environments. Scalable OFDMA (SOFDMA) is used to support scalable channel bandwidths [21].

Enhanced and new techniques to better support mobility are added to both the PHY and MAC layers, which will be addressed in the following sub-sections.

It should be noted that a smooth transition between fixed- and mobile WiMAX was planned, but it became clear that this will not be realised because of the different physical layers adopted in the two versions. Mobile WiMAX is considered to be more interesting since it delivers both mobility and the benefits from the fixed part, and is therefore often referred to as universal WiMAX. Future benefits for the fixed part over the mobile part are backhauling, mesh and Point-to-Point (PtP) due to great link capacity. Fixed WiMAX is well suited for home-subscribers in rural areas, whereas mobile WiMAX targets mobile wireless broadband services in addition to the support of fixed wireless broadband.

The following subsections describe the PHY and MAC layers of mobile WiMAX.

2.3.1 PHY Layer

Many of the parameters from the Fixed WiMAX part is kept in mobile WiMAX, but enhancements are done as listed in Table 3.

	Fixed WiMAX (IEEE 802.16-	Mobile WiMAX (IEEE
Multiplexing	OFDM	(S)OFDMA
FFT size	256	512, 1024
Duplexing mode	TDD, FDD, HFDD	TDD
Modulation	BPSK, QPSK, 16-QAM, 64-	QPSK, 16-QAM, 64-QAM
Channel bandwidth	3.5, 7, 10 MHz	5, 7, 8.75, 10 MHz
Frequency	2 GHz – 11 GHz	2.3-2.5 GHz

Table 3 Comparing Physical Layer in mobile and fixed WiMAX

As can be seen from the table, BPSK is removed as an alternative for modulation. TDD is the only choice of duplexing. OFDM has been enhanced by the OFDMA multiplexing technique. Two FFT sizes are decided for use in S-OFDMA. The enhanced multiplexing technique adds sub-channelization. The two key smart antenna methods favoured by the WiMAX Forum, MIMO and AAS or beam forming, could increase coverage from two to nine kilometres radius for an urban base station with mobile support, a 20-fold increase in subscriber capacity [22]. Some of these important topics are to be discussed in the following subsections.

For the mobile part lower frequencies are used due to improving deployment in a mobile channel where Doppler effects [23] and multipath fading [24] are frequently. Radio signals penetrate better and the NLOS requirement is possible to overcome at lower frequencies.

Other advanced features in mobile WiMAX are Adaptive Modulation and Coding (AMC), Hybrid Automatic Repeat Request (H-ARQ) and Fast Channel Feedback (CQICH). These were introduced with mobile WiMAX to enhance coverage and capacity for WiMAX in mobile applications [25].

2.3.1.1 OFDMA

Orthogonal Frequency Division Multiple Access (OFDMA) adds Multiple Access to OFDM. This is achieved by splitting the broad channel into multiple narrowband channels. Each channel is mapped by a set of sub-carriers, and increased bandwidth and data capacity is achieved in addition to multiple access. OFDMA allows simultaneous transmissions from several users, with only a fraction of the narrowband channels assigned to each user. All channels are orthogonal to each other, which stems from the orthogonality between the sub-carriers. Thus no overlap or interference is present between the sub-channels.

Fig. 14 illustrates OFDMA where broad channels are split into sub-channels which are mapped by sub-carriers. In this example Sub-channel 2 is mapped by the sub-carriers 2, 3 and 5. This illustrates that the sub-carriers used by one channel need not be adjacent.

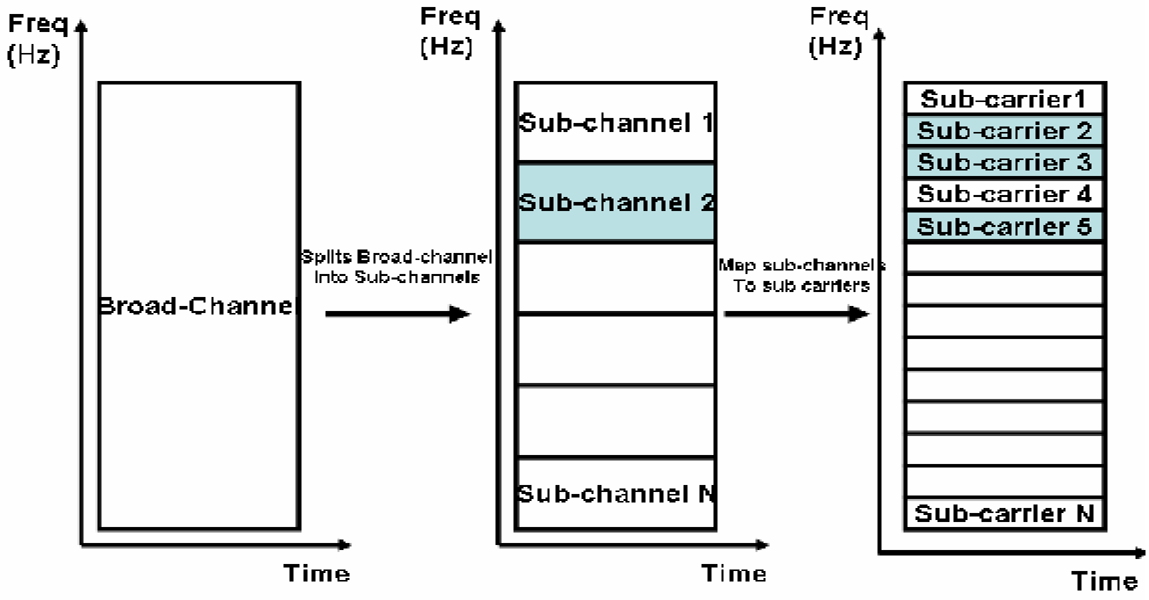


Fig. 14 OFDMA Illustrated

The sub-carrier to sub-channel mapping may be performed with random allocation or contiguous allocation. Random or more correctly semi-random allocation provides frequency diversity and inter-cell interference averaging [18]. Sub-channels requiring great link quality are mapped by the sub-carriers with best conditions, therefore semi-random.

2.3.1.2 Scalable OFDMA

The IEEE 802.16e-2005 Wireless MAN OFDMA mode is based on the concept of scalable OFDMA (S-OFDMA), which supports a wide range of bandwidths to flexibly address the need for various spectrum allocation and usage model requirements [25]. This is realized through fixing the sub-carrier frequency spacing at 10.94 kHz and adjusting the FFT size. So for example a Subscriber moving in a BSs cell may receive 512 FFT or 1024 FFT depending on factors such as channel size.

2.3.1.3 Frame Structure

The frame structure in OFDMA, depicted in Fig. 15, differs from OFDM in that multiple users may access the air interface in parallel through allocation of sub-channels. Since different sub-carriers can be allocated to different sub-channels, the same FFT instance can be allocated to different bursts. A subscriber uses one burst. The OFDM frame (Fig. 8) was viewed as a one-dimensional structure, whereas the OFDMA frame is viewed as a two-dimensional structure.

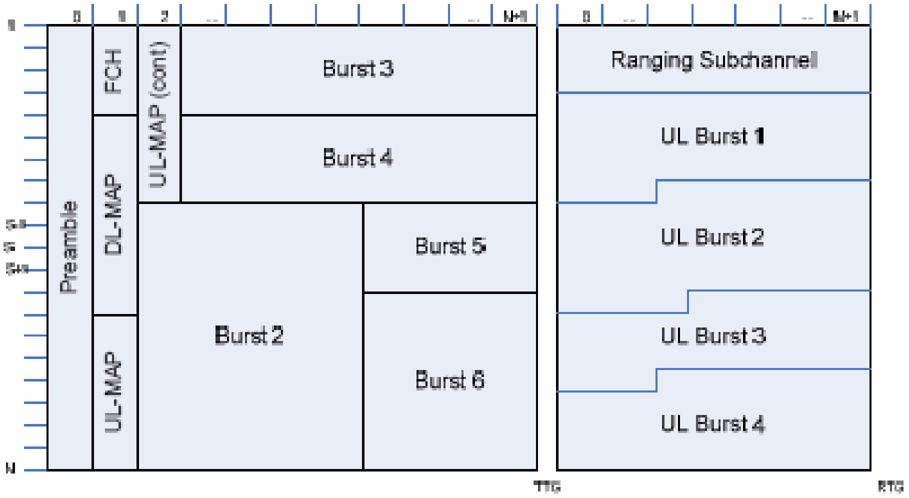


Fig. 15 OFDMA Frame Structure [3]

Each burst may utilize modulation and encoding scheme independent of the other bursts. Burst 2 may for example utilize convolutional coding and QAM64 modulation, whereas Burst 3 uses CTC turbo coding and is modulated with QAM16. The two bursts will then carry different amount of bits with each sub-carrier.

The "Ranging Subchannel" in the UL frame part is allocated for mobile stations to perform closed-loop time, frequency and power adjustment as well as bandwidth requests [21].

Two additional sub-channels are added to the OFDMA DL frame part, but not viewed in Fig. 15. These are UL CQICH for fast feedback about channel state information, and UL ACK to feedback DL HARQ acknowledgement [21].

2.3.1.4 TDD

Time Division Duplex (TDD) is selected as duplexing technique in mobile WiMAX, even though IEEE 802.16e supports FDD. This is a more complex technique than the FDD when considering synchronization, but improves the performance in various ways. A single channel alone is provided for both UL and DL, thus only a single main-carrier is used. Asymmetric uplink and downlink is common in communication, most often in that downlink may be more used than uplink which is efficiently supported by TDD in that more time is allocated for downlink than uplink.

2.3.2 MAC Layer

The Media Access Control (MAC) sublayer has been enhanced especially with the need to support mobility. This includes power management and handover between base stations. Scheduling is also enhanced due to a more varying channel.

Mobile WiMAX has the same support for QoS as the fixed profile (Table 2), with the addition of the QoS-profile enhanced real time-Polling Service (ertPS). It was mainly introduced to support variable sized packets for VoIP. Unsolicited Grant Service (UGS) and rtPS are combined, in that it allows unsolicited bandwidth grants like UGS, but with dynamic sizes as rtPS.

The scheduler is more advanced due to more varying conditions caused by the mobile environment. Available resources are scheduled in response to bursty data traffic and time-varying channel conditions. Fast channel feedback is provided by the CQICH channel, and the adaptive modulation and coding (AMC) combined with Hybrid Auto Repeat Request (H-ARQ) provide robust transmission over the time-varying channel. As in the fixed part, scheduling is performed for both DL and UL traffic. Dynamic Resource Allocation is supported, where resource allocation may be changed on a frame-by-frame basis in response to traffic and channel conditions. Frequency selective scheduling is also supported, where mobile users with strict resource demands are allocated to the strongest sub-channels that are composed of the best sub-carriers [25].

Battery is a critical subject in mobile devices, and should be spared as much as possible for longer duration. Two modes for power efficient operation are therefore added. The first is idle mode, where the mobile station (MS) on the move only is available for DL broadcast traffic messages without registration to a specific BS. Handoff management will therefore not be considered if the MS is in idle mode. The second is sleep mode, where pre-negotiated periods of absence are announced from the MS to the BS. Power usage and radio resources are minimized [25].

Handover must to be supported to obtain mobility. Three mobility modes are supported. The first and only mandatory is Hard Handover, where the connection with the BS is ended first before the MS switches to another BS (break-before-make). The second and optional is Fast Base Station Switching (FBSS) where the BS and MS maintain an active set, which is a list of BSs involved in the FBSS. The MS monitors the active set, and performs handover based on the signal strength from the CQI channel (make-before-break). Thirdly an optional Macro Diversity Handover (MDHO) method may be used, where an active set is kept in the MS and BSs and transmissions are performed from the MS to all the BSs and vice versa. A MDHO starts when a MS decides to transmit or receive unicast messages and traffic from multiple BSs in the same time interval [25].

2.3.3 Network Architecture

Based on the standard IEEE 802.16e, mobile WiMAX is specifying a system that will support mobility. The IEEE 802.16e specifies the MAC and PHY layers, but specification for network layer functionality is needed to support true mobility. Aspects such as inter-network and inter-vendor interoperability for roaming, multi-vendor access networks and inter-company billing [25] must be dealt with. WiMAX forum have therefore formed two additional working groups for these purposes. WiMAX Forum Network Working Group creates higher level networking specifications for fixed, nomadic, portable and mobile WiMAX systems beyond what is defined in the standard. The second is a Service Provider Working Group which connects service provider participation within WiMAX [26].

An end-to-end network architecture [27] is developed by WiMAX forum, with support for services and applications as well as interworking and roaming. Several aspects are considered, which roughly summarized are mobility and handover, QoS, security and multi-vendor interoperability. A logical representation of the network architecture can be identified by the Network Reference Model (NRM) as depicted in Fig. 16.

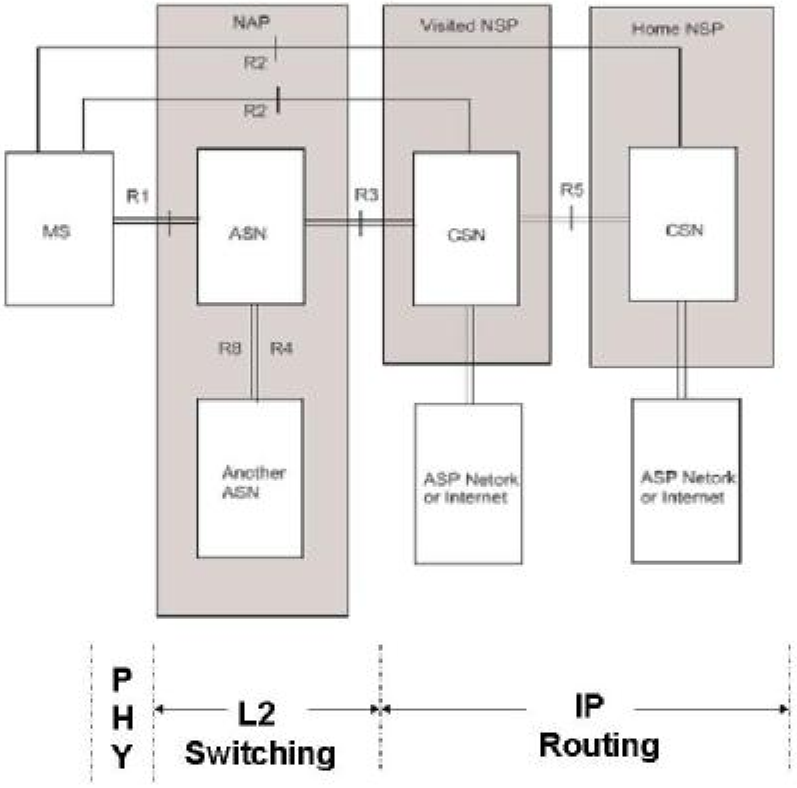


Fig. 16 WiMAX Reference Model

A Mobile Station (MS) is connected with an Access Service Network (ASN) consisting of base stations and one or several ASN Gateways. Interface R1, between MS and ASN, involves Medium Access Control (MAC) functions for station-locating, paging, Radio Resource Management (RRC) and mobility between base stations. ASNs are located within a Network

Access Provider (NAP). Several ASNs may be located within a NAP. ASNs manage the radio links, whereas the NAPs are logical business entities which controls and deploy the ASNs.

Layer 2 (L2) connectivity is provided within the ASN, before the control is handled to a Connectivity Service Network (CSN) which provides IP connectivity (L3). Connection to internet through gateways and routing is kept at this level. Authentication, Accounting and Authorization (AAA) is administrated in this entity by servers and proxies. Gateways for interworking with other networks and MobileIP Home Agents (MIP-HA) may also be present in a CSN. Content services as well as IMS services, support systems for billing and operation will be important. The logical entity maintaining the CSN is a Network Service Provider (NSP), where the amount and type of provided functionality will differ in various NSPs.

Mobility and handovers will be widely supported in the network architecture. Handover-support between WiMAX NSPs as well as with other technologies as for instance WiFi and 3G systems will be provided. Mobility is a requirement and may be supported for IPv4 or IPv6.

QoS will emerge to be an important subject in future and present networks. Extensive QoS support is offered in the WiMAX radio access domain, both per MS and per service flow for the MSs. Services are differentiated and will have the ability to be supported throughout the network by QoS mechanisms as for instance Differentiated Services (DiffServ) [28, 29]. Bandwidth management and admission control is addressed. Policies regarding QoS, as defined by different NSPs, will be implemented through Service Level Agreements (SLA).

Interoperability of equipment from multiple different vendors, within and across ASNs, is a key aspect for system diffusion. Operators will have a scalable, extensible operation and flexibility in selection of network architecture. For instance how to design the network with pico-, micro- and/or macro base-stations. Options for which backhauling technology to use will be flexible, for instance with options for wire line and/or wireless technologies with different qualities.

2.3.4 Advanced Futures

2.3.4.1 Smart Antenna Technologies

OFDMA is well-suited to support smart antenna technologies, which enhances system performance. Smart antenna technologies typically involve complex vector or matrix operations on signals due to multiple antennas. OFDMA allows smart antenna operations to be performed on vector-flat sub-carriers. Complex equalizers are not required to compensate for frequency selective fading. OFDMA therefore, is very well-suited to support smart antenna technologies.

MIMO-OFDM is included in IEEE 802.16e, which holds the potential to drastically improve the spectral efficiency and link reliability [30].

The smart antenna technology beamforming [31] uses multiple antennas to transmit weighted signals to improve coverage and capacity and reduce outage probability. Space Time Coding (STC) is a method used for transmit diversity such as Alamouti code [32, 33], which provides spatial diversity and reduces fade margin. Spatial Multiplexing (SM) [34, 35] transmits multiple streams over multiple antennas to take advantage of higher peak rates and increased throughput.

2.3.4.2 Fractional Frequency Reuse

Fractional frequency reuse [25, 36] is supported in that all cells may operate on the same frequency, where users at the cell edge in adjacent cells uses different sub-channels. Spectral efficiency is maximized and all sectors can use the bandwidth available.

2.3.4.3 Multicast and Broadcast Service

Mobile WiMAX supports a Multicast and Broadcast Service (MBS) which combines the best features of DVB-H [37], MediaFLO [38] and 3GPP E-UTRA [2]. An MBS zone is constructed in the downlink frame, and may operate alone or along with unicast services.

The MBS service can either operate at one single-BS or multi-BS. If multi-BS is used, multiple BSs are providing the same MBS service. Diversity can be provided in that the different BSs transmit the same data at the same sub-channels with the same Connection Identifiers (CID) (IEEE 802.16e [4], section 6.3.23.2). A requirement for MBS service diversity is that the BSs transmit at the same frequency.

2.4 Background Summary and Future Potential of WiMAX

WiMAX has been around for a while, and the fixed part is already rolled out in many countries. Great performance is promised considering some important attributes as bandwidth, coverage and QoS. A cite from WiMAX forum home page says *"WiMAX Forum Certified™ systems can be expected to deliver capacity of up to 40 Mbps per channel, for fixed and portable access applications. This is enough bandwidth to simultaneously support hundreds of businesses with T-1 speed connectivity and thousands of residences with DSL speed connectivity"* [1]. Capacity and other performance attributes remain to be tested throughout this thesis.

As for the mobile part, it is expected to provide up to 15 Mbps of capacity within a cell radius coverage of up to 3 kilometres. Handheld devices, notebooks, laptops and PDAs are expected as targets for the future mobile WiMAX market. As the future cellular systems migrate towards an IP-core, WiMAX is based on an all IP-core and moves towards the mobile power of cellular systems. The two systems seem to meet in the middle, where both the cellular- and computer-originating systems have strengths and weaknesses. Interoperability and interworking will be an important topic for the systems to emerge together while targeting a mobile IP-core. WiMAX is often compared with 3G and WiFi successive systems, and has properties from both of them. Mobility, capacity, all-IP and QoS are important properties.

WiMAX gives its profile specifications based on the IEEE 802.16 standard and specifications, and is a subset of IEEE 802.16 as described in the introduction. A study of mobile WiMAX shows that this is not the case anymore, since the specification includes subjects regarding the network layer. Fig. 17 depicts how these are related, where mobile WiMAX includes a part that is not a subset of the IEEE 802.16 standard, which is the specified subjects regarding the end-to-end WiMAX network architecture. The fixed and mobile WiMAX profiles have much in common, which is described by overlapping the two inner circles in Fig. 15.

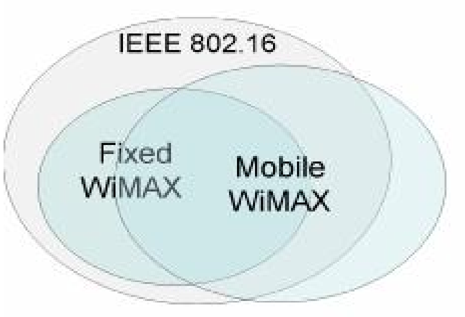


Fig. 17 Fixed and Mobile WiMAX based on IEEE 802.16

WiMAX surely takes these actions to enhance the mobility, which may be necessary to obtain mobile performance on level with the cellular systems. This is a noticeable step in that an extraction is added to the IEEE 802 reference model.

Future amendments to the IEEE 802.16 standard are under development, where one is the IEEE 802.16m which aims at supporting the ITU bandwidth requirements for IMT-Advanced which are up to 100 Mbps during mobility and 1 Gbps for fixed and nomadic clients. 3GPP is not sitting on the fence either, but works toward a Long Term Evolution (LTE) specification [39]. LTE is promised to support 100 Mbps downlink and 50 Mbps uplink [39]. Common futures exists between WiMAX and LTE as OFDMA and smart antenna systems. And the LTE promises in terms of throughput are actually similar to WiMAX at present in a 20 Mhz channel as specified. WiMAX, as an OFDMA system, is in front of LTE with about two years in the standardization process. LTE stems from the 3GPP community which is widely established and has already achieved market acceptance. They will probably co-exist where interworking through systems as IP Multimedia Subsystem (IMS) [40, 41] will be important.

WiMAX forum is backed by heavy companies. To mention some, Intel provides chipsets which will be incorporated in for instance laptops. Nokia and Samsung will provide handheld devices with mobile WiMAX support. Alvarion, Nokia, Alcatel, ZTE and Motorola will provide base stations. Other companies will also provide chipsets which may be incorporated in a range of electronic devices. WiMAX forum ensures interoperability among all the equipment. All these factors will drive down cost and the market will adopt the technology faster and more widely. A global acceptance as for GSM and WiFi is targeted with the best properties from both, a wireless mobile broadband system.

The potential for WiMAX, and especially mobile WiMAX, is to be a global deployed communication standard tightly integrated with an existing global IP network. Based on IP and new innovations concerning performance it may out weight the future versions of today’s traditional mobile communications systems, or at least gain a substantial market share of the existing mobile and DSL communication market.

3 Fixed WiMAX Field Trial

WiMAX is expected to have great performance, rumoured to be hyped and abused by other parties. The goal of this chapter is to conclude upon fixed WiMAX performance with focus on throughput, coverage and link quality.

Since little or no information exists about fixed WiMAX performance in real life, we decided to setup a field trial and perform comprehensive measurements which are presented in this chapter. Other contributions are the derivation of a path loss model and analytical expressions for estimated UDP bitrate and signal to noise ratio as well as the explanation of system setup with system tuning and the implementation of automated measurement procedures for the field trial.

These fixed WiMAX field trial measurements and analysis have resulted in two conference papers (Paper 1 and Paper 2):

1. Grøndalen,O., Grønsund,P.,Breivik,T., Engelstad.P, "Fixed WiMAX Field Trial Measurements and Analyses", Noficated for Acceptance at Mobile Summit 2007, Budapest (Hungary), July 1-5, 2007

2. Grønsund,P., Grøndalen,O., Breivik,T., Engelstad.P, "Fixed WiMAX Field Trial Measurements and the derivation of a Path Loss Model", Submitted to Mosharaka International Conference on Communication Systems and Circuits (M-CSC 2007), Amman, May 21, 2007

This study will hopefully be of great importance and useful to students, operators, service providers and other instances involved in WiMAX.

3.1 Introduction

WiMAX performance is a much discussed topic. Equipment reached the marked in early 2006, and we decided to set up a test bed for real life measurements. The measurements were planned in two steps. First a rough measurement procedure, called "Preliminary Measurements" was performed. Equipment used in these tests was not WiMAX certified, but compliant with the IEEE 802.16 standard. Results from these measurements were used as input to a more extensive and exactly constructed field trial, which will be the focus in this chapter. The "Preliminary Measurements" was important in to eliminate errors in the field trial setup which will be discussed in a sub-section.

The system used in the more extensive field trial was upgraded to be WiMAX certified. Network- and Operating System (OS) specific system parameters were tuned such that the WiMAX system could achieve optimal performance in the field trial, which also will be important for a real life deployment. Python scripts were implemented to automate the measurements, where suitable measurement tools were utilized. A range of locations were decided upon in advance to measure the various scenarios for distance between base station (BS) and Subscriber Unit (SU), elevation over sea and sight capabilities.

Throughput measurements were performed with the protocols FTP, TCP and UDP. The TCP Windows Size was tuned to be high enough to achieve the maximum throughput on both the client and server side for TCP and FTP measurements. Simultaneous uplink (UL) and downlink

(DL) throughput tests were performed for TCP and UDP. Several simultaneous TCP and UDP connections in each single direction from a single subscriber were also measured.

Link Quality tests were utilized to study the physical medium. These included Signal to Noise Ratio (SNR) and Received Signal Strength Indication (RSSI) for UL and DL as well as RX rate, TX rate and TX power. The reason for measuring TX power is that an Automatic Transmission Power Control (ATPC) was used by the SU, where different levels of power can be transmitted dependent on the present link quality.

Based on the field trial measurements over the WiMAX certified equipment, we performed extensive analysis. The RSSI measurements were related to distance and compared against well known path loss models, where our measurements ranges between the free space loss models and the Cost 231 Hata model for suburban areas. The SNR was related to the RSSI and a mathematical expression was derived for this relation. Throughput was analyzed for UDP, TCP and FTP where the results were related to the distance between the BS and SU for discussion.

The RSSI results were used to derive a path loss model concentrated on the locations with Non Line of Sight (NLOS) capabilities. The derivation of the path loss model is explained in detail and compared with other well known path loss models. Two analytical expressions were derived for UDP throughput, where the first as a function of RSSI and the other as a function of distance between the BS and SU.

The rest of this chapter is organized as follows: Chapter 3.2 presents the measurement setup where the preliminary measurements are presented in a condensed form and further used for system tuning. In chapter 3.3, the physical performance is discussed for RSSI and SNR. Throughput performance is presented and analyzed in chapter 3.4. The derivation of the path loss model is described in chapter 3.5. Analytical expressions for UDP throughput are derived in chapter 3.6, before the measurements are summarized in chapter 3.7. All the measurement data for this field trial are given Appendix A, and the preliminary measurements are given in Appendix B.

3.2 System Description and Measurement Setup

The test bed was set up with Alvarion's BreezeMAX 3500, a WiMAX system operating in the 3,5 GHz frequency band. An overview of the measurement setup is roughly a radio access system. Where a WiMAX Base Station (BS) was connected to a VLAN, and a Subscriber Unit (SU) connected to a subscriber as illustrated in Fig. 18. The equipment used in the "Preliminary Measurements" and the "WiMAX Measurements" was the same, where the firmware is upgraded to be WiMAX certified in the latter measurements.

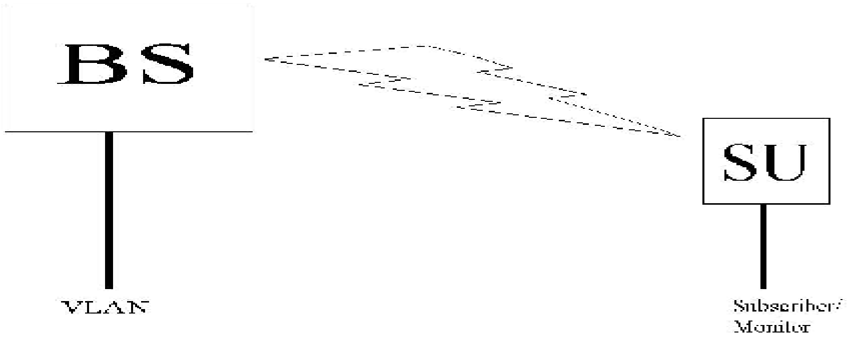


Fig. 18 Measurement Setup with BS and SU

The general Radio parameters in the system were as specified in the fixed WiMAX profile specification, where some parameters were specific to the equipment vendor used. A Frequency Division Duplexing (FDD) technique utilizing two 3.5 MHz channels was deployed, one for UL and one for DL. There was also an option to use 1.75 MHz channels. Adaptive modulations and convolutional coding is used. The parameters used in the system are shown in Table 4.

Table 4 General Radio Specifications

Item	Desciption	
Frequency	Uplink (MHz) 3450-3500, Downlink (MHz) 3550-3600	
Operation Mode	AU	FDD, Full Duplex
	SU	FDD, Half Duplex
Channel bandwidth	3,5 MHz, 1,75 MHz	
Channel Frequency Resolution	0.125 MHz	
CPE-ODU-AV Integral Vertical Antenna	18dBi, 15$_o$ AZ x 18$_o$ EL, vertical polarization, compliant with EN 302 085, V1.1.1 Range 1	
Antenna Port (CPE-ODU-E, AU-ODU)	N-Type, 50 ohm	
Max. Input Power (at antenna port)	AU-ODU	-60dBm before saturation, -17dBm before damage
	SU-ODU	-20dBm before saturation 0dBm before damage
Output Power (at antenna port)	AU-ODU	28dBm +/-1dB maximum. Power control range: 15dB. 18-28dBm @ +/-1dB, 13-18dBm @ +/ 2dB
	SU-ODU	20dBm +/-1dB maximum, ATPC Dynamic range: 40 dB
Modulation	OFDM modulation, 256 FFT points; BPSK, QPSK, QAM16, QAM64	

FEC	Convolutional Coding: 1/2, 2/3, ¾

The UDP throughput in 3.5 MHz channels when 10 CPEs are given in Table 5 as presented by the equipment manufacturer.

Table 5 UDP Throughput with 10 CPEs, packet size 1518 Bytes in 3.5 MHz channels as presented by Alvarion [42]

	DL (Mbps)	UL (Mbps)
QAM64 ¾	9.8	7.8
QAM64 2/3	8.3	6.0
QAM16 ¾	6.3	4.8
QAM16 ½	4.2	3.3
QPSK ¾	3.1	2.2
QPSK ½	2.1	1.6
BPSK ¾	1.3	1.1
BPSK ½	1.0	1.8

3.2.1 Base Station

The BS delivered by Alvarion, was connected to VLAN700, a Telenor internal network. Fig. 19 illustrates the configuration of the BS where three of the slots were used. Two slots were allocated to Access Units (AU-IDU) and one for Network Processing Unit (NPU). The AU-IDUs were connected to Access Unit Outdoor Units (AU-ODU), which again were connected to the antennae. This was the interface to the wireless domain as illustrated in Fig. 21.

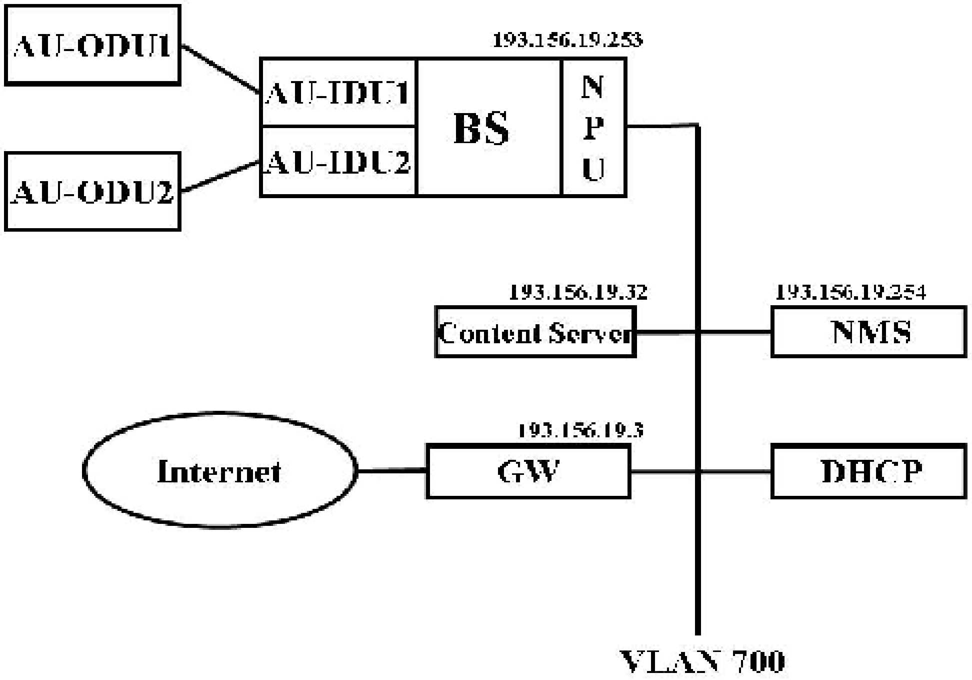


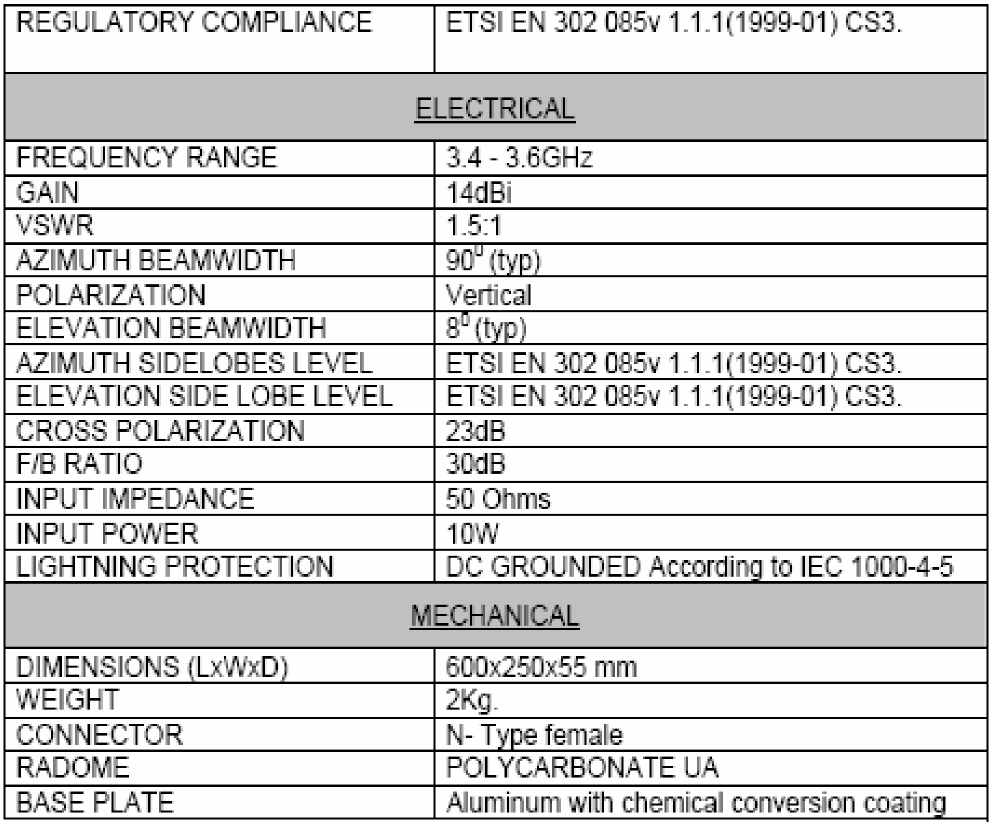
Fig. 19 Base Station connected to VLAN700

The NPU was the heart of the BS where traffic were aggregated from the Access Units and transferred to the VLAN, or backbone, via a network interface. What is meant by expressing that the NPU is the heart of the BS, is that this is where most of the BS functionality is placed. This includes Traffic Classification, connection establishment, Policy Based data switching, Service Level Agreements (SLA), an agent that manages cell sites (AUs), registered SUs, alarms management and synchronization, including GPS, clock and IF reference and A Simple Management Network Protocol (SNMP) agent that enables In Band (IB) management of the Base Station and all its managed SUs. A dedicated 10/100 Base-T interface supports Out Of Band (OOB) management. There were allocated two slots for NPUs in the BS chassis to provide redundancy [43].

The IP-addresses are included for the BS, management system, Gateway (GW) and Dynamic Host Configuration Protocol (DHCP) server in Fig. 19. The Network Management System (NMS) uses SNMP and controls among other things the BSs, subscribers and their services. The DHCP server allocates IP-addresses to the VLAN700 and WiMAX subscribers. The GW is the route to internet where the firewall is controlled. A content server is also included, which will be used to host a server for throughput measurements.

The AU-IDU and AU-ODU was connected via an Intermedia Frequency (IF) cable. The IEEE 802.16 MAC and modem was handled by the AU-IDU. Wireless network connection establishment and bandwidth management was also performed by the AU-IDU. The AU-ODU was a high power, full duplex multi-carrier radio unit that connected to an external antenna. There was support for 14MHz bandwidths with high system gain and interference robustness utilizing high transmit power and low noise figure [43].

Directional antennae were used with azimuth beamwidth at 90° and a maximal gain of 14 dBi. The electrical and mechanical parameters are listed in Fig. 20. Two antennae that point in different directions were used as pictured in Fig. 21.



REGULATORY COMPLIANCE	ETSI EN 302 085v 1.1.1(1999-01) CS3.
ELECTRICAL	
FREQUENCY RANGE	3.4 - 3.6GHz
GAIN	14dBi
VSWR	1.5:1
AZIMUTH BEAMWIDTH	90^0 (typ)
POLARIZATION	Vertical
ELEVATION BEAMWIDTH	8^0 (typ)
AZIMUTH SIDELOBES LEVEL	ETSI EN 302 085v 1.1.1(1999-01) CS3.
ELEVATION SIDE LOBE LEVEL	ETSI EN 302 085v 1.1.1(1999-01) CS3.
CROSS POLARIZATION	23dB
F/B RATIO	30dB
INPUT IMPEDANCE	50 Ohms
INPUT POWER	10W
LIGHTNING PROTECTION	DC GROUNDED According to IEC 1000-4-5
MECHANICAL	
DIMENSIONS (LxWxD)	600x250x55 mm
WEIGHT	2Kg.
CONNECTOR	N- Type female
RADOME	POLYCARBONATE UA
BASE PLATE	Aluminum with chemical conversion coating

Fig. 20 Antenna Technical Specification (3.4 - 3.6GHz 90/V, P.N. 300067)

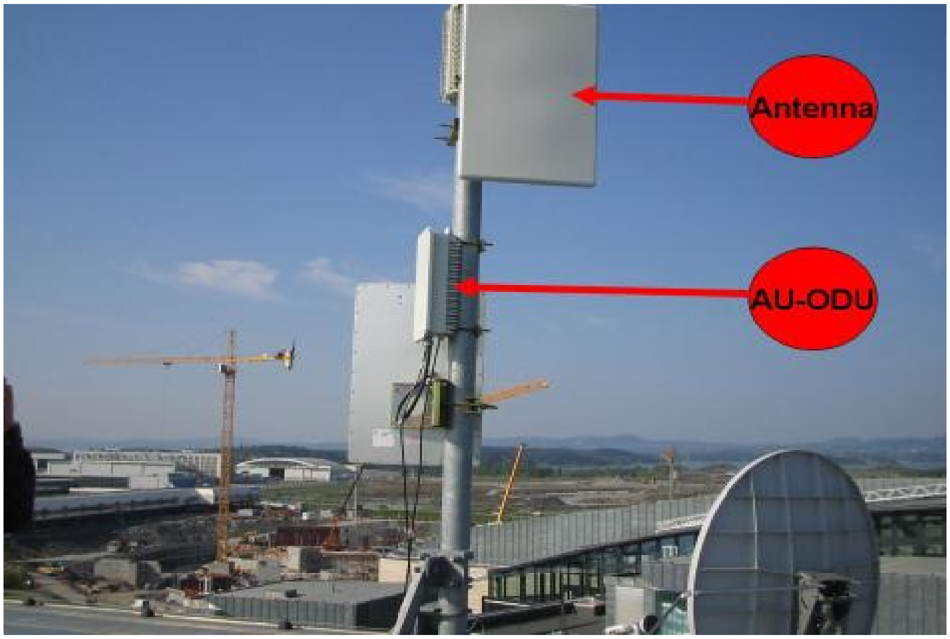


Fig. 21 Base Stations ODU & Antenna

3.2.2 Subscriber Unit

The SU installed at the client side, comprised an Indoor Unit (SU-IDU) and an Outdoor Unit (SU-ODU). These are pictured in Fig. 22. The setup of the subscriber, which was the client side, is illustrated in Fig. 23. The "SU monitor" (PC) was configured with a static IP-address to create a local LAN between the PC and the SU. The purpose of the "SU-monitor" was that it should connect to the SU-IDU and carry out performance monitoring. Functionality for performance monitoring was provided by the SU-IDU.

Fig. 22 SU-IDU (left) and SU-ODU (rigth) [10]

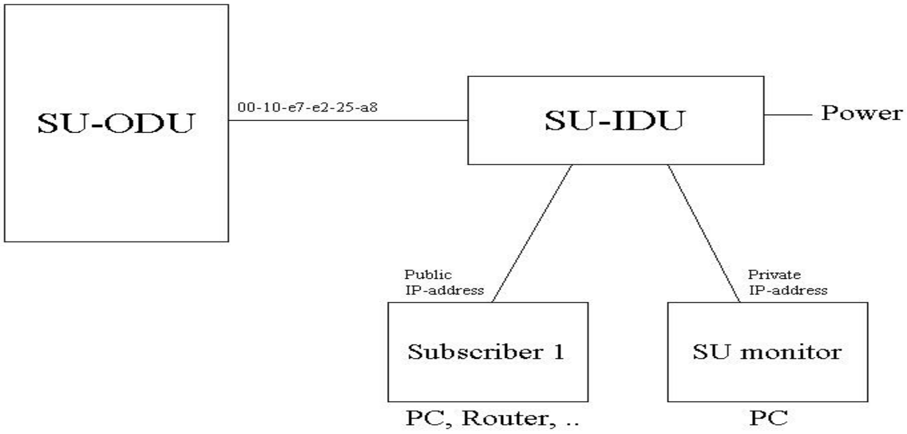


Fig. 23 Subscriber 1 and SU monitor connects to SU

“Subscriber 1” obtained a dynamic IP-address from a DHCP server on VLAN700 located behind the BS. The subscriber should generate traffic and measure the throughput achieved. Both the “SU monitor” and “Subscriber 1” ran the OS Windows 2000. The SU-ODU contained all the active components and an integral high flat antenna. The SU-IDU was powered and connected to the AU-ODU via a category 5 Ethernet cable. This cable carried both data and power between the two units. The AU-IDU acted as a data bridge between the wireless and wireline media, supporting up to 512 MAC addresses. It connected the subscriber’s data equipment via a standard IEEE 802.3 Ethernet 10/100-BaseT interface.

3.2.3 Services

A service is a virtual connection between a subscriber’s application and the Network Resource. The Network Resource could be internet, Content Provider, Corporate Network, etc. A subscriber is an entity that may be associated with devices connected to SUs. The Service Domain is illustrated in Fig. 24.

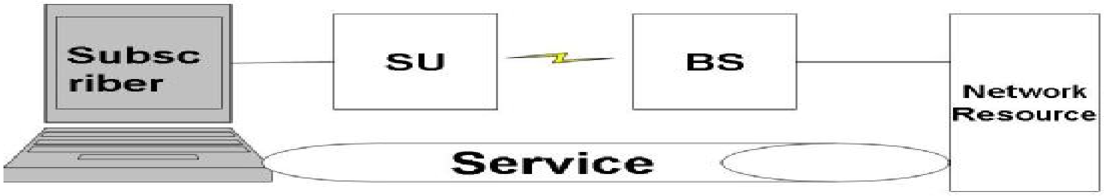


Fig. 24 Service Domain

The Services were implemented as IEEE 802.16 connections within the wireless domain. Each Service associates a certain Service Profile with a specific Subscriber's device behind a specific SU. A diagram of how Services are composed is illustrated in Fig. 25, where the entities that constitutes a Service are listed and described shortly as follows:

Subscriber: subscribes to a Service Profile behind a specific SU.

Service Profile: defines the properties of the specific service, and is associated with a specific Forwarding Rule and Priority Classifier.

Forwarding Rule: defines the attributes that affect forwarding and switching of data.

Priority Classifier: defines the QoS Profiles to be allocated to users/sessions differentiated by DSCP or 802.1p priority classifiers. It defines Uplink and Downlink QoS Profiles.

QoS Profile: defines the Quality of Service parameters that are applicable when the QoS Profile is used.

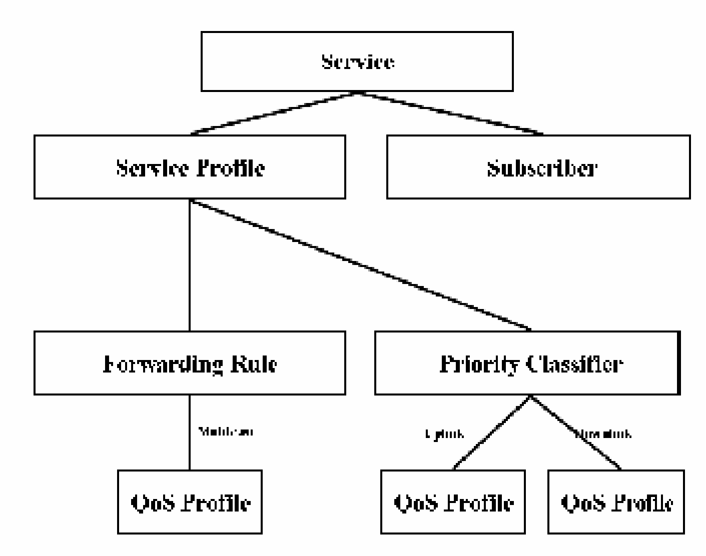
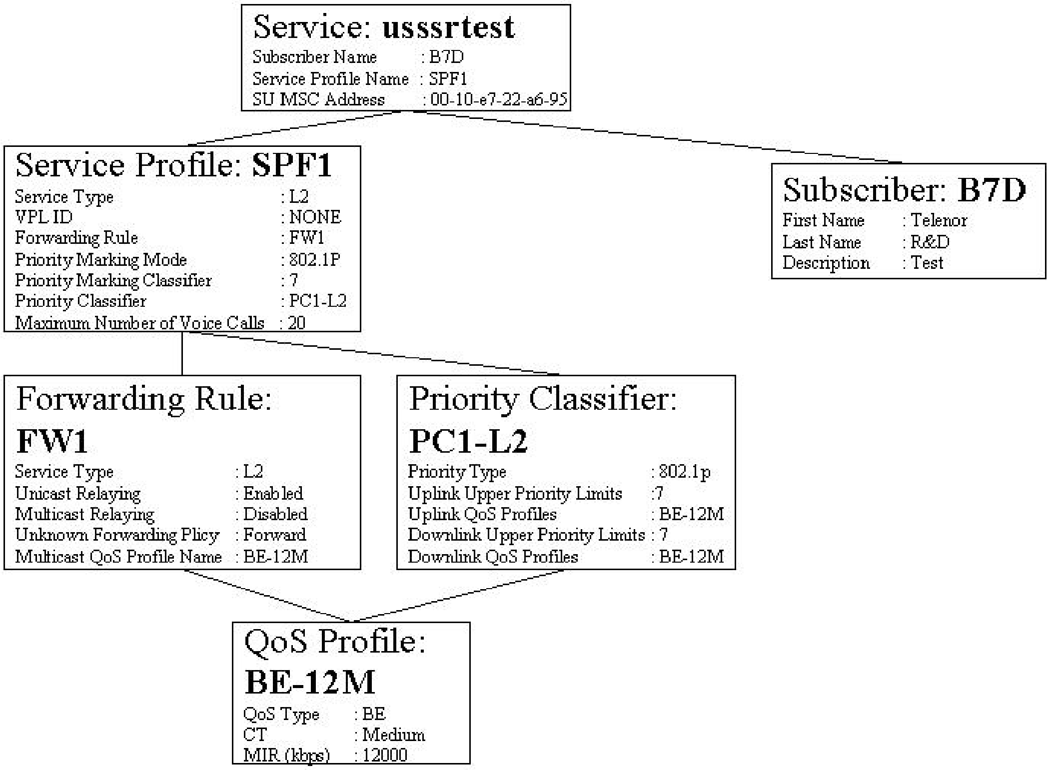


Fig. 25 Service Diagram

3.2.3.1 Implementation of Service used in the Measurements

A service named "usssrtest" was implemented illustrated in Fig. 26. It defines a Service Profile named "SPF1" for subscriber "B7D"s station behind the SU with MAC Address 00-10-e7-22-a6-95. The implementation of the service is described below.



Service: **usssrtest**
Subscriber Name : B7D
Service Profile Name : SPF1
SU MSC Address : 00-10-e7-22-a6-95

Service Profile: **SPF1**
Service Type : L2
VPL ID : NONE
Forwarding Rule : FW1
Priority Marking Mode : 802.1P
Priority Marking Classifier : 7
Priority Classifier : PC1-L2
Maximum Number of Voice Calls : 20

Subscriber: **B7D**
First Name : Telenor
Last Name : R&D
Description : Test

Forwarding Rule: **FW1**
Service Type : L2
Unicast Relaying : Enabled
Multicast Relaying : Disabled
Unknown Forwarding Plicy : Forward
Multicast QoS Profile Name : BE-12M

Priority Classifier: **PC1-L2**
Priority Type : 802.1p
Uplink Upper Priority Limits :7
Uplink QoS Profiles : BE-12M
Downlink Upper Priority Limits : 7
Downlink QoS Profiles : BE-12M

QoS Profile: **BE-12M**
QoS Type : BE
CT : Medium
MIR (kbps) : 12000

Fig. 26 Implemented Service

The Service Profile "SPF1" was defined with service type L2, which transports Layer 2 (Ethernet) frames in the Service Domain. That is between the subscriber's site and the Network Resource located in the provider's backbone, and/or between the subscriber's sites. "SPF1" was associated with the Service Profile "PC1-L2" and Forwarding Rule "FW1". The Priority Marking Mode was chosen to be VLAN tagging of the type 802.1p. The Priority Marking Classifier was set to 7, which is the highest value used by 802.1p. VPL ID was set to NONE because no virtual private LANs are implemented.

The Forwarding Rule "FW1" was set to use Service Type L2. Multicast Relaying was disabled and Unicast Relaying enabled. The Unknown Forwarding Policy was set to "Forward", meaning that transmission of all packets is enabled. It defined the Multicast QoS Profile "BE-12M" to be used for all multicast and broadcast messages.

The Priority Classifier "PC1-L2" was setup with 802.1p as priority type. A QoS Profile "BE-12M" was defined for both UL and DL. Upper Priority Limits was set to 7, thus all packets tagged with values between 0 and 7 would have priority as defined in the QoS profile for the respective direction.

The QoS Profile "BE-12M" was setup with QoS type BE (Best Effort). The Maximum Information Rate (MIR) the system will allow for the connection was set to 12 Mbps. The Committed Time (CT) was set to medium that will be 100 ms. CT defines the time window over which the information rate is averaged to ensure compliance with the MIR parameter.

3.2.4 Preliminary Measurements

An agile planning procedure was examined for the preliminary measurements. The system was set-up as explained in the preceding sections and a procedure of measurements was constructed to be performed at various locations decided upon. Sessions of FTP transmission was used to measure the throughput. Files were uploaded and downloaded to measure uplink and downlink throughput respectively. A link quality display was performed by the "Monitor PC" behind the SU to monitor the physical characteristics of the system.

3.2.4.1 Results Preliminary Measurements

Four locations were elected as described in Fig. 27, where various distances, elevation over sea and sight capabilities was present. The fourth location is not present in Fig. 27 since it was at the same location as the BS at a distance of 150 m. Micro position offsets were performed at each location, with the purpose to observe the degree of impact this causes to the signal quality. Different sight capabilities were considered when choosing the micro position offsets.

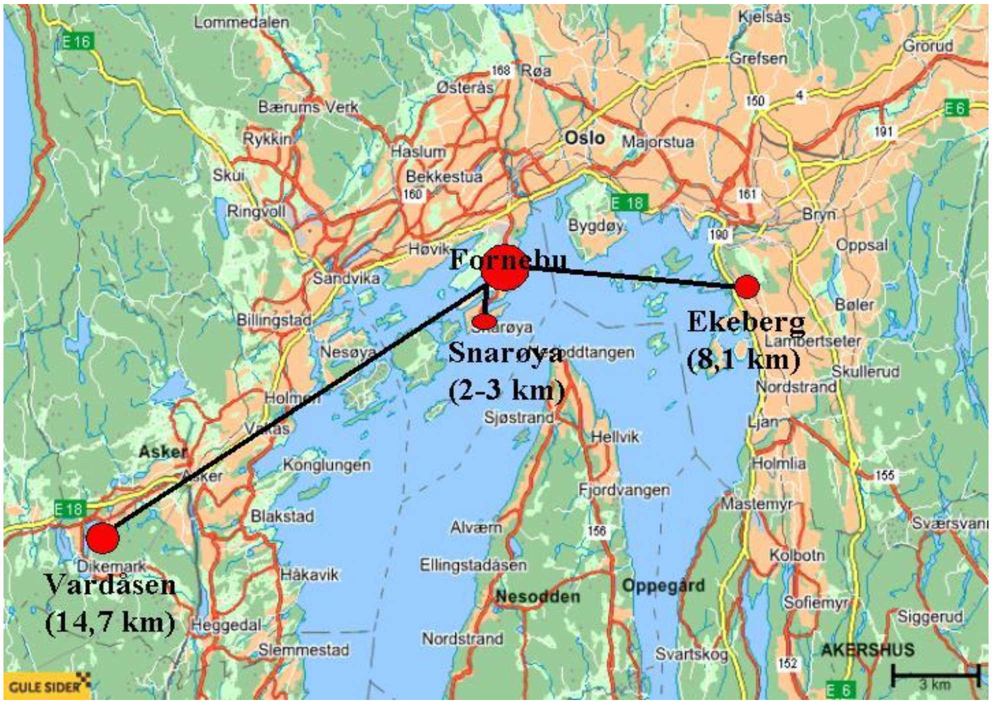


Fig. 27 Preliminary Measurement Locations

A measure of the link quality was performed at each location. At the locations Vardåsen and Ekeberg, positions with Non Line of Sight (NLOS) showed varying signal quality, where at some points the signal quality was as weak that no IP connectivity was obtained Throughput measurements could not be performed in these positions. Expected system behaviour was observed, where signals in NLOS conditions performed better at short distances. Signals in LOS conditions performed good at both short and farther distances.

The overall FTP throughput results achieved way less than expected. Table 6 presents throughput achieved in a condensed form (raw results are given in Appendix B). A comparison with the results presented by the equipment manufacturer gave results divided by three in general when higher order modulations were used. The throughput did not always confirm to the theoretical bitrate for the respective modulation rates. The reason for this was probably that the SU used some time to decide upon modulation rate, thus the notified result might have been read to early.

Table 6 Condensed Throughput Preliminary Measurement

Modulation	DL (Mbps)	UL (Mbps)	Location
QAM64 ¾	3,72	2,39	Fornebu
QAM64 ¾	0,82	2,42	Vardåsen
QAM64 ¾	3,88	1,86	Vardåsen 2
BPSK ½ / QAM64 ¾	1,08	1,6	Ekeberg 2
BPSK ½ / QAM16 ½	1,05	2,22	Snarøya 2
BPSK ½	1,01	1,86	Snarøya 2
BPSK ½	0,99	0,37	Ekeberg 1
BPSK ½	0,78	0,32	Ekeberg 3
BPSK ½	0,96	0,8	Ekeberg 4

A range of questions emerged when analysing these results. The throughput results should have achieved higher values. Different aspects of the system and measurement procedure were analysed. Firstly the application layer protocol FTP was analysed. A high BER rate may have caused erroneous frames, thus forcing FTP to trigger retransmissions which would have caused a reduction in throughput. At the location "Fornebu", 150 meters from the BS, BER tests was performed. These happened to be greater than expected, ranging between 5.3E-4 to 1.2E-5, but not too high to be an argument for the low throughput performance. Another topic discussed concerning FTP, was the overhead produced from the higher layer protocol.

FTP uses the protocol TCP, thus communication protocols at the network layer were consulted. These are UDP and TCP. A measurement tool TPTEST [44] was utilized to measure the throughput with these protocols. Remarkable results were achieved. TCP performed similar to FTP with low throughput, whereas UDP performed more similar to the results presented by Alvarion. Table 7 presents these results in an averaged form. Because of the remarkable results, a more thorough analysis of the protocols followed.

Table 7 Averaged TCP and UDP, Preliminary Measurements

Protocol	UL/Send (Mbps)	DL/Receive (Mbps)	Symmetric (Mbps)
TCP	6,32	3,92	9,9
UDP	7,78	7,89	N/A

3.2.4.2 TCP window size

The TCP window size (TWS), is the amount of data in transmission between sender and receiver that awaits acknowledgements. The congestion window starts at bottom with a slow start before an exponential increase follows to a given threshold. From this threshold an additional increase follows until a maximum value is reached, which is the limit for the congestion window. This maximum value, TWS, is set different in the TCP implementations for the various Operating Systems.

The best throughput performance is achieved when the network pipe between the sender and receiver is kept full of data. TCP needs to acknowledge each TCP segment (typically 1460 bytes) before they can be let loose from the TWS. A useful quantity to use for a full network pipe is the bandwidth-delay product (BDP) that is obtained by multiplying the bandwidth with the delay (round trip) on the link

$$BDP = bandwidth * delay \tag{1}$$

To achieve the best possible performance, we want TWS set to BDP

$$TWS = BDP\ . \tag{2}$$

In our case where the maximum bandwidth is 12 Mbps with a delay that vary, but averaged to 36 ms (measured with ping) at the WiMAX hop, gives us

$$TWS = 12Mbps * 0.036s = 432Kb / 8 = 54\ KB\ . \tag{3}$$

Since the delay vary when communicating with different hosts, the TWS is difficult to estimate, and may usually vary from 45 KB (delay 30 ms) to 150 KB (delay 100 ms) with a 12 Mbps bandwidth in the WiMAX domain.

The TWS is limited in most operating systems. If the TWS was set too large or unlimited, it could fill up the total available memory when many TCP connections were present at the same time. In Windows 2000, as is used in the above measurements, the TWS is set to 17520 bytes. If we compare the estimated TWS needed for maximum throughput and the given TWS, we observe that

$$54\ 000\ >\ 17\ 520\ , \tag{4}$$

which states that a too short TWS is allocated for a 12 Mbps bandwidth in Windows 2000 when the delay is 36 ms.

With TWS set to 17 520 and 36 ms delay as in the “Preliminary Measurements” we can use the formula for TWS to estimate the available throughput

$$Bandwidth = TWS / delay = 17\ 520 Bytes / 0{,}036s = 3.89Mbps\ , \tag{5}$$

which is a good estimate compared to our measurements under perfect conditions with QAM64 ¾ modulation rate.

To achieve full throughput with the default TWS (17KB), we can easily estimate the maximum allowed delay

$$Delay = TWS / Bandwidth = (17520 * 8) bits / 12Mbps = 11ms\ . \tag{6}$$

Measurements were performed with TWS set to 64 KB, which returned satisfying throughput values compared to the vendor specification. Higher TWS values was also measured, but returned approximately similar throughput values as when the TWS was set to 64 KB.

When the TWS was adjusted at the SU, downlink TCP throughput achieved better, but this was not the case for uplink TCP throughput. The TWS must be adjusted high enough at both the sending and receiving sides to achieve appropriate throughput in both directions. The results obtained are given in Table 8. DL FTP traffic achieved more satisfying throughput, but this was not the case for UL FTP traffic. TWS should also be tuned at the receiving side for optimal FTP and TCP throughput in the UL.

Table 8 FTP throughput when tuning the TCP Windows Size compared with Alvarion [11]

Concern	DL (Mbps)	UL (Mbps)	DL + UL (Mbps)
Alvarion	9,0	7,3	16,3
Telenor R&D	7,74	1,06	N/A

Though TWS seemed to be the main problem for lower performance when using TCP connections, it would be difficult to tune the TWS in all terminals in a WiMAX deployment. A patch could be used to set the TWS to an adequate size. But considerations should be taken to the tradeoff that much memory is used for each TCP connection. Other solutions to the TCP window problem should be indicated if possible.

It is worth to notice that the full bandwidth for a service could be utilized while running several simultaneous TCP-sessions and/or UDP sessions. The TCP window problem applies to a single TCP connection that is affected by the TWS limit. If a subscriber has a 12 Mbps connection, a single TCP connection performing 12 Mbps could not be used without tuning the TWS. To utilize the total bandwidth, for instance 4 simultaneous TCP connections performing 3 Mbps each could be used. 3 simultaneous TCP or FTP connections with 3 Mbps each may be more virtually according to Table 8, where 9 Mbps was stated to be the maximum system performance. This remains to be tested.

Different Operating Systems (OS) exist, each having their own definition of maximum TCP window size. Windows 2000 with 17.5 KB was used in these measurements. An example of different OSs TWS are given in Table 9 where the theoretical throughput is calculated when the delay is set to 35 ms.

Table 9 TCP window size in Windows 98, 2000 and XP

Operating System	TWS (KB)	Teoretical Throughput (Mbps)
Windows 98	2	0,47
Windows 2000	17,5	4,01
Windows XP	64	14,98

An observation here is that Windows XP would perform with maximum throughput in the WiNAX system, while Windows 98 will have a poor performance. Future OSs (for instance Windows Vista) and FTP implementations are expected to, or do already dynamically adjust the TWS according to the bandwidth and delay offered.

3.2.5 Measurement Procedure

The measurement procedure was optimized for the "WiMAX Field Trial" to perform additional tests to those performed in the "Preliminary Measurements". These include FTP, TCP and UDP for throughput. Link Quality tests as in the "Preliminary Measurements" was used for monitoring the physical medium. Burst Error Rate (BER) was also measured.

An automated measurement procedure was been implemented by using the programming language Python for scripting. The procedure was implemented to perform all the above mentioned measurements. All the planned measurements could now be executed at each location by doing a single click and inserting location specific parameters such as location name, distance to BS and elevation over sea. GPS was used such that the position on earth could be notified at each location.

A number of locations were decided upon in advance, and several micro position offset movements was to be performed within most of the locations. Totally 14 different locations were decided upon. Including all the micro position offsets performed, a total of 50 measurements were performed.

The amount and kind of micro position offset movements within each location was decided upon when arriving. Different questions came clear because of various conditions at the respective location. Reflection and diffraction from surrounding objects was important subjects that were considered at each location.

3.2.5.1 Measurement Execution Process

The measurement processes that were executed by an automated procedure at each location are listed in the correct order as follows:

1. Link Quality
2. BER
3. TCP: UL and DL simultaneously
4. TCP: UL and DL
5. TCP: 2 threads UL and DL
6. TCP: 4 threads UL and DL
7. TCP: 5 threads UL and DL
8. TCP: 10 threads UL and DL
9. UDP: UL and DL simultaneously
10. UDP: UL and DL
11. FTP: UL and DL, 10 MB file
12. Link Quality

Before the automated measurement procedure is started the Link Quality Display at the SU should be monitored to be sure that the link has stabilized, and the antenna should be pointed in the direction where the best Link Quality is found. This may be in the opposite direction of the BS because of possible reflections from surrounding objects. Therefore the landscape surrounding the measurement location must be studied when searching for the best link quality.

3.2.6 Measurement Locations

The BS was located at Telenor premises at Fornebu. The SU was moved to different locations with varying distances between the BS and SU, elevations and sight capabilities. At the locations we wanted to test LOS, near LOS and NLOS (NLOS). A short description of these sight capabilities follows:

LOS – optical sight to BS (neglect Fresnel)

Near LOS – optical sight to BS but branches or obstacles may cause interference to the radio signal

NLOS - No sight to BS, but obstacles may reflect the radio signal in such a way that they may reach the BS

The Fresnel zone is the area around the visual line-of-sight that radio waves spread out into after they leave the antenna. The area covered by the zone must be clear or else signal strength will weaken (Fig. 28).

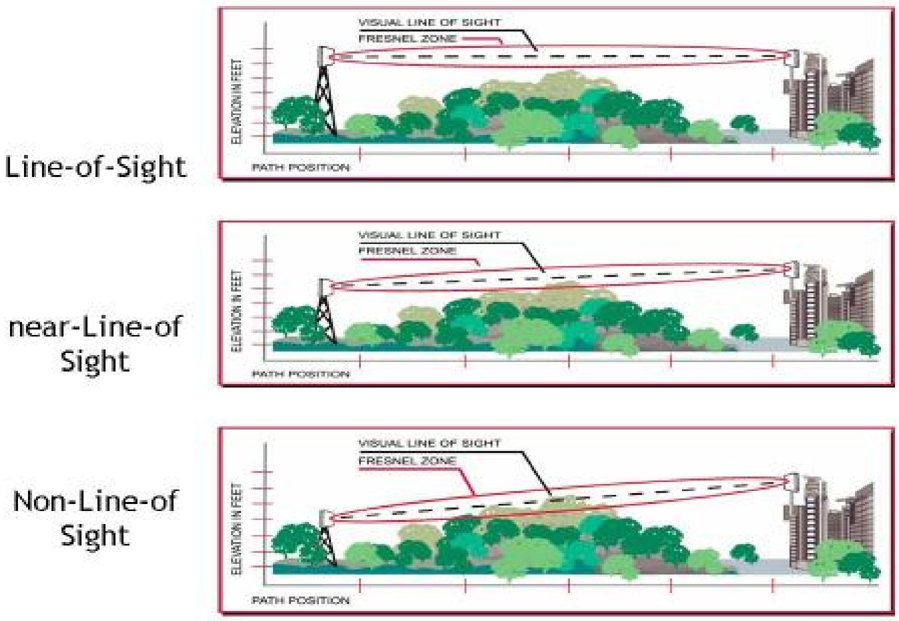


Fig. 28 Fresnel Zone illustrated for LOS, near LOS and NLOS

14 different locations were decided upon in advance. These were named {Location0, … , Location14}, where location5 is absent. Each was studied upon arrival for points where the satisfying conditions was met. Micro offsets were performed at most of the locations, and a new measurement was taken for each micro offset.

Distance from the BS varied from 0.5 km to 11.4 km in suburban and urban surroundings. Elevation over sea level varied from 3 m to 251 m. The Measurements were performed in Oslo, Norway. All the location details are described in Table 10.

Table 10 List of Locations

Location	Distance (km)	Elevation (m)	Location Name
Location 0	0,15	35	Fornebu, Telenor
Location 1	0,516	16	Martin Linges Vei
Location 2	0,906	16	Indoor Golf Centre
Location 3	0,87	9	Paelvika
Location 4	0,87	9	Paelvika Halden Terrasse
Location 6	0,818	21	Oksenoyveien
Location 7	1,17	30	Michelets Vei
Location 8	3,84	20	Skoyen
Location 9	4,4	29	Gustav Vielands Vei
Location 10	11,4	251	Lachmansvei
Location 11	8,6	161	'Upper' Solvang Kolonihage
Location 12	5,6	68	Borgen, Svaldbarveien
Location 13	5,72	80	Tuengveien
Location 14	9,05	190	Songsveien X Kongleveien

Two maps are used to describe the measurement locations. Fig. 29 maps [Location0, … , Locatoin7] which were approximately within one kilometre and less from the BS. Fig. 30 maps [Location8, ... , Location14] which were farther away from the BS.

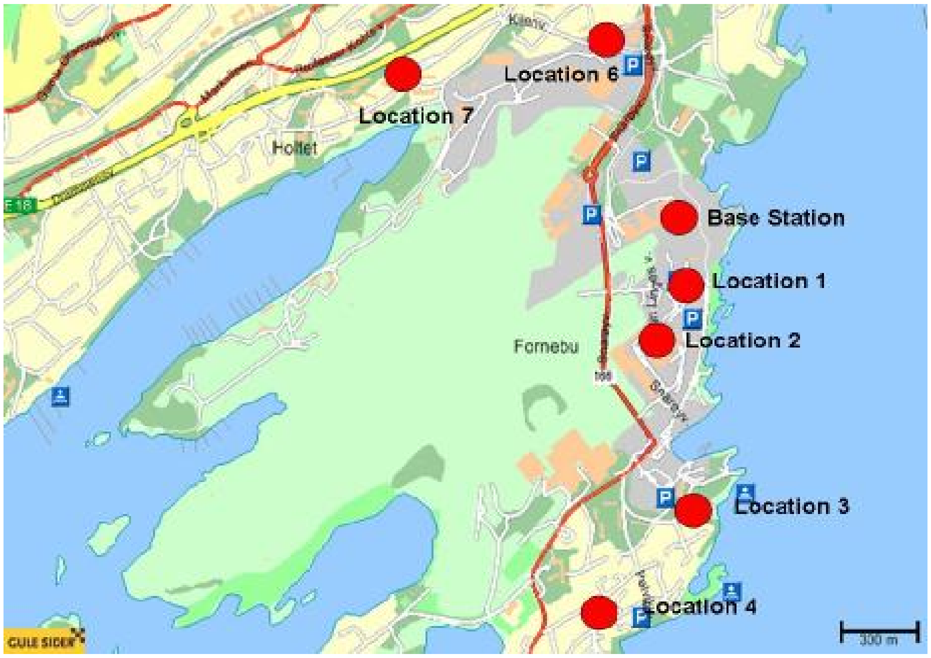


Fig. 29 Nearby Measurement Locations (map-source [45])

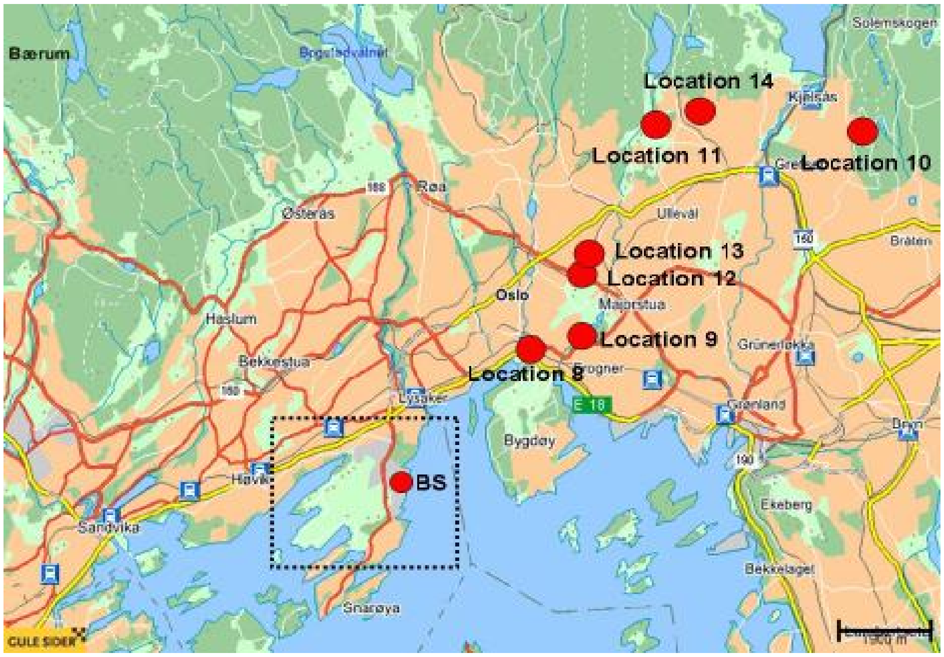


Fig. 30 Far Measurement Locations (map-source [45])

3.3 Physical Performance

3.3.1 Received Signal Strength Indicator

The equipment reported the Received Signal Strength Indicator (RSSI) value which represents the received signal strength in dBm. The RSSI is specified in the IEEE 802.16-2004 standard [1], sect. 8.3.9. The following is a text extract from the standard:

> *"When collection of RSSI measurements is mandated by the BS, an SS shall obtain an RSSI measurement from the OFDM downlink preambles. From a succession of RSSI measurements, the SS shall derive and update estimates of the mean and the standard deviation of the RSSI, and report them via REP-RSP messages.*
>
> *Mean and standard deviation statistics shall be reported in units of dBm. To prepare such reports, statistics shall be quantized in 1 dB increments, ranging from -40 dBm to -123 dBm. Values outside this range shall be assigned the closest extreme value within the scale."*

Note that the Subscriber Unit (SU) is referred to as SS (Subscriber Station) in the IEEE 802.16 standard.

It is interesting to compare the Received Signal Strength to the distance between BS and SU, which is performed in the following subsections for both DL and UL.

3.3.1.1 Downlink

Fig. 31 shows the measured RSSI values for all downlink measurements. The points inside the blue circles are Line-Of-Sight (LOS) measurements. The LOS measurement on the top left was performed with the receiving antenna directed towards a side lobe of the base station antenna to avoid saturating the receiver.

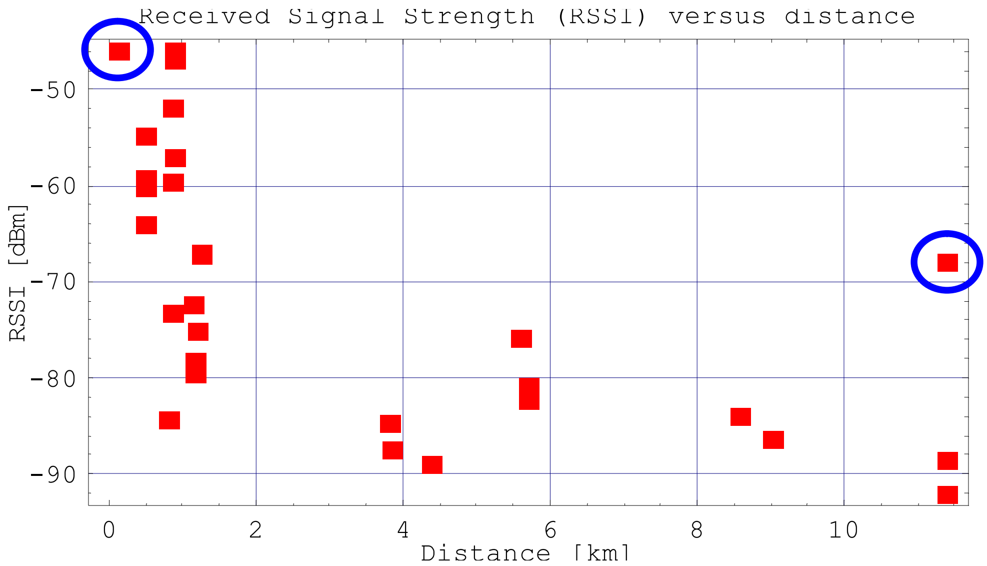


Fig. 31 DL received RSSI values as a function of the distance between the BS and the SU

Fig. 31 only contains measurements where we actually got a connection. For small distances (say less than 2 km) we got a connection almost everywhere. As the distance to the BS was increased, it became more difficult to find places with connection and we had to pick locations where we believed we had a fair chance of getting it. Also the measurements were taken in different environments representing both typical suburban and urban receiving conditions.

The measurements were classified according to whether they represented a LOS or NLOS condition, whether the receiving conditions were considered as better, typical or worse than average receiving conditions in the area and whether the environment was urban or suburban.

Fig. 32 shows the measurements which were classified as typical and NLOS.

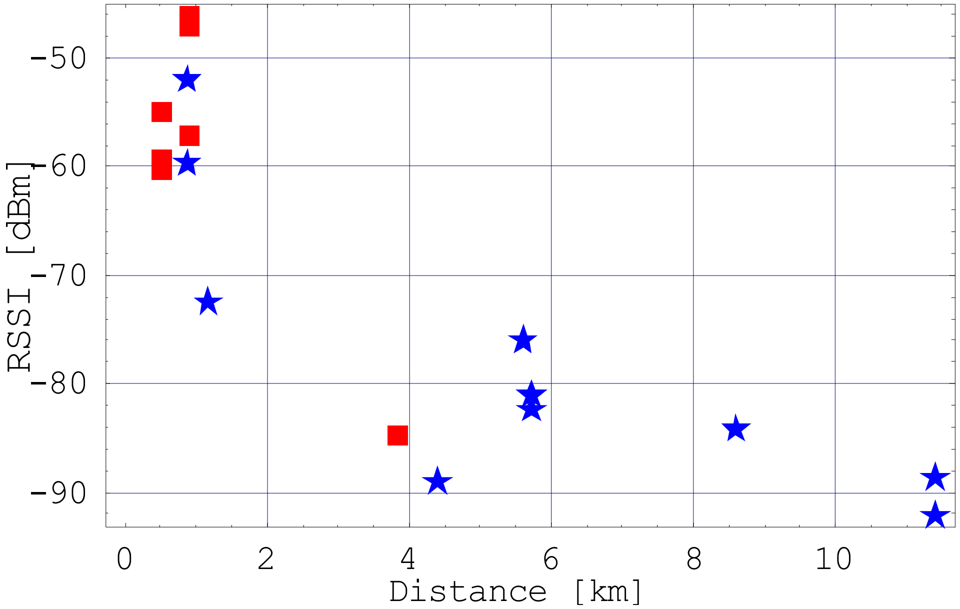


Fig. 32 DL RSSI values as a function of distance for measurements classified as NLOS and typical in urban (squares) and suburban (stars) environments

It is interesting to compare the measured received signal strength to what is predicted by path loss models.

In Fig. 33 the measured RSSI values are plotted together with the RSSI values corresponding to the COST-231 Hata models for path loss in urban and suburban environments and the values corresponding to the free space path loss model.

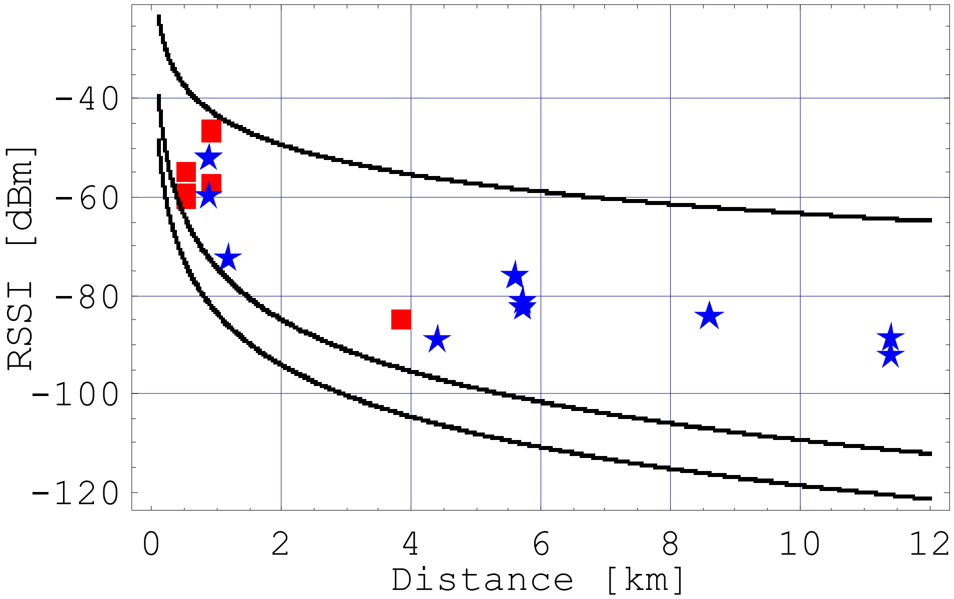


Fig. 33 DL RSSI values for locations classified as NLOS and typical compared to three path loss models: free space loss (topmost line), Cost-231 Hata suburban (middle line) and Cost-231 Hata urban (lowest line)

Fig. 33 shows that all signal strength measurements classified as typical are better than the Cost-231 models for urban and suburban environments. The reasons for this are probably:

The terrain around Fornebu is very favourable with respect to radio propagation since it is first flat then gradually increasing in height as the distance from the BS increases.

The antenna placement was optimized somewhat when we stopped the van. This is somewhat similar to finding the optimum placement of the antenna on a house and can therefore represent the realistic situation.

3.3.1.2 Uplink

Fig. 34 shows the received signal strength indicator values for all uplink measurements. The points inside the blue circles are Line-Of-Sight (LOS) measurements. The LOS measurement on the top left was performed by receiving the signal on a side lobe of the base station antenna to avoid saturating the receiver.

The relatively small dynamic range compared to the corresponding downlink measurements is due to the use of Automatic Transmission Power Control (ATPC) at the user terminals.

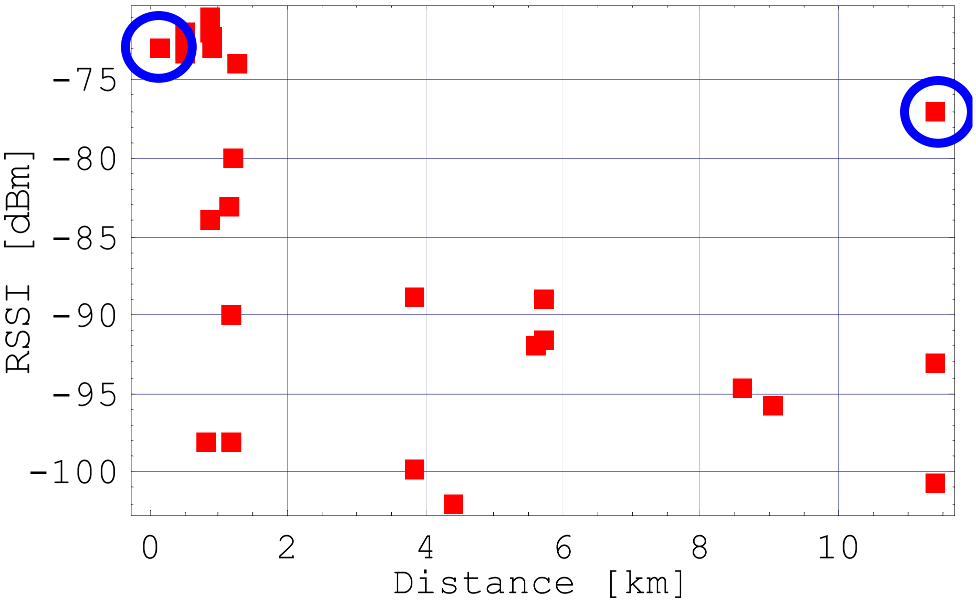


Fig. 34 RSSI values at the base station (UL) as a function of the distance between the BS and the SU

As for the downlink case, the measurements were classified according to whether they represented a LOS or NLOS condition, whether the receiving conditions were considered better, typical or worse than average receiving conditions in the area and whether the environment was urban or suburban. In addition the actual transmission power used by the user terminals was registered.

Fig. 35 shows the normalized uplink RSSI measurements due to use of Automatic Transmission Power Control (ATPC) at some locations, which were classified as typical and NLOS in urban and suburban environments. The normalization is done by adding the transmission power back-off (relative to the maximum value of 20 dBm) to the measured RSSI values.

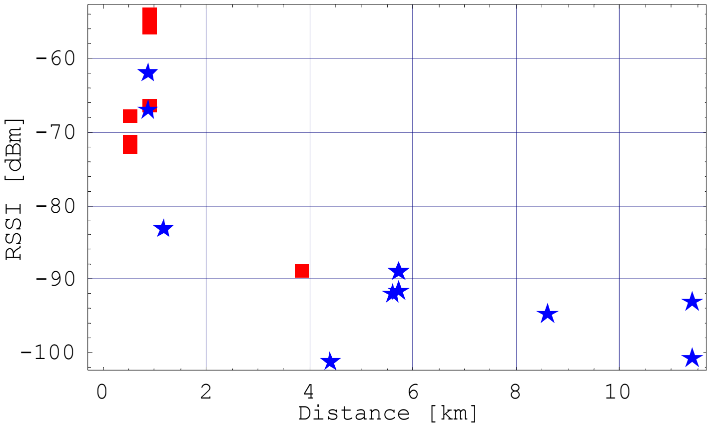


Fig. 35 UL RSSI values as a function of distance for measurements classified as NLOS and typical in urban (squares) and suburban (stars) environments. The RSSI values have been normalized to correspond to a transmitted power of 20 dBm

As for the downlink case, it is interesting to compare the measured received signal strength to what is predicted by path loss models.

Fig. 36 shows that the normalized uplink signal strength values classified as typical are better than the COST-231 models for urban and suburban environments, just as for the downlink case.

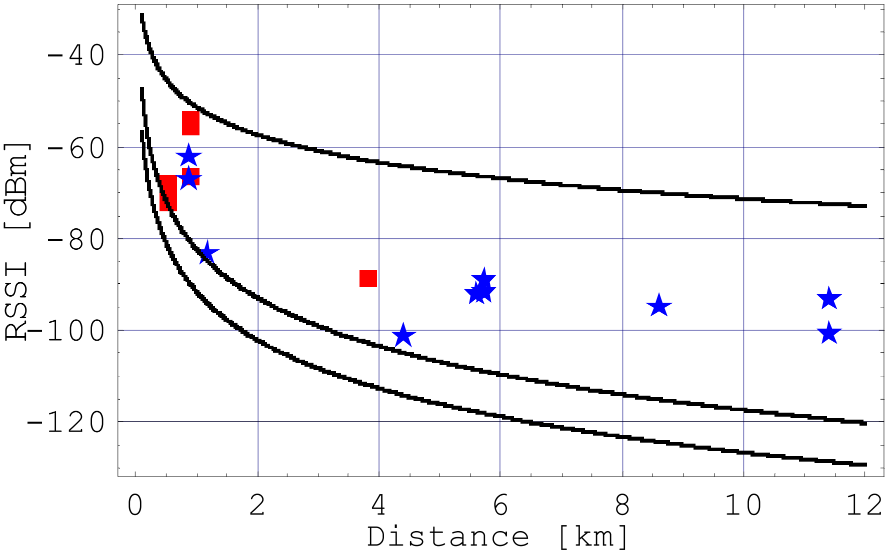


Fig. 36 Normalized UL RSSI values compared to three path loss models: free space loss (topmost line), Cost-231 Hata suburban (middle line) and Cost-231 Hata urban (lowest line)

3.3.2 Signal to Noise Ratio

The Signal-to-Noise Ratio (SNR) is a better measure for the actual operating conditions of the receiver than the RSSI value, since the SNR value takes into account interference and noise conditions in addition to signal strength. On the other hand, the SNR and RSSI values should be closely correlated and result in a linear graph if noise is constant and interference absent.

Fig. 37 shows the SNR versus RSSI for all DL measurements carried out. For the low RSSI values there seems to be a linear relationship between the RSSI and SNR values as expected, where a 1 dB increase in SNR gives a 1 dBm increase in the RSSI. For higher RSSI values, the SNR approaches a limit which is because the SU cannot measure higher SNR values.

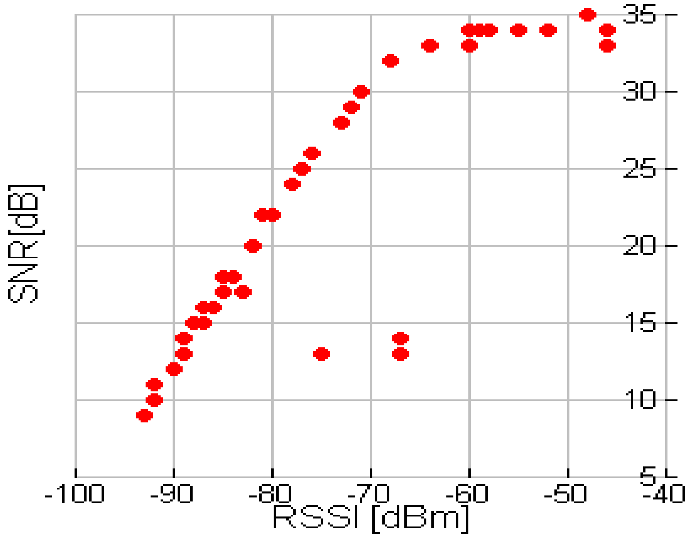


Fig. 37 SNR as a function of RSSI

Three of the measurements stand out by having significantly lower SNR values than should be expected from the other measurements as illustrated by the function drawn. These low SNR values for relatively good RSSI values might be caused by interference.

It would be useful to have an expression for the SNR versus RSSI, which could be useful to reveal interference and as to illustrate the RSSI and SNR expected by the system in use. By definition, the relationship between SNR and RSSI can be written as:

$$(N+I)_{dBm} = RSSI_{dBm} - SNR_{dB}, \qquad (7)$$

where N and I are noise and interference respectively, denoted in dBm.

An expression for SNR as a function of RSSI could be derived based on the measurements, where the linear relationship between SNR and RSSI stand out as the basis for the expression. Since only one BS and one SU are present, CCI interference from other BSs and SUs are assumed to approximate zero. We therefore have that:

$$SNR_{dB} = RSSI_{dBm} - N_{dBm}, \tag{8}$$

where the N constant used in the expression was determined based on the median from the measurements, which was found to be different in the DL and UL. The approximations for SNR in the DL and UL were found to be:

$$SNR\_DL_{dB} = RSSI_{dBm} + 102, \text{ and} \tag{9}$$

$$SNR\_UL_{dB} = RSSI_{dBm} + 106, \tag{10}$$

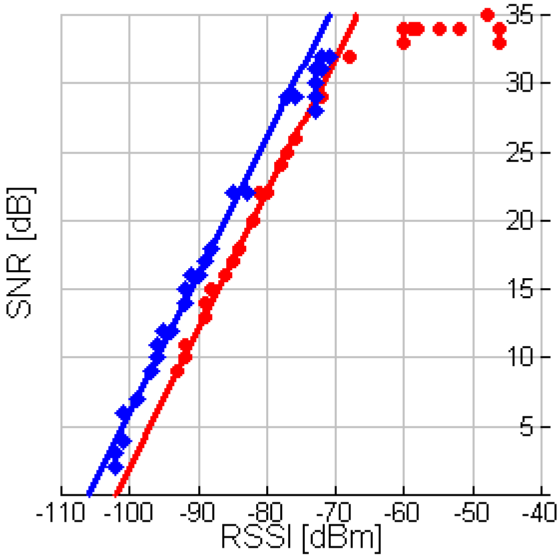


Fig. 38 DL (red) and UL SNR (blue) versus RSSI

The reason for the flatten-off observation in the DL is most probably because the SU cannot measure higher SNR. The noise plus interference (N+I) power levels for DL and UL was found to be -102 dBm and -106 dBm respectively.

3.4 Throughput Performance

3.4.1 UDP

Compared to TCP and FTP, the UDP performance is the most appropriate protocol to use to determine the real UL and DL system capacity. UDP does not use acknowledgments so there is no interdependency between the bitrates in the two directions. Since the SU used was a half duplex unit, the UL and DL were tested consecutively and not simultaneously.

Fig. 39 shows the measured UL and DL UDP performance for all locations.

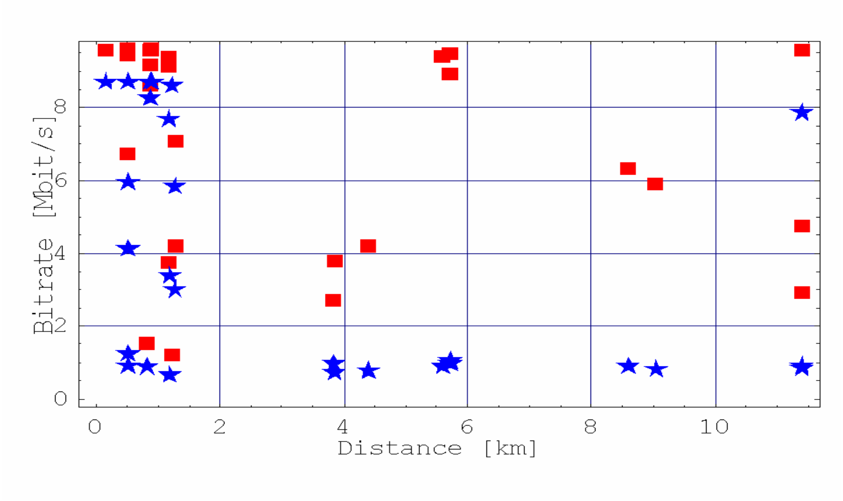


Fig. 39 Measured UL (stars) and DL (squares) UDP performance for all locations

In Alvarion's manuals for the BreezeMAX system, the maximum bitrate is listed as 12.71 Mbit/s for 64-QAM with ¾-rate FEC. The maximum measured UDP bitrate was 9.6 Mbit/s, so the useful bitrate was only 76 % of the maximum bitrate. This may have many explanations, such as UDP overhead and allocation of capacity for management traffic.

Fig. 39 shows that the measured UL bitrates are much lower than the corresponding DL bitrates for distances above about 2 km. The main reason for this is that the power amplifier in the user terminal can only deliver maximum 20 dBm, compared to the 28 dBm for the amplifier in the Base Station.

To verify that it is the difference in UL and DL transmission power that is the reason and not differences in sensitivity, the measured UDP bitrates for both UL and DL are plotted against RSSI values in Fig. 40. The figure shows that the UL and DL mainly have the same performance for the same RSSI. But the DL bitrates are marginally higher than the corresponding UL bitrates.

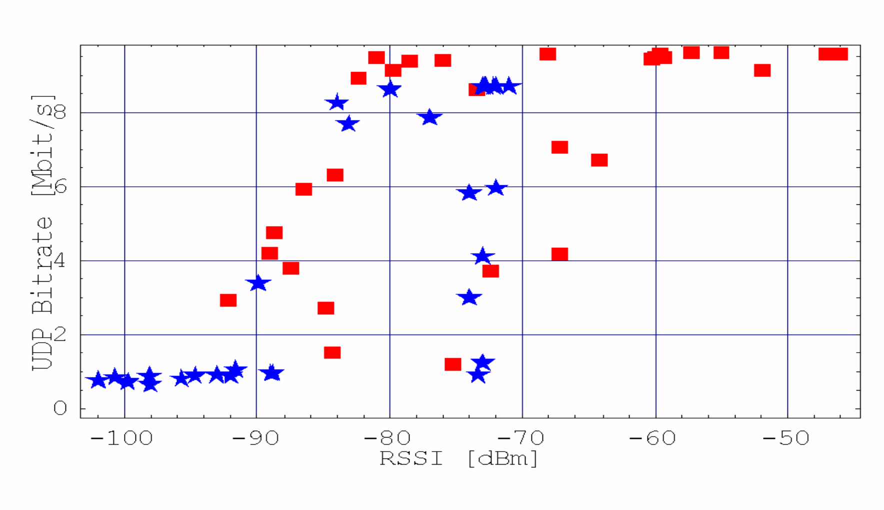


Fig. 40 UDP bitrates as a function of RSSI for the UL (stars) and DL (squares)

3.4.2 TCP

Any TCP connection involves both UL and DL communication since acknowledgment messages must be sent in the opposite direction of the information stream. Hence, the bitrate in one direction depends on the channel conditions in both directions. Since the SU used was a half duplex unit, the UL and DL were tested consecutively and not simultaneously.

Fig. 41 shows a plot of the measured TCP bitrates as a function of the distance between the BS and SU. The maximum measured UL and DL TCP bitrates were 8.4 and 9.0 Mbit/s respectively.

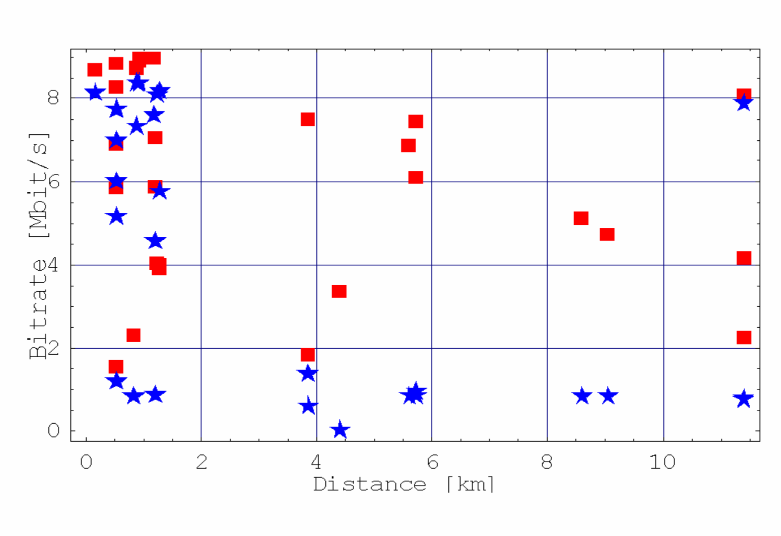


Fig. 41 Measured TCP performance for all locations for UL (stars) and DL (squares). Six simultaneous TCP connections were used in the measurement and the bitrate is the aggregate bitrate for these connections

3.4.3 FTP

Since FTP is based on TCP, any FTP connection involves both UL and DL communication. Hence, the bitrate in one direction depends on the channel conditions in both directions. Since the SU used was a half duplex unit, the UL and DL were tested consecutively and not simultaneously.

Fig. 42 shows a plot of the measured FTP bitrates as a function of the distance between the BS and SU.

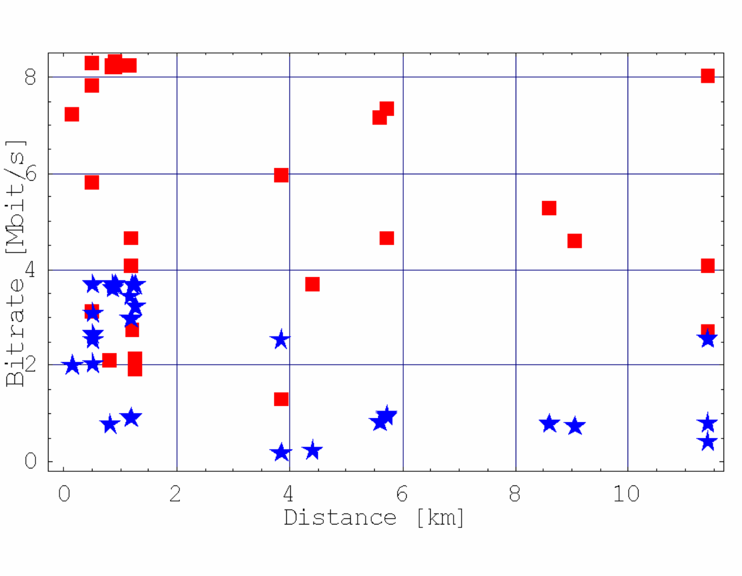


Fig. 42 FTP performance for all locations for UL (stars) and DL (squares)

The maximum measured FTP bitrates were 8.3 and 3.7 Mbit/s for DL and UL respectively.

According to the Alvarion documentation, the maximum FTP bitrates are 9.0 Mbit/s for DL and 8.3 Mbit/s for UL. We have not been able to establish definitely the reason for the low UL bitrate, but the most probable cause is that the computer with the FTP server had a too small TCP window size. The FTP tests were done by connecting to a different computer than the one used for the UDP and TCP tests.

3.5 Propagation Model

A radio propagation model is an empirical mathematical formulation for the characterization of radio wave propagation as a function of frequency, distance and other conditions. Propagation models are much used in network planning, particularly for conducting feasibility studies and during initial deployment. Empirical propagation models are based on observations and measurements, which are mainly used to predict the path loss. It would therefore be interesting to deduce a path loss model based on the data obtained from the measurements. Since the data obtained are based on measurements performed over a field trial, this is more correctly stated as an experimental propagation model.

Path loss is the attenuation undergone by an electromagnetic wave in transmit from a transmitter to a receiver in a telecommunication system [46]. Path loss is usually expressed in decibels as the ratio of the transmitted to received power. Many effects affects the signal propagation, thus a loss in power is caused to the signal. These effects may be the free-space loss, reflection, refraction, diffraction, absorption and aperture-medium coupling loss. Calculation of a path loss model will not provide exact results, but a prediction based on measurements and observations.

Different path loss models are suited for different frequencies and landscapes. Examples of non-time dispersive empirical models are ITU-R [47], Hata [48] and the COST-231 Hata model [49]. These models are designed for mobile systems, and uses great amounts of measurement results to predict their constants. The most used COST-231 Hata model is designed for systems operating in frequencies up to 2 GHz. The WiMAX system in used operates in the 3.5 GHz frequency range, but due to the simplicity and availability of correction factors, the COST-231 model have been widely used for path loss calculation at higher frequencies.

3.5.1 Cost-231 Hata and Free Space Loss Models

The Cost 231 Hata model is formulated as:

$$COST231 = 46.3 + 33.9\log(f) - 13.82\log(Hb) - Ch + (44.9 - 6.55\log(Hb))\log(d) + Cm \quad . \qquad (11)$$

where ‘f’ is the frequency in MHz for the system in use, ‘Hb’ is the height of the BS antenna and ‘d’ is the distance between the BS and the SU. ‘Cm’ is a parameter defined as 0 dB for rural and suburban areas and 3 dB for urban areas. ‘Ch’ is a correction factor for the mobile station antenna height, which has one definition for urban areas (Eq. 12) and another for rural and suburban areas (Eq. 13) as follows:

$$Ch = 3.20(\log(11.75Hr))2 - 4.97, \forall f > 400MHz \text{ and} \qquad (12)$$

$$Ch = (1.1\ \log(f) - 0.7)Hr - (1.56\log(f) - 0.8), \qquad (13)$$

where ‘Hr’ is the height of the SU antenna above ground level.

When calculating the Cost-231 Hata model for WiMAX, the parameters applied is listed as follows:

- Operating Frequency : 3.5 GHz
- Channel Bandwidth: 3.5 MHz
- BS Transmitted Power: 28 dBm
- BS Antenna Gain: 14 dBi
- BS Antenna Height: 32 meter
- SU Transmitted Power: 20 dBm (ATPC)
- SU Antenna Gain: 18 dBi (vertical polarization)
- SU Antenna Height: 5 meter

A calculation was made for the Cost 231 Hata suburban and urban models with the parameters as specified above.

The Free Space Loss (FSL) model was calculated, because it was interesting in the comparison with a WiMAX Path Loss model. FSL is calculated as follows as follows:

$$FSL = 32.45 + 20\log(f) + 20\log(d), \tag{14}$$

where ‘f’ is the system frequency in MHz and ‘d’ is distance in kilometers.

Fig. 43 plots the FSL (blue), Cost 231 suburban (red) and urban (green).

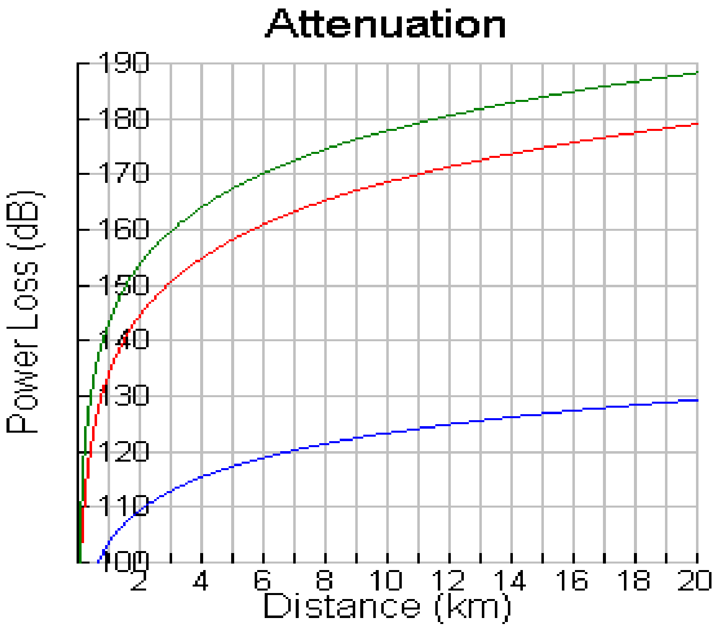


Fig. 43 Path Loss models for FSL from Eq. 14 (bottom line), Cost231 suburban Eq. 11 with Eq. 13(middle line) and Cost231 urban Eq. 11 with Eq. 12 (bottom line)

The Received Power for the three path loss models may be derived from the simple link budget equation:

$$\mathrm{Re}\,ceived\ Power(dB) = Transmitted\ Power(dBm) + Gains(dB) - Losses(dB) \tag{15}$$

Received Power will be the same as the RSSI obtained in the WiMAX measurements. Transmitted Power value is the power transmitted from the BS. Gains are the added antenna gains for the BS and SU and Losses is the Path Loss calculated in the Path Loss models for the respective model. Fig. 44 plots RSSI for the FSL and the Cost-231 Hata suburban and urban path loss models.

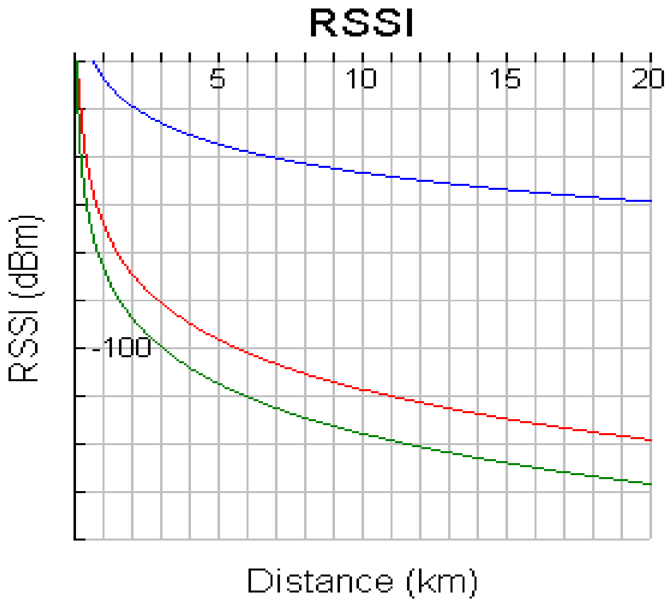


Fig. 44 RSSI for FSL (topmost line), Cost-231 suburban (middle line) and urban (bottom line)

The three Path Loss models discussed in this section will be used in comparison with the Path Loss model that is to be derived for the WiMAX measurements.

3.5.2 WiMAX Path Loss Model Calculation

The Cost-231 Hata models are based on a great amount of measurements, which is important to achieve an accurate model. The measurements performed in this study consisted of a less amount of results, but it would be interesting to construct a model, since little work exists in this area for WiMAX. To calculate a model based on as many measurements as possible, the downlink and uplink was combined. Uplink traffic were based on different power levels transmitted by the SU since ATPC was used, thus a normalization of these power levels was needed for the RSSI uplink values to be used in a path loss model as follows

$$RSSI\_UL\_NORM = (Tb - Ts) + (RSSI\_UL + (20 - SU\_TX)), \tag{16}$$

where ‘Tb’ is transmitted power by the BS (28 dBm) and ‘Ts’ is maximum transmitted power by the SU (20 dBm), which results in the difference 8 dBm. RSSI_UL is the actually Received Signal Strength Indication in the uplink at the BS and SU_TX is the transmitted power by the SU where ATPC may cause lower power levels than 20 dBm to be transmitted. Thus the RSSI_UL_NORM is normalized to be on level with the downlink signals.

A model for the Path Loss (PL) model was targeted to be on the form

$$PL = A + B\log(d), \tag{17}$$

where ‘d’ is the distance between BS and SU.

Fig. 45 shows the RSSI values for downlink and uplink normalized NLOS measurements plotted against the logarithm of the distance between the BS and SU. It could be feasible to concentrate on particular classifications of LOS, near LOS and NLOS in addition to urban, suburban and rural area classification. Optimal models would have been achieved with these classifications, but few values would have been placed under each model. Two of the results which are LOS were left out from the plot. The remaining plots are considered as suburban and NLOS measurements. A linear graph should be derived from the plots. Some of the most divergent measurements are confirmed to be taken in more untypical and rural environments.

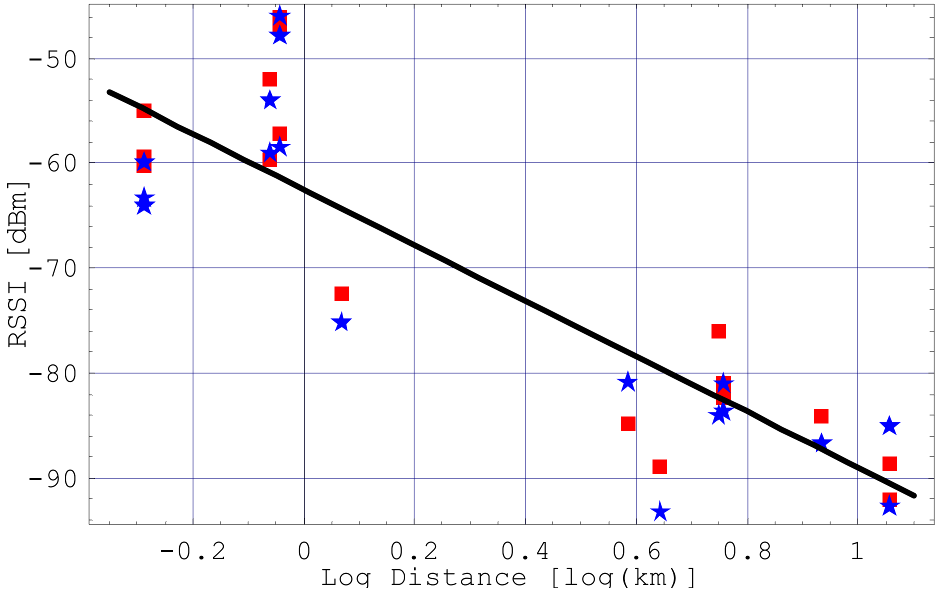


Fig. 45 RSSI plotted for DL and UL normalized vs. log(distance). DL (purple) and UL (pink)

If we apply linear regression on the points in Fig. 45, we obtain the following equation for WiMAX RSSI:

$$RSSI = -62.5 - 26.5\log(d)\,, \tag{18}$$

where ‘d’ is the distance between BS and SU in kilometre.

Fig. 46 shows the WiMAX RSSI attenuation as a function of distance. It is plotted together with the FSL and Cost-231 models.

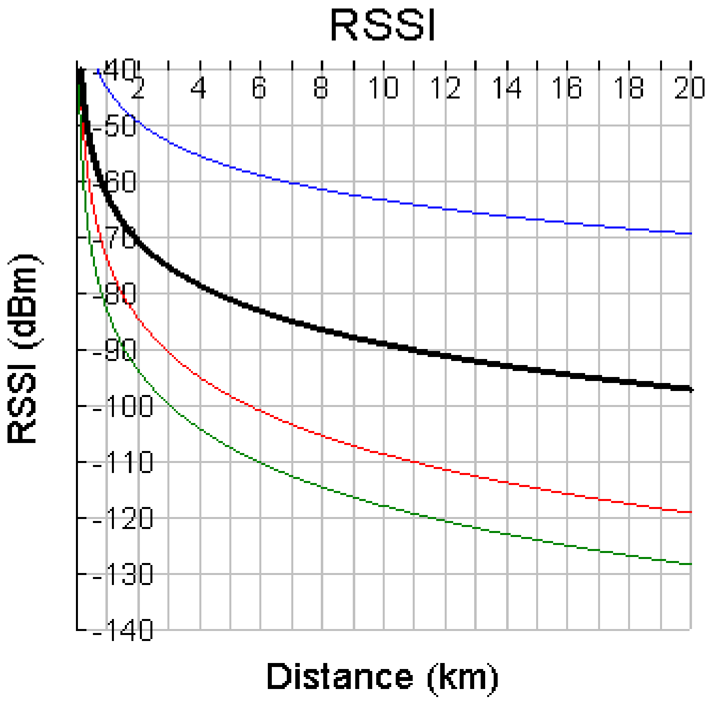


Fig. 46 The WiMAX RSSI attenuation as a function of distance for NLOS measurements from Eq. 18 (thick line). Attenuation models FSL (topmost), Cost 231 Hata Urban (bottom line) and Cost 231 Hata Suburban (next bottom line)

As can be seen in Fig. 46, WiMAX RSSI lies in between the FSL and Cost-321 models. An obvious reason for this is that the Cost-231 models are mounted on mobile systems, where the mobile unit is placed at random. The WiMAX measurements were performed in a nomadic manner, where the best positions were found within each location, thus better signal paths should be obtained as reflected from the comparison in Fig. 46.

RSSI was found as a function of distance, thus the Path Loss model for the system used can be deduced from the simple link budget formula:

$$PL = Transmitted\ \ Power(dBm) + Gains(dBi) - RSSI(dBm) \tag{19}$$

$$PL = Tb + Gb + Gs - RSSI\ , \tag{20}$$

where ‘Tb’ is transmitted power level from the BS, ‘Gb’ and ‘Gs’ are antenna gains for the BS and SU respectively and RSSI is the formula as calculated above. The Path Loss model (PL) for the system used is then:

$$PL = 28dBm + 14dBi + 18dBi - (-62.5 - 26.5\log(d)) \tag{21}$$

$$PL = 122.25 + 26.5\log(d)\ . \tag{22}$$

Fig. 47 shows the Path Loss model for WiMAX as a function of distance. The FSL- and Cost-231 Path Loss models are plotted for comparison purposes. As can be seen, the WiMAX PL model ranges between the FSL and Cost-231 models which is commensurable with the RSSI attenuation.

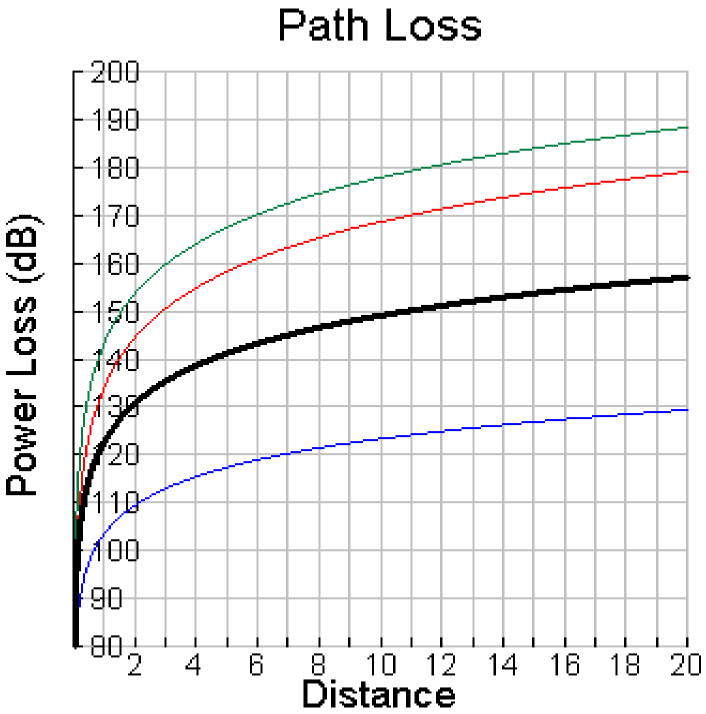


Fig. 47 The Path Loss model for WiMAX as a function of distance for NLOS measurements (thick line) from Eq. 22. FSL (bottom line), Cost 231 Hata Urban (topmost) and Cost 231 Hata Suburban (next topmost line)

3.6 Other relationships

3.6.1 Downlink UDP bitrate as a function of signal strength

Fig. 48 shows the measured downlink UDP bitrate as a function of the RSSI.

The most interesting measurements are those that are classified as typical, i.e. locations where the channel conditions are evaluated as neither significantly better nor worse than the average conditions in the area. These measurements are shown overlaid by green stars in Fig. 48.

In many situations it can be useful to have a mathematical expression that can be used to estimate the bitrate as a function of RSSI for typical NLOS situations. By using linear regression on the appropriate measurements in Fig. 48, an estimate of the bitrate was found to be:

$$UDP\ bitrate = Min\left[57.2 + 0.59 \cdot RSSI, 9.5\right], \qquad (23)$$

where the RSSI is in dBm and the resulting UDP bitrate will be in Mbps. This estimate is plotted along with the measured data points in Fig. 48.

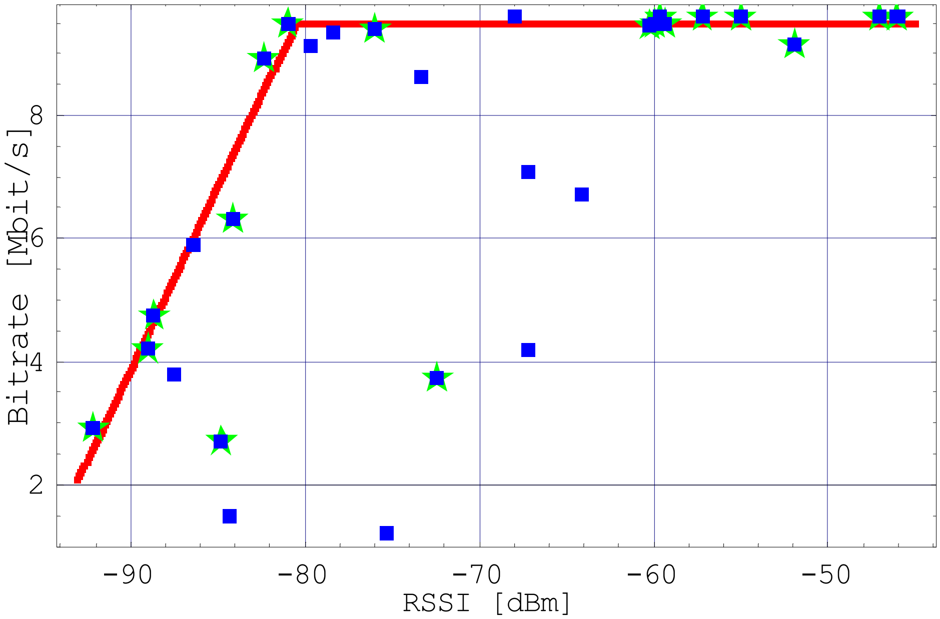


Fig. 48 Measured UDP bitrates as a function of RSSI. An analytical approximation to the bitrate versus RSSI relationship is also shown (line) valid for typical, NLOS situations. The measurements classified as typical and NLOS are shown overlaid by light stars

The values specified by Alvarion are listed in Table 11, and UDP bitrate that has been estimated to give 76% useful bitrate due to overhead.

Table 11 Bit Rate vs RSSI values presented by Alvarion, and the estimated useful UDP bitrate

RSSI Sensitivity	Alvarion physical Bitrate	Estimated Bitrate*0.76
-100	1,41	1,0716
-98	2,12	1,6112
-97	2,82	2,1432
-94	4,23	3,2148
-91	5,64	4,2864
-88	8,47	6,4372
-83	11,29	8,5804
-82	12,71	9,6596

Fig. 49 plots Eq. 23 and the bitrates vs RSSI values presented by Alvarion where the estimated useful UDP bitrate of 76% is added.

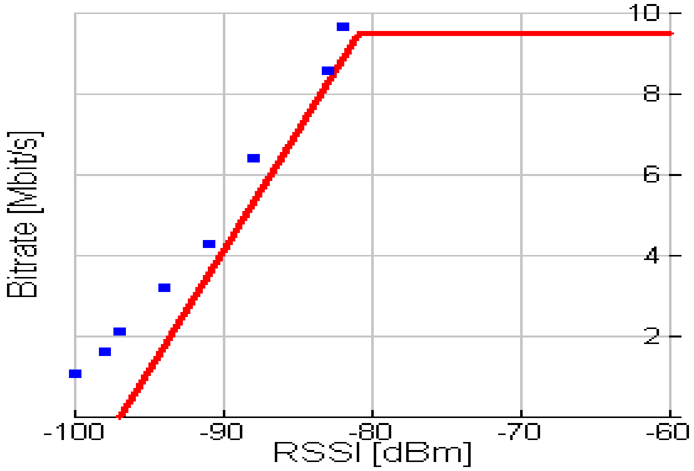


Fig. 49 Eq 20, and bitrate vs RSSI values presented by alvarion. The estimated useful UDP bitrate (76%) is considered

Alvarion have also presented UDP bitrate values achieved with the different modulation rates, which can be directly mapped to the RSSI sensitivity values from Table 11. The UDP packet size used was 1518 bytes. The mapping is shown in Table 12.

Table 12 Alvarion presented UDP bitrate vs Modulation rate for 10 SUs mapped to RSSI sensitivity

Modulation rate	UDP, 10 SUs	RSSI Sensitivity
BPSK 1/2	1	-100
BPSK 3/4	1,3	-98
QPSK 1/2	2,1	-97
QPSK 3/4	3,1	-94
QAM16 1/2	4,2	-91
QAM16 3/4	6,3	-88
QAM64 2/3	8,3	-83
QAM64 3/4	9,8	-82

Fig. 50 indicates that the estimated useful UDP bitrate based on the measurements out of the physical bitrates confirmes to the presented UDP bitrates by Alvarion.

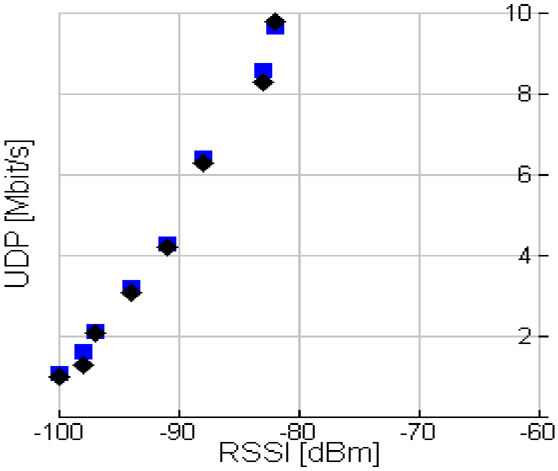


Fig. 50 Alvarion UDP bitrate vs RSSI for 10 SUs (black) and our estimted useful UDP bitrete from the physical bitrate vs RSSI (blue)

3.6.2 Analytical expression for the downlink UDP bitrate as a function of distance

To obtain an analytical expression for the downlink UDP bitrate as a function of distance, the analytical expressions for RSSI versus distance (Eq. 18) and downlink UDP bitrate versus RSSI (Eq. 23) can be combined.

The resulting expression is:

$$UDP\ bitrate = Min\left[20.2 - 15.7 \cdot \log_{10}(r), 9.5\right], \tag{24}$$

where ‘r’ is the distance between the BS and SU in km and the resulting estimate of downlink UDP bitrate is in Mbps. The analytical expression together with the measurement points are illustrated in Fig. 51.

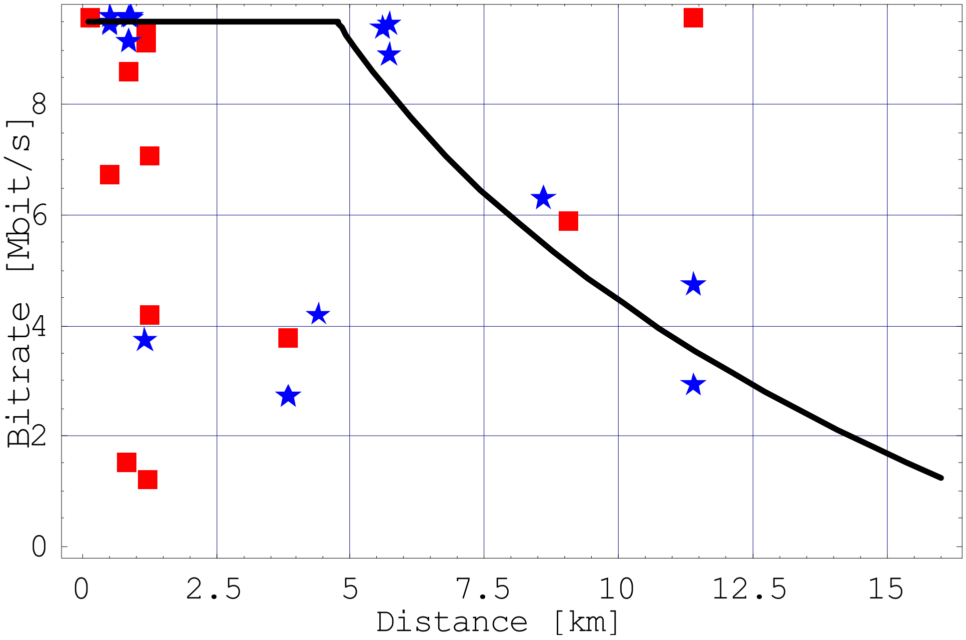


Fig. 51 All downlink UDP bitrate measurements, both NLOS and typical (stars) and others. The analytical approximation given by Eq. 24 is also shown (black line)

It should be realized that the expression given by Eq. 24 is based on relatively few measurements and hence its confidence is relatively low. On the other hand, the equation summarizes the measurement results in a very convenient form that can be used for further analysis.

The equation only represents the measurements characterized as typical and NLOS. Hence, there is also an uncertainty introduced by the subjective term “typical”. The measurements were also made in a terrain that is very favourable with respect to radio propagation, since it is flat out to a certain distance and then rises gradually with increasing distance.

3.6.3 TCP Throughput as a function of Signal to Noise Ratio

The Signal to Noise ratio (SNR) is a more confident measure than RSSI beacause it considers noise and interference. TCP throughput was measured at each location with various amounts of simultaneous TCP connections. DL TCP throughput and UL TCP throughput was measured separately to determine the maximum throughput. The measurements that showed to return a stable throughput for the different amount of simulateneous TCP connections were used to derive an analytical expression for TCP throughput as a function of SNR.

The measured TCP throughput for 2, 4, 6 and 10 simultaneous TCP connections are plotted in Fig. 52. It can be seen that the maximum system throughput was generally reached at around 29 dB in SNR. Linear regression was therefore performed over the SNR and TCP throughput values in the range 0 to29 dB SNR. The resulting analytical expression for TCP throughput as a function of SNR can be expressed as:

$$TCP\ Throughput = Min(0.31 \cdot SNR + 0.365,\ 9.0)\,, \qquad (25)$$

The expression is drawn together with the plotted values in Fig. 52.

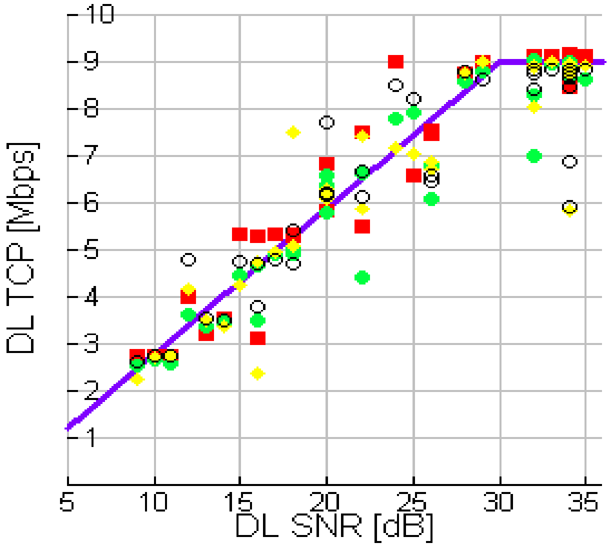


Fig. 52 TCP throughput vs SNR for the DL. The the anlytical expression (Eq. 25) is drawn (blue line). Measurements are 2TCP (red), 4TCP(green), 6TCP(yellow) and 10TCP (black circle)

The standard deviation in was found to be 2.22 Mbps.

The same plot is given for the UL TCP measurements versus SNR in Fig. 53.

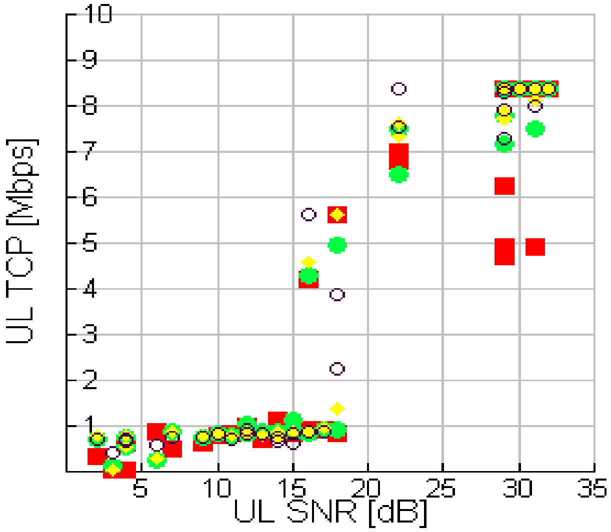


Fig. 53 UL TCP throughput vs SNR, with plots 2TCP (red), 4TCP(green), 6TCP(yellow) and 10TCP (black circle)

It can be seen that the measurements for UL TCP throughput in Fig. 53 naturally follows a similar increase in throughput as the SNR increases. It can be indicated that higher SNR is needed for the TCP throughput to increase above 1 Mbps than for for the DL. This observation can be described by the modulation rate used, where throughput increases as the modulation rate increases. The throughput values for 6 simultaneous UL TCP connections are plotted vs SNR in Fig. 54, where the different colors describe the modulation rate used.

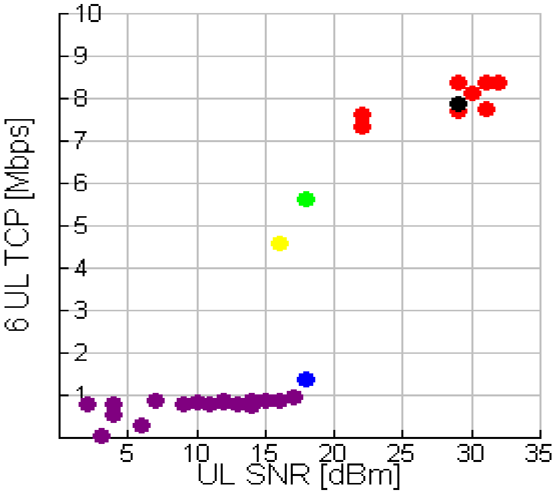


Fig. 54 Throughput for 6 UL TCP connections vs SNR. Modulation rates are BPSK ½(purple), QPSK ¾(blue), QAM16 ½(yellow), QAM16 ¾(green), QAM64 2/3(black) and QAM64 ¾(red)

One observation in Fig. 54 is that the yellow measurement has lower SNR and higher modulation rate than some of the other measurements with higher SNR and lower modulation rate. Another observation is that the blue measurement with modulation rate QAM16 ¾ should have better throughput performance. The reason for these observations is the use of adaptive modulation, and the fact that the throughput measurement and logging of the modulation rate was not performed simulataneously.

It is interesting to compare the results plotted in Fig. 54 with the UDP bitrates versus modulation rate from Alvarion listed in Table 12, where similar throughputs are observed when taken into account that UDP performs some better than TCP.

When comparing the DL and UL TCP throughput versus SNR, it can be seen that the same pattern is observed from around 16 dB SNR and higher, which is naturally due the modulation rates used.

TCP throughput showed to perform better in the DL than in the UL, which comport to FTP throughput specified in the technical specification delivered by the system manufacturer [42].

3.7 Summary of WiMAX Field Trial

A WiMAX certified system from Alvarion has been tested at a number of 15 different locations. A van was driven to a set of locations in Oslo city and parked. At each location, the antenna was placed on the roof of the van where measurements were performed. The measurements included the link quality for received signal strength and signal to noise ratio and the throughput for UDP, TCP and FTP traffic for both uplink and downlink.

Especially Non Line-Of-Sight (NLOS) sites have been tested at short and far distances. Great performance is achieved for NLOS locations within shorter distances, where farther distances show a reduction in throughput and link quality. Micro position offsets are performed at locations with NLOS conditions, showing that position offsets for the antenna may often be found to achieve suitable connectivity.

For LOS conditions between BS and SU, the signal strength performed great and the throughput performed to maximum at the longest distance 11.4 km.

The signal strength measurements for both uplink and downlink generally showed worse values as the distance increased as should be expected. When compared to the values predicted by the Cost-231 Hata models for urban and suburban environments, the fixed WiMAX measurements classified as typical and NLOS locations had generally less loss in signal strenght. This is partly due to the favourable radio propagation conditions in the trial area and to a certain optimization of the antenna placement done at each location. Secondly the Cost-231 Hata models are based on mobile systems, where the WiMAX measurements performed were performed in a nomadic manner.

A path loss model for the trial was derived based on measurements at locations classified as NLOS and typical. Due to the small number of measurements the model has a relatively low confidence. Still it can be useful as it summarizes the measurements in a convenient form for further analysis.

The UDP throughput measurements are the most appropriate ones to use to determine the real uplink and downlink capacity of the system, since UDP does not use acknowledgments so there is no interdependency between the bitrates in the uplink and downlink. The downlink measurements showed that good throughput values were obtained, even at the longest distance of 11.4 km. The useful bitrate was only 76 % of the maximum bitrate given in Alvarion's documentation of the system. This is due to many things, like the UDP overhead and that some of the capacity is used for management traffic.

The uplink UDP measurements showed good throughput values only for distances below about 2 km and for the LOS measurement at 11.4 km. At NLOS locations at distances beyond 2 km, the uplink throughputs were low. The main reason for this is that the power amplifier in the subscriber terminal can deliver only 20 dBm maximum compared to 28 dBm for the base station amplifier.

The TCP throughput measurements showed values slightly below those obtained with UDP, as should be expected due to more overhead caused by TCP than UDP. As for UDP, the TCP uplink throughputs were low for distances beyond about 2 km.

The downlink FTP throughput measurements showed values slightly below those obtained for TCP, which should be expected since FTP is based on TCP. The measured uplink FTP throughputs were significantly lower than what should be expected from the corresponding TCP measurements. The reason for this is probably that the TCP window size was set too low on the computer where the FTP server was running.

An analytical expression was found for the downlink UDP bitrate as a function of the distance between the BS and SU. An analytical expression was also found for the UDP bitrate as a function of the received signal strength. Due to the small number of measurements the estimations has a relatively low confidence, but can still be useful as it summarizes the measurements in a convenient form for further analysis.

Signal to noise ratio (SNR) is the ratio between the signal power and the noise power corrupting the signal. An analytical expression was derived for TCP as a function of SNR, which may be useful to predict the throughput for a subscriber unit in a deployment where interference may be present.

The measurements acted as for nomadic use, whereas the system is designed for fixed deployment. At each location the equipment was configured, and longer periods were spent waiting for the adaptive modulation technique to become ready. Thus, a more rapidly and effective decision on adaptive modulation should be implemented in the system for nomadic usage.

The results presented are viable for one WiMAX Subscriber, where the whole channel is available.

The trial indicates that the WiMAX equipment performs as promised by the vendor. Its main weakness is the limited transmission power in the subscriber terminals which results in low uplink throughputs for distances beyond 2 km. But the next generation of fixed WiMAX equipment will probably be able to use sub-channelization on the uplink, and then the total uplink capacity is expected to be almost the same as for the downlink. Another solution to enhance uplink performance will be to use diversity.

4 Fixed WiMAX Deployment Analysis

Prior to this thesis, little or no information existed about WiMAX performance. Our field trial performance measurements presented in Chapter 3 "Fixed WiMAX Field Trial" were satisfactory in that a conclusion could be drawn on performance with one subscriber present in the system, but it would be interesting to analyse the system performance with many subscribers. The goal of this chapter is to conclude upon performance in a fixed WiMAX deployment with the focus on the link quality and coverage.

As a real life fixed WiMAX deployment had expanded with a great amount of subscribers and base stations, we decided to analyze the deployment in early 2007. The physical parameters were extracted from all the present subscribers, over which we performed extensive analysis of the system performance. Signal propagation and system interference was analysed. We derived an accurate path loss model with great confidence because of the large amount of measurements obtained.

The fixed WiMAX deployment analysis resulted in one conference paper (Paper 3):

3. Grønsund,P., Engelstad,P., Johnsen,T., Skeie,T, "The Physical Performance and Path Loss in a Fixed WiMAX Deployment", International Wireless Communications and Mobile Computing Conference (*IWCMC*) 2007, Honolulu (Hawaii), August 12-16, 2007

This study will hopefully be of great importance and useful to students, operators, service providers and other instances involved in WiMAX. Especially the path loss model which is of great reference value is suited for use in simulations for further performance studies by students or deployment planning by operators.

4.1 Introduction

As a fixed WiMAX deployment has been operative for a year, the amount of Base Stations (BS) and subscribers present in the deployment have increased over time. A decision was made to extract the most important parameters from the system, which are Received Signal Strength Indication (RSSI) and Signal to Noise Ratio (SNR), over which extensive analysis was performed. GPS coordinates were also available for each of the subscribers, which was useful to determine the distance between the Base Station (BS) and Subscriber Unit (SU).

A path loss model was constructed in Chapter 3.5.2, but with low confidence due to the little amount of measurements. This study of a fixed WiMAX deployment in real life therefore aims at constructing a Path Loss model with great precision due to the large amount of measurements. The Path Loss model will be affected by possible co-channel interference (CCI) by the adjacent Base Stations, and will therefore reflect a real life WiMAX deployment. Frequency planning is an important subject in deployment of wireless communication studies, and will be analysed in context with CCI.

The organization of the rest of this chapter is as follows: Section 4.2 gives a description and overview of the fixed WiMAX deployment. The measurement procedures are explained in section 4.3. Section 4.4 describes the physical performance regarding signal strength and signal to noise ratio, before the Path Loss model is derived and analyzed in Chapter 4.5. Frequency planning and co-channel interference are studied in chapter 4.6 and some throughput results presented in Chapter 4.7. The measurements are summarized in Chapter 4.8. All the measurement data for this deployment analysis are given in Appendix C.

4.2 System Description

The system in use is a fixed WiMAX system operating in the 3.5 GHz frequency band, which is the same as system as used in the Fixed WiMAX Field Trial. Totally 10 Base Stations are deployed, where 850 Subscriber Units (SU) are operative. The system utilizes FDD with 3.5 MHz channels in both uplink and downlink. Each BS sector has a 90˚ beamwidth, and 4 licensed frequencies are available for use.

Each BS is configured to transmit at a 28 dBm maximum where the BS antenna gain is 14 dBi.

The SUs are fixed antennas, which are located outdoor at the house wall or roof. Automatic Transmission Power Control (ATPC) is enabled at all the SUs where the maximum transmitted power is 20 dBm. SU antenna gain is 18 dBi.

If possible, the SUs are setup within Line of Sight (LOS) to the BS, but there are also SUs with Non Line of Sight (NLOS) conditions. The NLOS sites are mostly present in areas close to the BS, whereas LOS becomes more important at farther distances.

The area of deployment consists of one medium sized town named Gjøvik with a population of 30.000, where the population density is low in the suburban areas outside the town centre and denser in the town centre with 5 floor high buildings. This town is covered by 3 BSs, where two of these BSs have four sectors and one has two sectors. The area of deployment also consists of two villages, one with 6,000 (Raufoss) and the other with 3,000 (Biri) inhabitants. One BS mainly covers Raufoss, with assistance from one sector at another BS. Biri is covered by one BS with two sectors. These villages may be considered as suburban areas where most of the settlement is houses. The other BSs cover rural areas. The number of subscribers served by each sector in each BS is given in Table 13. The 3 topmost BSs are in the city with 30,000 inhabitants (Gjøvik), and the fourth BS, “Moelv”, covers the village with a population of 3,000 (Biri). The village Raufoss is mainly covered by the BS “Lønneberget” and partly by “Lauvhogda”. The rest of the BSs cover rural areas and outer parts of the villages.

Table 13 Base Stations with the amount of Subscribers on each Access Unit (N/A means that there is no AU)

BS	AU1	AU2	AU3	AU4
Raadhus	15	9	45	3
Bergstoppen	8	70	37	23
Hunndalen	17	24	N/A	N/A
Moelv	29	19	N/A	N/A
Lønneberget	16	119	52	14
Lauvhogda	14	36	39	52
Redalen	15	1	N/A	N/A
Glaestad	17	2	N/A	N/A
Snertingdalen	10	10	N/A	N/A
Lena	6	23	49	9

As can be seen from Table 1, some of the sectors cover few subscribers. These sectors are set up for large institutions, like schools and companies and thus require great bandwidths.

A coverage map for the BS “Lønneberget” is given in Fig. 55. The plotted points are SUs connected to this BS. Some of the other BSs coverage areas can also be seen. “Lauvhogda” is to the South and “Lena” to the West. The BSs in the North is “Raadhus” and “Hunndalen” in Gjøvik City.

An observation drawn from the coverage map is that subscribers located far outside the estimated coverage area are connected to “Lønneberget” and not to the closest BS. This is due to LOS capabilities of “Lønneberget”. This phenomenon is also observed in the other coverage maps. Thus NLOS conditions are more commonly experienced by SUs located close to the BS, while LOS conditions are most frequent for SUs farther away from the BS. A reason for this is that high buildings inside cities interfere with the signal path between BS and SU, and that the BSs are often located near or within cities. SUs located at farther distances from the BSs require LOS for optimal performance.

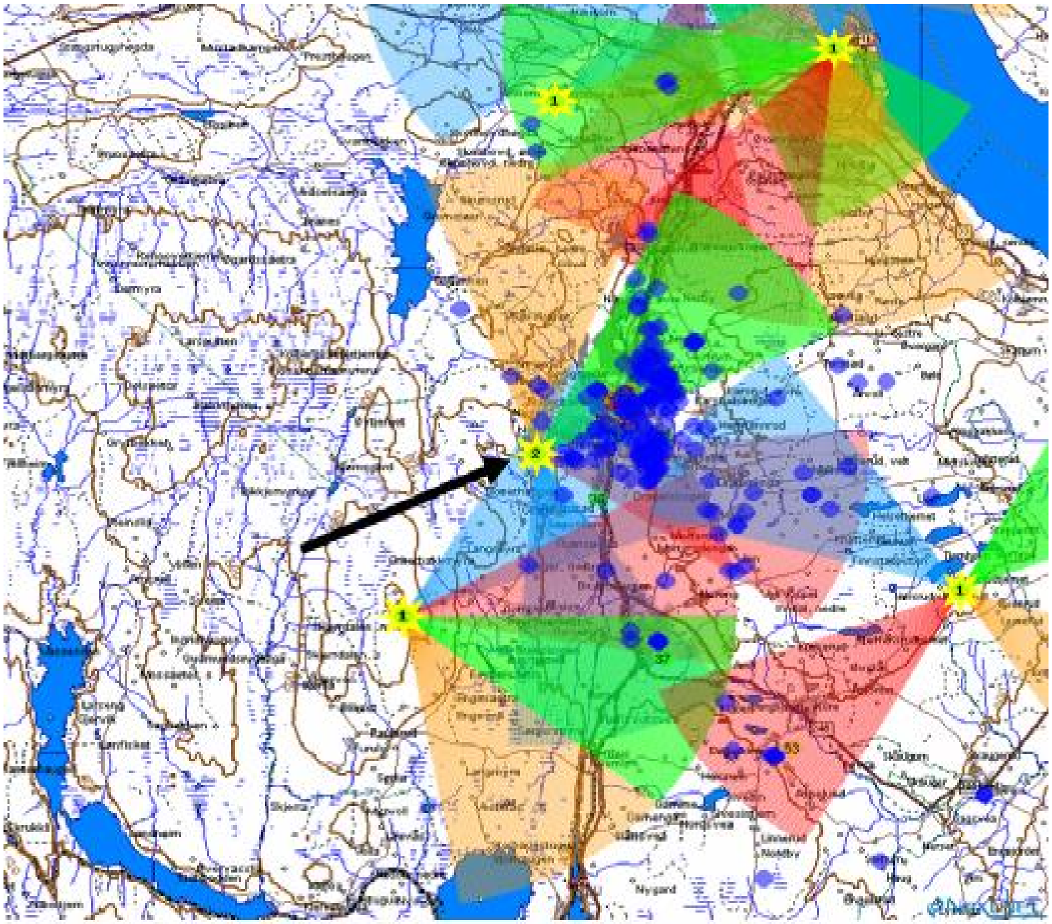


Fig. 55 Coverage Map of Raufoss city, where the plotted blue circles are subscribers using the BS "Lønneberget" (arrow)

The terrain where the measurements are performed is hilly, where interference is unlikely in the rural areas, but more probable inside Gjøvik City. All the base stations, with the frequencies used at each sector is given in Appendix C.C.3.

4.3 Measurements

A Network Management System (NMS) is used by the operator for administrating the BSs and SUs. The functionality in the BSs and SUs logs performance attributes. These performance attributes are DL and UL RSSI, DL and UL SNR, transmit (Tx) and receive (Rx) modulation rate and Tx power for the SU which is important due to the use of ATPC. The operator has implemented functionality to abstract the attributes and register them in a database. These attributes are logged for all subscriber each 5th minute for the last 4 months.

It was winter when the measurements were extracted. The landscape was covered with snow and the temperature was about –5˚C.

4.4 Physical Performance

4.4.1 Received Signal Strength Indicator (RSSI)

As specified in IEEE 802.16-2004 [3], sect 8.3.9, the WiMAX SUs and BSs have a Received Signal Strength Indicator (RSSI). The Network Monitoring System in use logs the RSSI for all the SUs which are operative during the day. The RSSI related to the distance between the SU and BS gives valuable information related to the power loss in the WiMAX system. The RSSI is measured for both uplink and downlink, and will be analyzed and compared to well-established models in the following subsections. The well established models will be Free Space Loss (FSL) and the Cost 231 Hata models for suburban and urban environments.

4.4.1.1 Downlink Signal Strength versus Distance

The downlink (DL) RSSI for each subscriber is plotted in Fig. 56 together with the well established models FSL and the Cost 231 Hata models for suburban and urban environments.

Most of the plotted subscribers are expected to be close to the FSL, since they were installed with LOS conditions to the BS if possible. But this is not always possible when deploying a wireless communication system in cities with high buildings. This is illustrated by the divergence in Fig. 56.

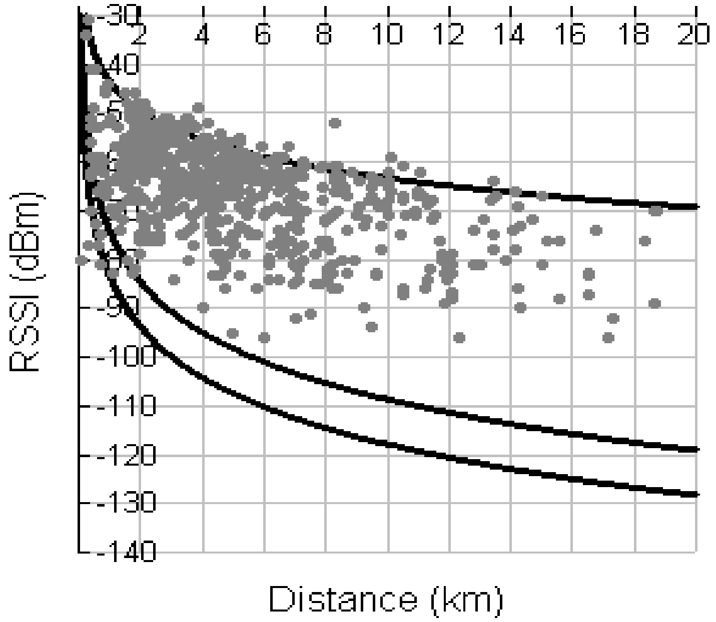


Fig. 56 RSSI vs. Distance for DL locations together with the FSL (topmost line), Cost 231 Hata Suburban (middle line) and Cost 231 Hata urban model (bottom line)

Some of the subscribers very close to the BS perform equal to or worse than the Cost 231 Hata models. This is mainly due to the fact that subscribers close to the BS are more frequently under NLOS conditions than subscribers farther away from the BS. The reason for the greater performance of this system than the Cost 231 Hata models is that this is a fixed system rather than nomadic or mobile as used when constructing the Cost 231 Hata models.

4.4.1.2 Uplink Signal Strength versus Distance

As for DL RSSI, the UL RSSI values for each subscriber are plotted in Fig. 57 together with the models FSL and the Cost 231 Hata suburban and urban models.

Since Automatic Transmission Power Control (ATPC) is used by the SU, normalization is performed on the RSSI values where the corresponding transmission power is below the maximum of 20 dBm. This is done by adding the transmission power back-off in dBm as follows:

$$RSSIULnorm = RSSIUL + (20 - TxPower)\,. \qquad (26)$$

The UL RSSI versus distance plot is similar to the DL RSSI versus distance plot with the exception that lower RSSI values are observed. This was expected due to the fact that the SU transmits with 8 dBm less power than the BS.

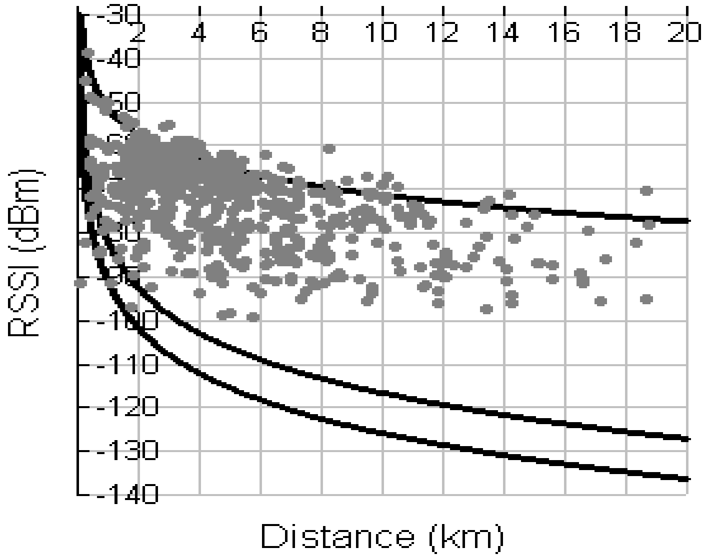


Fig. 57 RSSI vs. Distance for UL locations together with the FSL (topmost line), Cost 231 Hata Suburban (middle line) and Cost 231 Hata urban model (bottom line). UL RSSI values are normalized according to Eq. 26

4.4.2 Signal to Noise Ratio (SNR)

The Signal to Noise Ratio (SNR) is the power ratio between the signal and the background noise. SNR will give a better indication of the actual system conditions because interference and noise is revealed.

SNR and RSSI are measured at all locations and should be closely correlated, and a plot of RSSI versus SNR should give a smooth graph if the interference and background noise is absent. The following subsections analyses SNR for downlink and uplink.

4.4.2.1 Downlink Signal to Noise Ratio

The DL RSSI versus DL SNR is plotted for each subscriber in Fig. 58. The graph flatten off at around -65 dBm and outwards, which indicates that optimal performance could be achieved if RSSI is above -65 dBm and no interference or background noise is present. The results indicate that the maximum measurable SNR value at the SU is 36 dB.

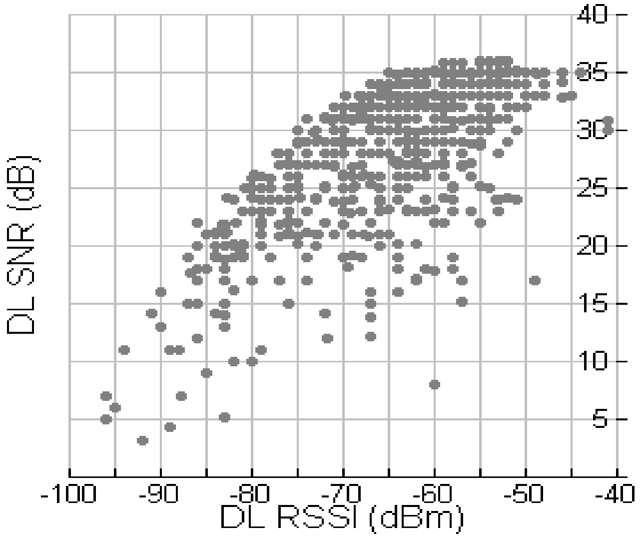


Fig. 58 Downlink SNR versus RSSI

Many of the subscribers vary from the linearity and the “flatten off” pattern, which indicates that interference is present. Since the system consists of 10 BSs, where 4 different frequencies are reused at adjacent BSs all sending with max power, there is a great possibility for CCI.

Even though the SU cannot measure higher SNR values than 36 dB, the RSSI continue to increase. The SNR values that layes below 36 dB as the RSSI increase may therefore not be valid, and not very influential as the RSSI increases.

Another observation is that the curve seems to decrease with 1 dB in SNR at around -50 dBm in RSSI and more, which may be due to saturation in the SU antenna.

4.4.2.2 Uplink Signal to Noise Ratio

Fig. 59 shows the uplink RSSI vs. SNR. A linear increase is observed, and the subscribers that deviate from this line are probably disturbed by interference.

The “flatten off” observation found in the downlink graph (Fig. 58) is not present in the uplink, which is because the SU transmits with less power than the BS. The maximum SNR value in the uplink is found at around -68 dBm RSSI which is a bit better than for the downlink.

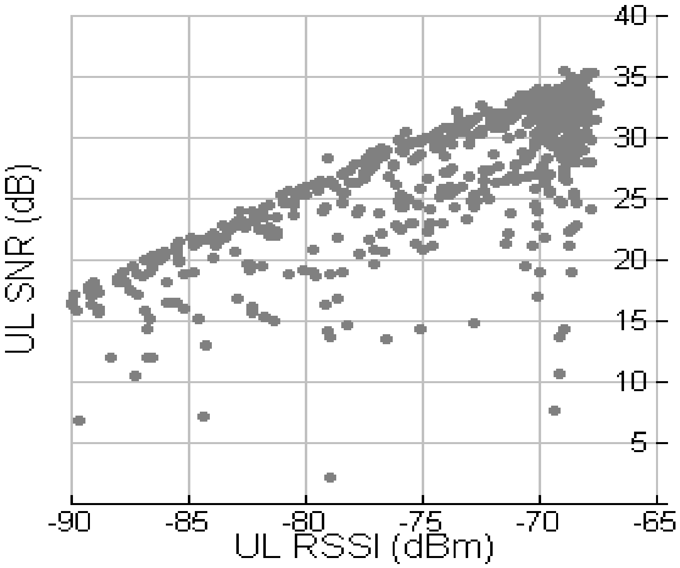


Fig. 59 Uplink RSSI vs. SNR

It is interesting to compute the cumulative distribution of SNR for different distance intervals as shown in Fig. 60, which illustrates that the probability to obtain a better SNR value at shorter distances is naturally higher than at farther distances in a WiMAX deployment.

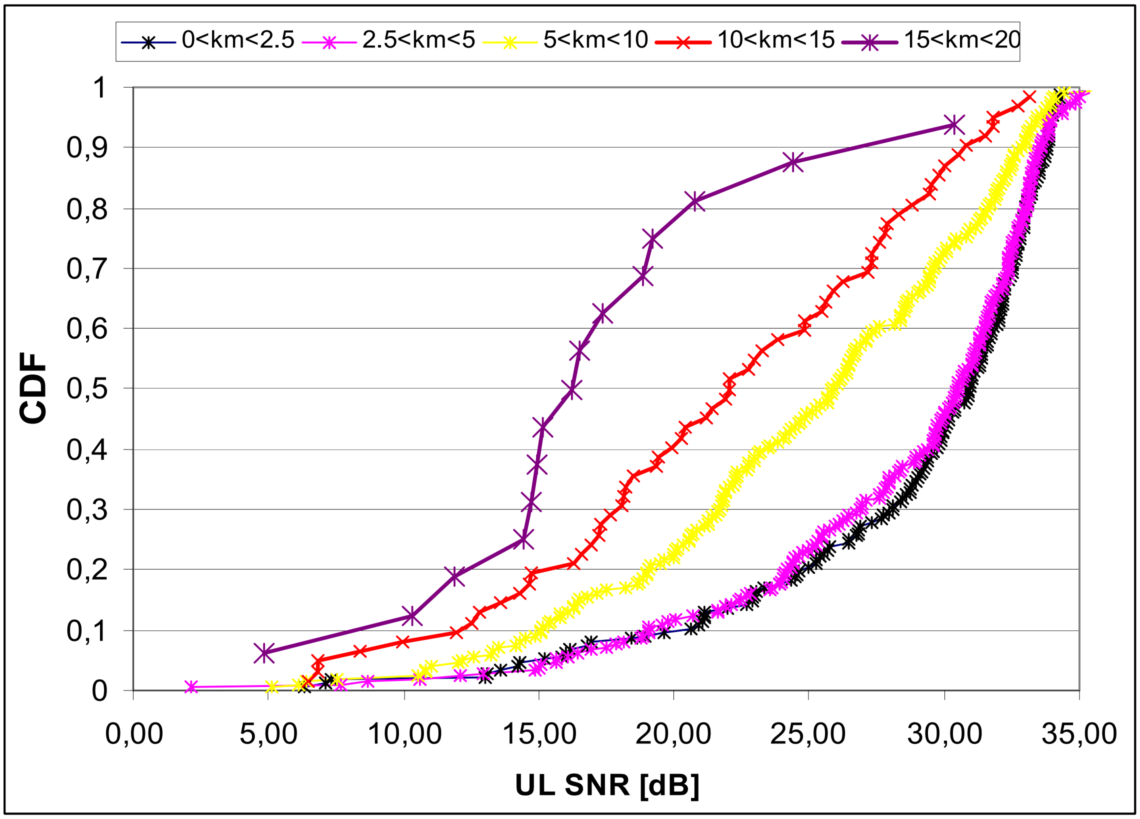


Fig. 60 Cumulative Distribution of SNR for different distances

4.5 Path Loss Model

A Path Loss model could be derived based on the high amount of RSSI values obtained in the distance range up to 20 km. The high amount of RSSI values made it possible to construct a Path Loss model with great accuracy.

Only SUs with LOS conditions are considered in the model. As many of the SUs at shorter distances to the BS have NLOS or near LOS conditions, the subscribers within 2 km are excluded from the model. The rest of the subscribers are classified, where NLOS subscribers are excluded. A total amount of 513 SUs were considered in the model after the classification. We used both the DL and UL RSSI values, thus the total amount was 1026 RSSI values. The UL RSSI values were normalized according to Eq. 26 because of the ATPC, and 8 dBm were added to these values because of higher DL output power from the BS.

We aimed at finding a model of the Path Loss model by the following equation:

$$PL = A + B\log(r)\,. \tag{27}$$

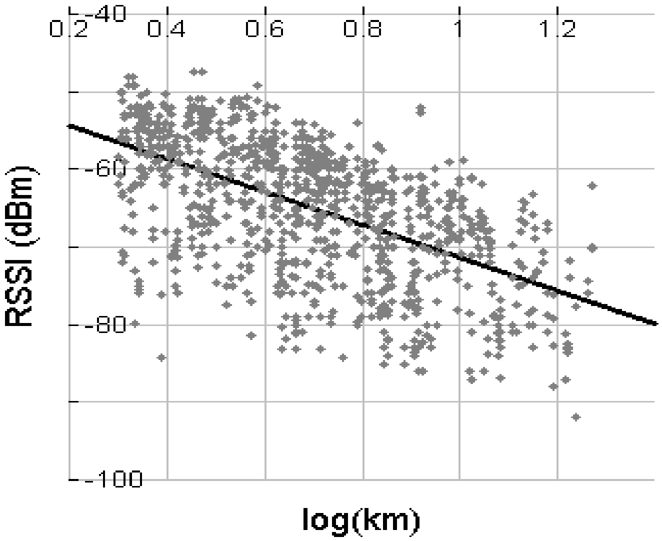


Fig. 61 RSSI vs. log(dist) for both DL and normalized UL RSSI values. The linear regression for DL and UL RSSI values are drawn

Fig. 61 plots all the RSSI values versus the logarithm of the distance between the BS and the SU. If the Path Loss confirm to a straight line with the form given in Eq. 27 a straight line should be drawn through the points in Fig. 61. The straight line was found by doing linear regression on the points:

$$RSSI = \text{-}50.11 \text{-} 21.29 \cdot \log_{10}(r)\,, \tag{28}$$

where ‘r’ is the distance between BS and SU, and the RSSI is denoted in dBm.

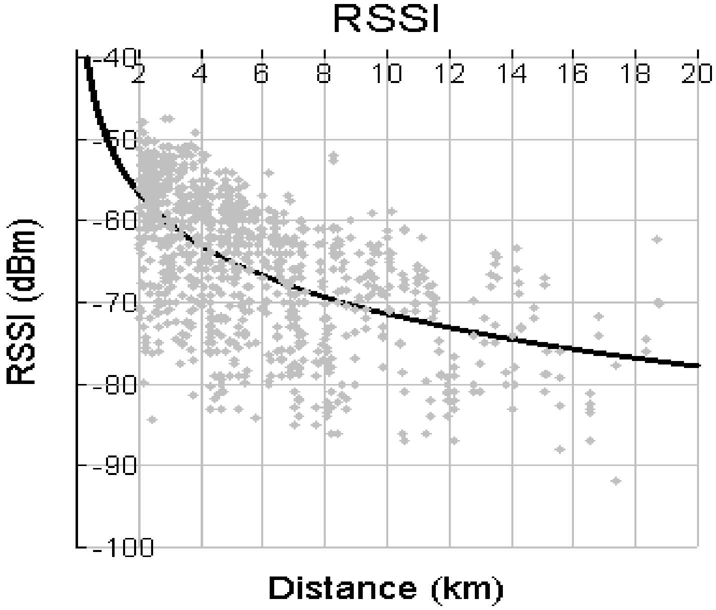


Fig. 62 Eq. 28 plotted together with all RSSI values

Eq. 28 is plotted together with all RSSI values in Fig. 62. The standard deviation for Eq. 28 was found to be 7.17. The mean RSSI value was -66.45 dBm.

A Path Loss model can be derived from

$$PL = TP + Gbs + Gsu - RSSI \,, \tag{29}$$

where ‘TP’ is Transmitted Power, ‘Gbs’ is BS antenna gain and ‘Gsu’ is SU antenna gain. The resulting Path Loss model for the measurements is given by

$$PL_{LOS} = 110.11 + 21.29 \cdot \log_{10}(r) \,, \tag{30}$$

where ‘d’ is the distance between BS and SU, and the Path Loss is denoted dB.

It can be seen that the loss exponent in Eq. 30 is similar to the free space loss, which was as expected for the SUs with LOS conditions.

It is interesting to compare the Path Loss model to the Free Space Loss model (FSL) and the Cost 231 Hata [48] models for suburban and urban areas. These models are plotted together in Fig. 63.

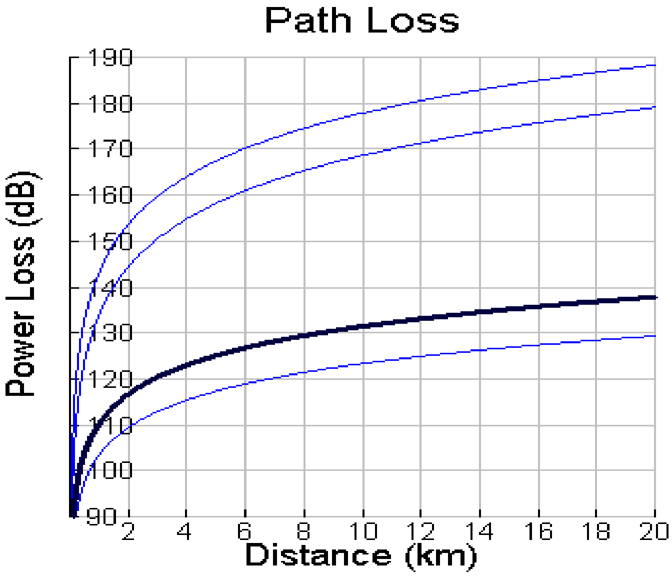


Fig. 63 Path Loss Models Compared. Our Fixed WiMAX Path Loss Model from Eq. 30 (thick line), FSL (bottom line), Cost 231 Hata Urban (topmost line), Suburban (middle light line)

As expected, the Path Loss model approaches the FSL model because most of the subscribers have LOS capabilities. The Cost 231 Hata models for suburban and urban environments have greater Path Loss because they are based on mobile systems, whereas the fixed WiMAX Path Loss model is based on a fixed system.

It is also interesting to compare our Path Loss model and the model deduced in field trial measurements in Chapter 3, which was based on measurements with NLOS conditions in the range up to 12 km. The comparison is illustrated in Fig. 64.

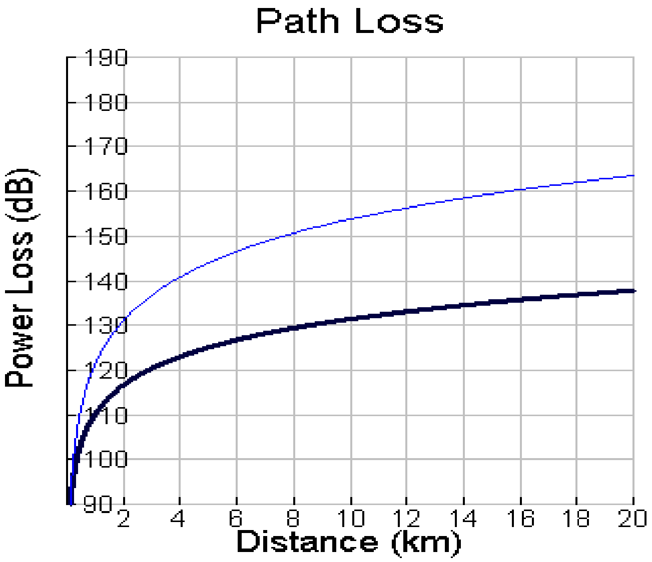


Fig. 64 Path Loss model from WiMAX deployment (thick line) mainly based on LOS conditions, compared to Path Loss model in WiMAX Field Trial (light line) based on NLOS measurements

The model for NLOS was based on measurements in urban areas, and the model for LOS mainly in urban and suburban areas. The urban area in the NLOS model was medium-sized and the urban areas in the LOS model were small-sized, but the NLOS landscape was more favourable to radio propagation. The great differentiation in both loss exponent and the system loss constant is clearly due to the different sight capabilities.

4.6 Frequency Planning and Co-Channel Interference

An illustration of the frequency planning is given in Fig. 65. This is the area where the BSs are most densely located. The city centre of the largest city (Gjøvik) lies in between the three topmost BSs, where more suburban areas are found towards the BS "Lonneberget". The whole frequency planning is described by maps in Appendix C.3.

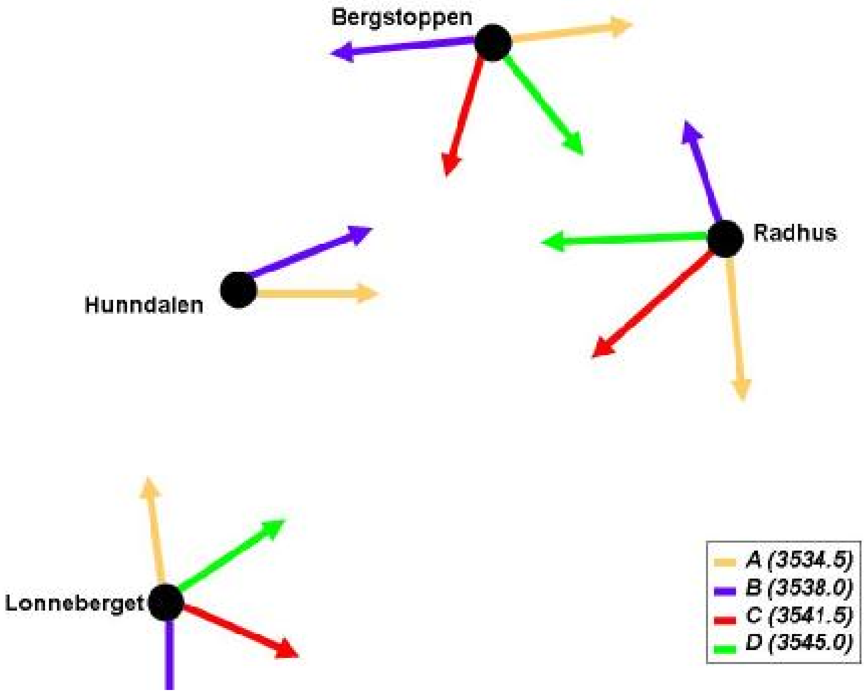


Fig. 65 Illustrated snapshot of the frequency planning. Frequencies are in MHz

Table 14 lists all the Noise plus Interference (N+I) power levels in dBm averaged for all SUs serverd by each AU in the WiMAX deployment. To calculate the (N+I) values, the following equation was used:

$$(N+I)_{dBm} = RSSI_{dBm} - SNR_{dB}\,. \tag{31}$$

Since the DL SNR values flatten off at RSSI values above -65 dBm, these are not included when calculating the average (N+I) values for each AU.

Table 14 N+I (dBm) for all AUs (sectors) for UL and DL, and frequencies at each secotr (MHz)

BS	AU	UL	DL	#SU	Freq [MHz]
Radhus	1	-98,50	-93,04	15	3534.5 (A)
	2	-98,08	-92,69	9	3545.0 (D)
	3	-99,99	-91,69	45	3541.5 (C)
	4	-102,02	-94,75	3	3538.0 (B)
Lonneberget	1	-103,81	-97,23	16	3534.5 (A)
	2	-102,96	-98,78	119	3541.5 (C)
	3	-99,72	-92,00	52	3545.0 (D)
	4	-100,28	-95,05	14	3538.0 (B)
Bergstoppen	1	-101,25	-92,57	8	3534.5 (A)
	2	-99,49	-94,91	70	3541.5 (C)
	3	-99,43	-96,45	37	3545.0 (D)
	4	-102,51	-96,91	23	3538.0 (B)
LenaOmformer	1	-104,09	-100,01	6	3541.5 (C)
	2	-103,84	-101,49	23	3534.5 (A)
	3	-99,15	-97,80	49	3545.0 (D)
	4	-102,13	-97,22	9	3548.0 (B)
Hunndalen	1	-96,85	-94,90	17	3534.5 (A)
	2	-101,06	-96,56	24	3538.0 (B)
Lauvhogda	1	-98,93	-93,15	14	3538.0 (B)
	2	-99,53	-93,22	36	3545.0 (D)
	3	-105,72	-98,71	39	3534.5 (A)
	4	-104,88	-101,48	52	3541.5 (C)
Snertingdalen	1	-104,39	-100,80	10	3545.0 (D)
	2	-104,26	-99,71	10	3538.0 (B)
Moelv	1	-103,82	-100,00	29	3534.5 (A)
	2	-103,68	-100,20	19	3541.5 (C)
Glaestad	1	-104,97	-100,98	17	3541.5 (C)
	2	-104,45	-100,38	2	3534.5 (A)
Redalen	1	-102,51	-98,76	15	3538.0 (B)
	2	-106,09	-100,87	1	3545.0 (D)
AVG/AVG/SUM		-101,946	-97,077	783	

An observation from Table 14 is that interference in the DL is greater than in the UL, i.e. approximately -97 dBm versus -102 dBm. The reason is that DL interference is caused by other BSs and UL interference is caused by the SUs, where BSs transmis with higher power (28 dBm) than the SUs (≤20 dBm (ATPC)). BS interference is therefore greater than SU interference.

The RSSI flattens off at about -65 dBm because the SUs cannot measure higher SNR. It is important to state that with greater RSSI values than -65 dBm, interference has less impact on the performance for the specific SU. This can be illustrated by the the analytical expression derived in the field trial measurements for UDP bitrate as a function of RSSI (Eq. 23), where maximum throughput should be achieved at around -82 dBm RSSI where minimal interference was present. We also see from the analytical expression from TCP throughput as a function of SNR (Eq. 25), that maximum throughput should be achieved, and the highest modulation rate used, at a minimum measure of 30 dB SNR.

4.7 Throughput Performance

Throughput measurements were not carried out because the SUs are located at customer premises.

Some throughput measurements were performed by the network provider, where customers requiring high throughput had to be tested in advance. These measurements were performed at an early stage without possible congestions in the wireless domain. Throughput for UDP and TCP were measured, but there were no additional data present regarding the physical attributes and distance between SU and BS. The same measurement tool (Iperf) as were used in the "Fixed WiMAX Field Trial" in Chapter 3, was used for these measurements. The results are given in Appendix C.2.

UDP throughput measurements for the bandwidth demanding subscribers in this deployment are shown for DL and UL in Fig. 66.

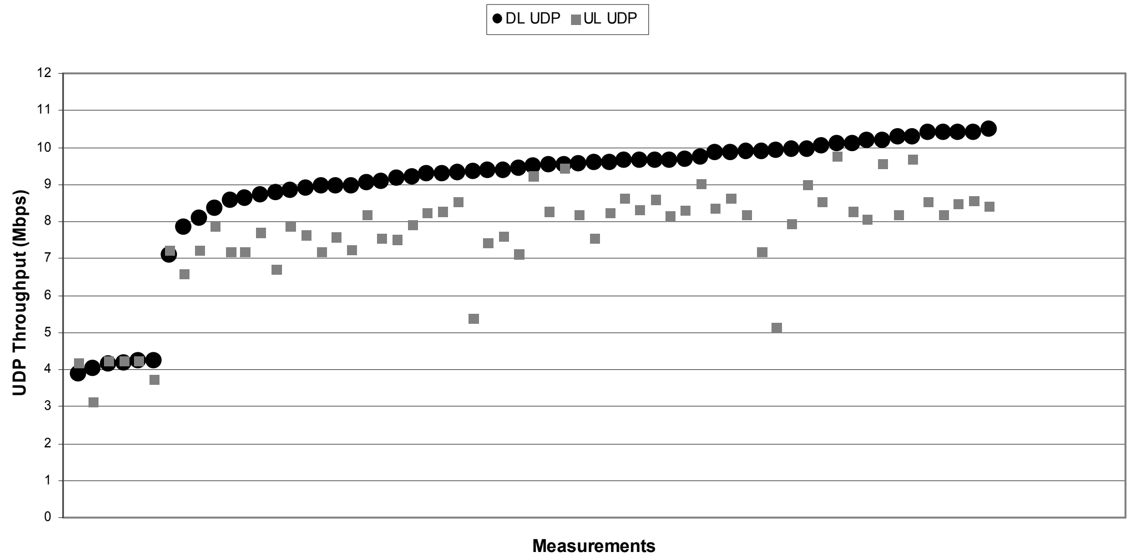


Fig. 66 UDP Measurements for DL (bullets) and UL (squares)

Maximum UDP throughput achieved was 10.5 Mbps, which is higher than what achieved in the "Fixed WiMAX Field Trial" in Chapter 3. Most of the measurements had LOS except for the ones with weakest throughput.

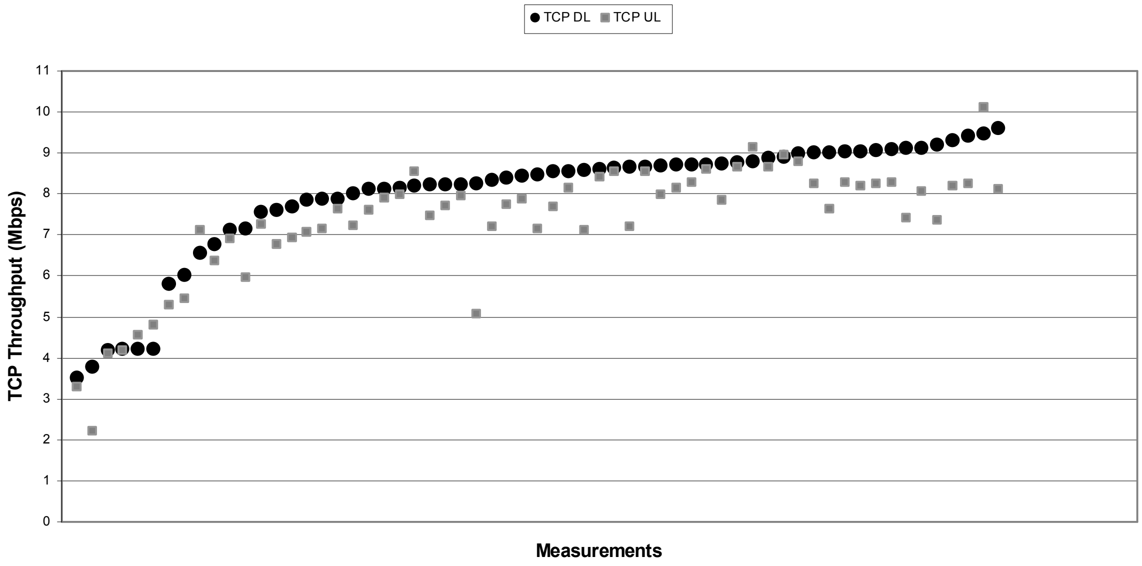


Fig. 67 TCP Measurements for DL (bullets) and UL (squares)

TCP throughput measurements for the bandwidth demanding subscribers in this deployment are shown for DL and UL in Fig. 67. Maximum TCP throughput achieved was 10.1 Mbps in the UL, which was higher than the maximum of 9.6 Mbps in the DL. This is higher than what was achieved in the "Fixed WiMAX Field Trial" in Chapter 3. The greater throughput values obtained in these measurements may be because of specific UDP and TCP protocols used, which may be specific to the operating system used. The measurements performed in the field trial used Windows 2000, whereas these measurements used Windows XP. A further study should be devoted to this observation.

It is worth noticing the lower throughputs achieved with the transport protocol TCP than UDP. This was averaged and calculated to differ with 1 Mbps in the DL and 0.26 Mbps in the UL. The reason for this is most probably protocol overhead.

4.8 Summary of WiMAX Deployment Analysis

A real life fixed WiMAX deployment with a total of 850 subscribers has been investigated and analyzed with focus on the physical performance attributes received signal strength (RSSI) and signal to noise ratio (SNR).

A plot of SNR versus RSSI showed that Co-Channel Interference (CCI) is present at many locations in the system deployment. This could have been avoided if more frequencies had been available for use or with more suitable tuning of the BS transmitting power.

A Path Loss model based on the RSSI values from the fixed WiMAX deployment was derived, which is of great reference value due to the large amount of measurements. The Path Loss model was compared to other well known Path Loss models, where the path loss in the fixed WiMAX deployment seems to approach the Free Space Loss model more than the Cost 231 Hata models for urban and suburban areas. This was as expected due to the fact that fixed WiMAX is setup with free propagation paths towards the base station where possible. Secondly, the Cost 231 models are based on mobile systems whereas the fixed WiMAX deployment operates with fixed mounted antennas at buildings. The Path Loss model can be considered as an empirical propagation model since it is based on a real life deployment.

An extract of the frequency planning was presented for the area where the BSs are most densely located, which also illustrated that there are high possibility for CCI. The average CCI power levels were presented for each cell, and demonstrate the levels of CCI present in the WiMAX deployment.

Throughput measurements performed by the Internet Service Provider responsible for the deployment corresponds to the difference between DL and UL throughput as found in the "Fixed WiMAX Field Trial". A difference was that higher throughput values were measured for both UDP and TCP, which should be devoted a further study.

5 Pre-Mobile WiMAX Field Trial

Mobile WiMAX is the feature profile of WiMAX also called universal WiMAX since it support the mobility in addition to the fixed services. The mobile WiMAX profile is hyped and told to surpass other mobile wireless access systems with a combination of broadband and mobility, but little or no information exists about performance in real life.

As a pre-mobile WiMAX system was available in February 2007, we sat up a field trial over which we performed measurements regarding throughput and physical performance at a range of random locations. The system was delivered with 4th order diversity, thus measurements were executed to study the impact of diversity. Analytical expression for the performance gain achieved as a function of diversity order. Another feature was sub-channelization in the uplink, which showed to improved coverage.

This chapter aims at uncovering the expectations brought to the mobile WiMAX profile. The scientific research performed may provide a framework for other researchers to perform measurements over the coming mobile WiMAX systems and other systems with similar functionality.

5.1 Introduction

At the time of writing this thesis, no published material exists about mobile WiMAX and real life field trial measurements. As a pre-mobile WiMAX system was manufactured in early 2007, a decision was made to set up a test bed and perform the most important measurements to analyze the system performance. Throughput was measured with the transport protocol UDP, and physical performance was measured for the most important attributes Received Signal Strength Indicator (RSSI) and Signal to Noise Ratio (SNR). An automated measurement procedure based on the procedure developed for the “WiMAX field Trial” was implemented (Appendix E).

The pre-mobile WiMAX system studied in this chapter operated in the 3.5 GHz frequency band, with a fully implemented TDD scheme where uplink/downlink ratio could be flexible adjusted over a total bandwidth of 5MHz. A partial implementation of OFDMA was used in the uplink with groups of 16, 8 or 4 sub-channels where one Subscriber Unit (SU) can transmit per symbol. Orthogonal Frequency Division Multiplex (OFDM) was used in the downlink. The Base Station (BS) was provided with 4th order diversity, and could with little effort be configured without and with 2nd order diversity.

More extensive measurements were performed at a subset of the locations in order to analyze the impact the different orders of diversity had on system performance. The measurement procedure was executed to measure performance for no-, 2nd- and 4th order diversity.

The main contribution of this chapter is to present measurement results and comprehensive analysis over a real life pre-mobile WiMAX field trial, where expected path loss and throughput are presented. A second contribution is a study on performance for diversity applied in the pre-mobile WiMAX system, and the derivation of expressions for expected performance for RSSI, SNR, UDP throughput and modulation rate as functions of different diversity order.

The organization of the rest of this chapter is as follows: Section 5.2 presents the system setup. The measurement procedures are given in section 5.3. Section 5.4 and 5.5 presents the result for physical and throughput performance respectively. The impact of diversity and different diversity orders are given in section 5.6 before conclusions are drawn in section 5.7. All the measurements for this field trial are given in Appendix D.

5.2 System Setup

5.2.1 System Description

BreezeMAX TDD delivered by Alvarion [50] is a WiMAX-ready platform operating in TDD mode with a 5 MHz bandwidth in the 3.5 GHz frequency band. It is a Point to MultiPoint (PMP) radio access system, where a BS serves mobile, nomadic and fixed Subscriber Units (SU).

The BS was setup with 3 Access Unit Indoor Units (AU-IDU), each constituting a sector with 120˚ beamwidth. The BS was configured with 4th order diversity. Both 4th order transmit diversity using Cyclic Delay Diversity (CDD) and 4th order receive diversity using Maximum Receive Ratio Combining (MRRC) were used at the BS. This was a setup with each of the three AU-IDU connecting to 4 AU Outdoor Units (AU-ODU), which was paired such that AU-ODU 1 and 2 form one pair and AU-ODU 3 and 4 form a second pair. Each pair was then connected to a dual polarization slant antenna as illustrated in Fig. 68. The total BS then consists of 1 NPU, which is the heart of the BS, 3 AU-IDUs, 12 AU-ODU and 6 antennas.

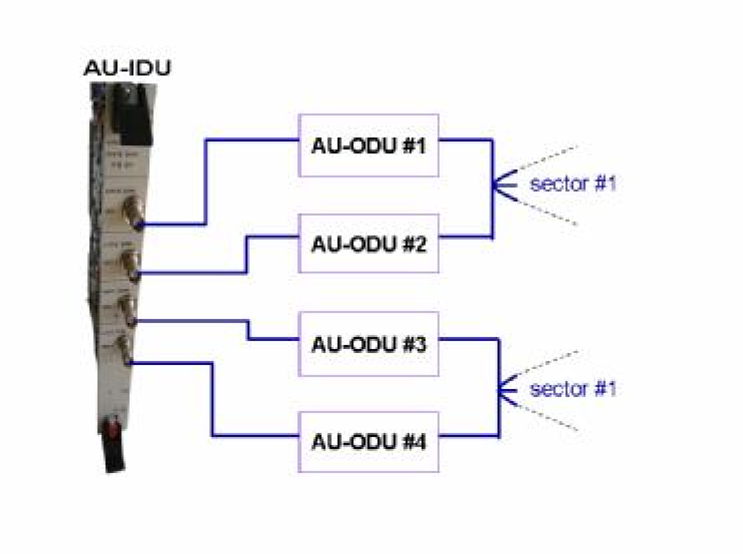


Fig. 68 AU-IDU connected to 4 AU-ODU paired 2x2 and connected to double polarized antennas

It can be seen from Fig. 68 that one dual polarization slant antenna was used for 2nd order polarization diversity. Two dual polarization slant antennas were used for 4th order diversity with space diversity and polarization diversity in each antenna.

All AU-ODUs was setup with the same frequency and transmit power, and all share a common MAC and modem. Output power at antenna port was 34 dBm for each AU-ODU. Total output power for each sector with four antennas is therefore 40 dBm. Each antenna has a 13 dBi gain, which will be 19 dBi for 4th order diversity.

The measurements were performed using a Self Install (Si) CPE which is a compact SU intended for indoor installations. The Si CPE includes 6 internal 60˚ antennas providing full 360˚ coverage and connects to the end-user equipment through a 10/100 Base-T Ethernet interface. It uses Automatic Transmit Power Control (ATPC) where the maximum transmission power is 22 dBm. Si CPE antenna gain is 9 dBi.

Sub-channelization was implemented in the UL by using OFDMA technique, with a limitation that only one SU can transmit per symbol as illustrated in Fig. 69.

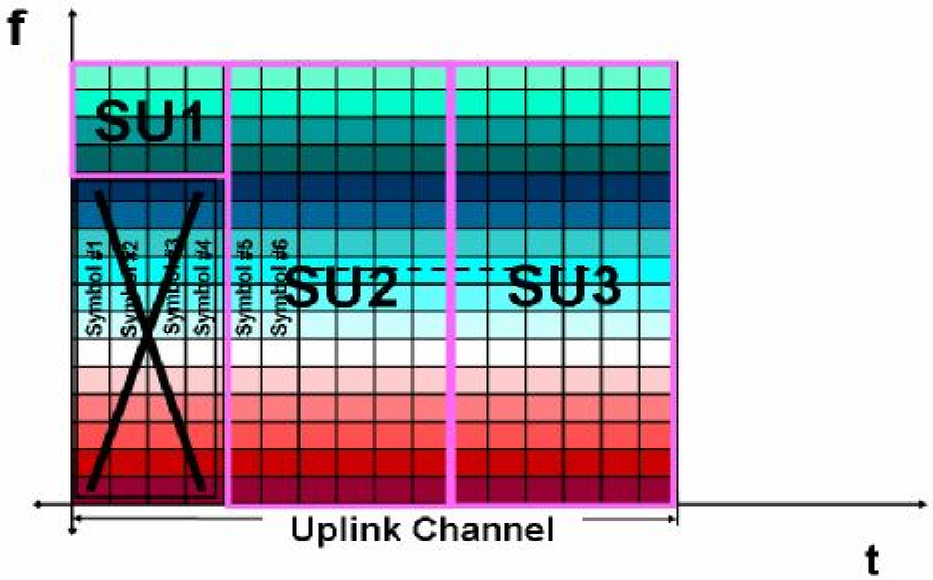


Fig. 69 Sub-channelization, with one SU per symbol

The gain will therefore not be multiple accesses over an OFDMA frame in parallel, but that one SU with weak link quality can focus the power onto fewer sub-channels to obtain connectivity. The sub-channels may be grouped in 16, 8 or 4. A 3 dB gain in RSSI should be obtained for the remaining subchannels when lowering one step in amount of sub-channels used. OFDM 256 FFT was used in the downlink.

The TDD ratio was set to 50/50, thus half the time was available for DL and the other half for UL. The theoretical bitrates are listed for each modulation rate in together with the DL and UL bitrates when TDD rate is set to 50/50 in Table 15.

Table 15 Teoretical bitrate in full TDD with 5 MHz bandwidth, and UL/DL TDD ratio 50/50

#	Modulation Rate	Bit rate (Mbps)	50/50 Bit Rate
1	BPSK ½	1.92	0.96

2	BPSK ¾	N/A	N/A
3	QPSK ½	3.84	1.92
4	QPSK ¾	5.76	2.88
5	QAM16 ½	7.68	3.84
6	QAM16 ¾	11.52	5.76
7	QAM64 2/3	15.36	7.68
8	QAM64 ¾	17.28	8.64

5.2.2 Measurement Area

The BS is setup in Hamar City in Norway. Hamar is a smaller city with a population of 27.600 and a total area of 351 square kilometres. The city centre where most of the measurements were performed consists of 5 floor high buildings, and most of the city may be considered as rural areas. A map of Hamar City is shown in Fig. 70, where the city centre is to the west from the BS.

Fig. 70 Hamar Map. BS is plotted where the arrows points in each sector shooting direction

The BS is elevated 20 meters above ground level, and is positioned at the roof of a building. The circle in Fig. 70 is the area where the measurements were performed. Weak link quality was observed at the edge of this circle.

5.3 Measurements

5.3.1 Throughput and Physical Performance

To measure physical and throughput performance, the SU was placed at the dash-board in a car. We drove around in Hamar and stopped at 40 locations where measurements were performed. Some of the measurements were also performed inside restaurants.

We implemented a measurement procedure to be performed at each of the locations. This procedure firstly accesses the SU and performs the physical measurements. This includes measuring the UL and DL RSSI, UL and DL SNR, UL and DL modulation rate, transmission (Tx) power and the amount of sub-channels used in the UL. Secondly the script performed throughput measurements with the transport protocol UDP for both UL and DL. Iperf [51] was used for throughput measurements.

5.3.2 Diversity Gain

We wanted to measure the difference and gain when using 4th order-, 2nd order- and no diversity. These measurements were also performed with the SU placed at the dashboard in the car. Upon arriving at a random location, we first measured without diversity. The physical and throughput measurements were performed. We then switched to 2nd and 4th order diversity and performed physical and throughput measurements for each. Diversity measurements were performed at 8 locations.

5.4 Physical Performance

5.4.1 Received Signal Strength Indicator

RSSI was measured at each location for both DL and UL. It is useful to relate RSSI to the distance between SU and BS which will give us an idea of the system path loss. To get a view of the system performance, it is interesting to compare the RSSI versus distance relation with well established path loss models. We used the Free Space Loss (FSL) model and the Cost 231 Hata [48] models for urban and suburban areas as comparison to our measurements. The UL RSSI values reported by the BS in the system version used are the maximum RSSI from the best antenna, and not the correlated RSSI from all antennas that would be the real situation. The BS receive diversity gain were therefore not included in these models.

Fig. 71 shows DL and UL RSSI values plotted versus distance between SU and BS, together with the well known path loss models configured with the properties of the system in use.

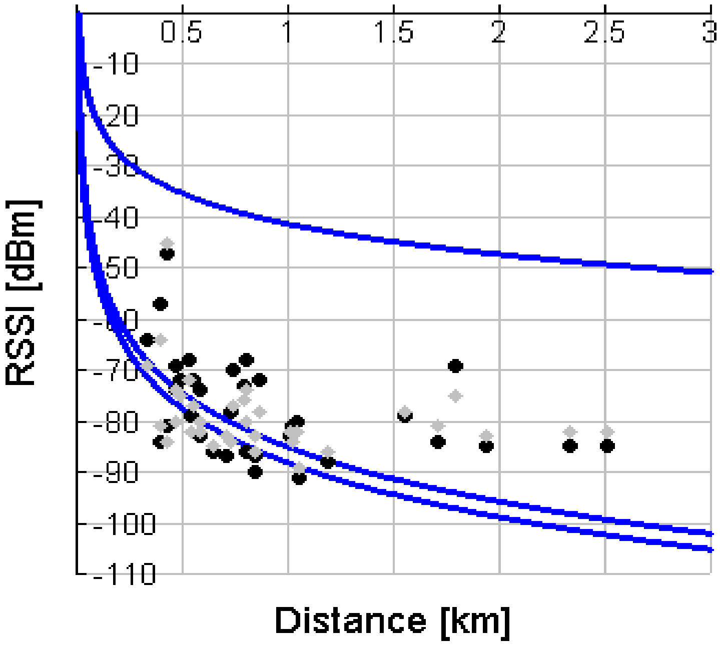


Fig. 71 RSSI versus Distance for DL (dark dots) and UL (grey triangles), plotted with FSL (topmost) and Cost 231 Hata models for suburban (middle line) and urban (bottom line) areas.

From the comparison in Fig. 71, the DL RSSI values are similar to the Cost 231 Hata models. This was expected due to the fact that we operate with a mobile system as used for constructing the Hata models. Measurements close to the BS is drawn near to the Cost 231 Hata model for urban areas whereas the farther distances are more similar to the Cost 231 Hata model for suburban areas. This confirms to our measurements, where locations at shorter distances were in urban areas and those with farther distances in rural areas.

5.4.2 Signal to Noise Ratio

SNR may sometimes be a better measure than RSSI because the background noise and interference are considered. Only one BS with three sectors operating in different frequencies is present in our measurements, and the SU is operating alone in the system. Thus little interference is expected. It is interesting to plot the SNR versus RSSI which should result in a smooth graph if no interference were present.

Fig. 72 shows the plot of SNR versus RSSI values in both DL and UL. A smooth graph is observed, where the UL SNR versus RSSI values are weaker than in the DL as expected.

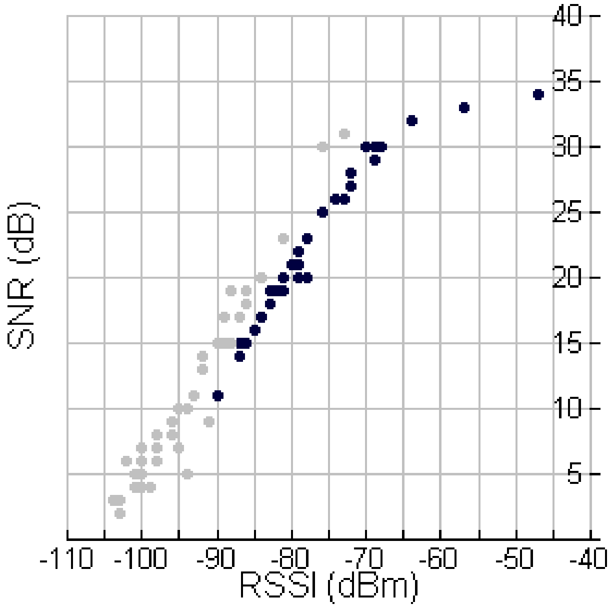


Fig. 72 SNR versus RSSI for DL (black points) and UL (light points)

It can be seen in Fig. 72 that the UL RSSI values are lower than the DL RSSI values which is due to less power transmitted in the UL than DL. The graph for DL RSSI bounces off at 35 dB which is close to the maximum measureable SNR at the SU. Since the RSSI reported by the BS is the RSSI from the best antenna, and not the correlated RSSI from all antennas when using MRRC diversity, these values should actually range higher.

It is also interesting to see how the SNR values versus distance follow the same pattern as RSSI versus distance which is plotted in Fig. 73.

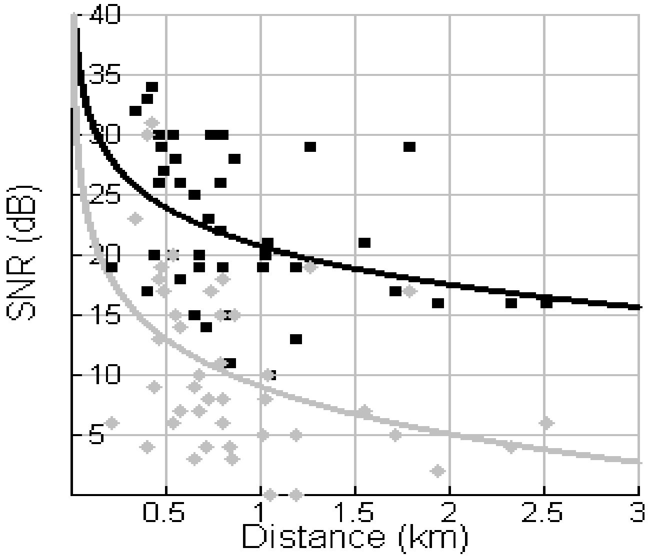


Fig. 73 SNR vs Distance and the logarithmic regressions for DL (black) and UL (light)

The points seem to follow a logarithmic decrease as expected from the linearity between SNR and RSSI values. We applied logarithmic regression on the UL and DL points separately. These equations will be on the form:

$$y = a + b\ln(d), \tag{32}$$

where 'a' is the SNR value in dB at no distance, 'b' the coefficient relative to the distance 'd'. Logarithmic regression for SNR in the DL and UL resulted in the formulas:

$$SNRDL = 20.8\ -\ 4.65\ln(d)\ \text{and} \tag{33}$$

$$SNRUL = 9.1\ -\ 5.78\ln(d). \tag{34}$$

It can be seen that the coefficient for SNR UL (Eq. 34) -5.78 has a greater decrease than SNR DL (Eq. 33) -4.65. A reason for this may be higher gain in SNR from the BS transmit diversity than BS receive diversity. Another point is that UL SNR dropped to null at locations with bad sight capabilities which did not happen for DL SNR values.

5.5 Throughput Performance

Throughput was tested with the transport protocol UDP at all locations. UDP is suitable for throughput testing purposes because it best simulates the actual bitrate due to the minor overhead added by the protocol.

It is interesting to study the bitrates obtained at locations relative to the distance between the SU and BS. Fig. 74 plots UDP bitrate versus distance, where it can be seen that it is difficult to state a formula for a given bitrate relative to the distance. All locations where randomly chosen and are considered to have NLOS capabilities. The actual propagation paths towards the single BS deployed was different from location to location, and it is therefore difficult to state a model from this based on the little amount of measurements. More suitable propagation paths could have been obtained if more BSs had been deployed.

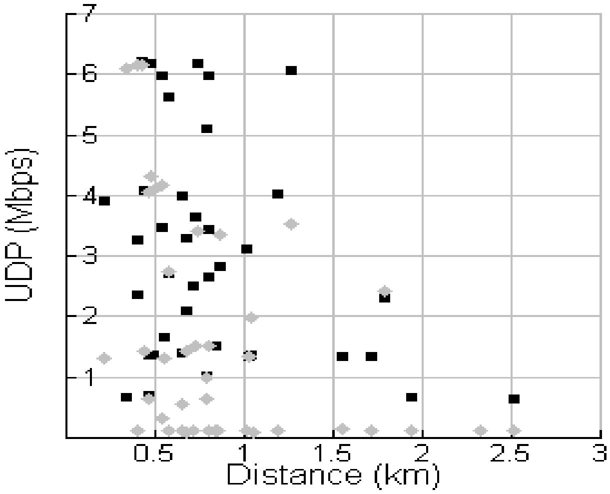


Fig. 74 UDP bitrates plotted versus Distance for DL (black squares) and UL (light triangles)

It can be seen from Fig. 74 that UL throughput is much weaker than DL at most of the locations. One reason for this is that the BS transmits with greater power than the SU.

It is difficult to express any coverage range based on the amount of measurements, but with NLOS conditions one should generally stay within 1 km to be able to perform adequate in UL. It is important to note that the measurements were performed with an indoor unit in NLOS environments.

Table 16 summarizes the maximum, minimum and average results obtained from the UDP bitrate measurements.

Table 16 Max, min and average UDP bitrate results

	UL (Mbps)	DL (Mbps)
MAX	6,16	6,20
MIN	0,094	0,61
AVG	1,59	2,66

It may be more interesting to compare the UDP throughput to the SNR measured. The plot of UDP throughput versus SNR should show an increasing graph, where throughput increases as the SNR increases. DL UDP versus SNR and UL UDP vs SNR are plotted in Fig. 75. An analytical expression representing the most dominating results for both the DL and UL UDP throughput results as a function BER is also drawn, which was found by considering the most dominant measurements that was centered as a linear increase:
$TCP\ Throughput = Min(0.31 \cdot SNR + 0.365,\ 9.0)$

$$UDP_{Mbps} = Max(0.1,\ Min(6.2,\ 0.27 \cdot SNR - 1.25)), \qquad (35)$$

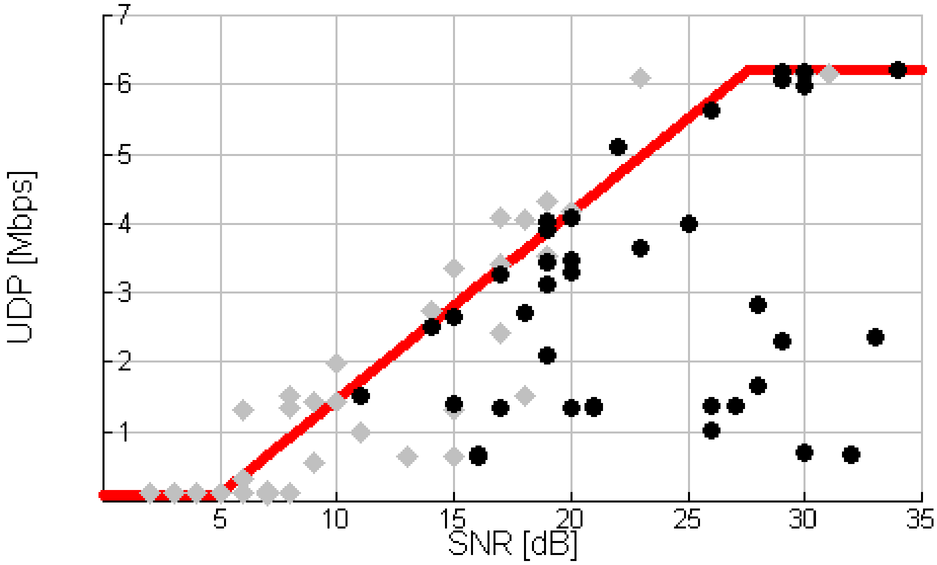


Fig. 75 UDP versus SNR for DL (black) and DL (grey), and the analytical expression from Eq. 35

It can be seen from Fig. 75 that there are som large deviations from Eq. 35, which is most probably due to the fact that the SNR value plotted is taken at a single point in time during the measurement and not the average SNR during the throughput measurent. This is considered as a weakness in the measurement procedure. The standard deviation of UDP throughput was found to be 2.64.

Subchanneling is used in the UL. The measurements with weakest SNR used 4 subchannels and some 8 subchannels. Each halved amount of subchannels results in halved bandwidth, and therefore also halved UDP throughput.

If we compare the analytical expression from Eq. 35 to the analytical expression found for TCP throughput as a function of SNR (Eq. 25) in the “Fixed WiMAX Field Trial”, we find that these have similar growth in SNR, 0.27 versus 0.31 respectively. This is naturally since both systems uses OFDM with 256 FFT symbols and the same modulation types. The maximum in these equations values are 9.0 Mbps in the fixed WiMAX versus 6.2 Mbps in this pre-mobile WiMAX system. This is can also be compared in that a 3.5 MHz channel is used in fixed WiMAX with FDD versus 50 % time of a 5 MHz channel in pre-mobile WiMAX with TDD. We can then see that

$$\frac{bw_{mobWiMAX} \cdot TDDratio}{bw_{fixWiMAX}} = \frac{5MHz * 0.5}{3.5MHz} = 0.71, \tag{36}$$

$$UDP_{mobWiMAX} = \frac{bw_{mobWiMAX} \cdot TDDratio}{bw_{fixWiMAX}} \cdot TCP_{fixWiMAX} = 0.71 * 9.0 = 6.39, \tag{37}$$

where bw is the bandwidth in MHz used by the systems, TDDratio is the time in percent used for transmission in the actual direction. Even though UDP was compared to TCP, it can be seen that the similar performance is observed for one SU present in the system. With UDP instead of TCP, we would have UDP throughput instead of TCP throughput for fixed WiMAX in Eq. 37, 9.6 Mbps vs. 6.2 Mbps, the simulated UDP throughput for mobile WiMAX would have been

$$UDP_{mobWiMAX} = 0.71 \cdot 9.6 = 6.8, \tag{38}$$

which is greater than achieved in the measurements. A reason for this might be that mobile WiMAX uses TDD, and needs to add a guard band between time for transmission and receiving times in the frame. This is not needed in FDD, and thus more overhead causes a reduction in utilization of the bandwidth. Better utilization of the bandwidth might be achieved when more SUs are using the channel simultaneously, but remains to be studied.

5.6 Diversity Impact

Measurements were performed at 8 locations, where no diversity, 2nd order and 4th order diversity were measured. It is interesting to survey the gain when adding an order of diversity. The following subsections present the diversity gains in the downlink and uplink.

5.6.1 Cyclick Delay Diversity Gain in the Downlink

The technique used for transmit diversity was Cyclic Delay Diversity (CDD) for both 2nd and 4th order. Cyclic Delay Diversity (CDD) is a simple approach to introduce spatial diversity to an Orthogonal Frequency Division Multiplexing (OFDM) based transmission scheme that itself has no built-in diversity. It also can be regarded as a Space-Time Code (STC). But in contrast to that there is no additional effort in the receiver necessary, since the different codewords result in a changed channel impulse response in the receiver. They insert virtual echos and thus increase the frequency selectivity of the channel seen by the receiver [52].

The effect of the diversity impact on system performance may be described by analyzing the DL SNR values achieved when increasing levels of diversity order. These are plotted in Fig. 76.

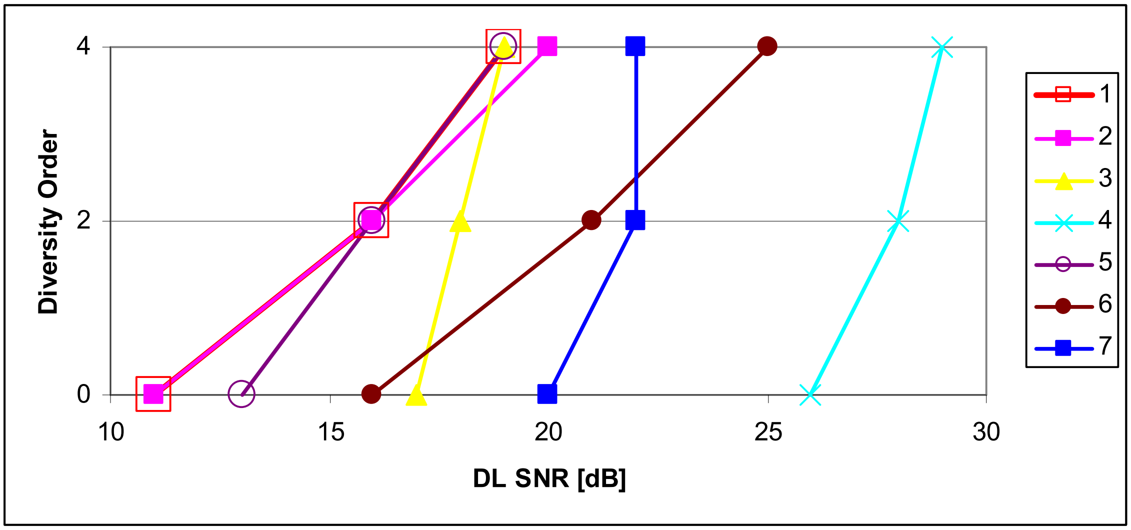


Fig. 76 SNR values with 1st, 2nd and 4th order diversity in DL at 7 locations

One measurement is left out from the plot in Fig. 76, which because of extremely varying conditions at the measurement location and is therefore not comparable to the other diversity measurements.

The gain in SNR seems to be greater from 1st to 2nd than from 2nd to 4th order diversity, with an SNR average of 3.29 dB versus 2.29 dB respectively. The total average SNR gain is then 5.58 dB.

It is now interesting to compare the gain in SNR for different diversity order to the gain in UDP throughput for different diversity order (Fig. 77). UDP may be the best describing measurement for diversity gain since the measurements are performed over time.

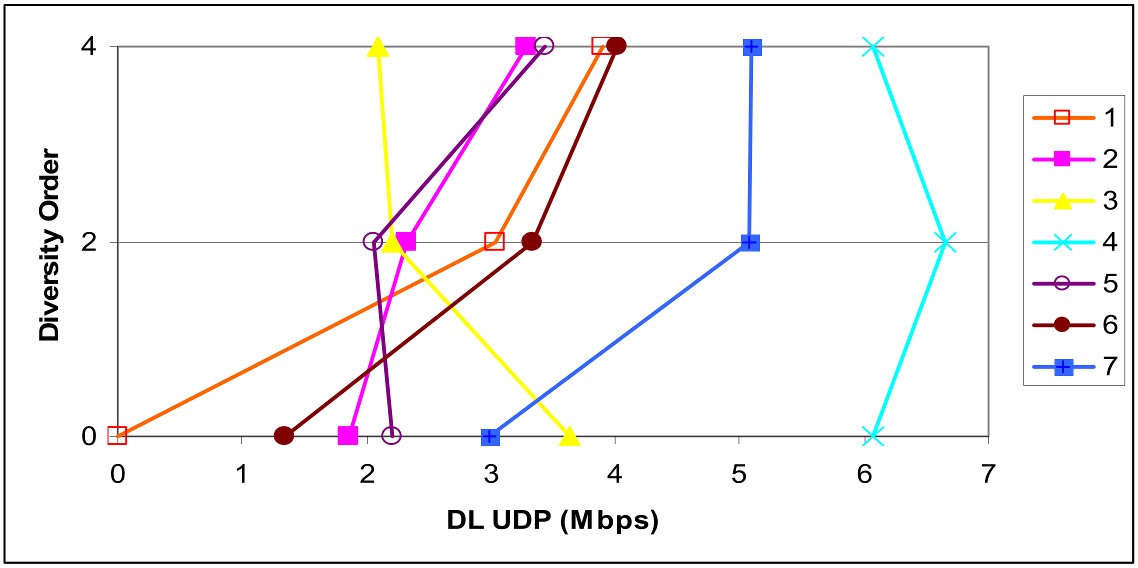


Fig. 77 UDP values for 1st 2nd and 4th order diversity in DL at 7 locations

Gain for UDP throughput corresponds to gain in SNR for the different orders of diversity in most of the measurements. Especially measurement '3' differentiate between the two figures (Fig. 76, Fig. 77), which is caused by one level decrease in modulation rate from the measurement with 1st order diversity to the two others. Measurement '3' was rather not the measurement with strongest gain in SNR for the diversity shifts. Also measurement '4' has a drop in modulation rate in the 1st to 2nd order diversity shift, which causes a loss in throughput. Average increase was 0.78 Mbps for 1st to 2nd and 0.60 Mbps from 2nd to 4th order diversity.

Fig. 78 plots UDP versus SNR in the DL, where lines are drawn from diversity shift from 1st to 2nd and 2nd to 4th order for the measurements performed at each location. The lines must be read from left to right to find gain or loss in UDP throughput versus SNR for the shift in diversity order.

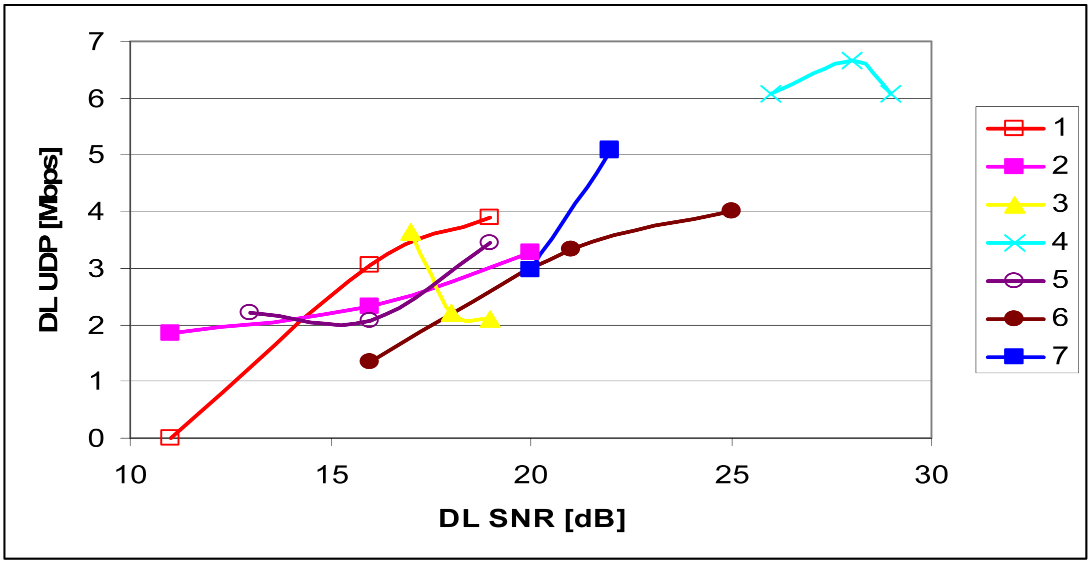


Fig. 78 DL UDP versus SNR, where the lines are the diversity shifts 1st to 2nd and 2nd to 4th order

Fig. 79 illustrates the gain in RSSI for the diversity order shifts.

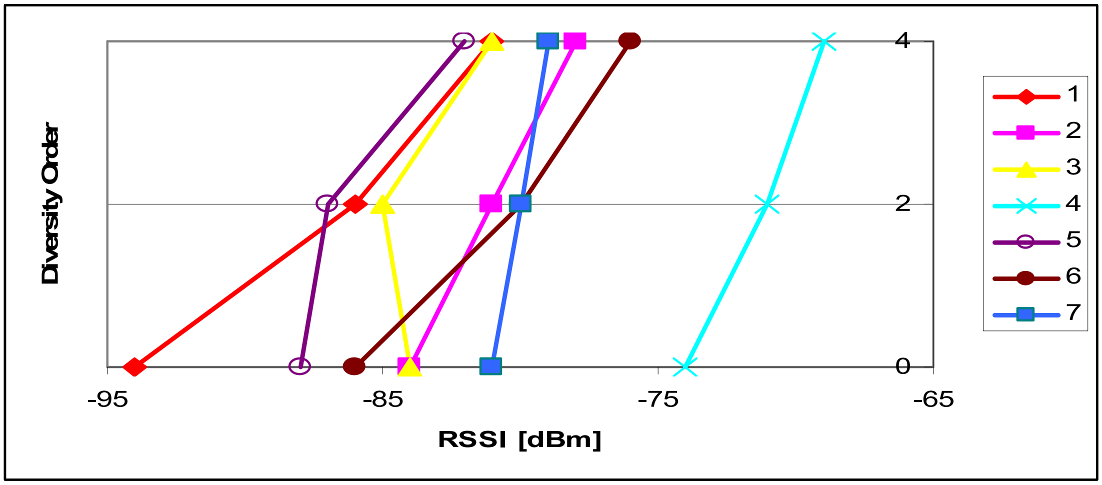


Fig. 79 RSSI values for 1st 2nd and 4th order diversity in DL at 7 locations

5.6.2 Maximum Receive Ratio Combining Diversity Gain in the Uplink

With Maximal Ratio Combining (MRC), the diversity brances are weighted by their respective complex fading gains and combined [53].

The system used was a beta release, where the UL RSSI values reported by the BS were the values from the best antenna. The most useful parameters to analyse the UL diversity gain are the SNR and UDP throughput measured.

Fig. 80 plots 6 of the measurements for UDP throughput measurements for 1st, 2nd and 4th order diversity in a zoomed view, and Fig. 81 plots all the 7 measurements together. Since subchannelization is used in the UL, the amount of subchannels used for each measurement is listet in the legend to the right as (1st, 2nd, 4th).

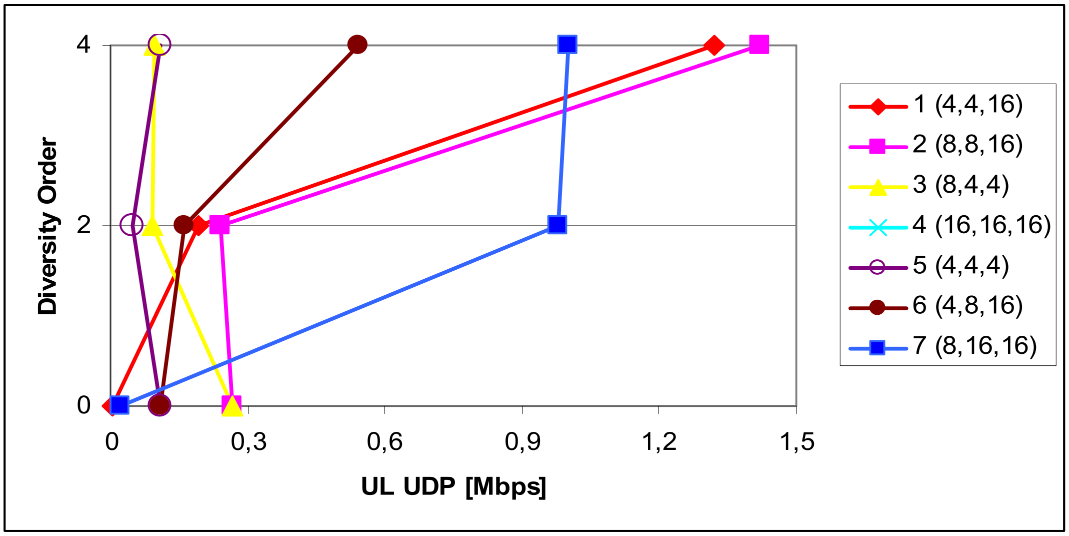


Fig. 80 UDP throughput 1st, 2nd and 4th order diversity in DL for 6 of the locations

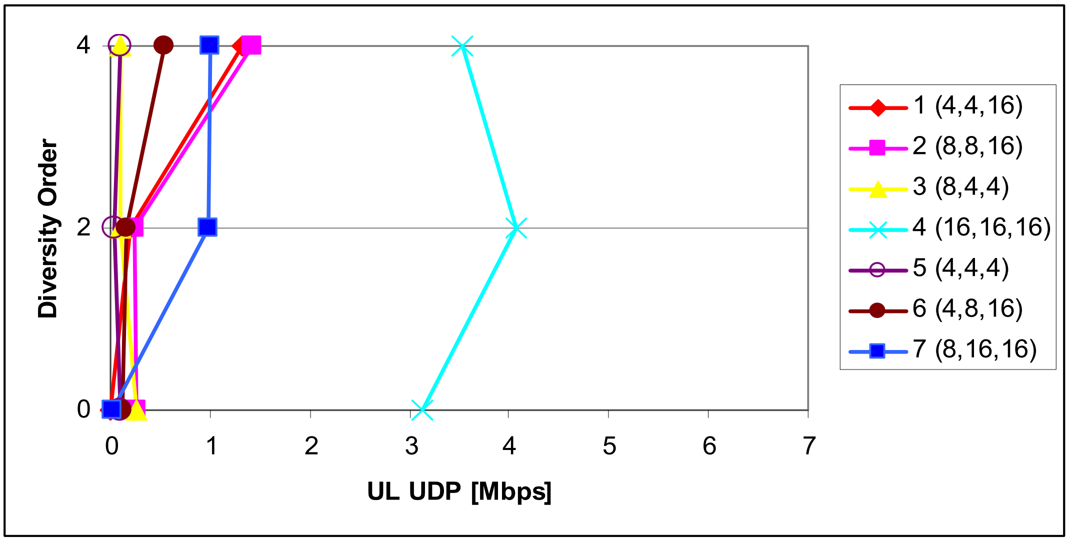


Fig. 81 UDP throughput for 1st, 2nd and 4th order diversity in DL for all 7 locations

A double increase in subchannels used means also that double bandwidth is used, which can be observed from Fig. 80 and Fig. 81 where the UDP throughput achieves a great increase. The throughput will also increase because higher modulation rates are used in many occasions. More subchannels and higher modulation rates follows directly from the SNR gain.

The total SNR obtained is the summation of the SNR from the antennas if they are uncorrelated:

$$SNR_{total} = \sum_{k=0}^{N} SNR_k,\ k \in \{1,2,4\}, \tag{39}$$

where N is the diversity order in use.

Fig. 82 plots the SNR values for the different orders of diversity at the measurement locations.

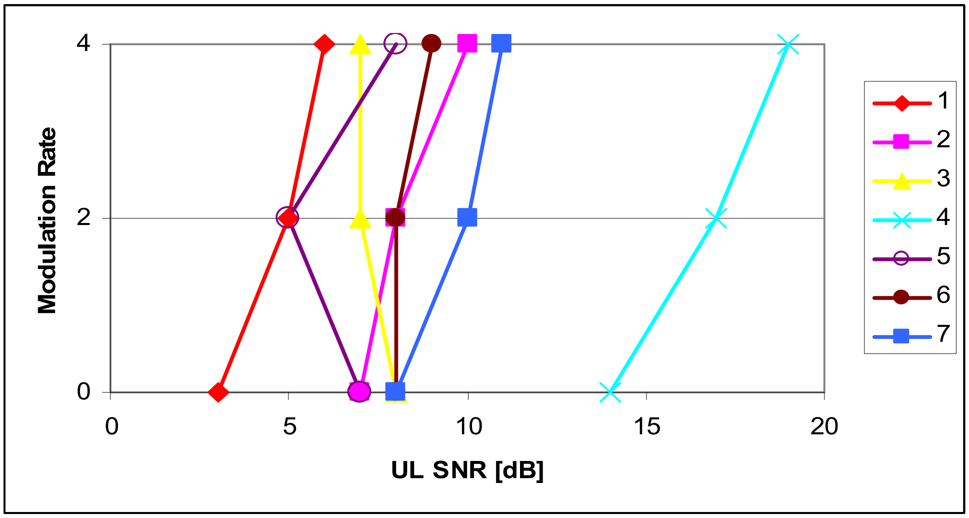


Fig. 82 SNR for 1st, 2nd and 4th order diversity in DLfor all 7 locations

Even though the BS only reports the RSSI value from the best antenna, there is a great probability that a better RSSI value is found at one of the antennas when more antennas are used for diversity. This was observed for some of the measurements as shown in Fig. 83, but not at all locations presumably because of varying link conditions.

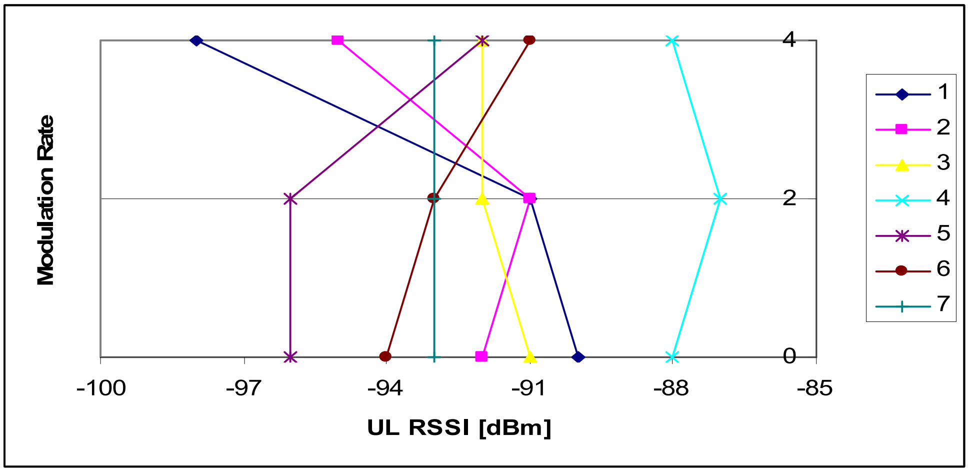


Fig. 83 RSSI for 1st, 2nd and 4th order diversity in DLfor all 7 locations

5.7 *Summary of pre-mobile WiMAX Field Trial*

Field trial performance measurements have been performed over a pre-mobile WiMAX system, where the most important features are sub-channelization and BS transmit and receive diversity. UDP bitrate for throughput and the link quality attributes RSSI and SNR have been measured at a range of random locations with NLOS capabilities.

Based on these results we have found that the Cost 231 Hata model for urban environments fits the system propagation, which is natural due to the mobile characteristics in an urban environment with NLOS conditions. The diversity impact on system performance has been analyzed, and formulas for expected performance gain as a function of diversity order have been derived for RSSI, SNR, modulation rate and UDP bitrate.

The pre-mobile WiMAX system used had limited functionality compared to the original mobile WiMAX profile, but the features implemented gave indications for what to expect from the mobile WiMAX second wave of certification in mid 2007. Sub-channelization was implemented in the uplink with a limitation that only one SU could transmit per symbol, thus the multiple access part per symbol in parallel of OFDMA was not supported. But an important experience was increased coverage for subscribers with weak link quality in the uplink. Subscribers are now able to focus the transmitted power on fewer sub-channels and obtain connectivity with weak link quality. This will be an important feature in mobile WiMAX for both downlink and uplink, where coverage and spectral efficiency due to multiple accesses on the physical medium through OFDMA will be enhanced.

A second feature was the BS transmit and receive diversity, which enhanced performance in both downlink and uplink. Better link quality, coverage and throughput were obtained.

UDP throughput performance was especially weak in the uplink at many locations. Maximum performance was 6.2 Mbps in both directions, but the uplink dropped to 100 Kbps at certain locations. However, without the sub-channelization, connectivity would not have been obtained at all locations.

The coverage is difficult to determine where the sight capabilities are crucial. A rough sketch is that one should stay within one kilometre to securely obtain connectivity in NLOS environments.

It should be noted that this system operated in the 3.5 GHz band, and that mobile WiMAX is mainly targeted for the 2.5 GHz band where signal propagation in multipath NLOS environments is facilitated. Path loss is lower in the 2.5 GHz band and larger coverage areas will be obtained [54].

6 Conclusion

The main contribution and objective of this thesis was to uncover the WiMAX performance and conclude upon the hype and expectations, through extensive field trial measurements and real life deployment analysis. A detailed analysis and discussion on the throughput, coverage and physical system performance has been subject for research. Based on the measurements, we have derived analytical expressions and models useful for determining performance and modelling WiMAX systems. This conclusion is based on data and analysis from scientific experimental and empirical research methods, which both are scientific research methods.

Then, how does WiMAX perform in real life according to the theoretical limitations given by the standard specifications?

The measurements performed have proven that WiMAX performance is much similar to what could be expected by the theoretical limitations for the physical medium specified in the standard. Claims like *"WiMAX can transfer data at rates around 70Mbps with a range of close to 30 miles"* [55] are found in the media, and if we compare this claim to the theoretical limitations we find that it may be achievable in a 20 MHz channel with perfect link quality where the whole channel is allocated for transmission in one direction with line of sight (LOS) capabilities, especially with advanced antenna systems deployed. Secondly, the claim applies to only one subscriber that operates in the system alone. All these requirements are hardly ever obtained at the same time in real life, and it is therefore understandable that WiMAX is rumoured to be hyped. The claim further states the bitrate over the physical medium, whereas the end user measures throughput at higher layer protocols that achieves lower values due to protocol overhead.

As for the fixed WiMAX field trial in this thesis, with a 3.5 MHz channel bandwidth and LOS conditions, maximum 9.6 Mbps was obtained out of theoretical 12.71 Mbps (76 %). The variance is considered to be overhead from the transport protocol UDP and management traffic, and the results were similar to the system vendor specification. The throughput was difficult to determine because of much variance, where different distances and sight capabilities among others were determining.

The same applies to the coverage in WiMAX, where great distances are achieved under ideal conditions with line of sight to the base station and no interference. Sub-channelization, which is optional in fixed WiMAX and mandatory in mobile WiMAX, showed to improve the coverage under difficult conditions with non line of sight (NLOS) to the base station (BS). Diversity also showed to improve both coverage and throughput.

These results showed that performance is dependent on a range of factors. Throughput and coverage in WiMAX should be considered as dependent variables, and not constants as is more common in wireline systems. It is therefore necessary to explain throughput and coverage (path loss) as analytical expressions and models for the representation of performance, where these dependent variables take the underlying performance attributes into account. Without these considerations in mind, the hypothesis is easily falsified by the general public and the system may easily be abused due to hype and high expectations. Based on this understanding of wireless systems, analytical expressions were derived that aims to determine and model WiMAX performance.

Two analytical expressions were derived for UDP throughput, one as a function of the received signal strength and the second as a function of distance.

An analytical expression was derived for TCP throughput as a function of signal to noise ratio, which is important since interference is considered when calculating throughput.

Two path loss models were derived, one based on measurements with NLOS and the second with mostly LOS to the BS. The LOS model approached the free space loss model.

Under imperfect conditions, which is the normal case, it is important to consider the relations between the variables, parameters and functionalities found in a given WiMAX system to optimize and survey the overall performance. This thesis reveals some of these relations and put emphasis on link quality attributes which have impact on throughput and coverage performance. The most important relation was in general the signal to noise ratio (SNR) as a function of UDP and TCP throughput, which presents useful expressions to model throughput in scenarios where interference is present. SNR was also related to the received signal strength, which is a useful to determine the presence of interference. The received signal strength related to different distances for a given system is useful to predict.

Analyses of the BS transmit and receive diversity gains improved both throughput and coverage. These measurements showed that advanced antenna systems will improve the performance for the mobile WiMAX profile. Sub-channelization in the uplink increased coverage a lot, where a 3 dB increase in signal strength was obtained for each lowered factor of sub-channels in use. A complete implementation of OFDMA and sub-channelization in both uplink and downlink should enhance the spectrum efficiency and coverage in both directions.

7 Future Work

The analytical expressions for UDP throughput as a function signal to noise ratio, TCP throughput as a function of signal to noise ratio and the path loss models could be used as input to already existing simulation models as ns-2 [56], or as a starting point for the development of other simulation models. The dependent variables (output) in the model could further be verified against the experimental and empirical throughput and coverage data from this thesis field trials and deployment analysis.

The underlying field data, analytical expressions and analysis could be the basis for a more thorough and complete prediction of different variables in an experimental or empirical study of WiMAX. As an example the present work could make a basis for predicting the throughput and coverage as dependent variables of a given WiMAX system, experimental or empirical, based on all the underlying attributes and analytical expressions covered in this thesis.

A third performance attribute is the extensive Quality of Service (QoS) mechanisms offered in WiMAX. These were briefly addressed in Appendix F. We measured the Real Time (RT) QoS profile, which performed as expected. The functionality of the QoS mechanism in a scenario with congestion in one cell and several subscribers with RT QoS profiles communicating simultaneously was not tested. It would also be interesting to follow up the mapping between WiMAX and DVB-RCS for the constant bit rate VoIP QoS profile.

Two path loss models were derived in this thesis, where the first for NLOS measurements had a range of 12 km and the second for LOS had a 20 km range. Measurements at farther distances would be interesting to expand the range of these models. Additional measurements would also be useful to give a more confidential path loss model with NLOS conditions.

Co-channel interference was revealed in the “Fixed WiMAX Deployment Analysis”. It would be interesting to investigate this in more detail with the use of a spectrum analyser, and propose an adequate frequency planning.

A great amount of measurements are gathered from a WiMAX deployment, where physical measurements for most of the subscribers are have been measured over a time of four months, with a measurements every 5th minutes. These could be subject to further studies on co-channel interference over time.

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A. Fixed WiMAX Field Trial Results, Measurements and Locations Information

A.1 Locations

It was decided to focus on WiMAX NLOS characteristic. 14 different locations have been selected, see Table 1. Common for all these sites is that they are located at places that as such can be seen from the Base Station (BS) antenna, however when being at site with a 5 m high antenna, NLOS conditions will exist caused by buildings and vegetation at site. Locations were decided upon in advance, but when going there, each was studied upon arrival for points where the satisfying conditions are met.

Table 1 Measurement sites

Location	Distance (km)	Elevation (m)	Location Name
Location 0	0.15	35	Fornebu, Telenor
Location 1	0.516	16	Martin Linges vei
Location 2	0.906	16	Indoor Golf Centre
Location 3	0.87	9	Pælvika
Location 4	0.87	9	Pælvika Halden terrasse
Location 5	10.7	185	Grefsenveien
Location 6	0.818	21	Oksenøyveien
Location 7	1.17	30	Michelets vei
Location 8	3.84	20	Skøyen
Location 9	4.4	29	Gustav Vigelands vei
Location 10	11.4	251	Lachmans vei
Location 11	8.6	161	Solvang Kolonihage
Location 12	5.6	68	Borgen, Svalbardveien
Location 13	5.72	80	Tuengveien
Location 14	9.05	190	Sognsveien X Kongleveien

Micro offsets are performed at most of the locations and a measurement is taken for each micro offset. Distance from the BS will vary from 0.5 km to 11.4 km in suburban and urban surroundings. Elevation over sea level varies from 3 m to 251 m. The measurements are performed in the neighbourhood of Telenor's building at Fornebu and at sites in Oslo, starting at Skøyen and going up to Grefsen.

Maps are used to point out the measurement locations; see Figure 1. The two maps show the sites close by at distances less than 1.5 km and the further away locations with up to 11 km distance to BS.

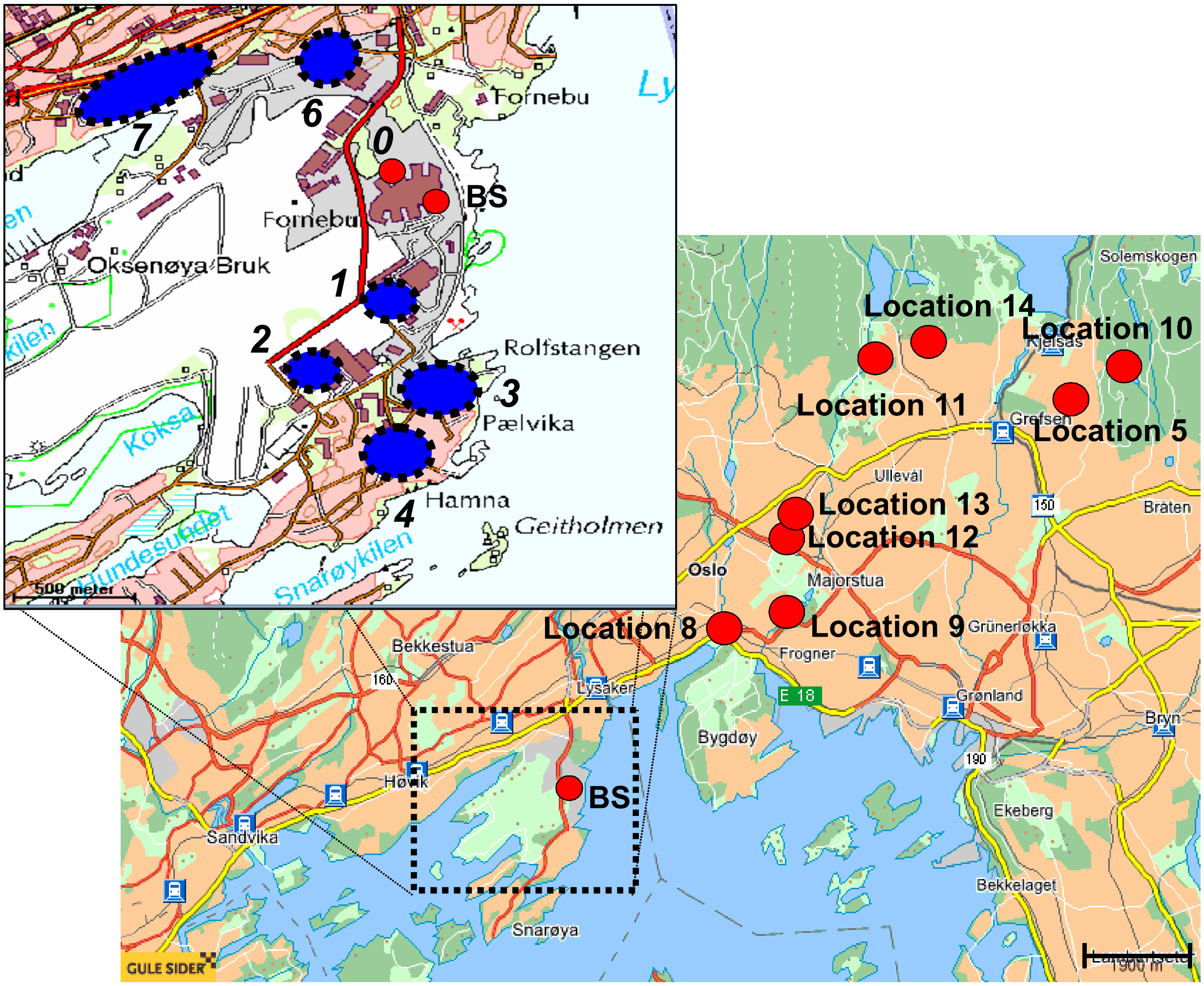


Figure 1 Measurement locations

A.2 Site descriptions and some measurement values

For each site a local map and pictures are presented showing buildings and vegetation in the SU environment and a short description of the location is given. Micro movements at the sites are stated, and the direction of the SU antenna is indicated, see Figure 2. Measured uplink and downlink values for Received Signal Strength Indication (RSSI) and throughput for UDP and TCP (10 connections) are presented in tables. For each site the result table also states the calculated “local NLOS loss”.

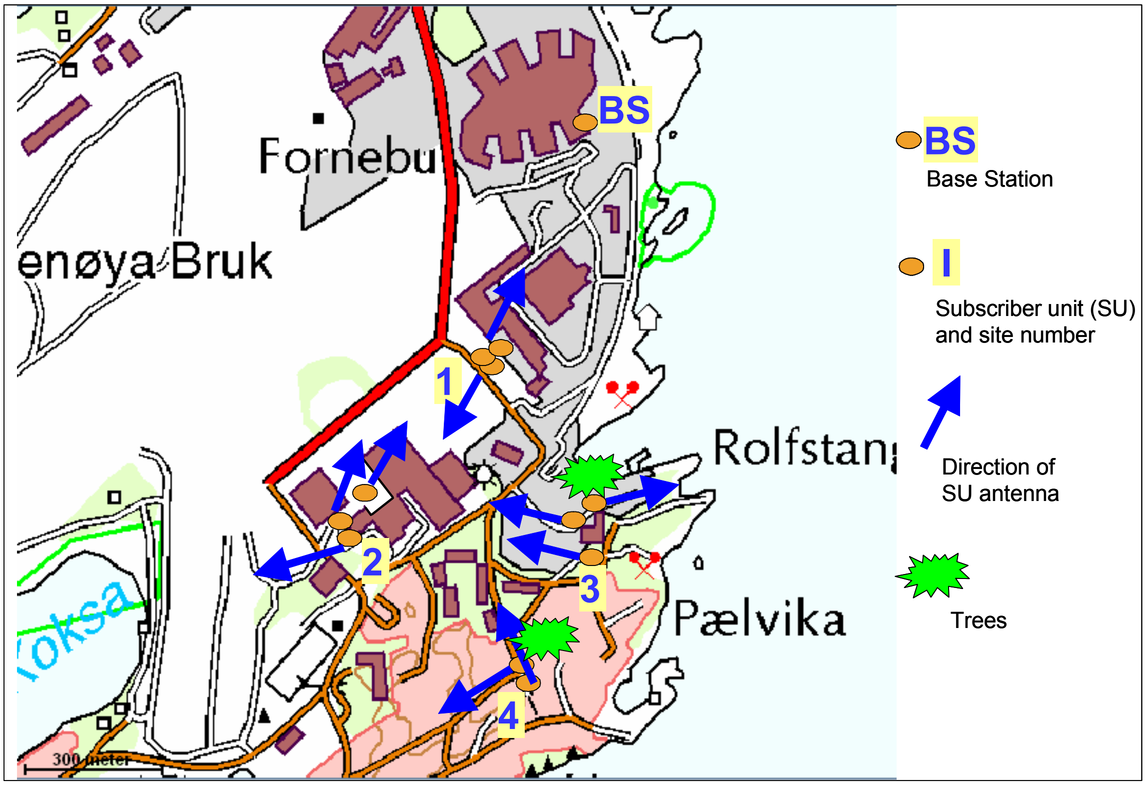


Figure 2 Measurement locations south of Telenor

A.2.1 Location 0 (Telenor Premises at Fornebu)

A reference measurement is performed at the Telenor premises, and the Subscriber Unit (SU) is located on the roof of the Telenor building 150 m away from where the Base Station is installed. To avoid saturation at such a short distance, the signal strength is reduced by letting the SU antenna point away from the BS.

Table 2 Values measured at Telenor site

At Telenor		Distance to BS: 0.15 km			Cal. Free space loss: 86.8 dB				
Measurement no	At site movement rel. start-point O2	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		Throughput measured for UDP [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
1	0	-46	-73	19	38	8.74	7.99	9.59	8.71

WiMAX Down Link (DL) quality is very good under these conditions which are indicated by the throughput results. Up Link (UL) quality is not that perfect because the radio signal does not obtain a direct path to the BS. The result of this “reference measurement” is presented in Table 2.

A.2.2 Location 1 (Martin Linges vei)

“Martin Linges vei” is 0.5 km distant from the BS. The SU is placed behind a massive building with obvious NLOS conditions.

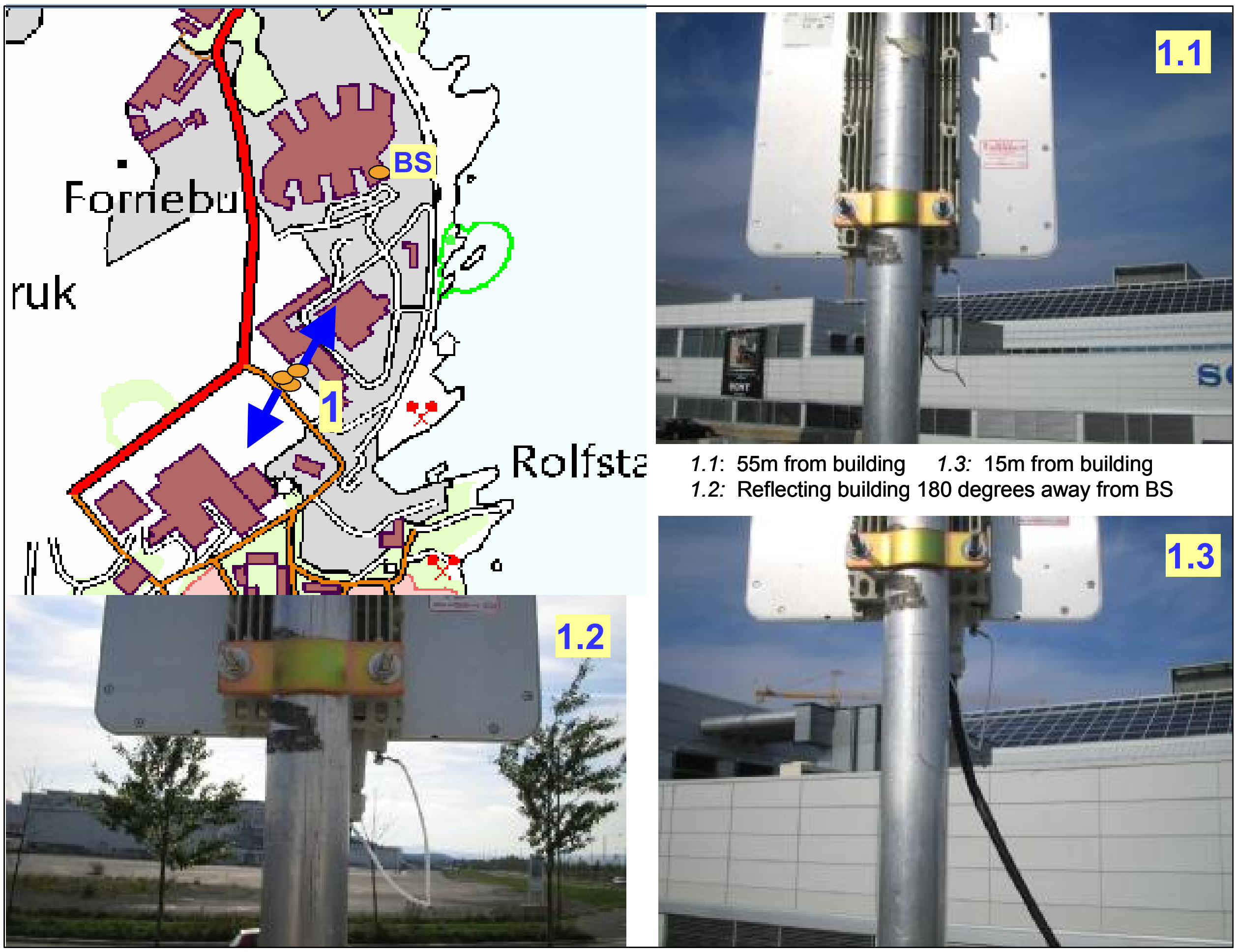


Figure 3 Behind buildings in Martin Linges vei

A massive building is placed 300-400 metres behind the SU and may be a good subject for reflections. The building in front of the SU may also be an object for diffractions. This site is classified as an urban area because of the type of buildings and the lack of vegetation.

Measurements were performed 50 m from the building in front, at two spots with 10 m distance. At the measurements the SU antenna was pointing towards the building in front (and the BS), Figure 3; 1.1, and then turned 180 degrees pointing towards the background building, Figure 3; 1.2.

A last measurement was made close up to the building at a 15 m distance, Figure 3; 1.3. The results is fairly good considering the NLOS conditions, and notice that at the spot for measurements 1.3 and 1.4, TCP UL throughput is better than DL throughput.

Table 3 shows UL throughput only of order 1 Mbit/s for three of the measurements.

Table 3 Parameter values at Marin Linges vei

Martin Linges vei		Distance to BS: 0.52 km			Cal. Free space loss: 97.3dB				
Measurement no	At site movement rel. startpoint [m]	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		Throughput measured for UDP [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
1.1	0	-59	-73	22	27	5.93	1.12	9.48	1.24
1.2	0,(180°)	-64	-73	27	26	6.81	3.05	6.72	0.92
1.3	10	-60	-73	23	25	5.64	7.07	9.45	4.13
1.4	10, (180°)	-55	-73	18	24	6.89	8.39	9.6	8.71
1.5	40	-60	-72	23	27	7.15	1.14	9.49	5.96

A.2.3 Location 2 (Outside Indoor Golf Centre)

Looking at Figure 2 it seems obvious that location 2 can be classified as an urban area. There are several big buildings between BS and SU but no trees. At the start SU is placed on the square between houses, see Figure 4; 2.1. The antenna is placed between 20 metres high buildings on three sides.

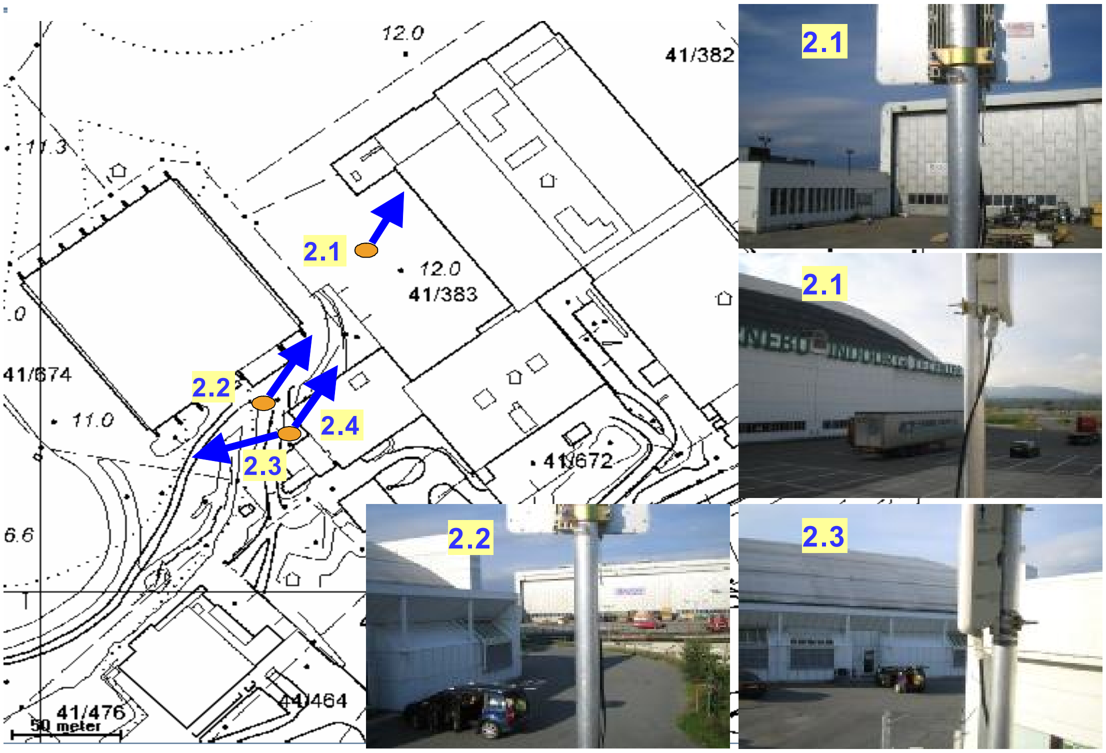


Figure 4 Description of site at Golf Centre

Reflections or diffraction are the options for SU to receive signals from BS. This is also valid for the second measurement, 100 m further away from BS and for the fourth measurement hidden around the corner. At these three measurements the SU antenna is pointing towards BS, while at measurement 2.3 the antenna is pointing away from BS. As seen from Table 4 the two latter measurements perform pretty equal whether the SU is rotated 180 degrees or not. Reflection from many buildings is probably the reason. The calculated local NLOS attenuation is of order 10 dB in DL direction.

Throughput results are convincing considering the NLOS conditions. Comparing these results with the previous Location 1, the throughput here is better. High SNR is observed and the modulation rates used are QAM64 ¾ at all positions.

Table 4 Parameter values obtained at Golf Centre

Snarøyveien, Golf Centre		Distance to BS: 0.91 km			Cal. Free space loss: 102.5 dB				
Measurement no	At site movement rel. start-point [m]	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		Throughput measured for UDP [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
2.1	0	-46	-73	3	6	8.83	8.39	9.59	8.71
2.2	100	-47	-73	4	4	8.84	8.39	9.59	8.71
2.3	100, (180°)	-58	-73	15	17	8.65	8.39	9.1	8.71
2.4	100	-57	-72	15	3	8.82	8.39	9.6	8.71

A.2.4 Location 3 (Paelvika)

Pælvika is best classified as urban because of the proximity to buildings and not too many trees in this area. At the first measurement spot there is light trees in between BS and SU. At the second spot there are even more trees and a mound in the direction of BS, and at the third measurement the SU is placed around a house corner. For all measurements at this location the antenna is not pointing direct towards the BS, but towards reflecting objects.

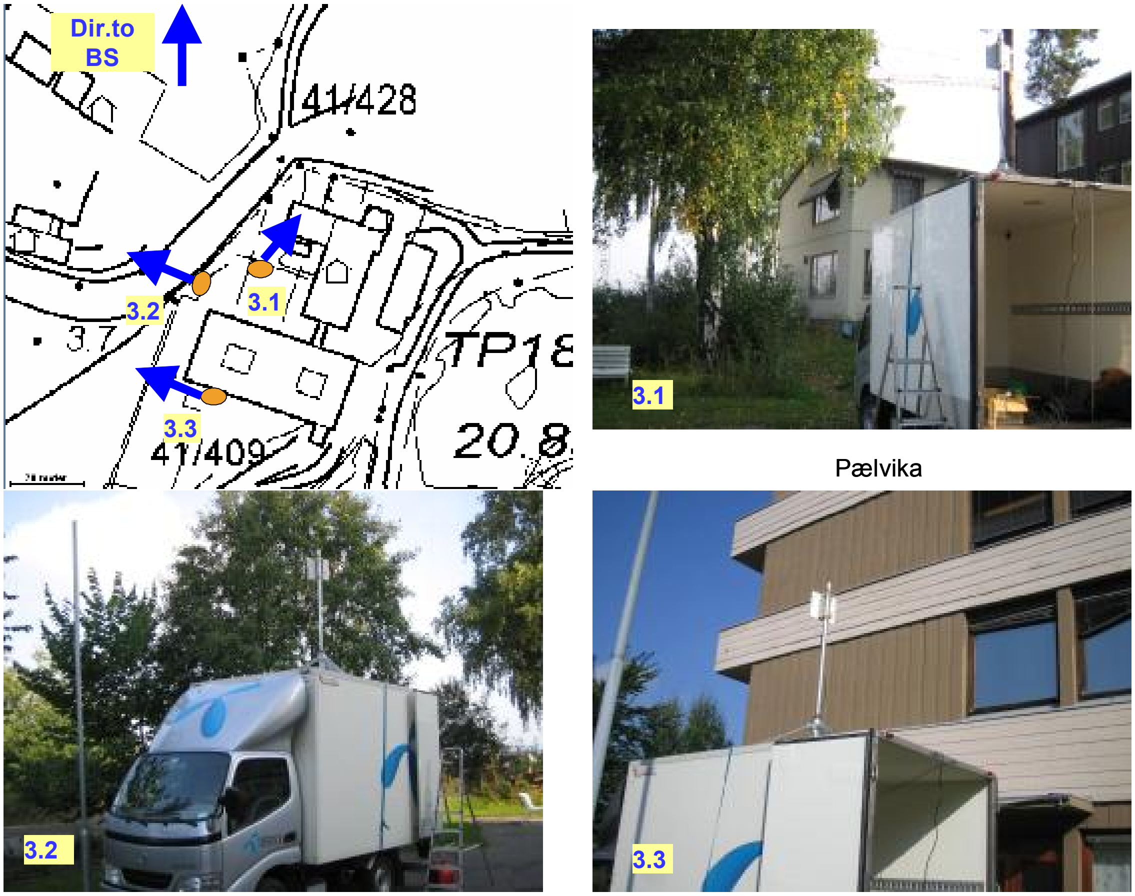


Figure 5 Description of the measurement site Pælvika

It was noticed that for measurement spot 3.1 we also got a pretty good signal when letting the SU antenna point at the building behind, 180° away from BS.

Table 5 Results obtained at Pælvika

Pælvika		Distance to BS: 0.87 km			Cal. Free space loss: 102.2 dB				
Measurement no	At site movement rel. start-point [m]	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		Throughput measured for UDP [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
3.1	0	-60	-72	17	17	8.47	8.37	9.59	8.71
3.2	10	-52	-71	10	12	8.82	8.38	9.15	8.71
3.3	35	-73	-84	31	34	8.81	8.38	8.62	8.27

A.2.5 Location 4 (Paelvika – Halden Terasse)

For this site there is a favourable terrain profile see Figure 6, but a lot of trees and houses prevent free sight to BS. The location is classified as suburban. It is assumed that the vegetation attenuates both direct signal and reflections.

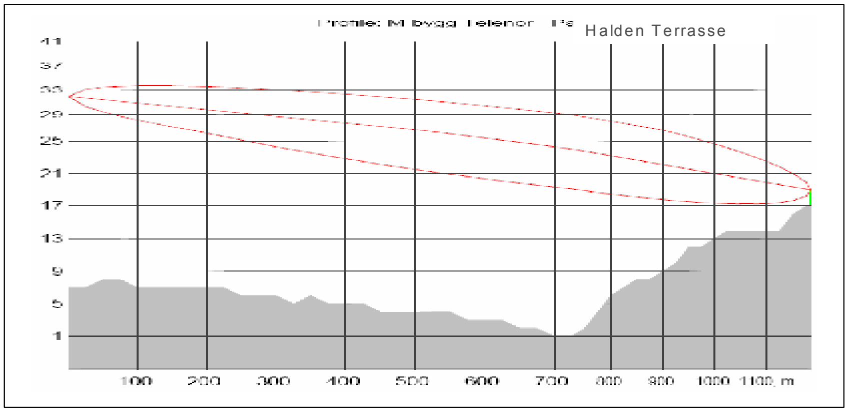
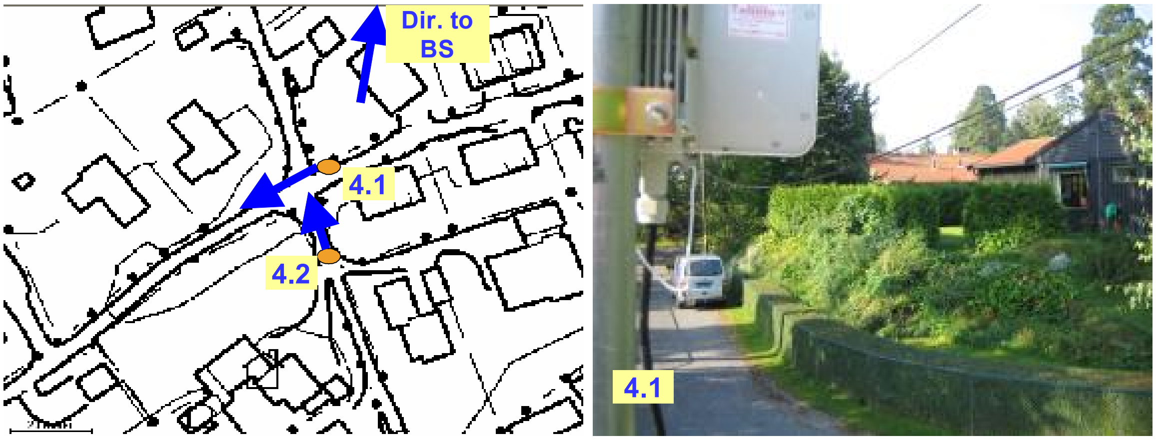


Figure 6 Terrain profile between BS and Halden terrasse



Pælvika, Halden terrasse

Figure 7 Site description for Pælvika, Halden Terrasse

The initial position at this location was behind a big tree as seen from BS, see site 4.1 Figure 7. A weak signal quality was achieved when pointing the SU towards the BS. When turning the SU 110 degrees away from the BS a better signal strength was achieved and hence the measurement was performed. Varying signal quality and modulation rate were observed with both antenna directions. As can be seen from this first measurement, the DL throughputs are weak. Selective fading is probably the reason for this.

The micro position offset with 10 metres gives better link quality and thus better throughput, see site 4.2 Figure 7. The best signal is here achieved by letting the SU antenna point towards the BS. A higher SNR is observed with less BER.

At this site we have a belt of trees and houses of some 200 m between BS and SU, and even if the terrain profile is favourable, the local attenuation is significant. Throughout the measurements at this location the Signal Quality measurement varied a lot.

Table 6 Parameter values obtained at Halden terrasse

Pælvika, Halden terrasse		Distance to BS: 1.19 km			Cal. Free space loss: 104.9 dB				
Measurement no	At site movement rel. start-point [m]	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		Throughput measured for UDP [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
4.1	0	-80	-98	35	44	6.13	0.76	9.12	0.66
4.2	10	-78	-90	33	37	8.19	5.61	9.36	3.39

A.2.6 Location 6 (Oksenoyveien)

This location is north of the BS. The distance between BS and SU is short, but there are large buildings in between the SU and the BS.

The expectation was to receive diffracted signals from these buildings, see sketch Figure 8. The location is a totally Non LOS area and will in spite of the woods in the background best be classified as urban.

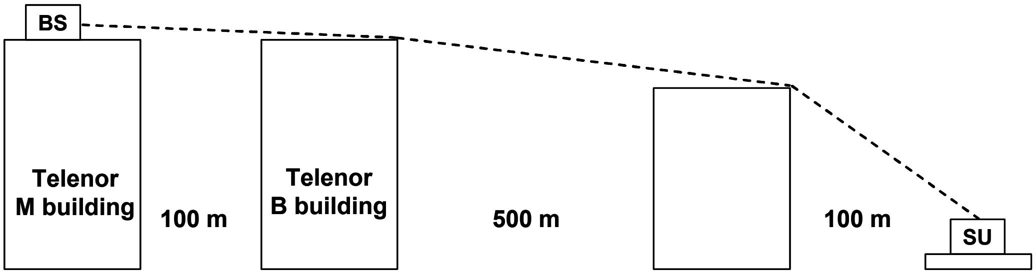


Figure 8 Possible signal diffraction at Location 6

Figure 9 Site description for Oksenøyveien

It was difficult to find good signal quality. The signal strength was low and with minor changes when rotating the SU antenna. The best signal was found when the antenna was pointing away from BS and the buildings lying in-between, and towards the woods some 200 m distant, see Figure 9. No obvious reflecting buildings could be pointed out.

A modest bit rate is obtained at the throughput test, which corresponds to the low link quality observed, i.e. low modulation rate, SNR and RSSI.

An observation made here is that with this low signal quality a significantly better throughput is achieved when more TCP connections are used. Retransmissions needed for each TCP-transmission may have caused this.

Table 7 Parameter values obtained at Oksenøyveien

Oksnøyveien		Distance to BS: 0.82 km				Cal. Free space loss: 101.6 dB			
Measurement no	At site movement rel. start-point [m]	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		Throughput measured for UDP [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
1	0	-84	-98	42	48	2.24	0.78	1.50	0.88

Varying RSSI was observed throughout the test.

A.2.7 Location 7 (Michelets vei)

There are NLOS capabilities at all the positions at this location. The distance is not very far (1.2 km), and the nearby buildings and trees disturbing the LOS are not very massive. The more massive buildings at a distance have good clearing in-between them.

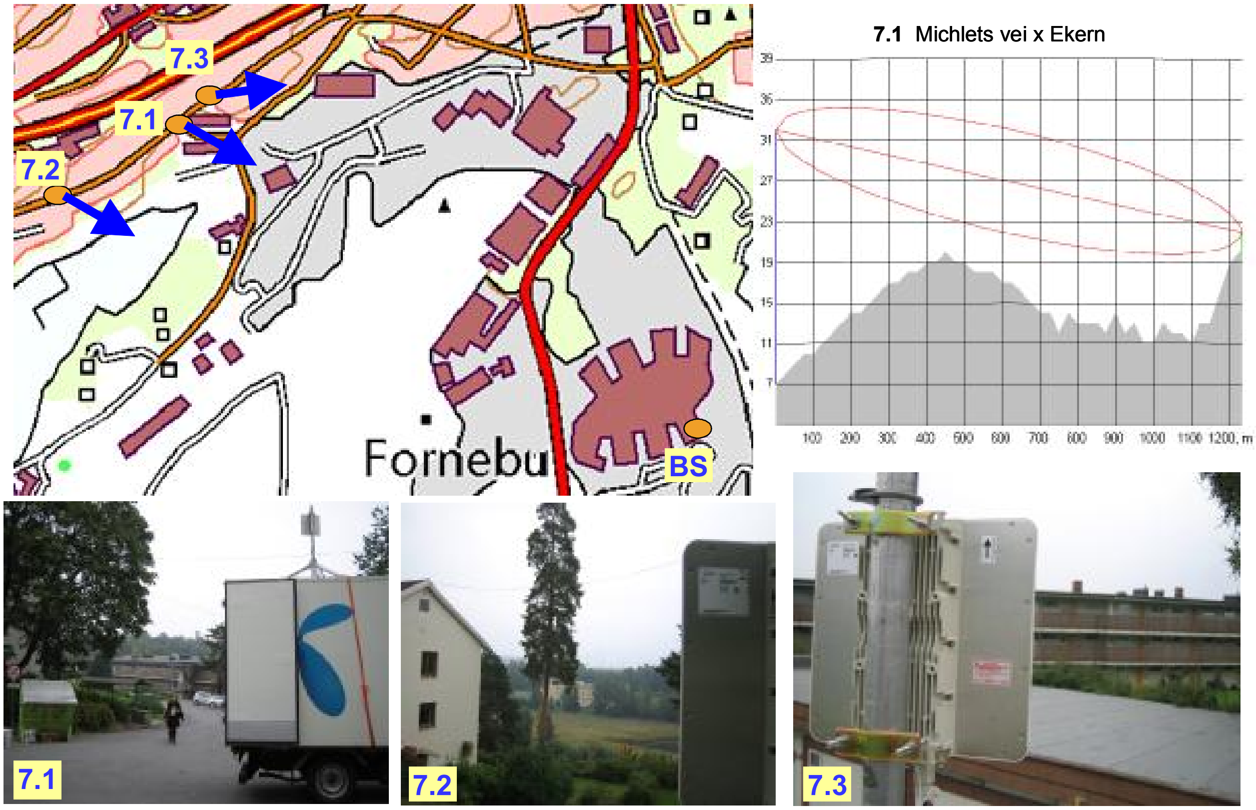


Figure 10 Site description for Michelets vei

As seen from the BS LOS is prevented caused by the Telenor building, see Figure 8. The system performance was poorer than expected considering the conditions, and we had to search for spots with sufficient signal level.
The position offsets for the different measurements at this location have to be considered as more than micro offsets (200 m), see Figure 10. The area is classified as suburban.

Performance observed in these measurements is interesting. The UL performs better than DL in more than half of the measurements. A reason for this may be selective fading or interference.

Table 8 Parameter values obtained at

Michelets vei		Distance to BS: 1.2 km		Cal. Free space loss: 104.7 dB	
Measurement no	At site movement rel. start-point [m]	RSSI Measured [dBm]	Calculated local NLOS attenuation [dB]	Throughput measured for TCP 10Conn [Mbit/s]	Throughput measured for UDP [Mbit/s]

		DL	UL	DL	UL	DL	UL	DL	UL
7.1	0	-75	-80	30	26	3.97	8.13	1.2	8.62
7.2.1	200	-67	-74	23	21	8.16	3.84	7.07	3.00
7.2.2	195	-67	-74	23	20	3.9	5.75	4.18	5.83
7.3.1	-100	-71	-84	28	32	2.27	6.66	2.18	7.10
7.3.2	-95	-72	-83	29	30	8.61	7.54	3.73	7.69

A.2.8 Location 8 (Skoyen)

Skøyen is a bit further away from BS than the previous locations (3.8 km), and at this location the surroundings are urban. The two positions at Skøyen are only 300 m apart, but differ a lot from each other. In position 8.1 Figure 11 the SU was placed at a position where LOS conditions were prevented by a railway bridge about 60 m in front and a close lightweight tree that was shadowing sight to the BS. The bridge is not filling up the horizon and has great possibilities for reflections and diffractions. Some trains passed by on the railway station while the measurement procedure was running, which may have influenced the signal. A link quality test was performed while a train was going by, and a reduction in SNR was observed of 2 dB.

Throughput at the first position is about what was expected considering the surroundings. The sight capabilities behind the railway station are excellent, see terrain profile 8.1 Figure 11. The varying modulation rates during the measurement may be caused by the activity at the railway station.

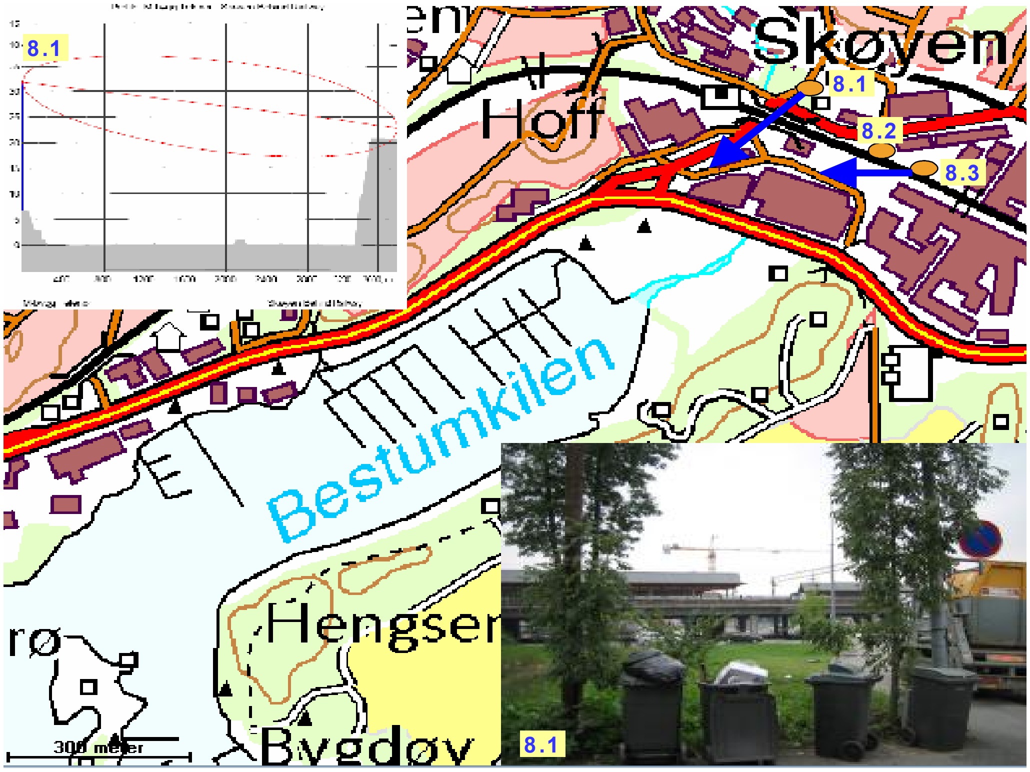


Figure 11 Site description for Skøyen behind Railway Bridge and among houses

It was observed that when a train is passing at the railway station, the SNR value drops from around 24 dB (+/-1) to 18/20 dB. When the train has passed the SNR goes back to its previous value.

Table 9 Parameter values obtained at Skøyen behind Railway Bridge

Skøyen at railway bridge		Distance to BS: 3.84 km				Cal. Free space loss: 115 dB			
Measurement no	At site movement rel. start-point [m]	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		UDP measured [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
1	0	-79	-88	24	25	5.43	2.24	2.71	0.967

The calculated local NLOS attenuation is nearly the same for both UL and DL signals.

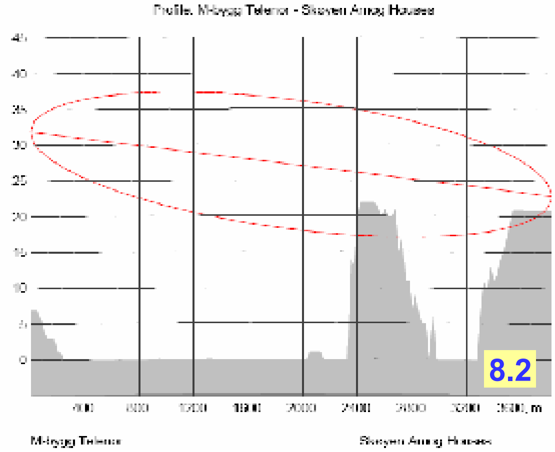


Figure 12 Site description for Skøyen among buildings

At position 8.2, see Figure 11, the SU is moved 200 metres eastwards surrounded by large houses causing NLOS. The building in front of the SU is not very massive, but high enough for there being little possibility of signals passing over them. The terrain profile is a bit changed as Figure 12 8.2 shows, and the SU antenna is here surrounded by buildings. This is a typical rural area. At position 8.2 the signal found was too weak to perform the measurement procedure. This was a bit surprising considering the great possibilities for reflections and diffractions between the buildings at the spot.

A 100 metre offset from this place was needed to obtain a link to the BS, see spot 8.3 Figure 11 and Figure 12. Several trains passed by at the railway track 10 meters beside the SU. When the trains were passing by a reduction in signal quality was observed at the SU display.

At position 8.3 connectivity was obtained, even if from an inspection of the location the expectation of finding signals here was less than for spot 8.2.

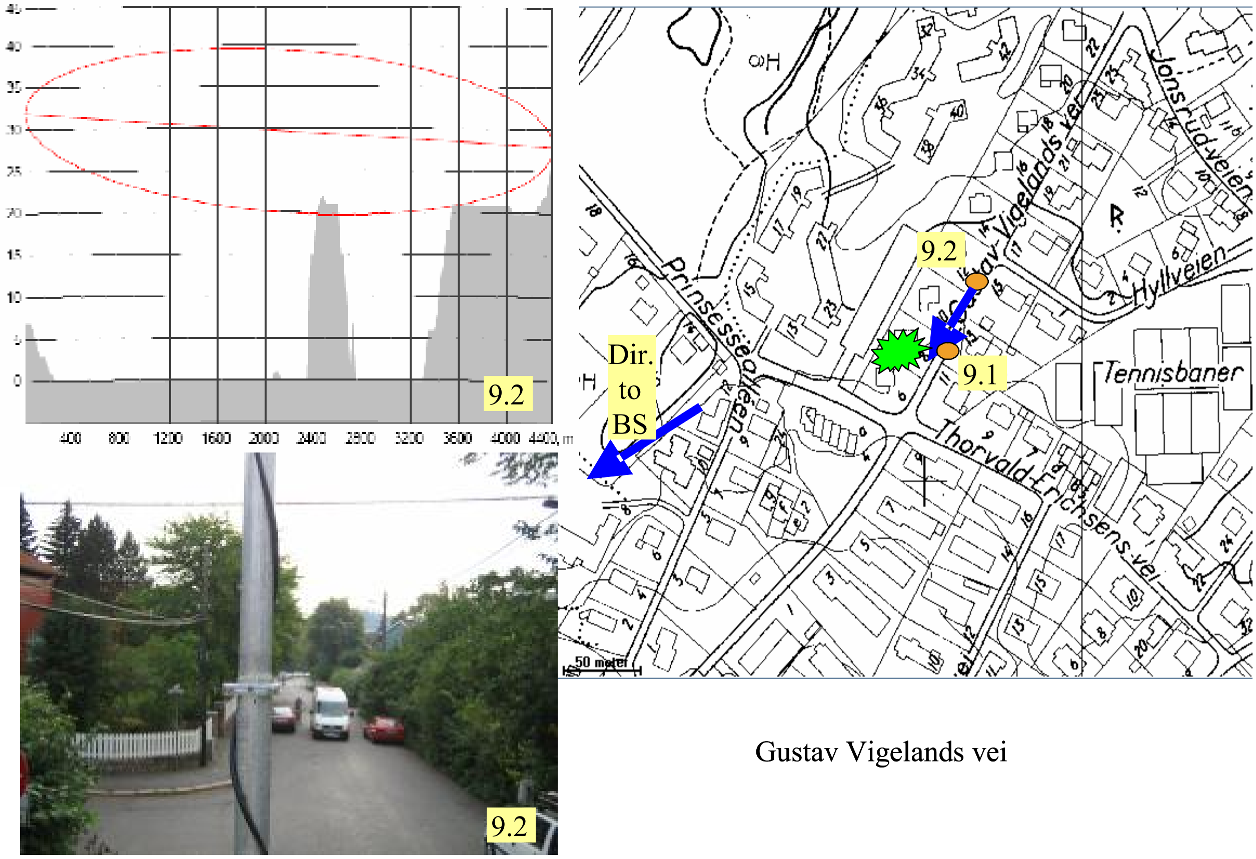
Table 10 Parameter values obtained at Skøyen among buildings

Skøyen among houses		Distance to BS: 3.85 km			Cal. Free space loss: 115 dB				
Measurement no	At site movement rel. start-point [m]	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		UDP measured [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
2	200	No signal		-	-	-	-	-	-
3	300	-87	-100	32	37	1.84	0.619	3.78	0.719

The execution of the throughput tests was slow. Link Quality parameters confirms the low throughput, with a low SNR especially in the downlink. Calculated local NLOS attenuation is 32-37 dB and UL throughput is of order 0.6 Mbit/s.

A.2.9 Location 9 (Gustav Vigelands vei 15)

The location is in a residential area with lots of trees and is classified as suburban, and the distance to BS is 4.4 km. The conditions are NLOS where the SU is located in a residential district, surrounded by two-storey high buildings. The terrain slopes downward toward Location 8; Skøyen.



Gustav Vigelands vei

Figure 13 Site description for Gustav Vigelands vei

No signal was found at the initial position in this area, spot 9.1 Figure 13, thus a 50 metre offset was done in search for better signal strength. A better signal was found, but with poor quality. The SU points almost in direction BS for optimal result, see spot 9.2 Figure 13. Better DL than UL is found in this measurement. Loss through vegetation is the reason for the measured signal level.

Table 11 Parameter values obtained at Gustav Vigelands vei

Gustav Vigelands vei 15		Distance to BS: 4.36 km				Cal. Free space loss: 116.2 dB			
Measurement no	At site movement rel. start-point [m]	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		UDP measured [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
0	0	No signal		-	-	-	-	-	-
2	50	-89	-102	33	37	3.5	0.42	4.2	0.77

A.2.10 Location 10 (Lachmanns vei)

This is the location most distant from the BS, 11.4 km and with the highest elevation, 240 m. The area is classified as suburban. Measurements were made at three positions within this location. The first position is with LOS capabilities and the last two with NLOS conditions.

Figure 14 Pictures from measurements at Lachmanns vei

As Figure 14 and Figure 15 show the first measurement spot has LOS to BS and the calculated local NLOS attenuation is only 3 – 4 dB.

At the next measurement 10.2 the best signal is obtained when the antenna points at the background cliff with a high wire fence, and this fence is clearly seen by the BS. Calculated local NLOS attenuation is now 21 – 23 dB.

At the third measurement 10.3 there is a narrow flat area with houses between SU and BS, and BS is probably below horizon as seen from SU. Reflexes or diffraction are assumed from wooden houses at 30 to 100 m distance. The best signal level is found letting the antenna point towards BS. Calculated local NLOS attenuation is here 27 – 29 dB.

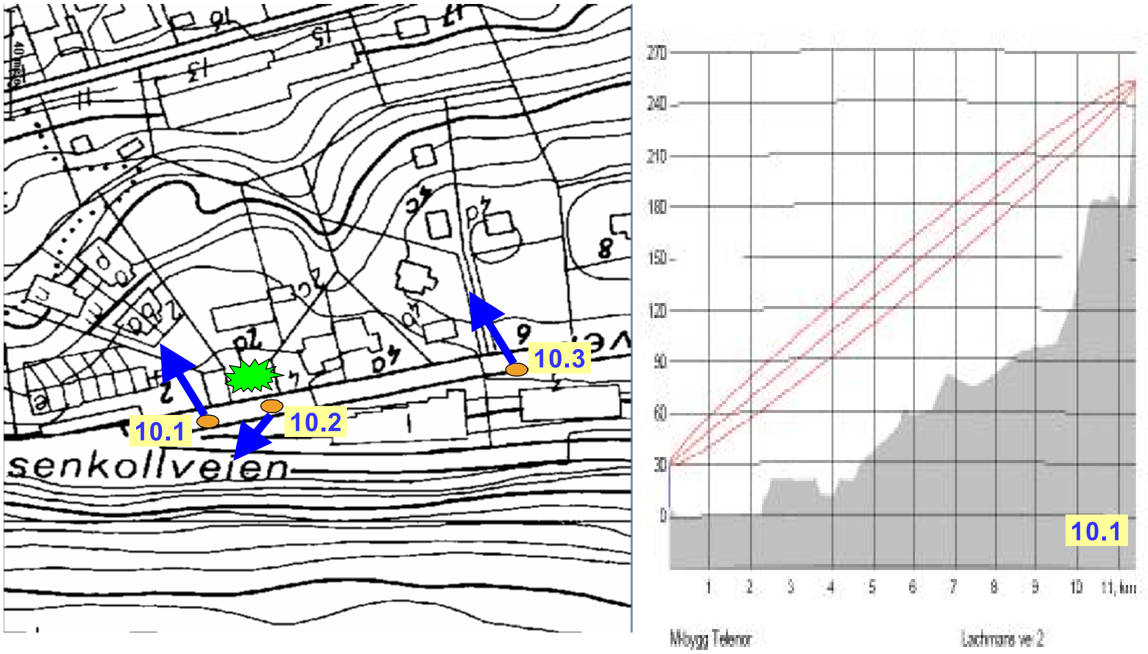


Figure 15 Site description for measurements at Lachmanns vei

Table 12 Parameter values obtained at Lachmanns vei

Lachmanns vei		Distance to BS: 11.4 km			Cal. Free space loss: 124.5 dB				
Measurement no	At site movement rel. start point [m]	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		UDP measured [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
10.1 (LOS)	0	-68	-77	3	3	8.77	7.29	9.59	7.87
10.2	10	-88	-93	23	21	4.79	0.76	4.75	0.91
10.3	100	-92	-101	27	29	2.62	0.70	2.92	0.85

A.2.11 Location 11 (Solvang Kolonihage)

Several measurements were made at Solvang Kolonihage. The first measurement attempt spot 11.1 Figure 16 was made south of the area (8.1 km to BS) and no connection was obtained.

The second measurement spot lies north of the Solvangen area at 8.6 km distance and at a 32 m higher elevation. Now the terrain profile shows that there is a LOS to the location, but the measurement spots 11.2 and 11.3 are NLOS caused by small wooden houses and trees. The location is suburban. These last measurements show a stronger signal level and a calculated local NLOS attenuation of 22 – 26 dB. Throughput figures are given in Table 13.

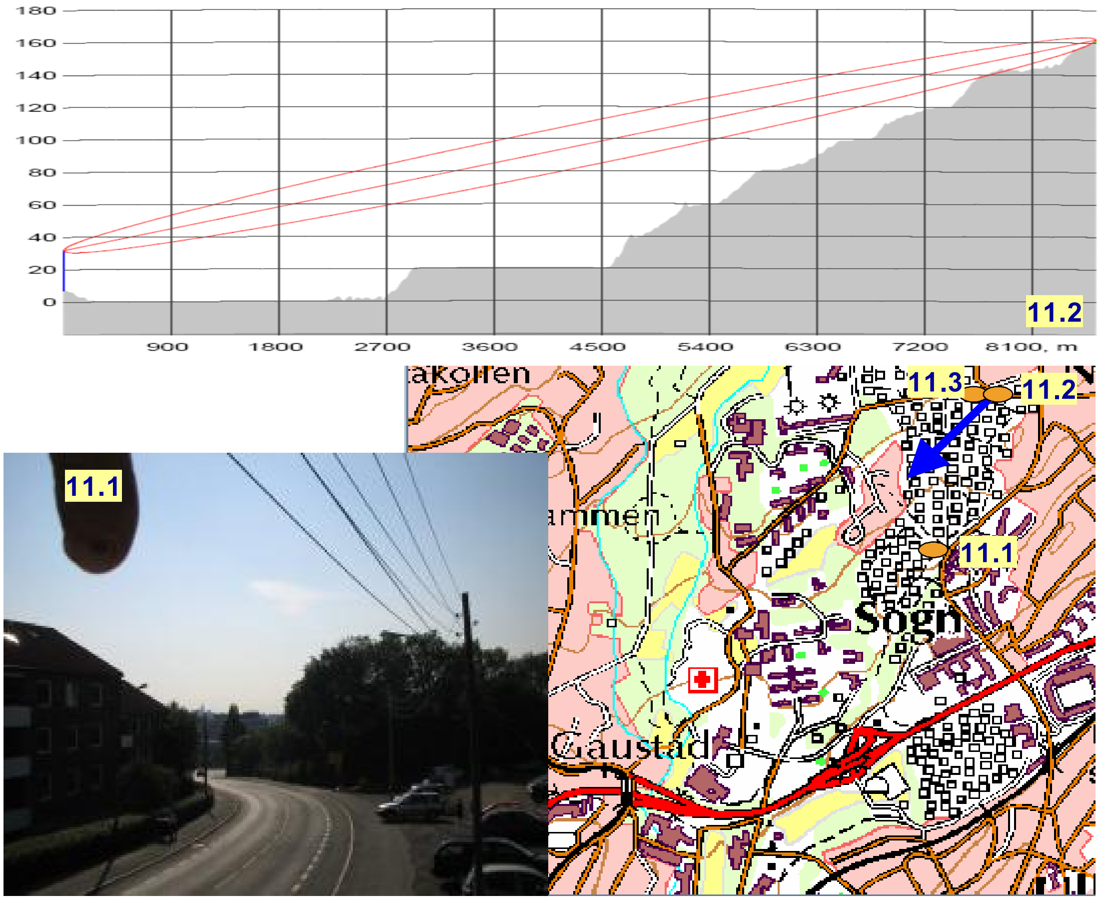


Figure 16 Solvang Kolonihage, south and north

Table 13 Parameter values obtained at Solvang Kolonihage

Solvang Kolonihage		Distance to BS: 8.6 km			Cal. Free space loss: 122.1dB				
Measurement no	At site movement rel. start point [m]	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		UDP measured [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
11.1	-500	No signal		-	-	-	-	-	-
11.2	0	-85	-96	23	26	4.79	0.71	1.73	0.89
11.3	5	-84	-95	22	25	4.72	0.82	6.31	0.89

A.2.12 Location 12 (Borgen, Svalbardveien14)

This location has a 5.6 km distance to BS, the elevation is 68 metres and there are NLOS conditions. This is a residential are with a lot of trees, and visual inspection indicated that a low signal level was to be expected. However, looking at Figure 17, it can be seen that the terrain profile is favourable and that the local loss would be the most significant. The area is classified as suburban.

Svalbardveien
Distance To BS is 5.6 km. Elevation Over Sea is 68 m.
Residential district with lots of trees. Antenna points towards BS. NLOS caused by vegetation.

Figure 17 Site description for Svalbardveien

At the measurement the SU points towards the BS for best signal. The calculated local loss is only 18 dB for DL and results in acceptable throughput, while for UL the throughput is low, se Table 14.

Table 14 Parameter values obtained at Svalbardveien

Svalbardveien 14		Distance to BS: 5.6 km			Cal. Free space loss: 118.3dB				
Measurement no	At site movement rel. start-point [m]	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		UDP measured [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
12	0	-76	-92	18	26	6.57	0.66	9.41	0.90

A.2.13 Location 13 (Borgen, Tuengveien5)

Distance to BS is 5.7 km and the elevation is here 80 m. This is a residential area with a lot of tall trees in-between SU and BS, and it is classified as suburban. To get an optimal signal the antenna is pointed towards BS at all measurements.

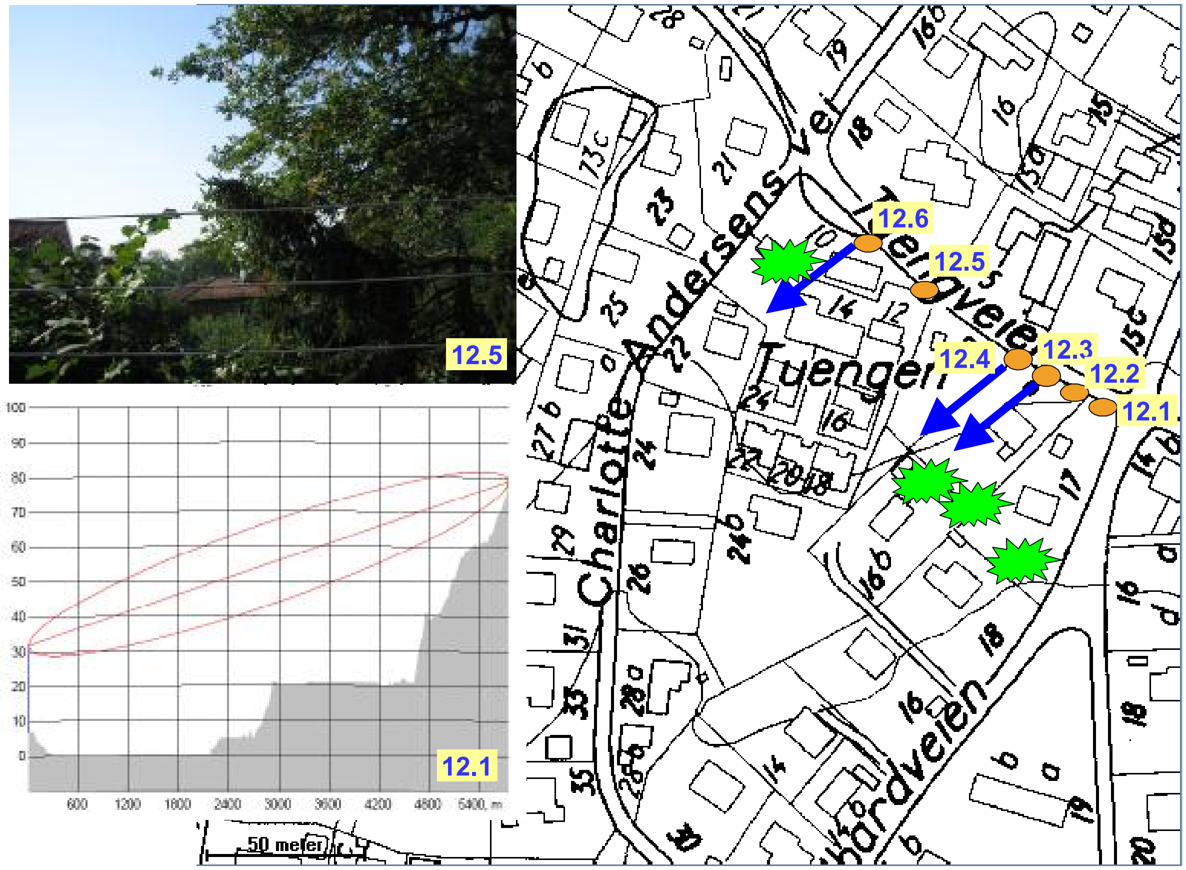


Figure 18 Tuengveien measurement site

Six measurements were performed at this location, see Figure 18. At the first measurement the SU seems to have unstable conditions. Its effect gauge goes to level 3 (of 9), but returns to zero after ca. one minute. When turning the antenna the gauge again goes up and then down in the same way. Link to BS could not be obtained at this spot.

We then moved 5 m to search for better signal at a second spot. Even here the antenna gauge indicated signal and then this indication disappeared after 1 min. At several antenna directions this was repeated, and we concluded that the SU itself turned off the indication of signal when there was not signal strength enough in both DL and UL. Even at this spot no link could be obtained.

Moved 5 m further for a third trial, see spot 12.3 Figure 18. With antenna pointing towards BS we found signal strong enough to establish a link and a measurement was performed. Link Quality test gave data, but a throughput test could not be done. Especially the UL RSSI was low.

An additional 5 m offset was made and we found a better signal, the antenna still pointing towards BS. Two test sequences were performed to investigate the stability of the local conditions.

Moved an additional 40 m to spot 12.5 and found no signal. Then we moved 10 m more to spot 12.6 Figure 18 and performed two test sequences there and obtained the best results for this location.

This location is very similar to Location 12, Svalbardveien in distance, elevation and surrounding characteristics. Results for throughput at these locations also correspond for both the uplink and downlink.

Table 15 Parameter values obtained at Tuengveien

Tuengveien 5		Distance to BS: 5.72 km				Cal. Free space loss: 118.5dB			
Measurement no	At site movement rel. start point [m]	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		UDP measured [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
12.1	0	No signal		-	-	-	-	-	-
12.2	5	No signal		-	-	-	-	-	-
12.3	10	-88	-102	29	36	-	-	-	-
12.4.1	15	-82	-92	23	26	6.18	0.84	1.01	0.9
12.4.2	15	-82	-91	23	25	6.20	0.88	8.92	1.05
12.5	50	No signal		-	-	-	-	-	-
12.6.1	60	-81	-89	22	23	8.08	0.937	2.47	0.93
12.6.2	6 0	-81	-89	21	23	6.65	0.89	9.48	0.96

A.2.14 Location 14 (SognsveienXKongleveien;)

At location 14 the distance to BS is 9 km and it is not far from Solvangen (location 11), but the elevation is increased by 30 metres. The surroundings show a residential district with sloping terrain and totally NLOS conditions regarding BS caused by near and distant trees and buildings. Also the terrain profile for spot 12.2 Figure 19 clearly shows that there is solid ground between SU and BS. In spite of this link to BS was established and a Link Quality test was done. Throughput test could not be done at this spot.

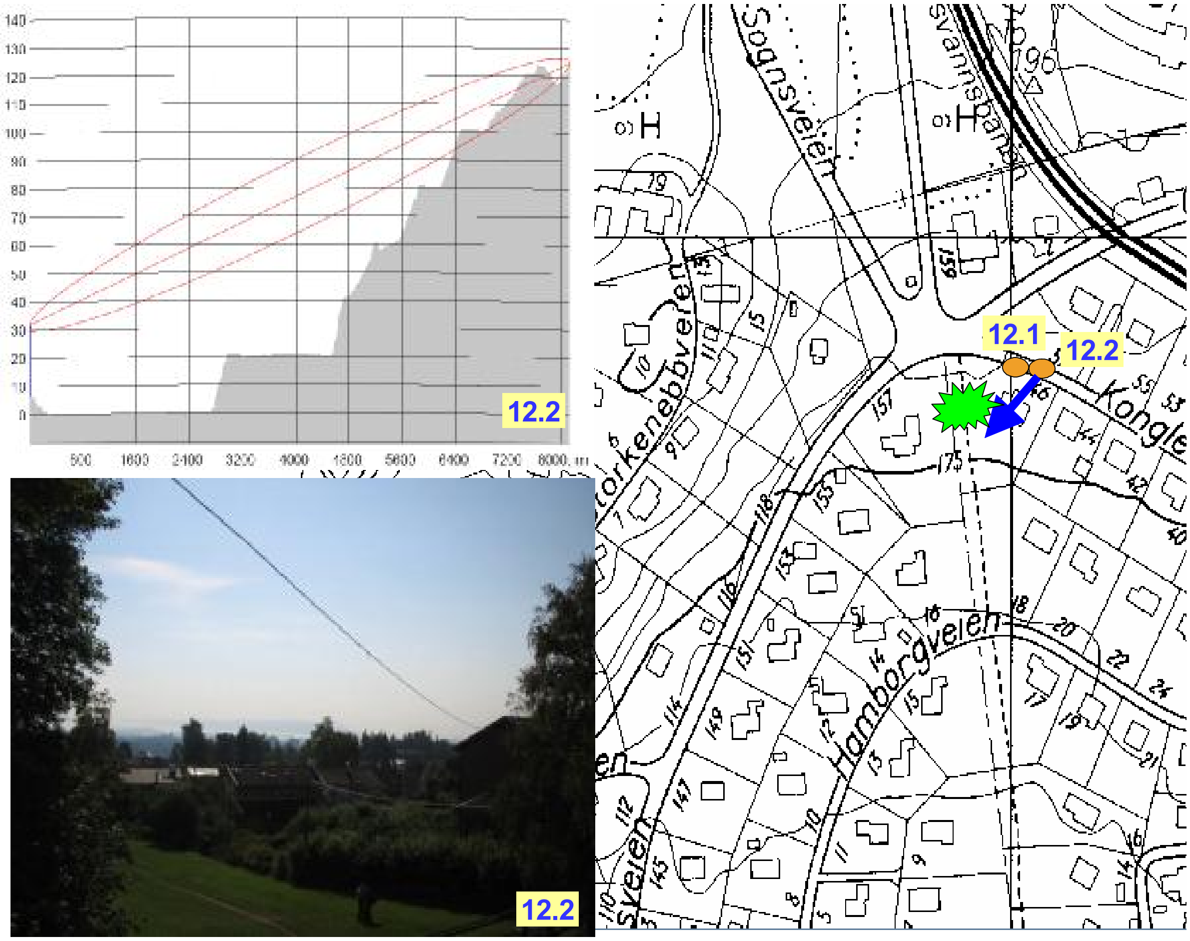


Figure 19 Site description for Sognsveien x Kongleveien

To perform a second measurement the SU antenna was moved 5 m to avoid nearby trees and to find an opening towards possible reflecting objects and the town further down. At this spot 12.2 Figure 19 the signal level was ca 5 dB better.

Table 16 Parameter values obtained at Sognsveien x Kongleveien

Sognsveien x Kongleveien		Distance to BS: 9.05 km			Cal. Free space loss: 122.5dB				
Measurement no	At site movement rel. start point [m]	RSSI Measured [dBm]		Calculated local NLOS attenuation [dB]		Throughput measured for TCP 10Conn [Mbit/s]		UDP measured [Mbit/s]	
		DL	UL	DL	UL	DL	UL	DL	UL
14.1	0	-91	-102	28	32	unstable		-	-
14.2	5	-87	-97	24	27	3.8	0.82	5.91	0.81

As can be seen from Table 16 this location is an example that shows system performance at distance even relaying distant reflexes or diffraction.

A.2.15 Location X (Grefsenveien 96)

This location is 10.7 km from BS and lies at 185 m elevation. This is a residential area with trees but not to the degree found at locations 9, 12 and 13. This is a suburban area. When setting up the antenna no signal could be registered, even moving along the street. This site is an example showing the impact on signal loss when the terrain flattens and the BS goes slightly under the horizon as seen from the test antenna, see terrain profile Figure 20. Also looking at the terrain profile for Lachmanns vei, Figure 15, it can be seen that the area Grefsenplatået is situated in the shadow as seen from BS for a distance of about 0.5 km.

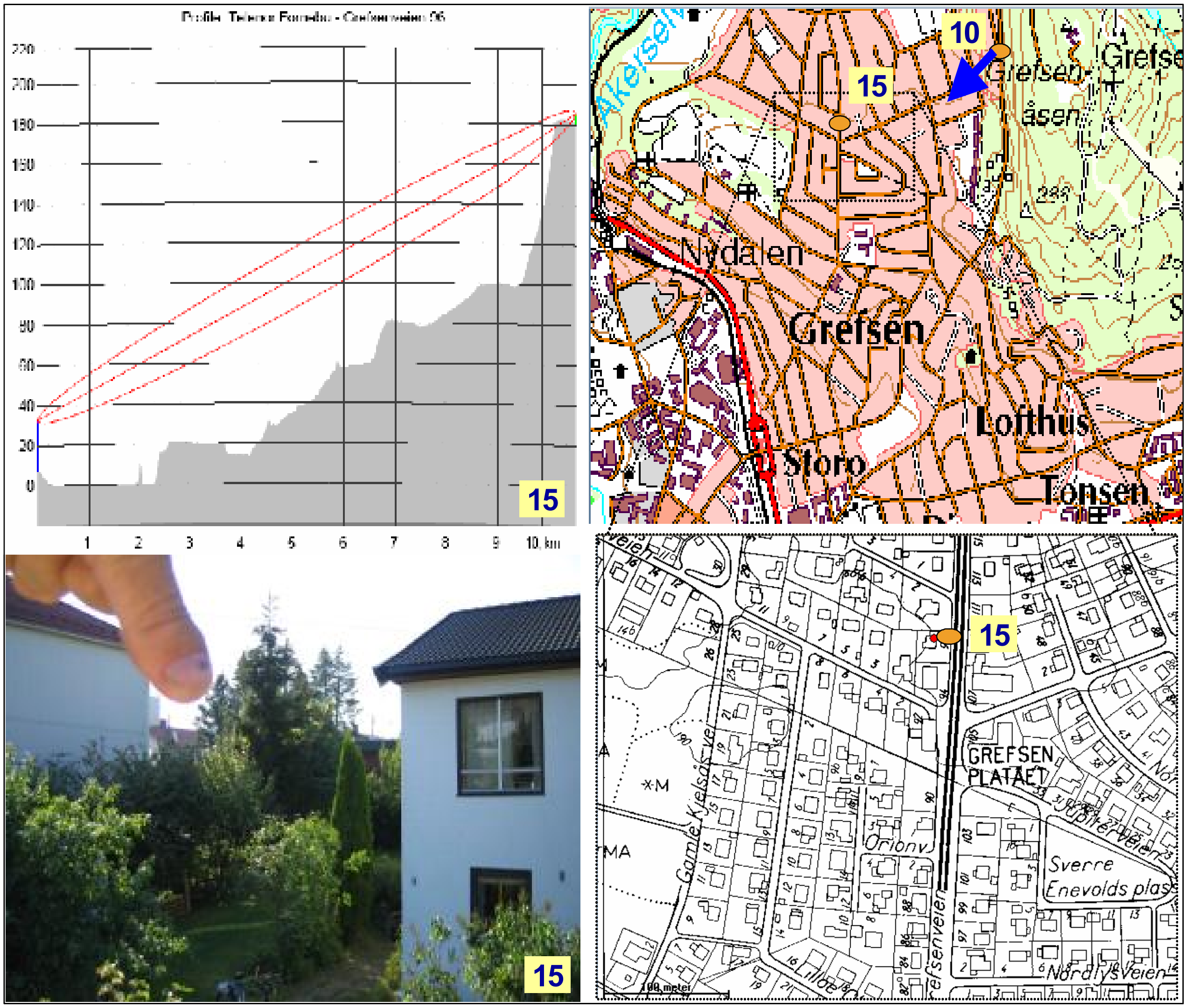


Figure 20 Site description for Grefsenveien

A.3 Results

A.3.1 Location 0 (Telenor Premises at Fornebu)

Table 17 Results Location 0 (Telenor Premises at Fornebu)

Offset		
Distance (km)		0,150
Elevation (m)		35
FTP	DL	7,222645
	UL	2,002529
UDP	DL	9,59
	UL	8,71
UDP Simultaneously	DL	4,54
	UL	4,76
TCP	DL	8,1
	UL	3,41
TCP Simultaneously	DL	7,07
	UL	0,929
TCP, 2 connections	DL	8,45
	UL	4,9
TCP, 4 connections	DL	8,87
	UL	7,51
TCP, 5 connection	DL	8,69
	UL	8,14
TCP, 10 connections	DL	8,74
	UL	7,99
SNR	DL	34
	UL	30
RSSI	DL	-45
	UL	-73
Rate	RX	QAM64 ¾
	TX	QAM64 ¾
Power	TX	20
BER	UL	7,8E-6

A.3.2 Location 1 (Martin Linges Vei)

Table 18 Results Location 1 (Martin Linges Vei)

Offset					**180°**	**10m**	**10m, 180°**	**40 m**
Distance (km)		0,516	0,516	0,516	0,516	0,516	0,516	0,516
Elevation (m)		16	16	16	16	16	16	16
FTP	DL	7,789242	8,426583	7,823436	5,800851	3,107476	8,290094	7,8187
	UL	2,981244	2,873634	2,543402	3,077684	2,648604	3,692732	2,0419
UDP	DL	8,84	9,21	9,48	6,72	9,45	9,6	9,49
	UL	7,64	2,61	1,24	0,915	3,78	8,71	5,96
UDP Simult.	DL	3,57	3,15	2,13	1,16	4,13	4,41	4,07
	UL	3,76	3,22	2,14	1,12	3,96	4,76	4,29
TCP	DL	6,93	2,8	8,14	5,58	8,17	9,12	1,14
	UL	2,48	2,99	4,79	9,14	4,07	7,44	4,59
TCP Simult.	DL	2,38	2,0	3,95	2,73	3,31	5,87	1,76
	UL	2, 54	0,856	1,45	1,4	0,111	2,12	4,06
TCP, 2 conn.	DL	4,07	8,85	9,12	7,73	4,71	9,12	4,86
	UL	4,47	0,856	6,27	7,53	3,81	8,36	5,03

TCP, 4 conn.	DL	8,87	6,74	8,92	6,74	8,25	8,69	8,95
	UL	5,03	5,93	4,8	4,41	3,2	8,38	7,13
TCP, 5 conn.	DL	6,05	8,66	5,83	1,2	8,25	8,84	1,54
	UL	4,89	6,44	7	6,89	5,17	7,74	6,01
TCP, 10 conn.	DL	7,6	8,57	5,93	3,05	5,64	6,89	7,15
	UL	4,73	7,77	1,12	6,81	7,07	8,39	1,14
SNR	DL	34	34	33	29	34	34	33
	UL	30	31	28	33	29	29	30
RSSI	DL	-59	-59	-58	-73	-60	-56	-60
	UL	-73	-73	-72	-63	-73	-72	-72
Rate	RX	QAM16 ¾	QAM64 ¾	QAM64 ¾	QAM64 ¾	QAM64 ½	QAM64 ¾	QAM64 ½
	TX	QPSK ¾	BPSK ½	BPSK ½	QPSK ¾	QAM16 ½	QAM64 ¾	QPSK ½
Power	TX	19	19	19	18	17	16	20
BER	UL	2,9E-3	4,6E-4	9,10E-4	2,2E-3	1,6E-3	7,9E-4	1,0E-3

A.3.3 Location 2 (Outside Indoor Golf Centre)

Table 19 Results Location 2 (Outside Indoor Golf Centre)

Offset			**100 m**	**100m, in corner,**	**100m, in corner**
Distance		0,906	0,906	0,906	0,906
Elevation		16	16	16	16
FTP	DL	8,204538	8,213307	8,745764	8,311252
	UL	3,676469	3,690993	3,682512	3,688461
UDP	DL	9,59	9,59	9,07	9,6
	UL	8,71	8,71	8,71	8,71
UDP Simultaneous	DL	4,53	4,54	4,6	4,48
	UL	4,77	4,78	4,78	4,77
TCP	DL	9,11	9,1	9,11	9,12
	UL	7,91	7,9	7,82	7,89
TCP Simultaneous	DL	5,85	5,86	5,85	5,8
	UL	2,19	2,11	2,17	2,18
TCP, 2 connections	DL	9,14	9,14	9,15	9,13
	UL	8,38	8,37	8,37	8,37
TCP, 4 connections	DL	8,94	8,62	9,01	8,65
	UL	8,38	8,39	8,39	8,38
TCP, 5 connection	DL	8,98	8,91	8,94	8,97
	UL	8,39	8,38	8,39	8,38
TCP, 10 connections	DL	8,83	8,84	8,65	8,82
	UL	8,39	8,39	8,39	8,39
SNR	DL	33	35	33	34
	UL	30	30	31	33
RSSI	DL	-45	-49	-52	-49
	UL	-72	-74	-72	-74
Rate	RX	QAM64 ¾	QAM64 ¾	QAM16 ¾	QAM64 ¾
	TX	QAM64 ¾	QAM64 ¾	QAM64 ¾	QAM64 ¾
Power	TX	3	1	14	1
BER	UL	1,0E-4	2,4E-4	1,9E-4	2,4E-4

A.3.4 Location 3 (Paelvika)

Table 20 Results Location 3 (Paelvika)

Offset			10m, behind big tree	30m, behind big house
Distance (km)		0,87	0,87	0,87
Elevation (m)		9	9	9
FTP	DL	8,232498	8,222638	8,202438
	UL	3,690101	3,69264	3,60777
UDP	DL	9,59	9,15	8,62
	UL	8,71	8,71	8,27
UDP Simultaneous	DL	4,58	4,54	4,13
	UL	4,76	4,78	4,23
TCP	DL	9,13	9,13	5,51
	UL	7,9	7,9	4,4
TCP Simultaneous	DL	5,69	5,61	5,47
	UL	2,07	2,05	1,58
TCP, 2 connections	DL	9,13	9,12	8,76
	UL	8,36	8,37	6,8
TCP, 4 connections	DL	9,02	8,67	8,59
	UL	8,38	8,38	6,49
TCP, 5 connection	DL	8,72	8,75	8,75
	UL	8,39	8,39	7,33
TCP, 10 connections	DL	8,47	8,82	8,81
	UL	8,38	8,38	8,38
SNR	DL	34	34	28
	UL	33	31	22
RSSI	DL	-60	-52	-73
	UL	-72	-71	-85
Rate	RX	QAM64 ¾	QAM16 ¾	QAM16 ½
	TX	QAM64 ¾	QAM64 ¾	QAM64 ¾
Power	RX	15	11	20
BER	UL	9,5E-4	1,4E-4	9,6E-4

A.3.5 Location 4 (Paelvika – Halden Terasse)

Table 21 Results Location 4 (Paelvika – Halden Terasse)

Offset				10m	10m
Distance		1,19	1,19	1,19	1,19
Elevation		21	21	21	21
FTP	DL	3,71752	4,092041	7,215192	4,638573
	UL	0,642155	0,917826	3,062323	2,977939
UDP	DL	1,14	9,12	2,86	9,36
	UL	0,656	0,656	5,16	3,39
UDP Simultaneous	DL	0,602	0,773	2,95	3,56
	UL	0,591	0,731	2,95	3,71
TCP	DL	3,23	4,58	8,17	8,54
	UL	0,874	0,985	5,43	3,02
TCP Simultaneous	DL	0,49	1,22	5,63	4,17
	UL	0,775	0,789	1,62	1,97
TCP, 2 connections	DL	6,24	5,52	9,0	6,58
	UL	0,991	0,503	5,61	4,22
TCP, 4 connections	DL	5,78	4,43	7,79	7,92
	UL	1,04	0,856	4,94	4,29
TCP, 5 connection	DL	6,15	5,87	7,15	7,04
	UL	0,885	0,881	5,62	4,58
TCP, 10 connections	DL	7,7	6,13	8,49	8,19
	UL	0,899	0,758	3,89	5,61
SNR	DL	21	22	24	24

	UL	4	7	20	17
RSSI	DL	-81	-80	-78	-79
	UL	-101	-99	-86	-89
Rate	RX	BPSK ½	QAM64 2/3	QPSK ½ - QAM64 ¾	QAM16 ¾ - QAM64 2/3
	TX	BPSK ½	BPSK ½	QAM16 ½	QPSK ¾ - QAM16 ½
Power	TX	20	19	20	20
BER	UL	1,1E-1	8,5E-2	4,3E-4	1,8E-3

A.3.6 Location 6 (Oksenoyveien)

Table 22 Results Location 6 (Oksenoyveien)

Offset		
Distance (km)		0,818
Elevation		21
FTP	DL	2,09311
	UL	0,785653
UDP	DL	1,5
	UL	0,877
UDP Simultaneously	DL	0, 589
	UL	0, 587
TCP	DL	1,34
	UL	0,872
TCP Simultaneously	DL	0, 271
	UL	0,8
TCP, 2 connections	DL	1,38
	UL	0,866
TCP, 4 connections	DL	2,06
	UL	0,744
TCP, 5 connection	DL	2,31
	UL	0,852
TCP, 10 connections	DL	2,24
	UL	0,778
SNR	DL	19
	UL	13
RSSI	DL	-83
	UL	-93
Rate	RX	BPSK ½
	TX	BPSK ¾ - QPSK ¾
Power	TX	19
BER	UL	2,5E-2

A.3.7 Location 7 (Michelets Vei)

Table 23 Location 7 (Michelets Vei)

Offset			**50m West**	**50m – 5m**	**100m East**
Distance		1,22	1,17	1,17	1,27
Elevation		19	30	30	30
FTP	DL	2,727933	1,224768	8,241324	1,912948
	UL	3,677436	3,314127	3,44394	3,22459
UDP	DL	1,2	2,18	3,73	4,18

	UL	8,62	7,1	7,69	5,83
UDP Simultaneous	DL	1,65	2,27	2,74	3,02
	UL	1,62	2,42	2,79	3,04
TCP	DL	4,04	1,27	8,4	3,66
	UL	7,85	4,34	5,41	5,74
TCP Simultaneous	DL	2,33	1,41	2,01	2,34
	UL	2,27	2,04	2,87	3,21
TCP, 2 connections	DL	3,91	1,94	9,02	3,75
	UL	8,16	5,42	7,01	5,75
TCP, 4 connections	DL	3,79	2,63	8,79	4,04
	UL	8,15	6,93	7,52	5,76
TCP, 5 connections	DL	4,04	2,76	8,98	4,0
	UL	8,1	6,69	7,61	5,77
TCP, 10 connections	DL	3,97	2,27	8,61	3,9
	UL	8,13	6,66	7,54	5,75
SNR	DL	13	14	28	14
	UL	24	20	20	28
RSSI	DL	-75	-79	-74	-68
	UL	-80	-86	-85	-74
Rate	RX	BPSK 3/4 – QAM16 ½	BPSK ¾ - QPSK ¾	QAM16 ½ - QAM64 ¾	QAM16 ½
	TX	QAM64 ¾	QAM64 ¾	QAM64 2/3 – QAM64 ¾	QAM64 ¾
Power	TX	20	20	20	19
BER	UL	2,5E-4	5,8E-3	5,6E-3	N/A

A.3.8 Location 8 (Skoyen)

Table 24 Location 8 (Skoyen)

Offset			**Among Houses, 300m East/North**
Distance		3,84	3,84
Elevation		3	20
FTP	DL	5,963572	1,283322
	UL	2,544965	0,189611
UDP	DL	2,71	3,78
	UL	0,967	0,719
UDP Simultaneous	DL	1,22	0,65
	UL	1,18	0,638
TCP	DL	2,54	0,889
	UL	0,892	0,118
TCP Simultaneous	DL	1,06	1,95
	UL	0,714	0,0785
TCP, 2 connections	DL	5,31	1,3
	UL	0,84	0,406
TCP, 4 connections	DL	4,91	1,75
	UL	0,915	0,243
TCP, 5 connection	DL	7,49	1,84
	UL	1,39	0,619
TCP, 10 connections	DL	5,43	11,7 (unlikely results)
	UL	2,24	1,63
SNR	DL	24	16
	UL	18	6
RSSI	DL	-78	-87
	UL	-88	-100

Rate	RX	BPSK ¾ - QAM16 ½	QPSK ¾ - QAM16 ½
	TX	BPSK ½ - QPSK ¾	BPSK ½
Power	TX	20	20
BER	UL	2,7E-2	4,7E-2

A.3.9 Location 9 (Gustav Vielands Vei 15 - Skoyen)

Table 25 Results Location 9 (Gustav Vielands Vei - Skoyen)

Offset			
Distance		4,4	4,4
Elevation		29	29
FTP	DL	3,463251	3,681984
	UL	0,368958	0,238282
UDP	DL	2,31	4,2
	UL	0,579	0,77
UDP Simultaneous	DL	0,699	0,704
	UL	0,638	0,642
TCP	DL	3,58	3,72
	UL	0,234	0,1
TCP Simultaneous	DL	0,949	3,31
	UL	0,515	0,0866
TCP, 2 connections	DL	3,2	3,56
	UL	0,337	0,0211
TCP, 4 connections	DL	3,38	3,44
	UL	0,7	0,123
TCP, 5 connection	DL	3,49	3,37
	UL	0,802	0,046
TCP, 10 connections	DL	3,56	3,5
	UL	0,728	0,415
SNR	DL	13	14
	UL	1	3
RSSI	DL	-89	-89
	UL	-103	-102
Rate	RX	BPSK ¾ - QAM 16 ½	QAM16 ½
	TX	BPSK ½	BPSK ½
Power	TX	20	19
BER	UL	1,8E-1	N/A

A.3.10 Location 10 (Lachmansvei)

Table 26 Results Location 10 (Lachmansvei)

Offset					**10m**	**10m**	**100m**	**100m**	**100m**
Distance		11,4	11,4	11,4	11,4	11,4	11,4	11,4	11,4
Elevation		251	251	251	251	251	251	251	251
FTP	DL	8,1277	8,8188	8,0116	5,0100	4,0908	2,8518	2,8307	2,7013
	UL	2,4657	3,4000	2,5604	0,9240	0,8037	0,5140	0,3379	0,4239
UDP	DL	1,51	9,58	9,59	1,75	4,75	1,47	3,14	2,92
	UL	7,96	7,5	7,87	0,909	0,912	0,782	0,825	0,846
UDP Simultan.	DL	2,04	4, 17	4, 05	0,683	0,806	0,614	0,678	0,725
	UL	2,04	4, 41	4, 17	0,65	0,75	0,578	0,609	0,677
TCP	DL	9,09	8,65	9,03	3,29	2,69	2,84	2,8	2,84
	UL	5,56	3,1	1,98	0,774	0,852	0,406	0,391	0,499

TCP Simultan.	DL	4,12	6,13	5,93	1,65	0,464	0,976	1,97	1,19
	UL	1,3	1,93	1,45	0,307	1,45	0,525	0,212	0,416
TCP, 2 conn.	DL	9,12	9,13	9,04	3,12	4	2,73	2,74	2,75
	UL	4,69	6,23	4,93	0,712	0,864	0,0617	0,872	0,615
TCP, 4 conn.	DL	6,99	8,29	9,06	3,51	3,61	2,57	2,67	2,55
	UL	7,17	7,81	8,38	0,861	0,856	0,522	0,235	0,747
TCP, 5 conn.	DL	8,89	8,91	8,06	2,36	4,17	2,77	2,72	2,26
	UL	7,72	8,38	7,89	0,783	0,767	0,544	0,271	0,784
TCP, 10 conn.	DL	8,85	8,43	8,77	4,7	4,79	2,73	2,74	2,62
	UL	7,91	8,29	7,29	0,836	0,762	0,686	0,568	0,698
SNR	DL	32	31	32	15	14	10	11	9
	UL	29	29	29	13	14	5	5	4
RSSI	DL	-69	-69	-68	-87	-88	-92	-91	-93
	UL	-77	-76	-77	-94	-92	-101	-100	-102
Rate	RX	BPSK ½	QAM64 ¾	QAM64 ¾	BPSK ¾ - QAM16 ¾	QPSK ¾ - QAM16 ¾	BPSK ½ - QPSK ¾	QPSK ¾	QPSK ¾
	TX	QAM16 ¾ - QAM64 ¾	QAM64 2/3 – QAM64 ¾	QAM64 2/3	BPSK ½	BPSK ½	BPSK ½	BPSK ½	BPSK ½
Power	TX	19	20	20	20	20	20	20	20
BER	UL	2,5E-2	1,9E-2	1,6E-2	1,5E-2	9,8E-3	1,1E-1	6,6E-2	5,1E-2

A.3.11 Location 11 (Upside Solvang Kolonihage)

Table 27 Results Location 11 (Upside Solvang Kolonihage)

Offset				
Distance		8,6	8,6	8,6
Elevation		161	161	161
FTP	DL	5,265886	5,388893	5,276837
	UL	0,662823	0,794313	0,798714
UDP	DL	1,73	N/A	6,31
	UL	0,89	N/A	0,891
UDP Simultaneous	DL	0,646	N/A	0,836
	UL	0,617	N/A	0,788
TCP	DL	5,3	N/A	5,34
	UL	0,711	N/A	0,887
TCP Simultaneous	DL	2,19	N/A	1,8
	UL	0,212	N/A	0,542
TCP, 2 connections	DL	5,35	N/A	5,35
	UL	0,842	N/A	0,857
TCP, 4 connections	DL	4,9	N/A	5
	UL	0,795	N/A	0,846
TCP, 5 connection	DL	4,96	N/A	5,1
	UL	0,771	N/A	0,854
TCP, 10 connections	DL	4,79	N/A	4,72
	UL	0,711	N/A	0,82
SNR	DL	17	18	18
	UL	12	12	12
RSSI	DL	-86	-84	-85
	UL	-95	-95	-94
Rate	RX	BPSK ¾ - QAM16 ¾	QAM16 ¾	QAM16 ¾

	TX	BPSK ½	BPSK ½	BPSK ½
Power	TX	20	20	20
BER	UL	2,8E-2	N/A	1,7E-2

A.3.12 Location 12 (Borgen, Svaldbardveien14)

Table 28 Results Location 12 (Borgen – Svaldbardveien14)

Offset			
Distance (km)		5,6	5,6
Elevation (m)		68	68
FTP	DL	7,499726	7,168263
	UL	0,858443	0,822987
UDP	DL	1,98	9,41
	UL	0,898	0,901
UDP Simultaneous	DL	0,744	0,893
	UL	0,715	0,816
TCP	DL	7,47	7,53
	UL	1,13	0,841
TCP Simultaneous	DL	1,25	3,26
	UL	0,566	0,437
TCP, 2 connections	DL	7,47	7,54
	UL	0,88	1,13
TCP, 4 connections	DL	6,09	6,81
	UL	0,876	0,864
TCP, 5 connection	DL	6,71	6,86
	UL	0,866	0,86
TCP, 10 connections	DL	6,47	6,57
	UL	0,606	0,661
SNR	DL	26	26
	UL	14	14
RSSI	DL	-76	-76
	UL	-92	-92
Rate	RX	BPSK ¾ - QAM64 ¾	QAM64 ¾
	TX	BPSK ½	BPSK ½
Power	TX	20	20
BER	UL	4,3E-2	2,6E-2

A.3.13 Location 13 (Borgen, Tuengveien5)

Table 29 Results Location 13 (Tuengveien5)

Offset				**50m**	**50m**
Distance (km)		5,72	5,72	5,72	5,72
Elevation (m)		80	80	80	80
FTP	DL	5,685622	4,636842	7,347326	7,328765
	UL	0,904041	0,977849	0,946949	N/A
UDP	DL	1,01	8,92	9,48	2,47
	UL	0,9	1,05	0,962	0,931
UDP Simultaneous	DL	0,623	0,904	0,946	0,83
	UL	0,597	0,832	0,851	0,751
TCP	DL	2,42	6,25	7,31	7,5
	UL	0,878	0,891	0,921	0,829
TCP	DL	0,532	0,765	0,873	0,594

	UL	0,544	0,699	0,241	1,62
TCP, 2 connections	DL	5,83	6,85	7,51	8,08
	UL	0,852	0,908	0,915	0,937
TCP, 4 connections	DL	6,6	6,37	6,62	N/A
	UL	1,11	0,853	0,905	0,829
TCP, 5 connection	DL	6,28	6,09	7,43	N/A
	UL	0,89	0,864	0,96	N/A
TCP, 10 connections	DL	6,18	6,2	6,65	N/A
	UL	0,842	0,88	0,892	N/A
SNR	DL	20	21	22	21
	UL	15	15	17	17
RSSI	DL	-82	-82	-81	-81
	UL	-92	-91	-89	-89
Rate	RX	BPSK ½ - QAM64 ¾	QAM64 ¾	QAM64 ¾	BPSK ¾
	TX	BPSK ½	BPSK ½	BPSK ½	BPSK ½
Power	TX	20	20	20	20
BER	UL	1,9E-2	4,6E-2	4,3E-3	1,1E-2

A.3.14 Location 14 (SognsveienXKongleveien)

Table 30 Results Location 14 (SognsveienXKongleveien)

Offset			**5 m**	**5 m**
Distance (km)		9,05	9,05	9,05
Elevation (m)		190	190	190
FTP	DL	N/A	3,500277	4,573337
	UL	N/A	0,583604	0,731889
UDP	DL	N/A	1,44	5,91
	UL	N/A	0,846	0,81
UDP Simultaneous	DL	N/A	0,668	0,811
	UL	N/A	0,635	0,733
TCP	DL	1,31	4,81	5,04
	UL	0,00847	0,521	0,898
TCP Simultaneous	DL	1,27	0,289	2,54
	UL	0,1	1,36	0,31
TCP, 2 connections	DL	N/A	5,33	5,31
	UL	N/A	0,643	0,805
TCP, 4 connections	DL	N/A	4,45	4,67
	UL	N/A	0,769	0,837
TCP, 5 connection	DL	N/A	4,25	4,73
	UL	N/A	0,792	0,847
TCP, 10 connections	DL	N/A	4,74	3,8
	UL	N/A	0,744	0,823
SNR	DL	13	17	14
	UL	3	9	9
RSSI	DL	-89	-85	-88
	UL	-102	-96	-97
Rate	RX	BPSK ½	BPSK ½ - QAM16 ¾	QAM16 ¾
	TX	BPSK ½	BPSK ½	BPSK ½
Power	TX	20	20	20
BER	UL	4,2E-1	4,9E-2	3,4E-2

B. Fixed WiMAX Preliminary Measurement Results and Location Information

B.1 Location 1 (Vardåsen)

Table 31 Measurement results at Location 1 (Vardåsen)

Offset (m)			**10N**	**10N+7E**	**100N, 20S**	**100**
Sight		LOS	nLOS	NLOS	NLOS	NLOS
Distance (km)		14,7	14,7	14,7	14,7	14,7
Elevation (m)		199	199	199	193	195
FTP	DL	0,82	3,88	N\A	No IP	No IP
	UL	2,42	1,86	N\A	No IP	No IP
SNR	DL	32	26	12	0	4
RSSI	DL	-66	-75	-93	0	-99
Rate	RX	QAM64 ¾	QAM64 ¾	BPSK ½	BPSK ½	BPSK ½
	TX	QAM64 ¾	QAM64 ¾	BPSK ½	No	BPSK ½
Power	TX	20	20	20	15	15

Fig. 22 gives a picture of the measurement positions at Vardaasen. A gives the initial position where there are clear LOS capabilities, B is the 10m North offset, C is 7m South from B, and D is the final 100N,. 20S offset. Fig. 21 gives a picture of the final offset that is 100m down a small road from position A, which is the same as 20m E from D.

Fig. 21 The final postionion at Vardaasen

Fig. 22 Positions at Vardaasen

B.2 Location 2 (Ekeberg)

The first two positions at Ekeberg is near line of sight with some branches disturbing the clear LOS path towards the BS. Great masses of sea is the landscape between the SU and BS. The thirds postion (Ekeberg2) is between houses, where there is little possibilities for reflections that may propagate to the BS. Ekeberg3 had little possibilities for reflections because of a house shadowing the initial position. The offset had only bush in between.

Table 32 Measurement results at Location 2 (Ekeberg)

Offset (m)		**Ekeberg1**		**Ekeberg2**	**13N+3U**	**Ekeberg3**	**10m E**
Sight		nLOS	nLOS	NLOS	NLOS	NLOS	NLOS
Distance		8,1	8,1	8,56	8,56	7,94	7,94
Elevation (m)		122	125	115	118	119	119
FTP	DL	0,994	1,078	No IP	0,776	No FTP	0,962
	UL	0,372	1,6	No IP	0,324	No FTP	800
SNR	DL	9	33	6	-8	-6	15
RSSI	DL	-94	-62	-97	-96	-99	-93
Rate	RX	BPSK ½	BPSK ½	BPSK ½	BPSK ½	BPSK ½	BPSK ½
	TX	BPSK ½	QAM64 ¾	BPSK ½	BPSK ½	BPSK ½	BPSK ½
Power	TX	20	18	15	20	20	20

Fig. 23 gives a picture of A-Ekeberg1, B-Ekeberg2, C-Ekeberg2 with offset and elevation, D-Ekeberg3.

Fig. 23 Positions at Ekeberg

B.3 Location 3 (Snaroya)

Two Locations was visited at Snaroya, where offsets were performed at each. All positions had totally NLOS capabilities. For the last position at Snaroya2, where a 90˚ is performed, similar rotations in all directions was performed with similar results.

Table 33 Measurement results at Location 3 (Snarøya)

Offset (m)		**Snaroya**	**2m, -30˚**	**2m, 60˚**	**Snaroya2**	**10m**	**10m, -90˚**
Sight		NLOS	NLOS	NLOS	NLOS	NLOS	NLOS
Distance		2,99	2,99	2,99	1,97	1,97	1,97
Elevation (m)		20	20	20	24	24	24
FTP	DL	No IP	Not FTP	No IP	1,016	1,053	IP OK
	UL	No IP	Not FTP	No IP	1,86	2,22	IP OK
SNR	DL	12	11	0	-81	-81	-89
RSSI	DL	-97	-93	0	17	14	10
Rate	RX	QPSK ½	-100	BPSK ½	BPSK ½	BPSK ½	QPSK ½
	TX	BPSK ½	0	BPSK ½	BPSK ½	QAM16 ¾	BPSK ½
Power	TX	20	15	15	20	20	20

B.4 Location 4 (Telenor Premises at Fornebu)

This is at the same location where the BS is located. A distance of 150 meters is present between the BS and SU. To avoid saturation, the SU points 90˚ away from the BS.

Table 34 Measurement results at Location 4 (Telenor Premises at Fornebu)

Offset (m)		Snarova
Sight		NLOS
Distance (km)		150
Elevation (m)		35, same as BS
FTP	DL	3,72
	UL	2,39
SNR	DL	34
RSSI	DL	-44
Rate	RX	QAM64 ¾
	TX	QAM64 ¾
Power	TX	20

B.4.1 UDP tests

We performed UDP tests at the location Telenor premises at Fornebu when attempting to achieve higher throughputs. A tool named tptest (*http://www.tptest.se/*) was used for this purpose. Higher troughputs was achieved as presented in Table 35.

Table 35 Preliminary Measurements UDP tests

UDP Downlink	UDP Uplink
9,01	7,72
7,56	7,76
8,01	7,87
5,94	N/A
7,85	N/A
8,59	N/A
8,28	N/A

B.4.2 FTP test with TCP window tuning

At the location Telenor premises at Fornebu, we performed experiments with TCP Windows tuning was performed as listed in Table 36.

Table 36 FTP test with TCP Window Size Tuning

TCP Window Size	Download (Mbps)	Upload (Mbps)
17KB (Default)	3,62	1,09
64KB	7,04	1,04
1MB	8,01	1,05
4GB	7,95	1,04

C. Fixed WiMAX Deployment Measurement Results

C.1 Physical Measurements for All Subscribers in Deployment

Table 37 presents the results from the fixed WiMAX deployment with a total of 658 subscribers. RSSIUL, RSSIDL, SNRDL and SNRUL are given in dBm. MaleID is an indentificationnumber of the subscriber. TxPower is given in dBm. Distance is given in kilometre.

Table 37 Results from a fixed WiMAX Deployment

MaleID	RSSIUL	SNRUL	RSSIDL	SNRDL	TxPower	Distance(km)
396	-92.31	14.21489	-80.07	23.00000	19.48	0.05
293	-69.00	29.38333	-34.00	32.00000	-3.71	0.21
909	-82.39	19.65556	-77.01	17.06944	19.79	0.29
276	-68.80	32.19600	-31.00	34.00000	-9.51	0.30
2050	-68.70	28.70950	-59.00	24.10500	16.24	0.38
1233	-68.50	28.42400	-55.92	27.08500	14.54	0.38
337	-76.41	26.89600	-70.00	18.93500	19.84	0.39
277	-71.50	26.46789	-62.00	17.00000	19.92	0.39
1261	-69.60	29.55206	-53.00	24.00000	10.48	0.40
1972	-69.60	25.53778	-41.00	30.90222	-1.08	0.42
1609	-69.60	25.71917	-51.00	24.00000	9.17	0.43
1505	-76.17	22.87750	-63.00	23.14833	19.85	0.43
264	-69.40	30.93672	-49.00	17.00000	10.40	0.45
1515	-70.76	28.75867	-61.00	34.12810	19.87	0.55
1283	-74.54	30.12767	-72.72	29.18444	20.00	0.55
475	-69.40	29.87467	-59.00	34.00000	16.64	0.56
270	-69.70	32.97067	-41.00	30.01222	-0.41	0.59
1491	-69.30	32.04178	-60.00	32.00000	19.50	0.64
2121	-84.32	12.99200	-77.12	20.87667	19.75	0.66
2052	-69.44	33.38944	-66.00	21.00000	19.46	0.66
297	-68.33	34.14300	-53.00	28.00000	11.44	0.66
2147	-84.39	7.10533	-75.00	20.12667	2.53	0.68
1393	-84.10	21.98789	-81.13	19.74889	20.00	0.71
1401	-72.16	32.18222	-59.00	34.86944	19.93	0.72
1656	-84.60	15.24133	-74.95	21.94667	20.00	0.74
1065	-73.12	23.33356	-62.00	32.00000	20.00	0.78
1523	-68.72	21.09029	-62.00	20.13143	15.86	0.80
711	-69.33	31.09250	-60.00	32.00000	17.60	0.80
1263	-79.35	26.42794	-64.54	27.27556	20.00	0.81
282	-69.16	32.16067	-66.98	31.02444	17.08	0.85
1407	-69.77	30.72622	-45.00	33.00000	1.16	0.86
1503	-71.70	31.40000	-46.00	34.14778	-2.29	0.89
472	-69.10	33.49600	-46.00	35.00000	2.75	0.90
476	-77.40	28.09894	-66.00	31.00000	20.00	0.93
288	-70.10	29.98000	-52.00	30.97333	9.89	0.93
487	-73.00	31.49306	-44.00	35.00000	-3.39	0.96
985	-73.60	25.70444	-64.04	18.00000	20.00	1.00
1443	-77.81	23.86944	-69.42	18.16667	19.99	1.02
415	-70.21	32.03156	-51.00	32.00000	10.60	1.04
1001	-91.56	6.32683	-82.96	17.07667	20.00	1.10
1351	-70.56	31.22550	-69.90	29.10500	20.00	1.14
805	-69.59	32.20838	-64.00	27.26095	19.69	1.18
1011	-78.39	24.60800	-71.00	26.92000	20.00	1.20
488	-71.96	30.88800	-56.90	35.00000	13.25	1.22
262	-68.80	29.22078	-53.00	23.00000	11.09	1.24
1924	-71.27	31.58189	-63.09	33.00000	19.94	1.26
268	-68.99	14.31222	-61.00	30.00000	17.47	1.31
2070	-86.00	20.64911	-69.00	32.00000	20.00	1.32

1573	-73.87	30.04419	-69.00	19.13952	20.00	1.35
1133	-83.81	21.12800	-73.94	19.06000	20.00	1.38
1435	-74.67	22.98800	-71.86	12.00000	20.00	1.39
749	-68.95	30.86800	-58.00	33.00000	15.91	1.42
486	-70.10	32.93233	-57.00	35.90333	19.18	1.42
429	-68.29	30.28278	-63.08	22.91722	17.46	1.42
799	-67.76	32.61986	-60.00	35.13857	16.56	1.44
1938	-70.70	32.50000	-61.00	26.00000	19.49	1.45
425	-71.29	26.84533	-64.00	29.00000	19.33	1.49
520	-71.39	32.04139	-62.00	26.00000	19.92	1.50
519	-69.80	32.49928	-58.00	29.00000	15.37	1.50
502	-69.20	29.16917	-46.00	32.89722	4.11	1.50
283	-69.69	32.07750	-55.00	33.02500	11.51	1.50
275	-67.80	27.97222	-65.00	29.98611	18.26	1.50
454	-71.85	31.73067	-64.09	32.08667	20.00	1.51
300	-68.59	29.32311	-56.00	33.00000	12.44	1.53
2016	-68.99	33.50444	-59.10	34.00000	20.00	1.54
2084	-68.30	29.73583	-60.00	33.23889	17.85	1.55
335	-73.00	26.76422	-48.00	33.00000	7.59	1.55
313	-68.99	33.41694	-55.04	34.00000	14.66	1.55
266	-75.40	23.05594	-63.00	32.00000	19.50	1.56
1676	-77.31	27.32450	-80.00	10.29000	20.00	1.57
1281	-69.80	31.30278	-59.00	26.00000	13.19	1.57
1251	-68.70	29.91411	-56.00	33.00000	15.47	1.58
526	-73.36	30.92250	-58.00	35.00000	18.10	1.59
461	-73.60	24.32667	-68.00	32.08889	1.78	1.60
1053	-69.20	28.61022	-50.00	32.00000	10.51	1.64
1714	-69.70	32.97467	-64.04	16.00000	19.87	1.66
1539	-69.20	33.81267	-48.87	34.86619	5.32	1.66
933	-68.54	25.23772	-51.00	30.00000	11.68	1.68
1469	-75.01	20.90978	-67.86	26.13556	20.00	1.70
1581	-97.09	7.31976	-82.86	24.14048	20.00	1.72
315	-67.51	32.76328	-50.00	34.00000	12.30	1.73
935	-68.70	33.85067	-54.00	29.97944	11.46	1.74
1766	-73.10	31.02300	-66.00	29.00000	19.86	1.75
430	-69.64	32.18333	-62.00	29.00000	17.69	1.76
973	-68.30	34.26700	-54.00	34.00000	14.37	1.80
532	-69.11	28.35889	-53.00	31.00000	11.12	1.80
695	-68.64	33.89689	-46.00	35.00000	5.57	1.81
693	-68.77	33.18400	-49.00	35.00000	10.61	1.81
1826	-68.61	30.36450	-61.00	32.14333	19.93	1.82
260	-69.90	27.73389	-55.01	30.99444	13.04	1.83
1400	-69.75	33.50000	-60.00	35.00000	17.47	1.84
1327	-89.76	15.84489	-81.90	20.10111	20.00	1.84
1345	-72.71	31.67933	-66.00	33.89667	20.00	1.86
1635	-69.10	32.40000	-57.99	34.99333	13.73	1.87
1229	-69.38	32.95222	-57.00	34.00000	11.11	1.87
2080	-69.40	29.82764	-59.00	22.00000	15.71	1.89
1105	-68.61	33.98350	-48.00	35.00000	10.30	1.90
1359	-70.21	24.46850	-62.00	28.00000	20.00	1.91
490	-69.86	32.75278	-49.00	33.00000	10.22	1.92
785	-69.45	33.19643	-58.00	19.00000	16.93	1.93
482	-69.42	32.78600	-51.00	35.00000	11.20	1.93
1605	-69.40	33.78917	-55.00	32.00000	12.80	1.94
1234	-85.24	15.98500	-75.00	25.08556	19.54	1.94
279	-68.40	33.07978	-50.00	34.98444	8.70	1.95
2111	-72.09	31.78633	-79.00	11.00000	20.00	1.96
2044	-76.78	29.12728	-66.90	12.20778	19.97	1.96
1507	-68.71	33.88511	-54.00	35.85111	10.88	1.97
977	-75.96	25.39333	-67.97	32.03333	20.00	1.97
1335	-84.81	21.11017	-76.00	27.00000	19.41	1.99
959	-69.50	32.63733	-62.00	26.02611	16.87	2.00
897	-68.90	32.70489	-56.00	33.00000	19.88	2.02
280	-68.00	31.31933	-49.98	33.98389	9.80	2.02
1998	-78.64	16.76289	-72.00	31.00000	19.81	2.04
1952	-71.42	31.96650	-63.00	34.00000	20.00	2.04

1704	-69.00	34.09639	-56.00	31.00000	14.27	2.04
312	-68.10	33.87900	-50.00	33.03500	11.20	2.04
1195	-70.29	21.13856	-53.00	23.07278	10.88	2.05
1131	-75.58	24.96539	-71.06	21.00000	20.00	2.05
1828	-69.11	30.88333	-59.00	30.00000	18.20	2.06
1185	-69.29	33.81467	-55.93	35.00000	15.27	2.07
518	-68.31	32.57667	-55.00	28.65000	16.13	2.07
281	-68.10	33.88044	-48.02	33.97556	8.90	2.10
1371	-68.02	32.07661	-52.00	31.00000	12.82	2.11
767	-71.61	30.78333	-64.00	26.00000	19.18	2.11
929	-73.90	25.26194	-68.00	28.03889	19.58	2.14
284	-69.20	29.55878	-48.00	33.97444	8.29	2.14
1855	-87.95	18.39233	-73.08	29.00000	20.00	2.15
1403	-71.02	27.68378	-62.00	17.13111	19.43	2.16
1243	-69.30	33.90189	-53.00	35.99056	7.88	2.16
1702	-69.71	33.21200	-55.00	22.03500	12.59	2.17
1309	-68.90	31.57822	-52.00	35.09778	11.07	2.18
2137	-70.39	32.15022	-53.00	34.87444	12.27	2.19
1664	-68.00	35.17689	-60.00	35.00000	18.19	2.19
1768	-82.32	16.11667	-76.00	15.05556	20.00	2.20
1591	-69.71	32.65676	-56.00	35.00000	15.37	2.20
939	-83.50	22.89350	-75.00	26.97833	19.70	2.20
1974	-70.10	16.96183	-62.00	28.09833	19.24	2.21
483	-68.63	32.93311	-53.00	35.90444	11.95	2.21
331	-68.52	22.68633	-52.06	32.06333	10.39	2.21
2048	-69.29	33.98950	-54.00	34.10500	11.68	2.22
1423	-68.69	31.69833	-60.00	8.00000	17.54	2.22
1007	-69.20	29.34500	-57.00	29.03944	11.53	2.23
291	-69.20	32.52850	-61.00	33.97278	18.56	2.23
289	-68.60	18.93733	-60.00	27.00000	19.43	2.23
1019	-69.80	30.38000	-54.00	35.95556	13.25	2.24
2131	-68.60	33.03750	-61.00	18.00000	20.00	2.26
1143	-68.31	28.91850	-54.07	30.87000	11.97	2.26
1321	-70.29	33.75000	-53.00	36.00000	10.63	2.28
1197	-68.44	33.21400	-50.00	33.92667	12.94	2.28
1381	-70.10	32.92222	-58.00	35.00000	13.19	2.29
1107	-69.12	33.56633	-58.00	34.00000	17.22	2.29
1932	-69.67	33.83506	-54.00	31.90722	10.32	2.30
1375	-69.20	32.20000	-58.00	30.10944	14.54	2.30
1015	-68.89	34.25889	-55.00	29.08222	12.53	2.30
1357	-69.97	30.06400	-54.00	25.00000	10.33	2.32
2046	-68.66	31.33778	-58.00	23.00000	17.25	2.33
1644	-69.40	33.30278	-57.00	31.98611	14.26	2.33
1319	-68.91	29.90939	-58.00	32.09944	15.36	2.33
801	-68.93	33.71067	-60.00	32.00000	17.34	2.34
685	-69.12	13.58794	-57.00	26.87278	16.99	2.34
1285	-75.91	24.50928	-72.00	25.18556	19.72	2.35
290	-72.92	30.14556	-68.97	21.05444	20.00	2.35
1343	-68.69	28.09667	-58.00	25.00000	14.55	2.36
1980	-69.10	29.00994	-55.00	25.09944	17.99	2.38
1483	-68.29	28.79111	-57.00	17.00000	14.33	2.40
895	-68.30	34.19667	-54.00	32.00000	14.17	2.40
1493	-68.90	33.62922	-60.00	35.00000	18.49	2.41
2012	-69.21	33.07956	-57.00	15.10222	16.27	2.42
1549	-69.99	32.48895	-53.14	24.00000	13.80	2.42
963	-69.00	26.79056	-55.00	29.05444	13.85	2.42
503	-92.25	13.11133	-76.11	22.00000	20.00	2.45
1249	-68.80	32.44422	-62.00	26.00000	20.00	2.46
2098	-69.15	31.00800	-56.00	28.88000	15.77	2.47
265	-68.60	32.78900	-54.99	30.00000	10.85	2.47
2086	-68.99	31.38400	-60.00	23.12000	18.62	2.48
1555	-70.19	32.29067	-54.00	35.00000	8.09	2.50
1439	-69.79	33.62089	-52.14	36.00000	9.95	2.50
1245	-75.98	28.96467	-62.00	31.00000	20.00	2.50
314	-68.11	28.95033	-54.00	31.03667	14.27	2.50
731	-69.20	33.94338	-57.00	35.00000	11.01	2.52

1822	-68.40	30.49333	-61.00	23.00000	18.21	2.53
457	-68.50	32.98072	-55.00	31.00000	18.78	2.54
451	-69.54	30.20533	-57.00	28.00000	13.87	2.54
1433	-79.13	26.28222	-71.27	30.86389	20.00	2.56
1099	-67.90	33.59761	-53.00	35.00000	13.17	2.56
1255	-67.68	35.37350	-58.00	34.08833	17.84	2.57
941	-69.31	33.22000	-52.00	36.00000	12.72	2.57
1589	-69.34	31.58714	-57.00	35.00000	14.95	2.62
1329	-68.81	29.73733	-58.00	25.10167	15.53	2.62
514	-78.47	25.52711	-75.00	30.00000	19.83	2.62
267	-77.70	24.19894	-73.00	20.98944	19.80	2.62
1239	-77.02	28.87417	-76.00	22.08611	20.00	2.63
725	-79.25	24.05571	-68.00	29.00000	20.00	2.64
1992	-68.81	33.15028	-59.00	34.00000	15.18	2.65
1101	-69.10	33.92922	-58.00	35.00000	18.24	2.66
1710	-70.41	33.06600	-63.04	34.96222	20.00	2.73
1772	-68.61	35.03200	-60.00	30.00000	20.00	2.74
295	-68.40	24.61156	-56.00	26.00000	14.25	2.74
2113	-68.09	34.63889	-54.00	34.00000	13.48	2.77
923	-69.30	32.39822	-57.00	35.00000	15.36	2.77
1209	-69.69	31.62750	-52.00	35.00000	15.90	2.79
1722	-67.70	32.81800	-51.00	35.00000	12.84	2.80
393	-74.27	29.23933	-65.00	30.92667	20.00	2.80
408	-68.45	32.75367	-52.00	34.00000	12.69	2.81
1730	-70.21	32.87200	-54.00	35.04667	9.73	2.83
1646	-77.00	28.30000	-70.00	31.00000	19.74	2.83
351	-75.41	28.17933	-69.00	31.00000	19.99	2.83
1780	-68.41	32.94583	-52.00	35.00000	14.51	2.84
278	-72.52	30.38200	-67.00	15.00000	19.94	2.84
410	-69.51	31.72333	-51.92	34.00000	6.43	2.86
1728	-68.90	34.32622	-59.00	35.00000	19.36	2.91
757	-70.30	32.37095	-51.00	35.12905	9.68	2.91
336	-80.52	23.60000	-71.00	31.00000	19.90	2.91
1559	-71.00	26.77900	-67.14	31.00000	20.00	2.92
1347	-69.60	32.17661	-56.00	34.00000	13.67	2.93
1115	-71.11	32.54006	-65.00	33.00000	20.00	2.94
529	-68.99	33.04028	-54.00	34.11944	14.27	2.94
471	-69.70	32.39061	-56.00	34.00000	15.53	2.94
453	-68.92	31.41194	-62.00	34.00000	19.38	2.94
401	-70.09	32.03833	-51.00	34.92333	9.71	2.96
2145	-78.85	26.37467	-70.00	32.00000	19.57	2.97
1690	-77.22	27.90322	-66.00	30.00000	19.45	2.97
1033	-69.29	33.87639	-52.00	36.00000	11.81	2.97
1027	-68.41	29.66400	-52.95	34.00000	7.40	2.97
464	-69.00	33.60000	-54.00	35.00000	14.24	2.97
533	-69.44	31.00589	-53.00	34.00000	13.06	2.99
330	-68.51	34.33678	-56.00	34.00000	11.85	2.99
1525	-75.15	29.67914	-65.00	33.86810	19.62	3.00
1369	-69.99	31.29800	-53.00	34.10889	10.58	3.00
516	-68.84	33.86089	-60.00	31.00000	19.98	3.00
1895	-68.39	32.37111	-54.00	35.00000	12.18	3.02
1859	-73.41	30.42333	-68.00	27.00000	20.00	3.04
723	-69.82	31.08267	-55.00	35.00000	12.45	3.04
317	-68.50	25.49467	-53.00	32.96222	11.71	3.04
787	-68.44	27.94943	-61.86	34.00000	19.53	3.05
1489	-74.31	29.63100	-65.00	33.14556	19.97	3.07
1696	-74.50	29.12950	-67.00	32.00000	20.00	3.08
997	-70.00	32.94533	-53.00	35.96222	12.72	3.08
494	-88.86	15.64000	-84.10	21.00000	20.00	3.09
403	-70.52	31.39967	-61.00	33.00000	20.00	3.09
1479	-72.11	31.18667	-64.14	34.85667	19.99	3.10
332	-69.29	30.67733	-53.00	34.00000	11.15	3.12
500	-82.60	22.68178	-70.00	26.10222	20.00	3.16
474	-80.40	25.10117	-67.00	32.99833	20.00	3.16
301	-68.90	31.74356	-62.00	33.96889	18.82	3.17
1147	-69.62	33.39333	-55.00	36.00000	16.66	3.21

1341	-69.80	32.39250	-56.00	34.89722	13.48	3.23
272	-69.10	31.81533	-54.00	33.00000	10.20	3.24
305	-69.40	7.70983	-58.97	34.00000	13.98	3.27
1363	-68.68	33.19944	-58.00	34.00000	16.12	3.29
271	-69.70	31.10122	-62.00	33.00000	19.59	3.30
1167	-68.70	31.02483	-58.07	18.00000	16.49	3.31
1409	-71.31	29.96833	-66.00	24.00000	20.00	3.32
478	-85.41	20.08100	-75.00	27.00000	20.00	3.34
1786	-68.11	30.17133	-64.00	30.00000	20.00	3.37
1563	-69.70	33.43762	-64.00	32.00000	19.16	3.38
951	-68.90	26.47578	-59.00	30.97556	14.51	3.38
436	-81.85	23.91667	-69.07	24.93056	19.56	3.39
1201	-70.11	33.06306	-54.00	34.92611	12.25	3.40
333	-67.60	31.49972	-52.06	32.00000	12.49	3.41
1625	-70.20	33.29378	-58.00	32.00000	14.74	3.42
477	-83.03	20.67839	-75.09	25.00000	20.00	3.42
1313	-69.40	31.51800	-56.00	34.00000	11.67	3.43
1325	-69.20	33.06144	-51.00	35.00000	10.09	3.45
509	-68.41	33.14556	-58.00	35.88611	17.30	3.50
350	-69.49	33.38633	-53.07	31.06833	11.56	3.50
302	-69.00	31.73800	-51.00	33.96833	9.79	3.52
1899	-80.45	25.46600	-64.00	30.00000	19.93	3.56
306	-68.58	31.87706	-52.00	33.00000	11.15	3.56
294	-80.49	24.44700	-74.00	28.00000	20.00	3.56
1700	-89.17	16.94822	-79.97	16.96556	20.00	3.57
1834	-69.71	33.14867	-57.00	34.92667	16.58	3.60
2006	-72.50	30.69833	-67.00	25.40667	20.00	3.63
1565	-72.31	32.12752	-65.00	33.13762	19.70	3.63
389	-69.89	31.03283	-63.00	33.00000	19.22	3.64
2135	-83.84	21.90000	-71.00	32.00000	19.95	3.65
310	-68.70	33.25933	-51.97	34.96611	10.02	3.66
1662	-77.48	27.96033	-67.00	33.00000	20.00	3.67
1716	-80.49	24.75294	-73.00	27.04278	20.00	3.69
1593	-69.09	31.61790	-57.00	33.00000	17.33	3.69
261	-69.90	31.29222	-61.00	27.99444	18.03	3.69
793	-68.91	32.40786	-58.00	34.87190	15.17	3.72
1213	-76.16	26.12089	-64.00	29.07556	19.51	3.73
943	-69.50	29.72506	-53.00	33.00000	12.08	3.73
341	-89.29	17.86033	-77.00	28.00000	19.88	3.74
1257	-75.91	22.50667	-70.91	23.91111	20.00	3.75
1013	-69.21	32.34461	-53.00	35.00000	13.66	3.76
1607	-68.80	32.70267	-59.00	35.00222	18.88	3.82
400	-68.75	32.69344	-56.92	34.00000	16.81	3.82
899	-68.50	33.89456	-59.01	35.00000	17.52	3.84
727	-69.20	32.50757	-49.12	35.00000	10.47	3.84
348	-68.92	27.07278	-59.00	34.00000	18.92	3.84
1417	-75.50	29.61333	-70.00	32.00000	20.00	3.86
303	-69.90	31.16333	-62.00	33.96833	19.90	3.86
1712	-70.29	32.23333	-61.96	28.04167	19.69	3.90
921	-69.00	28.42333	-56.00	35.00000	15.90	3.90
1307	-70.88	33.50000	-66.00	34.00000	19.91	3.92
1349	-73.69	30.41644	-65.00	32.89556	19.72	3.93
1708	-69.50	33.55906	-59.04	26.00000	14.64	3.94
1085	-69.08	31.65250	-57.05	32.05278	17.52	3.96
2066	-78.48	19.03567	-69.11	30.89278	19.80	4.00
417	-93.61	12.98083	-90.00	13.00000	20.00	4.01
287	-69.60	32.34594	-55.00	34.00000	10.99	4.01
340	-69.09	31.26694	-59.00	29.00000	15.99	4.02
927	-69.60	32.87544	-63.00	34.00000	18.25	4.03
1337	-68.80	34.37156	-59.00	35.89778	11.23	4.04
1796	-78.80	25.99750	-68.00	31.06389	19.41	4.07
735	-69.19	31.94000	-58.00	34.00000	15.34	4.09
318	-68.01	34.87317	-57.04	34.00000	18.52	4.11
1750	-68.51	33.77733	-60.00	35.00000	17.43	4.12
937	-68.00	27.93433	-60.00	32.97833	16.28	4.15
1557	-72.80	14.85167	-66.00	25.00000	20.00	4.16

1141	-68.23	33.43867	-59.00	35.00000	18.37	4.16
534	-68.71	32.14867	-55.00	35.87833	16.34	4.16
1816	-72.19	24.97222	-65.00	32.00000	19.82	4.18
395	-69.01	33.93350	-52.07	29.00000	13.50	4.19
498	-68.61	33.15950	-56.00	23.00000	17.55	4.21
292	-68.90	27.80556	-62.00	27.00000	16.93	4.21
903	-84.00	21.60083	-75.00	29.00000	20.00	4.23
542	-79.00	2.14594	-69.00	26.00000	19.99	4.25
298	-70.00	19.06600	-67.00	32.03000	20.00	4.26
319	-70.90	33.11917	-60.00	33.00000	19.91	4.27
2074	-80.76	18.84333	-72.00	29.00000	19.95	4.28
1905	-84.16	21.60750	-65.17	33.91278	20.00	4.28
1814	-72.83	24.41378	-64.00	24.06889	19.37	4.28
1551	-74.27	29.39500	-61.86	32.13571	15.56	4.28
409	-81.55	24.43111	-72.92	30.07778	20.00	4.28
729	-67.82	24.13200	-61.00	35.00000	20.00	4.31
1956	-88.35	12.06317	-83.10	21.90389	20.00	4.32
1770	-78.98	18.81222	-71.94	29.05611	20.00	4.32
1752	-77.10	19.74467	-69.95	25.00000	19.79	4.32
1441	-82.31	15.65967	-76.00	28.00000	20.00	4.32
1219	-68.48	31.49067	-61.00	29.00000	20.00	4.32
1529	-69.19	33.23829	-60.00	35.00000	18.77	4.35
1361	-68.41	29.87900	-57.11	30.89278	15.21	4.35
961	-81.20	23.53539	-68.00	33.00000	19.44	4.37
420	-80.02	25.32417	-75.00	29.00000	19.75	4.39
745	-90.84	14.98762	-79.00	23.00000	19.40	4.41
1221	-71.00	27.75772	-66.00	33.07611	19.35	4.43
1682	-69.20	10.60200	-63.00	28.12000	19.82	4.47
1599	-76.20	27.60100	-76.00	23.00000	20.00	4.51
481	-81.74	24.33800	-72.00	31.09500	19.77	4.54
512	-68.02	35.33433	-54.11	35.00000	16.98	4.60
1165	-90.19	16.46050	-79.00	25.00000	19.40	4.61
2143	-88.85	16.07122	-83.13	21.87389	20.00	4.62
2076	-73.20	30.50000	-62.00	35.00000	14.53	4.62
2040	-81.99	22.42800	-79.00	26.00000	20.00	4.62
1986	-75.06	29.91000	-67.00	34.00000	20.00	4.62
1911	-87.51	17.47350	-80.00	25.91167	20.00	4.62
1909	-73.47	30.62978	-67.09	31.00000	20.00	4.62
1903	-73.14	31.27867	-69.00	31.00000	20.00	4.62
1553	-72.71	30.34071	-56.00	35.00000	14.03	4.62
1391	-79.65	19.03733	-72.10	25.00000	20.00	4.62
1808	-74.87	29.99311	-65.00	35.00000	19.41	4.63
1756	-70.13	24.06250	-63.00	29.00000	19.46	4.63
1631	-70.60	32.50122	-60.00	30.99389	19.73	4.70
1225	-67.98	33.09233	-59.00	33.07667	19.48	4.70
915	-74.20	25.28244	-67.00	28.00000	19.60	4.70
993	-89.03	18.15533	-81.00	19.00000	19.99	4.74
987	-70.00	30.71333	-56.00	32.96389	11.58	4.76
327	-91.52	15.09378	-82.00	10.00000	19.88	4.76
1832	-69.69	28.40028	-57.00	32.07278	13.98	4.77
1385	-96.95	8.71312	-85.96	12.00000	22.00	4.77
353	-68.98	30.90333	-58.00	31.93111	14.56	4.77
299	-70.10	26.91917	-59.00	30.00000	13.11	4.77
1003	-84.00	22.10778	-76.00	21.00000	20.00	4.81
1740	-70.60	19.52861	-64.00	27.00000	20.00	4.82
783	-80.23	25.77305	-72.00	31.13476	20.00	4.82
285	-69.00	32.64072	-57.00	27.05222	15.33	4.82
274	-69.50	30.33889	-57.00	31.98611	19.85	4.83
971	-69.21	33.26172	-62.00	35.00000	19.06	4.85
1071	-68.01	30.53578	-59.00	28.00000	20.00	4.86
831	-68.50	29.60000	-59.00	32.00000	16.71	4.87
1966	-71.81	27.60833	-67.00	32.09722	20.00	4.88
388	-68.71	30.00450	-56.07	33.00000	18.19	4.88
1820	-69.60	26.96811	-58.00	35.00000	17.07	4.90
1738	-82.80	23.98000	-79.00	20.05000	20.00	4.90
1788	-68.00	33.85644	-58.00	35.00000	17.70	4.91

1996	-68.39	22.84144	-60.00	22.00000	17.25	4.92
1585	-78.46	26.95638	-74.86	24.14095	20.00	4.96
338	-69.49	32.54756	-63.00	33.00000	18.32	4.96
1437	-68.60	29.60239	-65.00	21.00000	20.00	4.98
1136	-68.21	34.88722	-59.94	29.00000	16.00	4.98
1946	-68.01	32.48500	-58.00	29.00000	17.90	4.99
2107	-98.37	7.51211	-95.00	6.00000	20.00	5.00
1897	-68.50	34.42778	-60.00	17.91389	20.00	5.00
296	-69.20	24.85017	-58.03	32.00000	13.24	5.03
1039	-85.51	21.16222	-77.00	27.00000	20.00	5.04
1451	-68.23	32.30600	-63.00	27.00000	20.00	5.05
1157	-77.22	28.82544	-66.00	33.00000	20.00	5.06
1317	-68.89	30.06922	-64.00	20.19778	19.00	5.07
1836	-75.56	29.43350	-75.00	25.07389	20.00	5.09
1784	-75.10	28.60589	-66.00	33.00000	19.77	5.09
316	-68.70	22.28133	-61.00	24.00000	18.24	5.09
721	-67.82	29.89524	-62.00	32.88190	20.00	5.11
1487	-68.40	29.10000	-59.00	32.85500	19.08	5.12
1145	-72.19	27.34911	-67.00	30.00000	19.49	5.13
1173	-68.79	32.53611	-58.00	24.00000	18.17	5.15
1627	-74.30	29.68250	-67.00	26.00000	19.60	5.17
541	-81.82	23.50133	-73.00	24.12333	19.89	5.18
2115	-87.03	18.72456	-83.12	18.87722	20.00	5.19
737	-69.91	30.97552	-62.00	26.00000	20.00	5.19
1179	-69.09	24.68500	-59.00	34.00000	15.35	5.20
1177	-69.70	33.24400	-58.07	11.93000	18.44	5.20
741	-83.48	21.76167	-69.12	24.00000	20.00	5.20
1838	-69.49	31.87444	-63.00	31.00000	20.00	5.21
1736	-70.50	26.90656	-62.00	26.04944	19.64	5.22
907	-70.20	25.80900	-64.00	25.02000	19.71	5.22
709	-73.71	29.43700	-66.00	23.86556	20.00	5.22
1191	-68.01	31.16611	-56.00	30.00000	16.59	5.23
1025	-70.00	32.11800	-55.00	36.00000	13.64	5.23
2129	-70.14	22.75600	-62.00	27.37333	19.83	5.26
1159	-69.19	33.18383	-59.00	35.00000	16.29	5.27
739	-70.16	29.63857	-58.88	31.87714	19.77	5.28
1067	-79.51	25.68267	-69.05	32.00000	19.07	5.29
1377	-68.49	31.24900	-58.00	30.89000	17.46	5.35
1311	-80.11	19.11956	-70.00	26.00000	20.00	5.37
1293	-69.51	29.27167	-59.91	32.00000	20.00	5.37
458	-68.91	32.72289	-61.00	33.00000	19.44	5.37
404	-69.20	31.90728	-59.00	26.92722	18.30	5.37
1587	-87.80	18.98586	-79.00	24.00000	19.54	5.41
1093	-68.61	33.94800	-58.00	35.00000	15.05	5.41
496	-81.61	22.72906	-74.00	29.00000	20.00	5.43
392	-81.95	23.55767	-71.00	30.00000	19.93	5.43
1297	-74.68	24.10450	-63.00	32.09500	18.31	5.44
1964	-86.30	19.97778	-68.00	31.70833	19.76	5.51
1958	-72.98	31.54200	-75.10	28.90333	19.64	5.54
1091	-69.69	33.97361	-59.00	27.05278	19.87	5.54
495	-68.91	26.70000	-62.00	29.79889	18.85	5.54
1917	-75.09	25.79111	-70.00	28.00000	19.44	5.55
1913	-70.89	26.74889	-63.00	32.08889	20.00	5.55
1043	-77.73	20.53822	-66.00	20.00000	19.71	5.56
1571	-74.14	22.96419	-63.00	30.00000	19.36	5.58
513	-79.02	28.35750	-68.00	32.00000	20.00	5.58
945	-72.40	26.50467	-64.00	28.97667	17.28	5.59
1269	-69.74	21.85678	-62.00	27.00000	18.44	5.66
1205	-72.79	25.39678	-60.00	32.00000	14.72	5.67
307	-69.61	33.45667	-62.00	34.96667	17.61	5.68
1241	-72.39	25.69933	-59.00	30.00000	15.45	5.76
308	-68.70	31.54000	-60.00	33.03333	18.46	5.76
1698	-92.22	14.48333	-74.97	27.03333	20.00	5.77
1650	-99.30	6.11711	-86.00	18.00000	20.00	5.79
1541	-70.15	29.60276	-63.00	32.86619	20.00	5.82
320	-68.80	31.97667	-63.96	33.96111	18.28	5.82

1583	-69.00	35.45786	-62.00	34.85952	19.98	5.88
1227	-68.90	31.70850	-57.00	16.92278	19.56	5.94
424	-69.60	33.75100	-67.00	22.00000	19.90	5.95
1231	-79.62	18.64050	-70.92	31.00000	19.19	5.99
1237	-93.49	5.11733	-95.99	7.01333	20.00	6.03
981	-72.91	24.89950	-65.04	23.14000	19.89	6.06
1611	-79.19	16.32067	-69.99	30.00667	19.61	6.08
1501	-76.09	29.77389	-69.85	33.00000	20.00	6.14
2072	-72.55	32.59417	-63.68	34.00000	13.78	6.16
1984	-72.08	31.36000	-79.70	26.20000	10.35	6.16
1760	-90.53	6.42156	-84.00	20.00000	20.00	6.16
1758	-87.30	10.53733	-81.00	23.00000	20.00	6.16
1413	-84.44	21.67428	-80.00	25.00000	20.00	6.16
1411	-73.76	27.42889	-60.00	33.00000	19.96	6.16
1853	-71.00	32.61628	-62.00	34.07611	19.19	6.27
1253	-86.90	19.97350	-77.00	24.00000	19.75	6.28
449	-69.60	32.99600	-60.92	29.00000	19.55	6.36
1527	-69.69	33.05276	-64.00	34.86810	19.13	6.39
1425	-68.57	33.78900	-61.00	34.00000	18.65	6.39
1207	-70.69	32.41489	-63.00	29.14889	20.00	6.39
803	-70.80	32.29767	-62.00	34.13952	20.00	6.40
1247	-69.40	33.02433	-59.00	28.00000	18.72	6.42
418	-73.84	29.94000	-69.00	32.00000	19.76	6.43
1762	-73.00	29.42978	-66.00	23.00000	19.53	6.46
1706	-73.80	30.88167	-66.00	33.00000	19.98	6.46
531	-80.92	24.63617	-76.00	26.00000	20.00	6.47
469	-82.31	24.07217	-74.09	21.09278	20.00	6.47
1537	-91.04	14.83333	-84.00	21.13333	20.00	6.48
1806	-74.80	26.63578	-66.00	26.00000	20.00	6.52
344	-70.20	29.40472	-63.00	26.00000	19.89	6.53
781	-74.13	25.68438	-64.00	32.00000	20.00	6.55
1203	-70.40	28.69211	-62.93	25.00000	19.85	6.57
484	-83.88	21.87894	-79.00	22.09611	20.00	6.60
827	-84.79	21.28457	-77.14	28.00000	20.00	6.61
1063	-72.88	31.30000	-65.00	33.00000	20.00	6.63
841	-86.60	12.00133	-75.00	26.00000	20.00	6.64
501	-74.22	25.10000	-59.10	32.10278	14.46	6.64
991	-75.51	22.94767	-70.00	21.89000	20.00	6.67
1802	-70.49	33.57311	-64.00	33.00000	19.59	6.75
1567	-71.39	22.17000	-62.00	23.00000	19.32	6.76
473	-75.90	24.30200	-68.00	22.99500	20.00	6.78
428	-73.88	25.92483	-57.00	29.00000	11.33	6.78
406	-86.51	20.09278	-79.00	21.85556	20.00	6.85
465	-79.08	14.15689	-69.00	26.90889	19.78	6.86
433	-85.90	18.23467	-70.00	26.00000	20.00	6.86
925	-80.00	26.00183	-73.00	30.00000	20.00	6.87
468	-79.71	26.16311	-70.00	23.00000	19.97	6.87
901	-83.80	21.89767	-76.00	27.00778	19.89	6.90
309	-68.50	34.05594	-63.97	33.03389	16.72	6.90
1353	-75.18	24.48056	-70.11	29.10556	20.00	6.94
1684	-70.99	26.46800	-66.00	30.03111	19.77	6.96
1774	-85.40	21.57167	-85.00	18.00000	20.00	6.99
1383	-74.01	27.16667	-67.00	13.88889	20.00	6.99
470	-90.89	15.05467	-81.00	20.00000	20.00	6.99
701	-79.17	24.25200	-72.87	21.00000	20.00	7.01
522	-89.99	16.27933	-92.17	7.71000	20.00	7.01
421	-70.80	30.37833	-62.00	23.00000	19.87	7.01
1155	-74.07	30.77967	-69.07	29.00000	20.00	7.03
485	-76.90	23.80708	-71.96	28.04462	20.00	7.10
1720	-86.22	20.56444	-78.00	25.00000	20.00	7.13
1575	-86.70	19.07400	-84.00	19.14000	20.00	7.13
1465	-83.96	20.15511	-81.86	22.00000	19.43	7.13
1397	-86.86	15.76128	-82.00	20.12611	20.00	7.13
452	-74.10	27.11656	-70.00	31.08556	20.00	7.13
2119	-81.33	15.05411	-74.12	23.00000	20.00	7.14
489	-83.30	22.31956	-78.10	25.90222	20.00	7.14

455	-71.22	32.86133	-63.00	34.00000	20.00	7.23
1792	-71.79	31.93767	-60.00	35.00000	20.00	7.25
1686	-69.11	33.33422	-61.00	32.00000	19.40	7.25
1419	-73.59	32.15272	-67.00	34.00000	20.00	7.25
747	-82.94	16.78700	-77.00	28.00000	20.00	7.28
460	-73.29	26.08233	-63.00	28.00000	18.62	7.28
423	-81.92	19.52667	-70.00	30.91833	19.86	7.28
1742	-69.29	33.41011	-60.95	35.00000	19.68	7.29
1922	-94.87	12.60900	-80.00	24.09000	19.96	7.31
1851	-68.97	27.57200	-61.00	30.00000	19.53	7.34
1473	-76.67	20.69822	-70.00	28.85778	20.00	7.35
1954	-93.39	13.20956	-91.00	14.09556	19.96	7.49
527	-90.82	15.80000	-79.00	23.00000	20.00	7.69
328	-85.21	18.85561	-85.00	21.00000	19.89	7.69
1692	-71.00	33.07378	-61.03	34.96722	19.63	7.79
707	-85.57	20.59917	-76.00	21.13389	19.87	7.80
775	-91.73	15.18667	-85.00	9.00000	20.00	7.81
1287	-74.23	30.05600	-65.09	34.00000	19.79	7.87
493	-83.12	22.67350	-77.10	21.90056	20.00	7.89
466	-70.66	28.14917	-61.00	35.00000	19.89	7.89
394	-75.33	28.35333	-68.00	28.00000	20.00	7.89
326	-78.11	26.26917	-72.00	28.00000	20.00	7.97
432	-82.53	19.66644	-72.08	31.00000	19.89	8.02
1800	-85.57	16.47333	-82.93	21.06667	20.00	8.03
979	-81.82	15.34233	-72.00	31.00000	20.00	8.03
1477	-83.63	21.74067	-76.00	27.14333	19.60	8.05
1824	-81.29	22.30067	-84.00	14.14333	19.93	8.07
506	-91.49	15.44556	-82.11	24.00000	20.00	8.07
334	-86.50	20.38083	-78.00	24.00000	19.98	8.14
1948	-81.04	25.25667	-80.91	23.00000	20.00	8.21
1547	-78.59	11.01929	-71.00	31.00000	20.00	8.21
1499	-84.79	18.98278	-82.85	21.14722	19.86	8.21
1497	-85.96	16.41867	-86.00	22.00000	20.00	8.21
2123	-68.70	32.23806	-52.00	24.12389	11.90	8.28
1109	-69.08	31.64028	-61.00	33.00000	19.90	8.29
347	-69.80	26.40083	-66.00	33.00000	19.47	8.29
311	-71.40	31.59011	-64.00	29.03444	19.85	8.29
431	-72.50	30.37550	-63.00	31.00000	19.92	8.32
715	-70.31	32.48633	-61.00	26.86333	20.00	8.37
1295	-76.66	28.50000	-69.91	30.00000	20.00	8.38
323	-90.21	16.10539	-86.05	15.00000	19.79	8.38
412	-70.51	33.03689	-63.00	28.00000	19.84	8.44
521	-71.00	31.86333	-64.00	30.88222	19.58	8.47
387	-89.32	17.48567	-80.00	9.92833	19.75	8.56
1187	-76.59	13.50300	-66.00	32.00000	20.00	8.57
1355	-74.09	28.50256	-65.00	28.00000	19.41	8.60
1830	-78.33	27.10722	-74.00	31.00000	20.00	8.66
755	-77.47	26.67000	-67.00	30.12857	19.46	8.67
1934	-89.85	17.11856	-83.00	21.00000	20.00	8.68
1323	-69.00	29.49217	-62.00	32.89944	18.69	8.84
1531	-84.90	21.86029	-80.00	23.00000	19.52	8.97
459	-81.54	22.06300	-70.91	26.91167	20.00	8.98
1893	-77.79	26.37911	-69.25	22.75333	20.00	9.07
839	-75.30	21.41200	-64.00	19.00167	20.00	9.07
322	-90.68	10.83067	-89.95	16.00000	19.88	9.26
1455	-78.96	26.48711	-73.14	29.85889	19.93	9.28
913	-74.80	22.30900	-72.00	26.98500	20.00	9.29
1561	-77.33	21.64457	-67.86	21.00000	19.73	9.38
1051	-74.35	30.44200	-65.00	34.00000	20.00	9.45
1041	-70.89	32.42356	-63.00	34.00000	19.64	9.47
1021	-70.10	33.94667	-67.04	33.00000	17.49	9.48
1804	-76.91	28.35378	-65.00	34.00000	19.87	9.50
1658	-95.45	10.80511	-93.95	11.02556	19.56	9.50
949	-71.50	21.27678	-64.00	31.00000	19.97	9.61
791	-75.08	14.31105	-68.14	33.00000	19.94	9.61
543	-92.52	13.29156	-83.12	13.00000	19.86	9.64

397	-94.72	12.20000	-83.00	20.00000	19.44	9.64
345	-72.01	28.59333	-63.93	29.00000	19.15	9.70
1732	-76.60	28.99528	-69.00	32.04722	20.00	9.76
1153	-82.17	23.20756	-78.00	25.00000	19.99	9.83
349	-82.27	23.10000	-73.00	24.06778	19.95	9.83
1754	-77.05	20.81033	-69.00	20.94833	20.00	9.95
538	-70.14	32.75800	-62.00	23.00000	19.37	10.00
2064	-71.89	30.83067	-68.00	31.21333	20.00	10.04
385	-71.91	26.27439	-64.00	33.00000	20.00	10.05
703	-72.69	24.80861	-65.00	33.00000	20.00	10.06
517	-78.98	13.61089	-70.88	31.00000	19.72	10.06
2103	-67.91	33.15178	-58.88	27.12056	19.38	10.14
1648	-71.90	31.79000	-66.00	33.00000	20.00	10.14
795	-83.07	22.76405	-75.00	20.86619	20.00	10.40
719	-74.49	29.52943	-68.00	26.00000	20.00	10.48
1595	-86.60	20.30000	-86.00	20.00000	20.00	10.49
797	-69.27	31.82238	-61.00	34.00000	20.00	10.54
829	-76.24	27.90333	-67.14	20.85810	19.97	10.55
325	-88.89	17.25600	-87.00	19.00000	19.90	10.55
304	-75.80	28.81611	-71.00	31.00000	19.83	10.59
769	-76.81	22.08681	-70.00	25.00000	20.00	10.88
953	-78.29	25.43750	-71.00	27.97500	20.00	10.93
1495	-73.46	31.53867	-66.00	34.00000	20.00	10.96
1305	-75.68	30.49367	-67.00	34.00000	19.80	10.97
893	-74.80	30.00200	-62.00	33.99500	19.84	11.10
2042	-74.20	29.80367	-67.00	32.00000	20.00	11.16
1481	-87.70	18.21367	-86.00	17.00000	20.00	11.22
1463	-93.46	12.48583	-84.00	19.00000	19.46	11.31
687	-76.06	24.80056	-68.87	25.12778	19.98	11.31
505	-91.84	14.65100	-81.93	20.07000	19.96	11.42
1415	-78.17	27.30000	-72.00	29.00000	20.00	11.47
1259	-77.11	27.63578	-67.91	32.91056	19.98	11.48
1059	-77.50	27.15439	-71.00	30.95056	20.00	11.53
1169	-77.39	28.30000	-71.00	29.06889	19.97	11.55
499	-82.81	23.28983	-76.00	24.00000	20.00	11.67
1365	-86.77	11.97333	-79.00	26.00000	19.86	11.76
1029	-89.71	6.81989	-80.00	23.00000	20.00	11.76
733	-93.09	6.84343	-83.00	5.12095	20.00	11.87
491	-95.82	6.44806	-89.00	4.29833	20.00	11.87
911	-89.00	17.67689	-80.00	23.00000	19.72	11.92
1301	-89.15	16.28078	-84.00	19.09611	19.65	11.93
390	-87.21	17.20000	-82.00	19.07111	20.00	11.93
1303	-90.14	16.93233	-82.00	16.19333	19.84	12.01
1640	-84.70	21.38900	-82.99	14.03667	20.00	12.12
1543	-90.03	14.70286	-87.87	7.00000	20.00	12.12
1449	-86.00	20.38600	-81.00	19.14000	19.95	12.12
1447	-88.03	18.10000	-79.00	21.00000	19.41	12.12
1445	-89.97	16.54444	-86.86	17.72222	19.69	12.12
1005	-87.41	19.41717	-96.00	5.03944	20.00	12.30
2101	-77.88	27.82411	-74.00	17.00000	20.00	12.77
789	-87.97	18.46833	-80.86	25.00000	20.00	12.79
497	-85.41	19.91467	-80.90	20.10111	20.00	13.02
1113	-83.00	23.00844	-72.00	21.94278	20.00	13.14
462	-74.59	21.19767	-68.00	19.00000	20.00	13.33
957	-74.19	25.89478	-64.00	32.00000	19.20	13.44
2058	-97.43	8.38933	-78.00	23.00000	20.00	13.45
705	-80.71	25.60000	-74.87	29.00000	20.00	13.45
955	-72.41	27.28978	-66.97	28.05111	20.00	13.51
398	-86.57	19.36978	-80.00	24.92444	20.00	13.80
759	-90.99	14.30362	-74.00	27.00000	20.00	14.05
463	-88.02	18.17200	-78.00	19.00000	19.96	14.12
1299	-71.28	23.82622	-65.90	28.00000	20.00	14.15
1017	-75.70	29.43417	-68.96	26.00000	20.00	14.25
713	-94.00	12.78311	-86.00	15.00000	20.00	14.25
1117	-95.99	9.95200	-90.00	16.00000	20.00	14.29
342	-81.29	22.06000	-73.00	20.00000	19.91	14.31

1129	-78.67	21.88256	-72.00	14.11778	19.95	14.73
269	-75.80	24.38250	-67.01	15.98833	19.86	15.04
537	-86.71	15.12278	-81.00	20.00000	20.00	15.05
771	-86.81	14.41543	-76.00	26.00000	20.00	15.15
1339	-87.19	18.85139	-76.10	25.00000	19.71	15.57
324	-90.70	11.86333	-88.00	11.00000	19.83	15.57
419	-89.21	17.35972	-87.00	15.00000	20.00	16.52
1267	-91.60	14.95500	-83.09	18.00000	19.68	16.55
1265	-90.52	16.24533	-83.00	15.00000	19.91	16.55
399	-79.71	20.75983	-74.00	29.00000	20.00	16.79
1776	-95.49	10.30978	-96.00	5.00000	19.73	17.15
1907	-85.74	16.49122	-91.91	3.17556	20.00	17.33
1863	-82.42	19.17833	-76.00	22.07833	20.00	18.36
530	-94.87	4.84800	-89.00	11.00000	20.00	18.67
1223	-70.21	30.40700	-69.92	19.07667	20.00	18.68
1798	-78.27	14.70000	-70.00	23.86778	20.00	18.72

C.2 Throughput Results for Customers with Demanding Capacity Requirements

Table 38 Throughput Measurements for Subscribers in the Deployment with Demanding Capacity Requirements (Mbps)

TCP UL	TCP DL	UDP UL	UDP DL
3.29	3.5	4.18	3.87
2.21	3.78	3.13	4.04
4.81	4.2	4.24	4.15
4.1	4.17	4.24	4.18
4.19	4.2	4.24	4.24
4.56	4.2	3.72	4.24
7.12	6.55	7.23	7.1
5.45	6.02	6.59	7.84
6.92	7.68	7.23	8.1
6.89	7.12	7.87	8.36
7.89	8.12	7.2	8.57
7.14	7.88	7.2	8.63
7.22	8.02	7.7	8.72
5.29	5.81	6.72	8.77
7.2	8.32	7.89	8.85
7.06	7.84	7.65	8.89
6.78	7.6	7.2	8.96
7.46	8.22	7.58	8.96
7.59	8.12	7.24	8.97
7.98	8.67	8.18	9.06
7.2	8.65	7.55	9.07
7.14	8.46	7.51	9.17
7.71	8.23	7.9	9.2
8.59	8.72	8.23	9.29
9.14	8.8	8.26	9.29
7.24	7.55	8.55	9.32
5.96	7.15	5.37	9.36
7.75	8.38	7.43	9.37
7.36	9.19	7.61	9.39
7.87	8.45	7.12	9.45
7.96	8.23	9.22	9.51
8.65	8.77	8.28	9.53
10.1	9.46	9.43	9.54
7.64	7.88	8.18	9.55
7.13	8.58	7.55	9.59
8.56	8.63	8.25	9.6
8.65	8.86	8.63	9.64
8.19	9.04	8.34	9.64

8.29	9.02	8.61	9.66
8.12	9.6	8.16	9.66
8.94	8.89	8.3	9.67
8.14	8.56	9.01	9.74
8.78	8.97	8.37	9.85
8.28	9.08	8.64	9.86
8.05	9.12	8.18	9.88
6.35	6.77	7.2	9.9
5.08	8.24	5.14	9.93
7.85	8.74	7.95	9.94
8.55	8.2	8.98	9.96
8.24	9	8.54	10.05
7.97	8.13	9.78	10.1
8.4	8.6	8.27	10.1
7.68	8.55	8.07	10.2
8.26	9.4	9.55	10.2
8.56	8.66	8.19	10.3
8.19	9.31	9.67	10.3
8.27	8.72	8.54	10.4
7.64	9.01	8.18	10.4
8.25	9.06	8.49	10.4
7.42	9.1	8.58	10.4
8.15	8.72	8.41	10.5

C.3 Frequency Planning Maps

This subsection contains a collection of screenshots of each of BSs with their sectors. The cells that are using the same frequencies have the same color. The BS in the center of each map with the BS's name serves the subscribers that are colored blue.

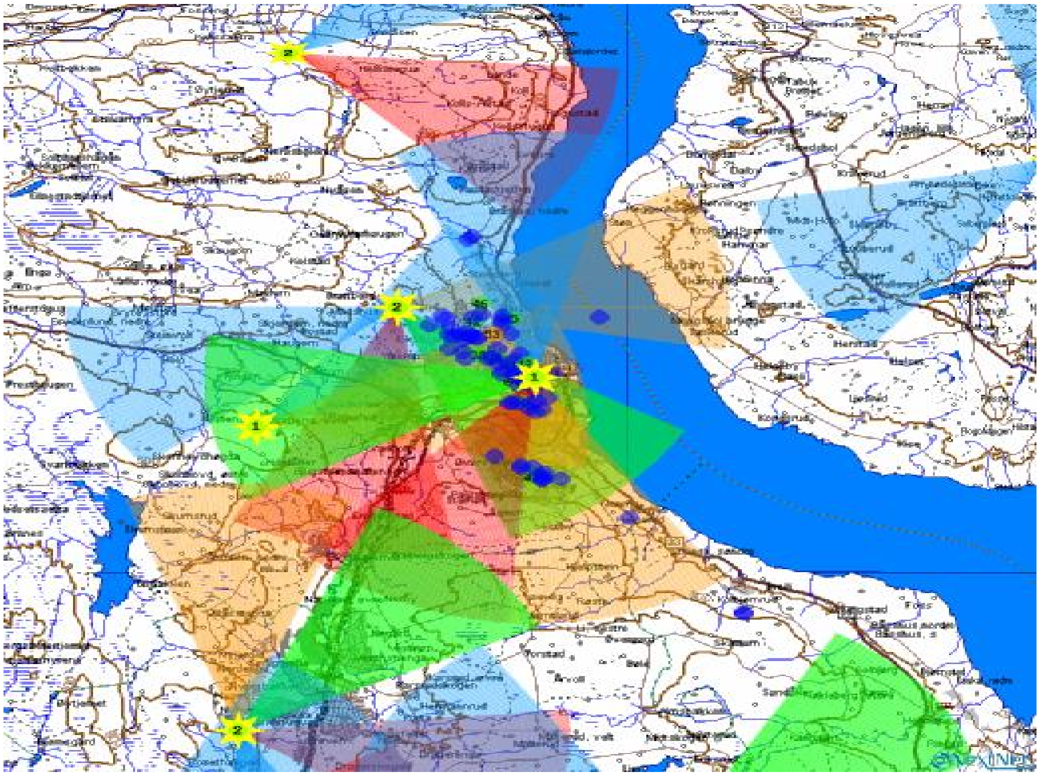


Figure 24 Radhus

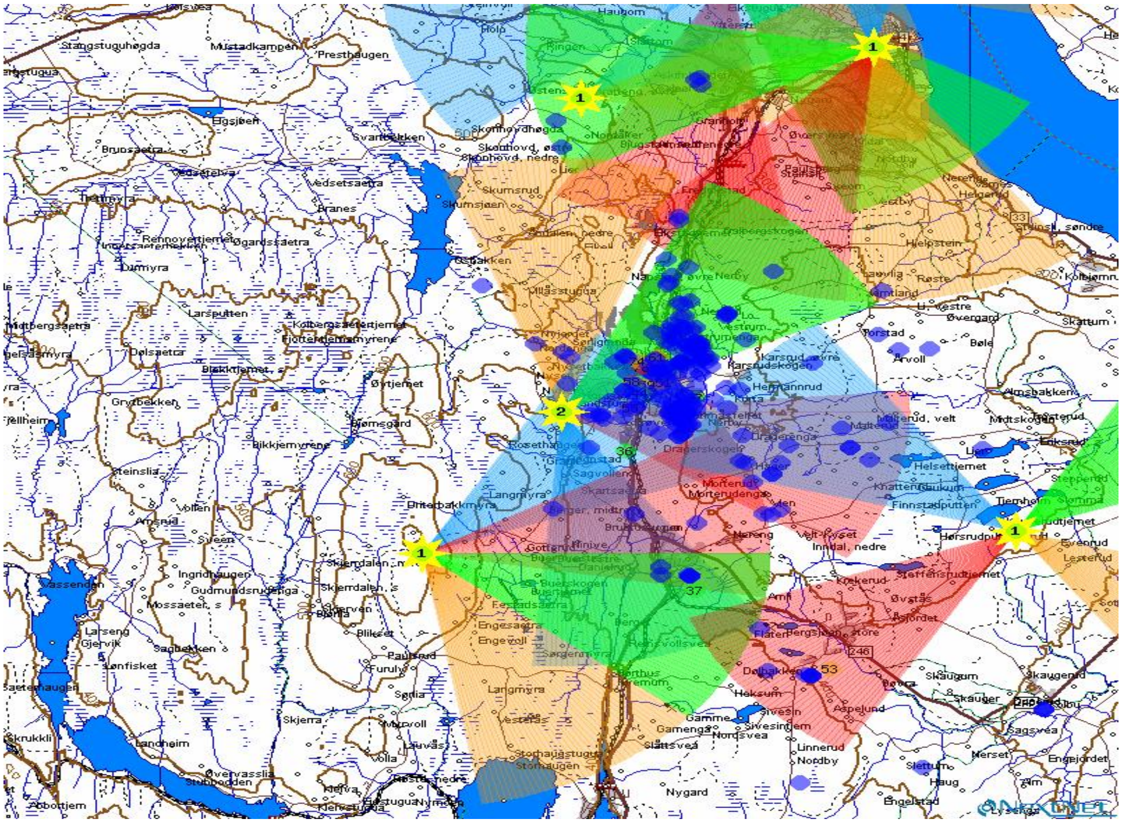


Fig. 25 Lonneberget

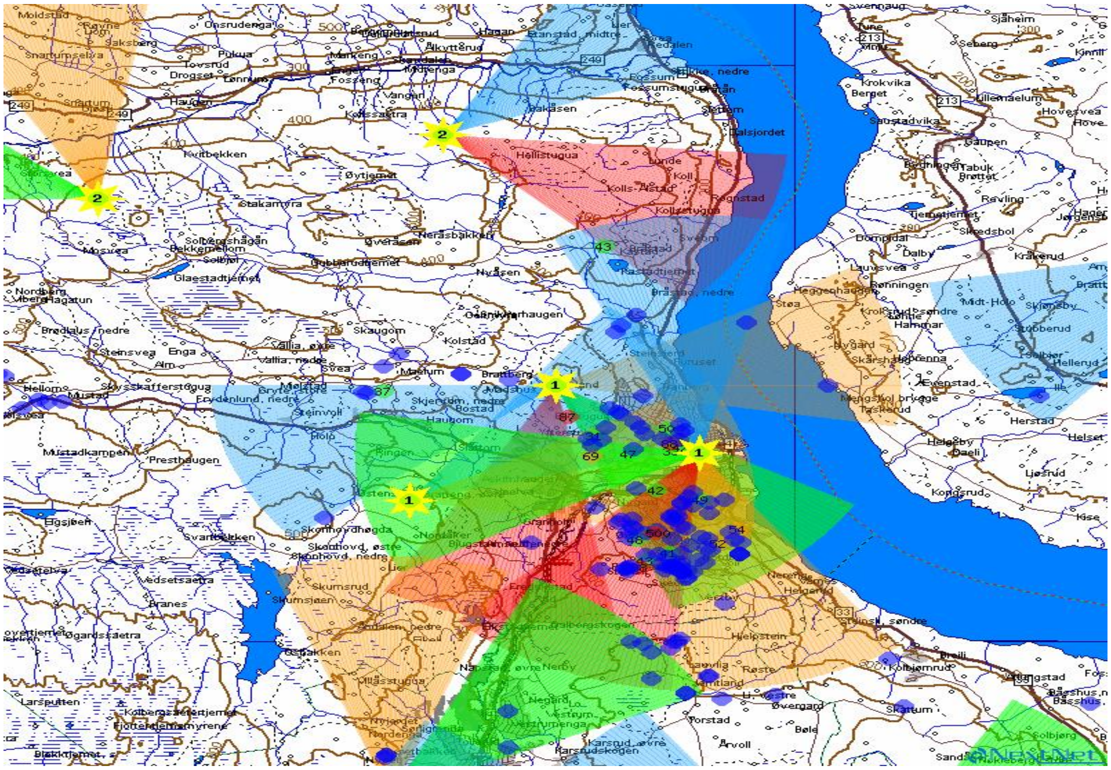


Fig. 26 Bergstoppen

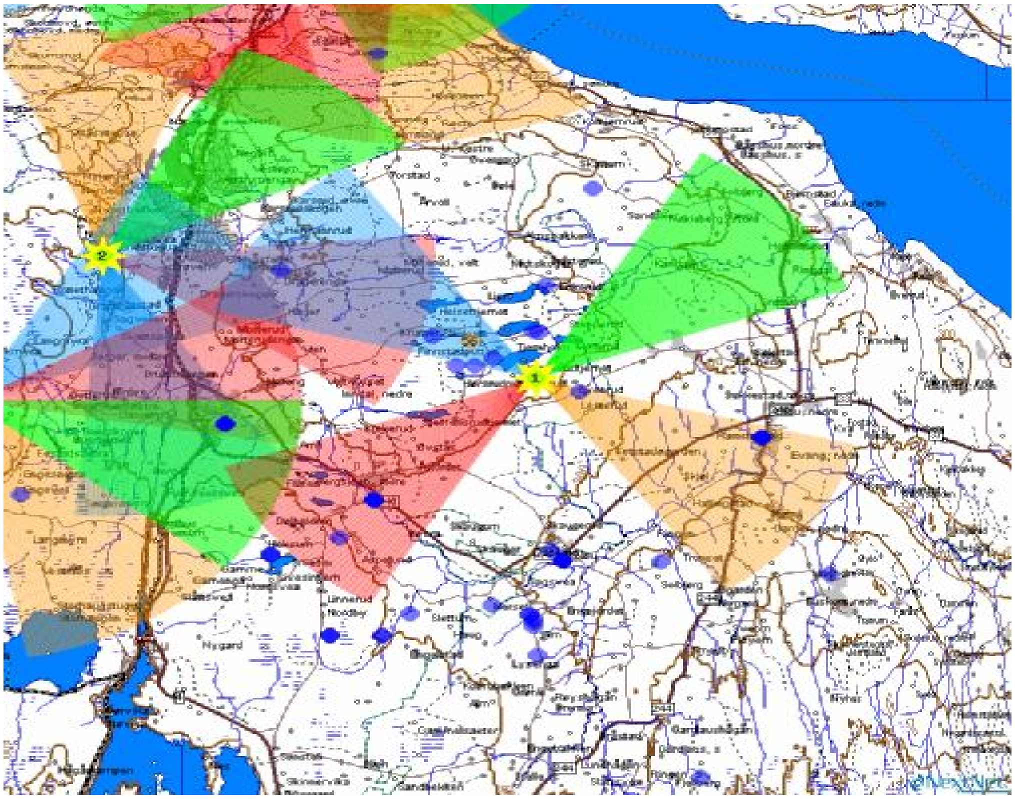


Fig. 27 LenaOmformer

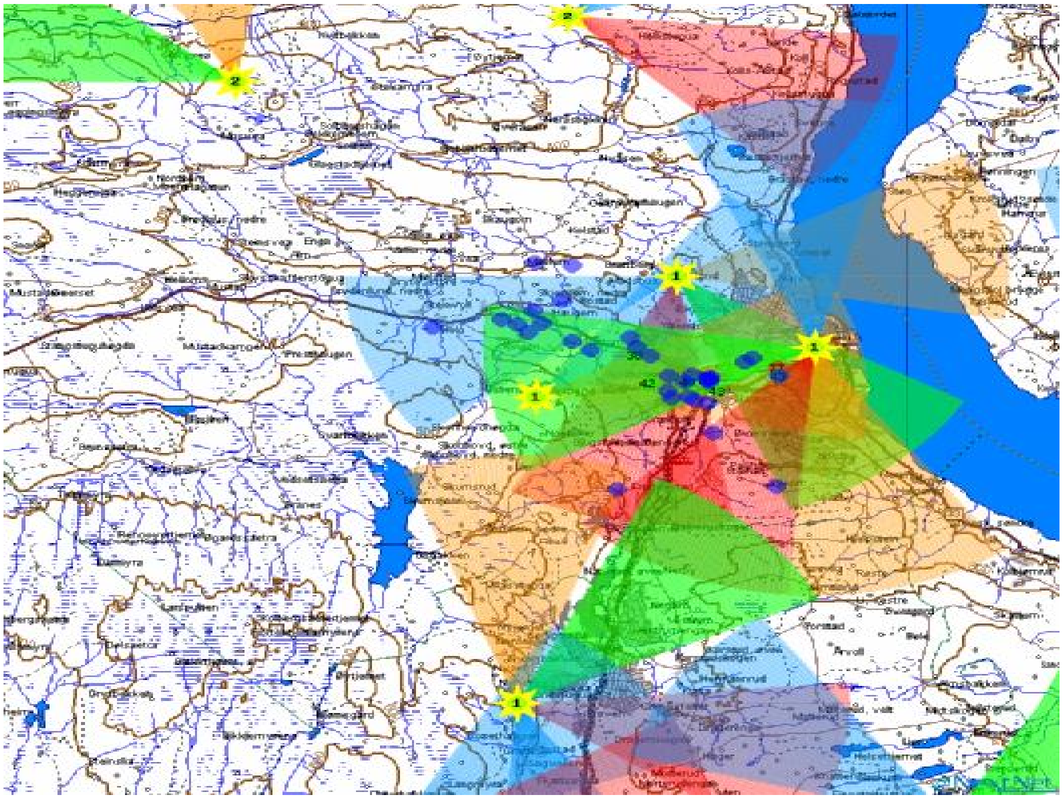


Fig. 28 Hunndalen

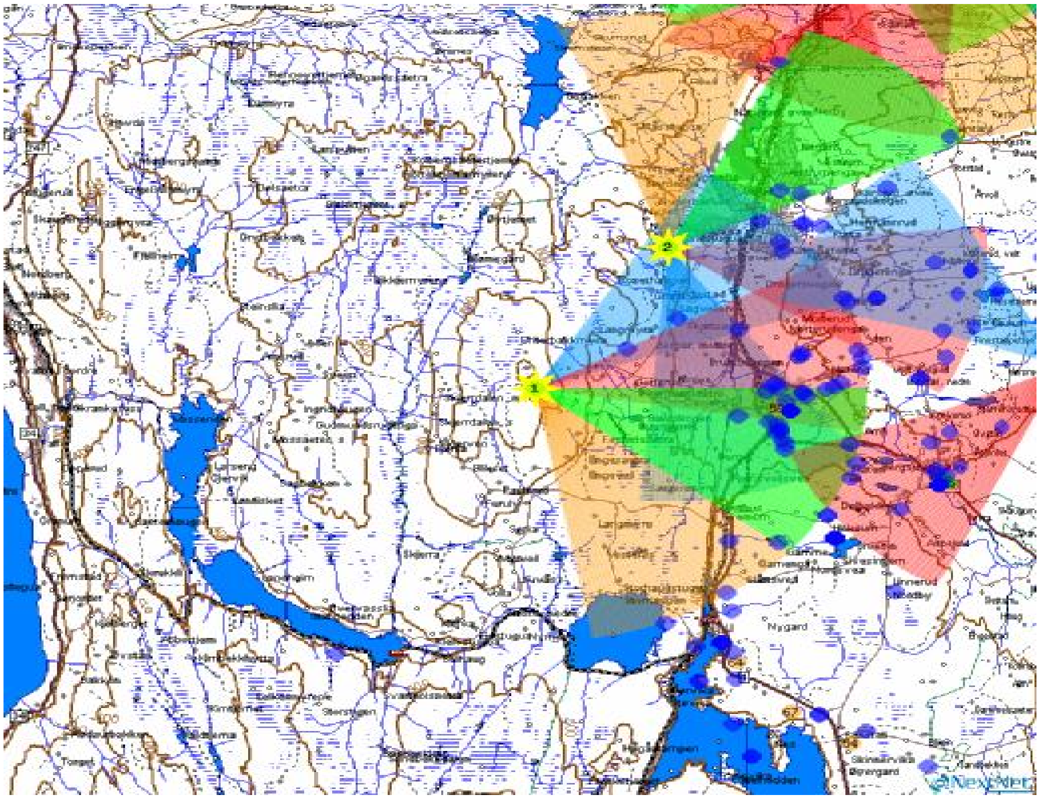


Figure 29 Lauvhogda

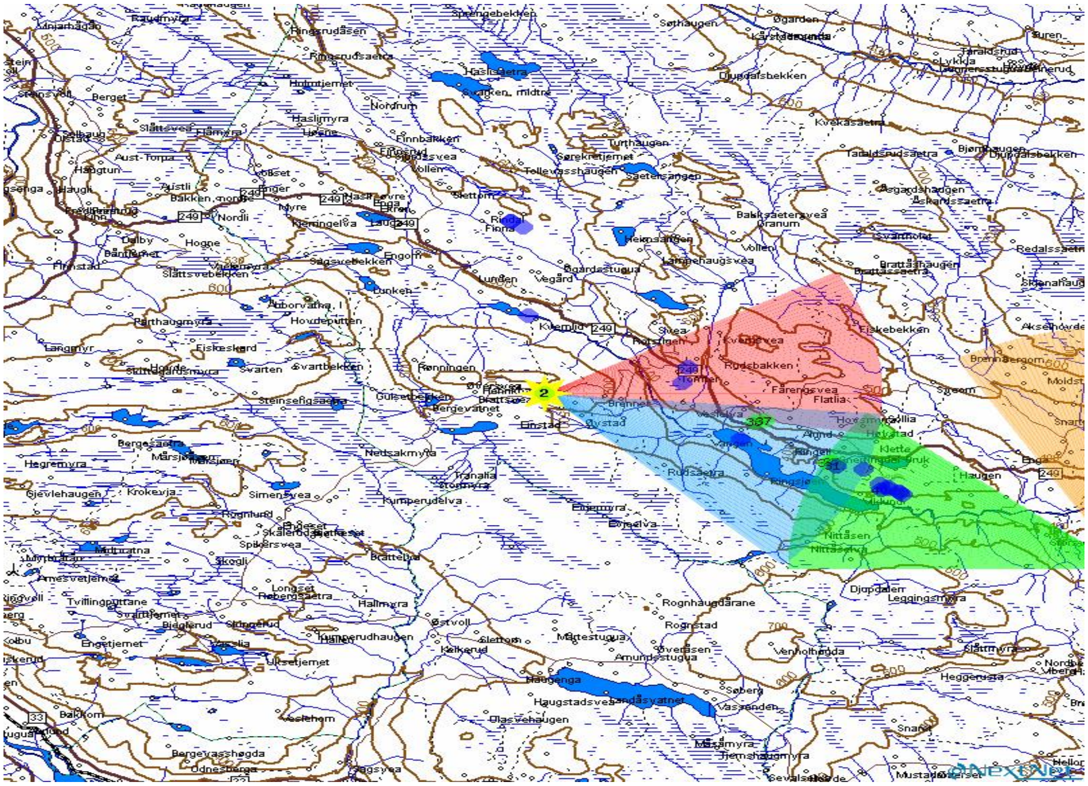


Fig. 30 Snertingdalen

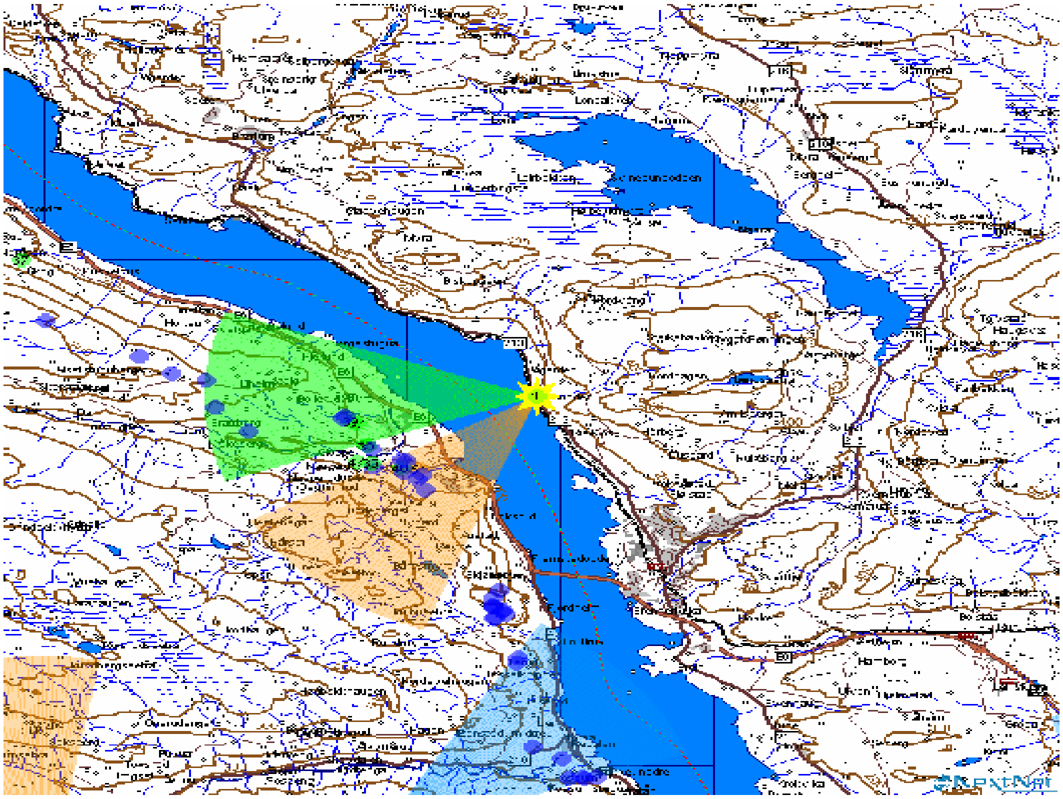


Figure 31 Moelv

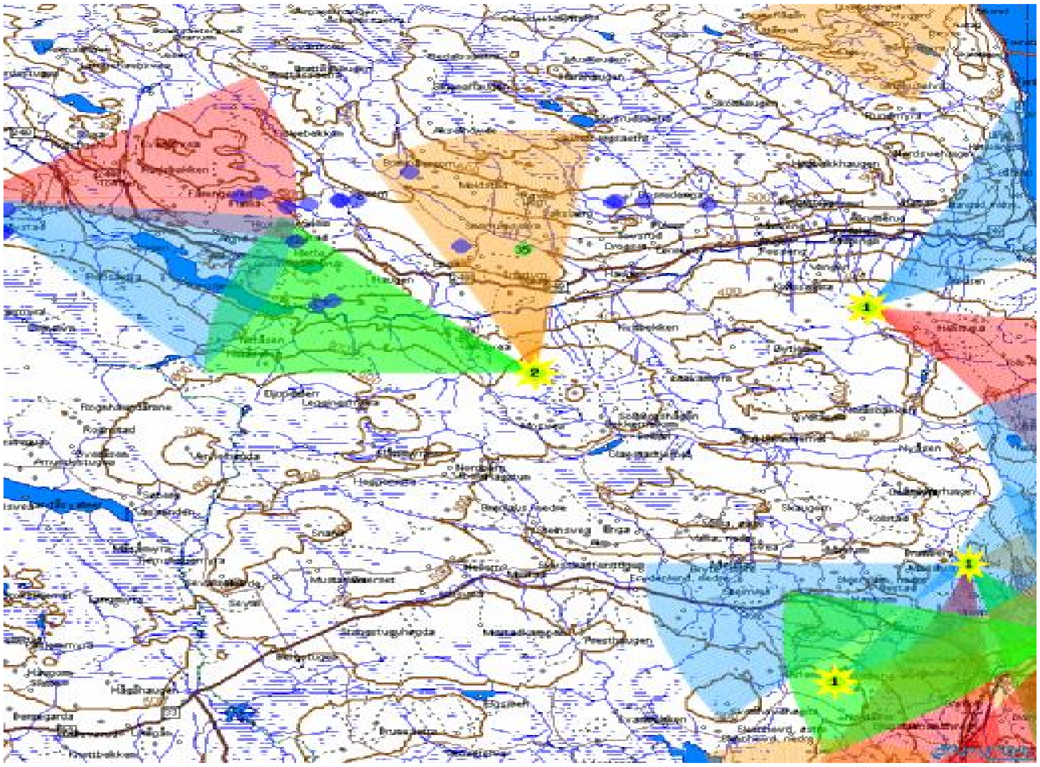


Fig. 32 Glaestad

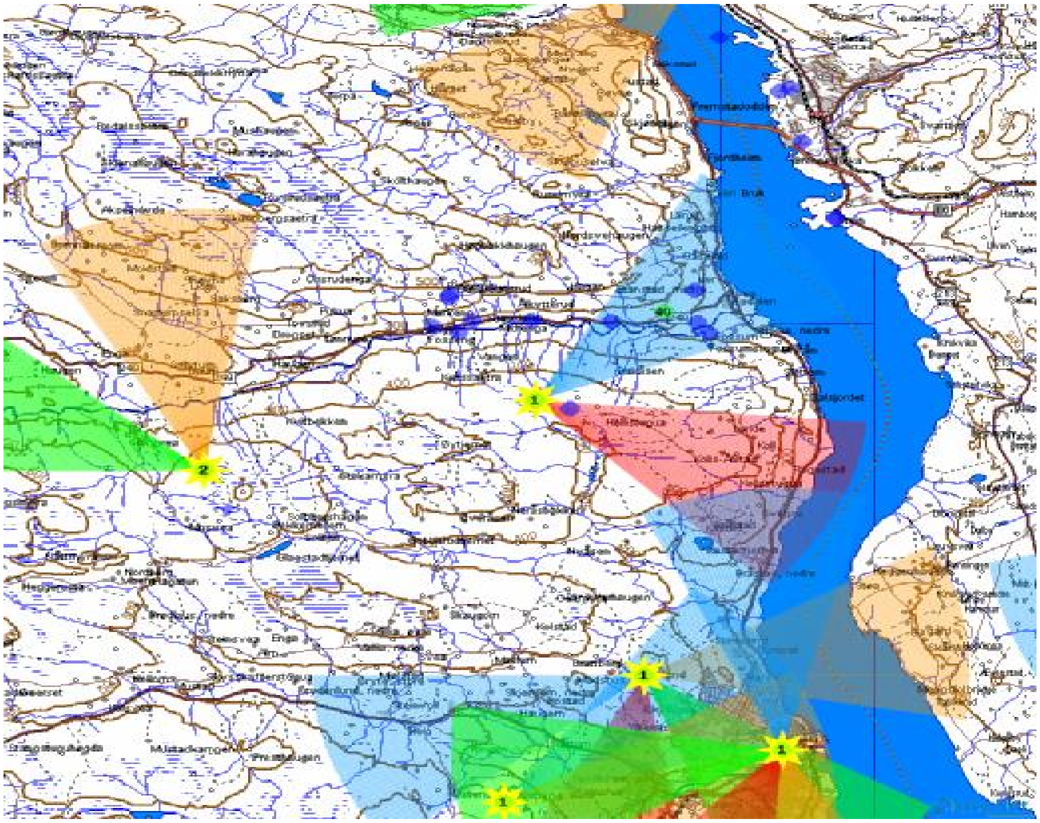


Fig. 33 Redalen

D. Pre-mobile WiMAX Field Trial Measurements Results

Table 39 displays the results taken in a pre-mobile WiMAX system. The Locations (Loc) are identified by numbers. Distance (Dist) in meters, UDP uplink (UL) and UDP dowinlink (DL) throughput is in Mbps. Signal to Noise Ratio in DL and UL is in dB. Received Signal Strength Indicator (RSSI) in DL and UL is in dBm. Modulation rate for RX is displayed with numbers. Adaptive Modulation is used where 1-BPSK ½, 2-BPSK ¾, 3-QPSK ½, 4-QPSK ¾, 5-QAM16 ½, 6-QAM16 ¾, 7-QAM64 2/3 and 8-QAM64 ¾. Transmitted Power (P_TX) is given in dBm. The amount of subchannels may be maximum 16, minimum 4 or 8. Diversity (Div) may be either 0-no diversity, 2-2nd order diversity or 4-4th order diversity.

D.1 Random Location Measurements

Table 39 Measurement taken at random locations in a pre-mobile WiMAX system.

		UDP		SNR		RSSI		ModRate			
Loc	Dist	DL	UL	DL	UL	DL	UL	RX	TX	P TX	SUBCH
1	213	3,9	1,32	19	6	-81	-98	6	6	22	16
2	336	0,669	6,11	32	23	-64	-81	3	8	22	16
3	394	2,37	6,16	33	30	-57	-76	4	8	22	16
4	396	3,28	0,109	17	4	-84	-93	5	1	22	4
5	426	6,2	6,15	34	31	-47	-73	8	8	14	16
6	432	4,08	1,43	20	9	-81	-96	7	3	22	16
7	465	0,7	4,06	30	18	-69	-86	2	6	22	16
8	465	1,36	0,635	26	13	-74	-92	3	1	22	16
9	472	6,19	4,31	29	19	-69	-86	8	6	22	16
10	485	1,37	4,07	27	17	-72	-87	4	6	22	16
11	532	5,99	4,18	30	20	-68	-84	8	7	22	16
12	537	3,47	0,329	20	6	-79	-96	6	1	21	4
13	551	1,65	1,32	28	15	-72	-89	3	1	22	16
14	579	2,71	0,109	18	7	-83	-94	5	1	22	4
15	580	5,63	2,73	26	14	-74	-92	8	5	22	16
16	645	1,4	0,108	15	3	-86	-97	5	1	22	4
17	653	4,01	0,544	25	9	-76	-91	5	4	22	16
18	670	2,09	0,095	19	7	-81	-92	7	5	22	4
19	679	3,29	1,42	20	10	-78	-95	5	3	22	16
20	711	2,51	0,109	14	4	-87	-95	5	1	22	4
21	729	3,64	1,52	23	8	-78	-96	5	3	22	16
22	739	6,18	3,4	30	17	-70	-89	8	4	22	16
23	784	5,1	1	22	11	-79	-93	7	1	22	16
24	789	1,01	0,645	26	15	-73	-88	4	5	22	16
25	797	3,44	0,109	19	8	-82	-92	6	1	21	4
26	797	5,99	1,53	30	18	-68	-86	8	6	22	16
27	802	2,64	0,109	15	6	-86	-94	5	1	21	4
28	839	1,53	0,107	11	4	-90	-95	3	1	22	4
29	845	N\A	0,108	15	3	-87	-98	5	1	22	4
30	865	2,82	3,36	28	15	-72	-90	6	5	22	16
31	1010	3,11	0,11	19	5	-83	-94	5	1	22	4
32	1020	1,35	1,34	20	8	-81	-96	3	3	22	16
33	1040	1,38	1,97	21	10	-80	-94	5	3	22	16
34	1050	N\A	0,0935	10	0	-91	-101	1	1	22	4
35	1183	4,02	0,109	19	5	-83	-94	8	6	22	16

36	1190	N\A	0,106	13	0	-88	-98	3	1	22	4
37	1260	6,07	3,54	29	19	-69	-88	29	19	22	16
38	1550	1,35	0,154	21	7	-79	-92	3	1	21	8
39	1710	1,35	0,109	17	5	-84	-95	3	1	21	4
40	1790	2,3	2,43	29	17	-69	-87	5	3	22	16
41	1940	0,66	0,108	16	2	-85	-97	2	1	21	4
42	2330	N\A	0,109	16	4	-85	-94	2	1	22	4
43	2510	0,652	0,105	16	6	-85	-94	2	1	22	4

D.2 Diversity Order Shift Measurements

Table 40 Measurement taken at 8 random locations with different order of diversity

			RSSI		SNR		ModRate		UDP			
Loc	Dist	Div	DL	UL	DL	UL	RX	TX	DL	UL	P TX	Subch
1	213	0	-94	-90	11	3	3	1	N/A	0,003	21	4
1	213	2	-86	-91	16	5	5	1	3,040	0,191	22	4
1	213	4	-81	-98	19	6	6	3	3,900	1,320	22	16
2	679	0	-84	-92	11	7	4	1	1,860	0,266	21	8
2	679	2	-81	-91	16	8	3	1	2,320	0,239	21	8
2	679	4	-78	-95	20	10	5	3	3,290	1,420	22	16
3	670	0	-84	-91	17	8	6	1	3,630	0,268	21	8
3	670	2	-85	-92	18	7	5	1	2,210	0,093	22	4
3	670	4	-81	-92	19	7	5	1	2,090	0,095	22	4
4	1260	0	-74	-88	26	14	8	5	6,070	3,130	22	16
4	1260	2	-71	-87	28	17	5	6	5,650	4,070	22	16
4	1260	4	-69	-88	29	19	8	6	6,070	3,540	22	16
5	797	0	-88	-96	13	7	3	1	2,210	0,109	22	4
5	797	2	-87	-96	16	5	5	1	2,060	0,047	22	4
5	797	4	-82	-92	19	8	6	1	3,440	0,109	21	4
6	653	0	-86	-94	16	8	3	1	1,340	0,111	22	4
6	653	2	-80	-93	21	8	5	1	3,340	0,162	21	8
6	653	4	-76	-91	25	9	5	4	4,010	0,544	22	16
7	1183	0	-83	-91	18	9	2	1	2,800	0,023	22	4
7	1183	2	-86	-94	16	7	3	1	2,400	0,109	22	8
7	1183	4	-83	-94	19	5	8	6	4,020	0,109	22	16
8	784	0	-81	-93	20	8	7	1	2,980	0,023	22	8
8	784	2	-80	-93	22	10	7	1	5,080	0,980	22	16
8	784	4	-79	-93	22	11	7	1	5,100	1,000	22	16

E. Automated Measurement Procedure Source Code

E.1 Scripts Fixed WiMAX Field Trial

E.1.1 Automated Measurement Procedure

The source code for the automated measurement scripts are given in Appendix E.

The object oriented programming and scripting language Python [1] was elected because of its simplicity and support of extensive libraries. Some of the libraries used are:

Telnetlib: a module that provides a Telnet class with an implementation of the telnet protocol

Ftplib: a set of routines that implements the FTP protocol

os.system: has many futures, but the implementation of the interaction with the command based interface was used extensively.

All the measurements that should be performed were automated by python scripting. A single script is generated for each specific part of the measurements, which all are executed by a superior script named Automated. An object-diagram (file-diagram) that illustrates the automated measurement scripts is illustrated in Fig. 34.

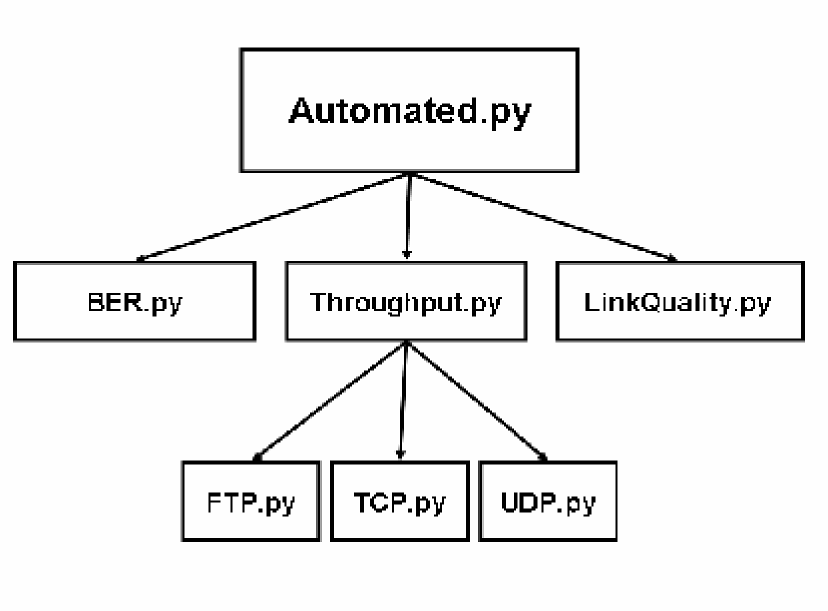


Fig. 34 Scripts that constitute the Automated Measurements

The files in the class/object diagram are described as follows:

Automated.py is the file that executes the automated measurements. This file is easily configurable for the addition of new automated measurements and for changing the measurements already setup. A description of how to do this together with examples is given in this file.

Manual.py (not included in the diagram) is a graphical user interface that offers the same operations as performed in Automated.py. A button can be pressed here to perform the automated measurements or the different measurement-scripts may be executed isolated on demand through a graphical user interface.

Throughput.py contains the class that is object for all the throughput measurements to be performed at one location. Objects are created of the decided UDP, TCP and/or FTP measurements to be taken.

UDPThroughput.py contains a class that creates an object for an UDP measurement taken at one location. Iperf [2] is used to perform the UDP measurements. A telnet-connection is made to a server, where an Iperf server is setup to listen on a specific port. Iperf is then started at the SU (running this script), which connects to the server iperf port. Specific UDP parameters is set on the server and the client side, where the bandwidth wanted is the most important. These arguments are sent as parameters to this object. The telnet connection is closed before this object is closed.

TCPThroughput.py contains the class that creates an object for a TCP measurement taken at one location. Iperf is used as described in UDPThroughput.py. A TCP-connection is set up, and procedures are used for measuring uplink and downlink throughput. Specific TCP parameters are set on the server and client side, where TCP Window Size is the most important. Other parameters are amount of connections, simultaneously or single. The telnet connection is closed before the object is closed.

FTPThroughput.py contains the class that creates an object for a FTP measurement taken at one location. Ftplib is used, which is a python-module for starting a FTP-server and a FTP-client. File-downloads is performed for measuring downlink throughput and file-uploads for measuring uplink throughput. Files of various sizes (1 MB, 10 MB, 50 MB, 100 MB) should manually created in advance for the downloads and uploads. A timer is running while the file-transfer is taking place, and the throughput is calculated when the FTP-connection is closed.

BER.py performs the Burst Error Rate (BER) test. The actual test is performed by the NPU in the BS. Since a telnet connection to the server is not possible from the WiMAX domain a python script at the Subscriber telnets to a server on the VLAN where the BS is connected. From the server another telnet-script is started, which telnets to the NPU in the BS. This is where the BER test is performed. Results are stored at the subscriber.

LinkQuality.py measures the Link Quality, which includes UL and DL SNR, UL and DL RSSI, RX and TX Rate, and TX Power. This is done by the Subscriber Unit which is configured with IP-address 192.168.254.251. A local LAN is automatically configured by set the Subscriber address to 192.168.254.250. Next a telnet connection is performed by the Subscriber to the SU (192.168.254.251). The Link Quality displaying function is started, and python sleeps for 15 seconds before the results are fetched. The IP-address is reconfigured to VLAN700 before the telnet connection is closed.

Iperf was chosen for bandwidth measurements. Both the protocols TCP and UDP are supported, where a range of different options are offered. Some important parameters are TCP Window Size tuning and bandwidth. Threads running simultaneous UDP-streams or TCP-connections and simultaneously bidirectional tests are possible.

Output from each of the measurement parts are a file containing the results. Each file is time-stamped. These files are collected in a directory named after the location. A python script named Results.py is generated to collect results from all files in all the location-directories into a single Microsoft Excel file for further analysis.

The source code for the scripts as described in the "Fixed WiMAX Field Trial" are given in this section. The scripts "ResultCollector.py" is omitted because of the great amont of complex code that is insignificant for the results of measurements performed.

E.1.2 Automated.py

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

""" Author: Pal Grønsund, Telenor R&D """
""" To be used when measuring throughput for a WiMAX system """

## This python-script is a list of commands to be used with
Throughput.py
## Required files are FTPThroughput.py, TCPThroughput.py,
## UDPThroughput.py, heloperMethods.py, Throughput.py

import Throughput
import LinkQuality
import BER
import helperMethods
import os

ROOT_DIR = "C:\\WiMAX_Measurements"

## IP ADDRESS FOR THE PC BEHIND THE SUbsCRiber UNIT
#IP_SU = '193.156.19.44' # SU3
#IP_SU = '193.156.19.45' # SU4
IP_SU = '193.156.19.46' # SU5

## MAC ADDRESS FOR THE SUBSRIBER UNIT
#MAC_SU = '00:10:e7:e2:24:5a' # SU3
#MAC_SU = '00:10:e7:e2:23:3c' # SU4
MAC_SU = '00:10:e7:e2:23:4f' #SU5

## LOCAL IP USED BY PC WHEN CONNECTING TO ANTENNA VIA LOCAL LAN
# LOCAL_IP_SU = '192.168.254.248' #SU3
# LOCAL_IP_SU = '192.168.254.249' #SU4
LOCAL_IP_SU = '192.168.254.250' #SU5

## Get Data from user (Locataion, Distance to BS, Elevation Over Sea
Level)
location = raw_input("Location(name): ")
distanceToBS = raw_input("Dstance to BS(km): ")
elevationOverSea = raw_input("Elevation Over Sea Level(m): ")

## Creates diretory for Location
LOCATION_DIR = helperMethods.createDir_GetPath(ROOT_DIR, location)
```

```
## Write information about location to file, if more is wanted: add a
infoFileWrite(<...>) line
infoFile =
open(LOCATION_DIR+"\\"+"LocationInfo_"+location+"_"+helperMethods.get_ti
me()+".txt", "wb")
infoFile.write("Location: "+location+"\n")
infoFile.write("Distance To BS (km): "+distanceToBS+"\n")
infoFile.write("Elevation Over Sea (m): "+elevationOverSea+"\n")
infoFile.close()

## LINK QUALITY DISPLAY MEASUREMENTS
## Creates a pointer to LinkQuality measurements, and performs
measurements
## Parameters to pass are IP address SU, local IP address and file-
directory for location
## Uncomment line for the SU that is beeing tested, and comment the
others

print "LINK QUALITY MEASUREMENTS"
try:
    LinkQuality.LinkQuality(IP_SU, LOCAL_IP_SU, LOCATION_DIR)
except:
    # Print error message and reset ip in case it is wrong
    print "Error with Link Quality Measurements"
    os.system("netsh interface ip set address name=\"Local Area
Connection\" static "+IP_SU+" 255.255.255.0")

## BER DISPLAY MEASUREMENTS
## creates pointer to BERtest, and fetches BER display from AlvariBasic
## Parameters to pass is the MAC address of the actual SU, and dile-
irectory for location
## Uncomment line for the SU that is beeing tested, and comment the
others

print "BER MEASUREMENTS"
try:
    BER.BER(MAC_SU, LOCATION_DIR, location)
except:
    print "Error with BER tests"

## creates a pointer to the class for throughput measurements
throughput = Throughput.Throughput(LOCATION_DIR)

## UDP THROUGHPUT MEASUREMENTS. Involves starting the iperf server,
## running the client and stopping the server.
## The argument that is passed is a lot of parameters to be used on
## the command line by iperf. Only desired parameters are passed.
## Parameters:
## -p, --port      #       server port to listen on/connect to
## -b, --bandwidth #[KM]   for UDP, bandwidth to send at in bits/sec
## -t, --time      #       time in seconds to transmit (default 10 secs)
## -P, --parallel  #       number of parallel client threads to run
## -d, --dualtest          Do a bidirectional test simultaneously
## Execute a command as below to perform a UDP measurement
try:
    throughput.udpMeasurement(" -b 12M -t 10 -P 1 -d ")
```

```
    #throughput.udpMeasurement("")            # no arguments is valid
    #throughput.udpMeasurement(" -b 2000K ")  # runs with bw 2Mbps
    #throughput.udpMeasurement(" -b 2M ")     # runs with bw 2Mbps
except:
    print "Error has occured during UDP Measurements"

## TCP THROUGHPUT MEASUREMENTS. Involves starting the iperf server,
## running the client and stopping the server.
## The argument that is passed is a lot of parameters to be used on
## the command line by iperf. Only desiredparameters are passed.
## Parameters:
## -w, --window    #[KM]   TCP window size (socket buffer size)
## -p, --port      #       server port to listen on/connect to
## -t, --time      #       time in seconds to transmit (default 10 secs)
## -P, --parallel  #       number of parallel client threads to run
## -d, --dualtest          Do a bidirectional test simultaneously
try:
    throughput.tcpMeasurement(" -w 64K -t 10 -P 1 -d ")
    #throughput.tcpMeasurement("")         # no arguments
    #trhoughput.tcpMeasurement(" -P 10 ")  # 10 paralell TCP sessions
    #throughput.tcpMeasurement(" -w 32K ") # TCP with 32KB window size
except:
    print "Error has occured during TCP Measurements"

## FTP THROUGHPUT MEASUREMENTES.
## Parameters (filename, action):
## Action (three possible options):
##       "DL"    : download the file
##       "UL"    : upload the file
##       "DL_UL" : download and upload the file
## (for single upload the file has to present in advance under
## C:\WiMAXMeasurements\)
try:
    throughput.ftpMeasurement("file10MB.txt", "DL_UL")  # DL & UL 10 MB
    #throughput.ftpMeasurement("file50MB.txt", "DL")    # DL 50MB
    #throughput.ftpMeasurement("file50MB.txt", "UL")    # UL 50MB
except:
    print "Error has occured during FTP Measurements"
```

E.1.3 Throughput.py

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

""" Author: Pal Grønsund, Telenor R&D """
""" To be used when measuring throughput for a WiMAX system """

import os
import helperMethods

## Tree structure: c:\WiMAX_Measurements\<location>\<test_type>\<test>
ROOT_DIR = "c:\\WiMAX_Measurements"
LOCATION_DIR = ''
SERVER = '193.156.19.32'   # bobby.nta.no
USER = 'usssr'
PASSWORD= 'usssr2all'
```

```
class Throughput:
    """class for measurements taken at one location
    @ivar location: Location where measurements are taken
    """

    def __init__(self, location):
        # A new direcotory is made with the name of the location
        global LOCATION_DIR
        LOCATION_DIR = location

    def udpMeasurement(self, iperfArgs):
        """Procedure that starts the UDP measurements
        If additional measurements are wanted, they must be added here
        @param iperfArgs: arguments to be inserted in the iperf command
        """
        import UDPThroughput
        print "UDP MEASUREMENTS STARTED"

        udpDir = helperMethods.createDir_GetPath(LOCATION_DIR,
"udpTests")

        # Start iperf server for udp traffic via telnet server
        udpTest = UDPThroughput.ThroughputUDP(SERVER, USER, PASSWORD,
udpDir)
        udpTest.startIperfServer()
        udpTest.runIperfClient(iperfArgs)
        udpTest.stopIperfServer()

    def tcpMeasurement(self, iperfArgs):
        """Procedure that starts the TCP measurements
        If additional measurements are wanted, they must be added here
        @param iperfArgs: arguments to be inserted in the iperf command
        """
        import TCPThroughput
        print "TCP MEASUREMENTS STARTED"

        tcpDir = helperMethods.createDir_GetPath(LOCATION_DIR,
"tcpTests")

        # Start iperf server for udp traffic via telnet server
        tcpTest = TCPThroughput.ThroughputTCP(SERVER, USER, PASSWORD,
tcpDir)
        tcpTest.startIperfServer("64K")
        tcpTest.runIperfClient(iperfArgs)
        tcpTest.stopIperfServer()
        print "TCP MEASUREMENTS FINISHED"

    def ftpMeasurement(self, filename, action):
        """Procedure that starts the FTP measurements
        If additional measurements are wanted, they must be added here.
        @param filename: name of file to be used
        @param action: action to be taken "DL", "UL" or "DL_UL"
        """
        import FTPThroughput
        print "FTP MEASUREMENTS STARTED"
```

```
        ftpDir = helperMethods.createDir_GetPath(LOCATION_DIR,
"ftpTests")

        ftpTest = FTPThroughput.ThroughputFTP("bobby.nta.no", USER,
PASSWORD, ftpDir)
        if (action == "DL" or action == "DL_UL"):
            ftpTest.ftpDL(filename)
        if (action == "UL" or action == "DL_UL"):
            ftpTest.ftpUL(filename)
        ftpTest.closeListingFile()

        print "FTP MEASUREMENTS FINISHED"

    def paralellFTPMeasurements(self, filename, action, ):
        """Procedure that starts the paralell FTP measurements
        If additional measurements are wanted, they must be added here.
        @param filename: name of file to be used
        @param action: action to be taken "DL", "UL" or "DL_UL"
        """
        import time
        import thread
```

E.1.4 FTPThroughput.py

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

""" Author: Pal Grønsund, Telenor R&D """
""" To be used when measuring throughput for a WiMAX system """

from ftplib import FTP
import os
import time
import pickle   # package for printing datastructures to files
import string   # package that is used for formatting the text
import helperMethods

class ThroughputFTP:
    """ Class that performas ftp uploads and downloads.
    Throughput is calculated and listed with relevant information.
    @ivar server: server-address to connect
    @ivar user:   username
    @ivar passwd: password for the connecting user
    @ivar curDir: path to directory where to place output data
    """

    ftp = 0           # ftp descripter for FTP connection
    listingfile = 0   # file descriptor for listing file

    def __init__(self, server, user, password, curDir):
        # Creates an instance of FTP object an logging in
        self.ftp = FTP(server)
        self.ftp.login(user, password)

        # Open listingfile, and write headers to file.
```

```
        self.listingfile =
open(curDir+"\\ftpTest_"+helperMethods.get_time()+".txt", 'wb')
        self.listingfile.write("Filename,")
        self.listingfile.write("Filesize(MB),")
        self.listingfile.write("Duration(seconds),")
        self.listingfile.write("Throughput(Mbps),")
        self.listingfile.write("Measurement time(seconds),")
        self.listingfile.write("Protocol,")
        self.listingfile.write("Link\n")

    def ftpDL(self, filename):
        """ Procedure for FTP Download, input: file to be downloaded
        @param filename: file to be downloaded
        """

        # Opens file for download
        DLfile = open(filename, "wb")

        # Set directory we want to download from
        directory = "/home/usssr/megabyte_files"
        self.ftp.cwd(directory)

        # Time is started and stopped around the actual download session
        start = time.clock()    # start timer
        self.ftp.retrbinary("RETR "+filename, DLfile.write)
        end = time.clock()      # stop timer
        duration = end - start

        # Call method that will list the results
        self.list_results(duration, filename, "DL")

        DLfile.close()

    def ftpUL(self, filename):
        """ Procedure for FTP Upload, input: file to be uploaded
        @param filename: file to be uploaded
        """

        # Opens file for upload
        ULfile = open(filename, "rb")

        # Set directory we want to upload in
        directory = "/home/usssr/uploaded"
        self.ftp.cwd(directory)

        # Time is started and stopped around the actual download session
        start = time.clock()    # start timer
        self.ftp.storbinary("STOR "+filename, ULfile)
        end = time.clock()      # stop timer
        duration = end - start

        # Call method that will list the results
        self.list_results(duration, filename, "UL")

        ULfile.close()

    def list_results(self, duration, filename, direction):
```

```
        """ Procedure calculates throughput and lists to file
        @param duration: duration of the ftp session
        @param filename: name of file in ftp session
        @param direction: Upload or Download traffic (UL/DL)
        """

        filesize = self.ftp.size(filename)/1000000
        throughput = (filesize*8)/duration
        this_time = time.asctime(time.localtime())

        # Prints to file. %3f means 3 siffers in float
        self.listingfile.write(filename+",")
        self.listingfile.write(`filesize`+",")
        self.listingfile.write(`'%3f'%duration`+",")
        self.listingfile.write(`'%3f'%throughput`+",")
        self.listingfile.write(`this_time`+",")
        self.listingfile.write("FTP,")
        self.listingfile.write(direction+"\n")

    def closeListingFile(self):
         self.listingfile.close()
         self.ftp.close()
```

E.1.5 TCPThroughput.py

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

""" Author: Pal Grønsund, Telenor R&D """
""" To be used when measuring throughput for a WiMAX system """

import os
import telnetlib
import sys
import time
import datetime
import string
import helperMethods

class ThroughputTCP:
    """ Class that performs udp uploads and downloads.
    Throughput is calculated and listed with relevant information.
    @ivar server: server-address to connect
    @ivar user:   username
    @ivar passwd: password for the connecting user
    @ivar curDir: path to directory where to place output data
    """

    ## Global declarations
    IPERFSERVER = ''
    USER = ''
    PASSWORD = ''

    OUTPUT_DIR = '' # for listing on client side
    SERVER_DOWNLOAD_DIR = '/home/usssr/iperflisting/tcptests' # for
listing on server side
```

```
    telnet = 0  # descritor for telnet connection

    def __init__(self, server, user, passwd, curDir):
        #sets variables received to equal global variabels
        self.IPERFSERVER = server
        self.USER = user
        self.PASSWORD = passwd
        self.OUTPUT_DIR = curDir

    def runIperfClient(self, iperfArgs):
        """ Procedure that performs a udp session
        @param window_size: TCP window size at client side
        """
        listingfile = "tcpTestClient_"+helperMethods.get_time()+".txt"

        # enter directory where iperf is located
        try:
            os.chdir("c:\iperf")
        except:
            pass
        # run client with attributes -c:client, -u:udp, -b:bandwidth.
        # Add a \ between directory- and filename
        os.system("iperf -c "+self.IPERFSERVER+ iperfArgs +" > 
"+self.OUTPUT_DIR+"\\"+listingfile)
        #os.system("iperf -c "+self.IPERFSERVER+ iperfArgs +" > 
"+self.OUTPUT_DIR+"\\"+listingfile)
        #os.system("iperf -c "+self.IPERFSERVER+ iperfArgs +" > 
"+self.OUTPUT_DIR+"\\"+listingfile)

    def startIperfServer(self, window_size):
        """ Procedure that starts the iperf server
        @param window_size: TCP window size at client side
        """

        # Creates a new telnet connection to the iperf server
        self.telnet = telnetlib.Telnet(self.IPERFSERVER)
        # Do the authentication procedure
        self.telnet.read_until("login: ")
        self.telnet.write(self.USER + "\r\n")
        self.telnet.read_until("Password: ")
        self.telnet.write(self.PASSWORD + "\r\n")

        # Enter iperf directory and start iperf server
        self.telnet.read_until("$ ")
        self.telnet.write("cd /home/usssr/iperf\r\n")
        self.telnet.read_until("$ ")

        # START server with attributes -s:server, -w:window size , 
  #-o:outfput to file
        serverListingFile = 
self.SERVER_DOWNLOAD_DIR+"tcpTest_"+helperMethods.get_time()+".txt"
        self.telnet.write("./iperf -s -D -w "+window_size+" -o 
"+serverListingFile+".txt\r\n")

        # Sleep a moment for the server to get ready
        time.sleep(3)
```

```
    def stopIperfServer(self):
        self.telnet.read_until("$ ")
        self.telnet.write("./iperf -s -R\r\n")
        self.telnet.read_until("$ ")
        self.telnet.write("exit\r\n")
        # To be secure that the telnet connection is terminated
        self.telnet.close()
```

E.1.6 UDPThroughput.py

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

""" Author: Pal Grønsund, Telenor R&D """
""" To be used when measuring throughput for a WiMAX system """

import os
import telnetlib
import sys
import time
import datetime
import string
import helperMethods

class ThroughputUDP:
    """ Class that performs udp uploads and downloads.
    Throughput is calculated and listed with relevant information.
    @ivar server: server-address to connect via telnet
    @ivar user:   username
    @ivar passwd: password for the connecting user
    @ivar curDir: path to directory where to place output data
    """

    # global declarations
    IPERFSERVER = ''
    USER = ''
    PASSWORD = ''

    OUTPUT_DIR = '' # for listing on client side
    SERVER_DOWNLOAD_DIR = '/home/usssr/iperflisting/udptests' # listing

    telnet = 0  # descritor for telnet connection

    def __init__(self, server, user, passwd, curDir):
        #sets variables received to equal global variabels
        self.IPERFSERVER = server
        self.USER = user
        self.PASSWORD = passwd
        self.OUTPUT_DIR = curDir

    def runIperfClient(self, iperfArgs):
        """ Procedure that performs a udp session in cmd
        @param iperfArgs: arguements to be used in with iperf command
        """
        listingfile = "udpTestClient_"+helperMethods.get_time()+".txt"

        # enter directory where iperf is located
```

```
        try:
            os.chdir("c:\iperf")
        except:
            pass
        # run client with arguments(iperfArgs) -c:client, -u:udp,
  #-b:bandwidth.
        os.system("iperf -u -c "+self.IPERFSERVER + iperfArgs +" >
"+self.OUTPUT_DIR+"\\"+listingfile)

    def startIperfServer(self):
        """ Procedure that starts the iperf server via telnet
connection"""

        # Creates a new telnet connection to the iperf server
        self.telnet = telnetlib.Telnet(self.IPERFSERVER)

        # Do the authentication procedure
        self.telnet.read_until("login: ")
        self.telnet.write(self.USER + "\r\n")
        self.telnet.read_until("Password: ")
        self.telnet.write(self.PASSWORD + "\r\n")

        # Enter iperf directory and start iperf server
        self.telnet.read_until("$ ")
        self.telnet.write("cd /home/usssr/iperf\r\n")
        self.telnet.read_until("$ ")
        # Start server with attributes -s:server, -u:udp, -o:file output
        serverListingFile =
self.SERVER_DOWNLOAD_DIR+"udpTest_"+helperMethods.get_time()+".txt"
        self.telnet.write("./iperf -s -D -u -o
"+serverListingFile+"\r\n")

        # Sleep a moment for the server to get ready
        time.sleep(3)

    def stopIperfServer(self):
        """Procedure that stops iperf server and exits telnet connection
        """
        self.telnet.read_until("$ ")
        self.telnet.write("./iperf -s -R\r\n")
        self.telnet.read_until("iperf$ ")
        self.telnet.write("exit\r\n")
        # To be secure that the telnet connection is terminated
        self.telnet.close()
```

E.1.7 BER.py

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

""" Author: Pal Grønsund, Telenor R&I """
""" To be used when measuring throughput for a WiMAX system """

import helperMethods
import telnetlib
from ftplib import FTP
```

```
class BER:

    BOBBY = '193.156.19.32'
    USER = 'usssr'
    PASSWD = 'usssr2all'
    LOCATION = ''
    LOCATION_DIR = ''

    def __init__(self, mac_address, location_dir, location):
        """ Procedure that telnets to a server and starts a python 
script that performs
        BER error tests. The file is uploaded via ftp to this computer
        @param mac_address: MAC address for SU that performs BER test
        @param location_dir: filesystem-directory for final file
        @param location: name of location where measurements are taken
        """
        self.LOCATION = location
        self.LOCATION_DIR = location_dir

        # command that should be performed in python at server side
        command = "BERtest.BERTest(\""+mac_address+"\", 
\""+location+"\")"

        self.performBER(command)
        self.getFileViaFTP()

    def performBER(self, command):
        """ Procedure that telnet to server, enter python and perform 
  BER test
        @param command: command that performs BER test at server
        """

        # Creates a new telnet connection to the antenna
        telnet = telnetlib.Telnet(self.BOBBY)
        telnet.read_until("login: ")
        telnet.write(self.USER+"\r\n")
        telnet.read_until("Password: ")
        telnet.write(self.PASSWD+"\r\n")
        telnet.read_until("$ ")
        telnet.write("cd BERtests\r\n")
        telnet.read_until("$ ")
        telnet.write("python\r\n")
        telnet.read_until(">>> ")
        telnet.write("import BERtest\r\n")
        telnet.read_until(">>> ")
        telnet.write(command+"\r\n")
        telnet.read_until(">>> ")
        telnet.close()

    def getFileViaFTP(self):
        """ Procedure that connects to the ftp server and download 
  BERtest file
  """
        # create FTP session and login
        ftp = FTP(self.BOBBY)
        ftp.login(self.USER, self.PASSWD)
```

```
        # open file at this client PC where file should be downloaded to
        DLfile =
open(self.LOCATION_DIR+"\\"+"BERtest_"+helperMethods.get_time()+".txt",
"wb")
        # change working directory to where the file is located
        ftp.cwd("/home/usssr/BERtests/"+self.LOCATION)
        # Download the file
        ftp.retrbinary("RETR
/home/usssr/BERtests/"+self.LOCATION+"/BERtest.txt", DLfile.write)

        # close file and FTP session
        DLfile.close()
        ftp.close()


##This line is for test purposes
#BER('00:10:e7:e2:23:4f', 'C:\\WiMAX_Measurements', 'telenor1')
```

E.1.8 LinkQuality.py

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

""" Author: Pal Grønsund, Telenor R&D """
""" To be used when measuring throughput for a WiMAX system """

import os
import telnetlib
import sys
import time
import datetime
import string
import helperMethods

class LinkQuality:

    LOCATION_DIR = ''
    ANTENNA = '192.168.254.251'
    PASSWORD = 'installer'
    MY_IP = 0   # IP-address of the user on this machine
    LOCAL_IP = 0
    ESC = chr(27)


    def __init__(self, my_IP,local_ip, loc_dir):
        """ class that peforms Link Quality Tests ofr a WiMAX antenna
        @param my_IP: ip address for the client
        @param local_IP: ip address for the client for the local network
                         between client and antenna
        @param loc_dir: direcory where result-file should be written
        """
        self.MYIP = my_IP
        self.LOCAL_IP = local_ip
        self.LOCATION_DIR = loc_dir

        self.setLocalIP()
```

```
        self.performLinkQualityDisplay()
        self.setGlobalIP()

    def setLocalIP(self):
        """ Procedure that sets the ip-address and the net mask
        """

        os.system("netsh interface ip set address name=\"Local Area
Connection\" static "+self.LOCAL_IP+" 255.255.255.0")

    def setGlobalIP(self):
        """ Procedure that exits telnet session, and resets ip-address
        """
        os.system("netsh interface ip set address name=\"Local Area
Connection\" static "+self.MYIP+" 255.255.255.0")

    def performLinkQualityDisplay(self):
        """ Procedure that connects to the antenna, and peforms Link
Quality Display
        """

        # Open listingfile for writing
        listingfile =
open(self.LOCATION_DIR+"\\linkQuality_"+helperMethods.get_time()+".txt",
'wb')

        # Creates a new telnet connection to the antenna
        telnet = telnetlib.Telnet(self.ANTENNA)
        # Do the authentication procedure
        telnet.read_until("password: ")
        telnet.write(self.PASSWORD+"\r\n")
        telnet.read_until("> ")
        telnet.write("6\r\n")
        telnet.read_until("> ")

        # Start Link Quality Display and Sleep 15 seconds
        telnet.write("1\r\n")
        time.sleep(15)

        # Stop the Quality Display and writes it to file
        telnet.write(self.ESC)
        listingfile.write(telnet.read_until('Path'))

        # clean up and exit
        telnet.close()
        listingfile.close()
```

E.2 Scripts Pre-Mobile WiMAX Field Trial

The throughput measurements for mobile WiMAX restricted to UDP only. The UDP measurements are the same as in the “Fixed WiMAX Field Trial” section E.1.6, but the link quality measurements had to be changed due to differences in the CPE firmware.

E.2.1 MobileMeasurements.py

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

""" Author: Pal Grønsund, Telenor R&D """
""" To be used when measuring throughput for a WiMAX system """

import os
import telnetlib
import sys
import time
import datetime
import string
import helperMethods


class LinkQuality:

    LOCATION_DIR = ''
    ANTENNA = '192.168.254.251'
    PASSWORD = 'installer'
    LOCAL_IP = '192.168.254.250'
    ESC = chr(27)

    def __init__(self, loc_dir):
        """ class that peforms Link Quality Tests ofr a WiMAX antenna
        @param my_IP: ip address for the client
        @param local_IP: ip address for the client for the local network
 between client and antenna
        @param loc_dir: direcory where result-file should be written
        """
        self.LOCATION_DIR = loc_dir

        self.setLocalIP()
        self.performLinkQualityDisplay()
        self.setGlobalIP()

    def setLocalIP(self):
        """ Procedure that sets the ip-address and the net mask """

        os.system("netsh interface ip set address name=\"Local Area
Connection\" static "+self.LOCAL_IP+" 255.255.255.0")

    def setGlobalIP(self):
        """ Procedure that exits telnet session, and resets ip-address
to MYIP """

        os.system("netsh interface ip set address name=\"Local Area
Connection\" dhcp")


    def performLinkQualityDisplay(self):
        """ Procedure that connects to the antenna, and peforms Link
Quality Display"""

        # Open listingfile for writing
```

```
        listingfile =
open(self.LOCATION_DIR+"\\linkQuality_"+helperMethods.get_time()+".txt",
'wb')

        # Creates a new telnet connection to the antenna
        telnet = telnetlib.Telnet(self.ANTENNA)
        # Do the authentication procedure and start Link Quality Display
        telnet.read_until("password: ")
        telnet.write(self.PASSWORD+"\r\n")
        telnet.read_until("> ")
        telnet.write("6\r\n")
        telnet.read_until("> ")

        # Start Link Quality Display and Sleep 15 seconds
        telnet.write("1\r\n")
        time.sleep(15)

        # Stop the Quality Display and writes it to file
        telnet.write(self.ESC)
        listingfile.write(telnet.read_until('Path'))

        # clean up and exit
        telnet.close()
        listingfile.close()


ROOT_DIR = "C:\\Measurements"

## Get Data from user (Locataion, Distance to BS, Elevation)
location = raw_input("Location(name): ")

## Creates diretory for Location
LOCATION_DIR = helperMethods.createDir_GetPath(ROOT_DIR, location)

## Write information about location to file, if more is wanted, add:
## infoFile.write(<...>) line
## infoFile =
open(LOCATION_DIR+"\\"+"LocationInfo_"+location+"_"+helperMethods.get_ti
me()+".txt", "wb")
infoFile.write("Location: "+location+"\n")
infoFile.close()

print "Start Link Quality"
# This sentence initiates the link quality measurements
LinkQuality(LOCATION_DIR)

time.sleep(20)

print "Start UDP"
udpfile = LOCATION_DIR+"\udp"+helperMethods.get_time()+".txt"
os.system("iperf -c 217.196.52.10 -u -r -b 6M > "+udpfile)

print "Start TCP"
tcpfile = LOCATION_DIR+"\tcp"+helperMethods.get_time()+".txt"
os.system("iperf -c 217.196.52.10 -r -w 64K > "+tcpfile)
```

E.3 Scripts for simulating VoIP traffic with QoS tagging

These scripts was used to simulate a VoIP session with the use of the G.729 codec. UDPsock.py is used to set up a server and a client socket. UDP sockets are set up, and the packets are tagget with a DSCP value in the TOS field. The simulateVoIP.py file sets parameters and uses the classes in UDPsock.py.

E.3.1 UDPsock.py

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

""" Author: Pål Grønsund, Telenor R&I """
""" Used when testing QoS for a WiMAX system backhauled by DVB-RCS """

import sys
import time
from socket import *
import os
import string

class Client:

      ## Declaration of variables set to initial or temporary value
      UDPsocket = 0

      def __init__(self, serverHost, serverPort, tosValue):
            """ An UDP socket is set up
            @param serverHost: IP address of server to send UDP packets
            @param serverPort: port number where server listens for
 incoming UDP packets
            """
            ## Create an UDP socket.
            self.UDPsocket = socket(AF_INET, SOCK_DGRAM)

            global SERVER
            SERVER = (serverHost, serverPort)

            ## Set the TOS, DSCP vale. Note: 8 bits to set, but the 6
## frontmost bits are DSCP.
            ## Thus 240 = 11111100 = 252, but the DSCP value is 63(max)
            self.UDPsocket.setsockopt(IPPROTO_IP, IP_TOS, tosValue)

      def sendData(self, packetSize, sampling, bytesToSend):
            """ Procedure that sends packets of size 'packetSize' with
      sampling-interval 'sampling'
            @param packetSize: bytes to be included in one packet
            @param sampling: how often to send backets in seconds
            """
            ## Read bytes from a file (file contains a seqence of 1's)

            streamfile =
open("D:\Master\Python\qosTest\streamfile100KB.txt", 'r')

            ## Reads amount of bytes specified by packetSize into data
```

```
            packet = streamfile.read(packetSize)

            i = 0
            while i < bytesToSend :
                  self.UDPsocket.sendto(packet, SERVER)
                  time.sleep(sampling)
                  i=i+packetSize


class Server:

    # Declaring variables and sets initial or temporary value
    UDPsock = 0

    def __init__(self, myHost, myPort):
        """ Class that sets up an UDP socket that receives data
      @param serverHost: IP address of server to send UDP packets
      @param serverPort: port number where server listens for incoming
                         UDP packets
      """
      addr = (myHost,myPort)

      ## Creates an UDP socket, and binds to the server port
      self.UDPsock = socket(AF_INET, SOCK_DGRAM)
      self.UDPsock.bind(addr)

      ## Enter a procedure that loops for incoming packets.
      self.recvData(20)
      self.UDPsock.close()

    def recvData(self, bytes):
        """ Procedure that receives data on UDP socket. Sampling
        interval is set to be 20 ms.
        @param bytes: bytes to be included in one packet
        """
        ## Start timer
        start = time.clock()

        i = 0
        while 1:
            ## maks received packetsize is 20KB, but may be editited
            data,recvAddr = self.UDPsock.recvfrom(20000)
            if data:
                print "Recv data from ", recvAddr ,", time:
",time.clock(),", nr: ",i
                i = i + 1

        ## Stop timer, calculate duration and print Throughput
        end = time.clock()
        duration = end - start
        print "Duration: ",duration,"  , throughput: ",80/duration,"
Mbps"
```

E.3.2 simulateVoIP.py

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

```
""" Author: Pal Grønsund, Telenor R&I """
""" Used when testing QoS for a WiMAX system backhauled by DVB-RCS """

## Import the file for the UDP socket implementation
import UDPsock

## The Server address has to be set for both the Server and the Client
server = 'localhost'
port = 5002

## Set the TOS, DSCP vale. Note: 8 bits to set, but the 6 frontmost bits
are DSCP.
## Thus 240 = 11111100 = 252, but the DSCP value is 63 (max).
tosValue = 240

## Ask user if she wants to start the client or server
clientOrServer = raw_input("Server(S), Client(C): ")

if clientOrServer == 'C':
      ## Create object of a Client -> creates a udp socket
      udpClient = UDPsock.Client(server, port, tosValue)

      ## Send data through udp socket
      ## args: packetSize, sampling-interval, bytesToSend
      udpClient.sendData(20, 0.02, 1000000)

      ## More UDP streams may be performed, just add lines below, i.e.
      #udpClient.sendData(1000, 0.2, 1000000)

elif clientOrServer == 'S':
      UDPsock.Server(server, port)

print "Avslutter"
```

F. Papers

The conference papers are:

1. Grøndalen,O., Grønsund,P.,Breivik,T., Engelstad.P, “Fixed WiMAX Field Trial Measurements and Analyses”, Noficated for Acceptance at Mobile Summit 2007, Budapest (Hungary), July 1-5, 2007

2. Grønsund,P., Grøndalen,O., Breivik,T., Engelstad.P, “Fixed WiMAX Field Trial Measurements and the derivation of a Path Loss Model”, Submitted to Mosharaka International Conference on Communication Systems and Circuits (M-CSC 2007), Amman, May 21, 2007

3. Grønsund,P., Engelstad,P., Johnsen,T., Skeie,T, ”The Physical Performance and Path Loss in a Fixed WiMAX Deplyment”, Submitted to International Wireless Communications and Mobile Computing Conference (*IWCMC*) 2007, Honolulu (Hawaii), August 12-16, 2007

where paper 1 and paper 2 is based on the “WiMAX Field Trial” and paper 3 is based on the “WiMAX Deployment Analysis”.

The three papers will follow consecutively.