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WiMAX in Coastal Traffic and Performance Prediction in a Geographically Challenging Environment

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Master of Science in Engineering Cybernetics
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Problem Description

Sjøfartsnasjonen Norge er også blitt et informasjonssamfunn, dette skaper et økende behov for å utvikle nye praktiske løsninger for å kunne transportere store datamengder ikke bare på land menogså til havs.
Blandt mange andre er transportnæringen en del av den norske økonomien som kan komme til å nyte godt av økt forutsigbarhet og effektivitet gjennom lettere tilgjengelig operasjonsinformasjon.
Mye av utfordringene i å utvikle nye løsninger ligger i geografien og værforholdene langs norskekysten ogproblemene dette fører med seg for implementasjon. Av alle mulighetene i teknologiløsninger i dag er WiMAX aktuell som hovedbestanddel i den nye infrastrukturen som må implementeres.
I lys av dette skal denne masteroppgaven behandle følgende hovedpunkter:

Hovedpunkter:
- Oppgaven skal være et litteratustudium
- Beskrive vanskelige norske værforholds påvirkning på WiMAX radiokanaler
-Utforsking av teknologiløsninger som muliggjør implementasjon langs norskekysten.

Assignment given: 01. September 2008
Supervisor: Amund Skavhaug, ITK

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Abstract

This thesis takes upon itself to describe the medium of the radio channel for a WiMAX installation in a difficult environment. Furthermore it investigates the possibility of modifying the WiMAX standard in order to increase performance in such an environment.

Channel estimators are crucial in optimizing throughput in WiMAX. Their performance is dependent on the amount of information in the pilot subcarriers of WiMAX. A way of adding information to the channel estimators without taking more of the bandwidth is to use a model in series with the data estimates. An already existing Kalman filter based algorithm for radio channel estimation is studied and compared to a WiMAX model. Modifications are suggested to fit the WiMAX signals.

To extend a network fast in areas where there is little or no infrastructure to begin with is a task that can be performed by ad hoc network solutions. A statistical model for outage in ad hoc networks is studied and an evaluation on WiMAX's capability of operating in an Ad hoc network structure is performed.

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Acknowledgements

One of the few places in this thesis where referring to the writer is not frowned upon, I will make a couple of remarks. I am thank my supervisor Assistant Professor Amund Skavhaug for valuable guidance and insight in the process of writing scientific literature. I would also like to thank Kay Fjørtoft and SINTEF MARINTEK for letting me follow the interesting process of starting up the Marsafe project, a collaboration between SINTEF MARINTEK and european contractors.

Preface

The following chapters are the result of my master thesis work at the Norwegian University of Science and Technology, Departement of Engineering Cybernetics. The thesis followed the start-up of a project called *Marsafe* which is a collaborative project between SINTEF MARINTEK and group of european contractors. The goals of Marsafe are accordingly stated:

> MarSafe North shall present the crucial needs and indicative solutions for maritime safety management means required to realize our future commitments in the High North, focusing on: 1. Nautical operations and Transport, 2. Dynamic Risk Assessment and Emergency Response, 3. Territorial Security Control and Resource Supervision, and 4. Infrastructure and Integrated Coastal Zone Management. This will be done by utilizing novel underpinning technologies for; Environmental Surveillance and Sensing, Arctic Communications, Radio Navigation and tracking [37].

My affiliation to Marsafe is through SINTEF MARINTEK. I was contacted early summer 2008 by Kay Fjørtoft at the departement for Maritim IKT at SINTEF MARINTEK and asked if I was interested in writing my master thesis in collaboration with the departement

In completing this work I have been fortunate to see the inner workings of a technology start-up. In addition I can with great satisfaction say that I have learned a great deal about WiMAX and many other aspects of radio technology. In particular I have gained insight into radio channel modelling, Ad hoc networking and yet another application of the Kalman filter.

I hereby certify that the work presented in this document is done by myself and that the work of other authors is properly cited.

-Jan Gerhardsen Formanek
Trondheim, January 2009

Chapter 1

Introduction

1.1 Motivation

The demand for sophisticated internet services and the development of new infrastructures for data transfers seem to accelerate each other towards a common end: Enabling the user to access and manipulate data regardless of geographical position.

One such user that would, without a doubt, benefit from better and more accessible information is the transport industry. There are unexplored possibilities in novel applications that would unfold at the prospect of ubiquitous high speed data links. Of the many worth mentioning are:

- Detailed real-time information on operating status of vessels

  Operating efficiency parameters for optimization of vessel performance and services. Increased efficiency of maintenance procedures due to updated logs, possibly transferred real-time to maintenance contractor.

- Passenger numbers oversight systems.

  Imperative in Search & Rescue for situation assessment. Also important on the operating efficiency level.

- Goods inventory oversight systems.

  Better Just-in-time efficiency for goods delivery, Search & Rescue: Toxicity of payload, amount.

- Traffic and Delay information systems.

  For dynamic routing of traffic to improve safety and efficiency.

- Improved weather forecast services.

  Integrated weather forecasts and electronic maps for safety and traffic assessment.

As already mentioned, increasing the mobility and available bandwidth of users is an ongoing process. Of other already emerging applications that are pushing for a development in this area are:

- Remote control of unmanned operations
- High speed online access for passengers
- Internet access for sailors, offshore workers and coastal traffic shift workers.

Norway and its infrastructure is dependent on getting workers out in the rural areas to take full advantage of the nations resources [22]. Extending the communications network through WiMAX may prove an economical and practical solution for making this happen.

In Norway, given that much of goods transporting and commuting is done by sea, an evolution to the next generation infrastructure would call for a more thorough look into possibilities for complete coverage of the coastal zone. WiMAX is one of the most promising new technologies possibly capable of that, both with respect to cost and the technology solution itself.

Furthermore, in order to determine a set of services which may be attainable with the future implementation of WiMAX a deeper look into the functionality of the technology is needed. The intention of this master thesis is therefore:

> *Via thorough investigation of the WiMAX system and other technologies, to obtain a set of feasible solutions for WiMAX deployment and operation along the coast of Norway.*

1.2 Problem Statement

A lot has been written about WiMAX and the different components of its system. There is a vast amount of sources and information about WiMAX on which discussions and conclusions can be made. The tech world has seen a large number of articles praising WiMAX as the next solution to wireless connectivity. It has been suggested on several occasions that these articles are part of a hype based on the optimism from the success of Wi-Fi [5][14]. The motivations for these suggestions taken aside, this criticism is not entirely unprecedented.

For a system like WiMAX to succeed in the way other technologies have succeeded there is a need to be specific about certain topics. Every technology that exists today has one or several applications. In light of this, what is the relevance of WiMAX and to what extent may WiMAX serve and improve existing applications as well as foster new ones? This is at the heart of what challenges WiMAX's birthright. Some of the current challenges that lay ahead are:

- There are still unanswered questions about frequency bands.
- There has yet to be announced an area of application where WiMAX has a foothold.
- Finally, WiMAX does not currently have a decided advantage over other existing technologies, even though WiMAX in many respects outperforms these technologies.

A good way to address these challenges would be to identify a specific application ready for an evolution in backbone technology. In order to identify such an area, an assessment of the capabilities of WiMAX in the context of the application would have to be made.

An eligible area in a norwegian context is communication with vessels and installations at sea. There is a serious lack of reliable communication solutions in many of the sectors under norwegian jurisdiction [22]. The coastline is covered to a certain extent but the northern parts of norwegian controlled areas at sea are for the most part barely covered at all. The prospect of business opportunities with regards to the petroleum industry and increased traffic as a result of ice free waters in combination of an almost non-existing infrastructure makes the area very interesting for implementation of WiMAX.

There is however the concern of WiMAX's capabilities that needs assessment. With the above mentioned application in mind, some of the most pressing issues are throughput, range and area of coverage. This thesis is concerned with how to model the radio channel and how the WiMAX standard may be extended to increase performance.

1.3 Studying Literature As A Scientific Method

> ”Copy from one, it’s plagiarism; copy from two, it’s research.”
> -Wilson Mizner

This master thesis is developed by studying publications of different types. Books, articles, theses and more have been investigated in order to provide a broad basis on which the conclusions of this thesis may stand.

The ultimate goal of studying scientific publications is to provide a good basis for research into new applications. The study of scientific literature is also important for documenting the work that has been done so far on the subject. This provides a perspective on the challenges within the field of research.

The literature basis for a scientific paper of this kind is organized in a certain manner. There are basically three types of sources:

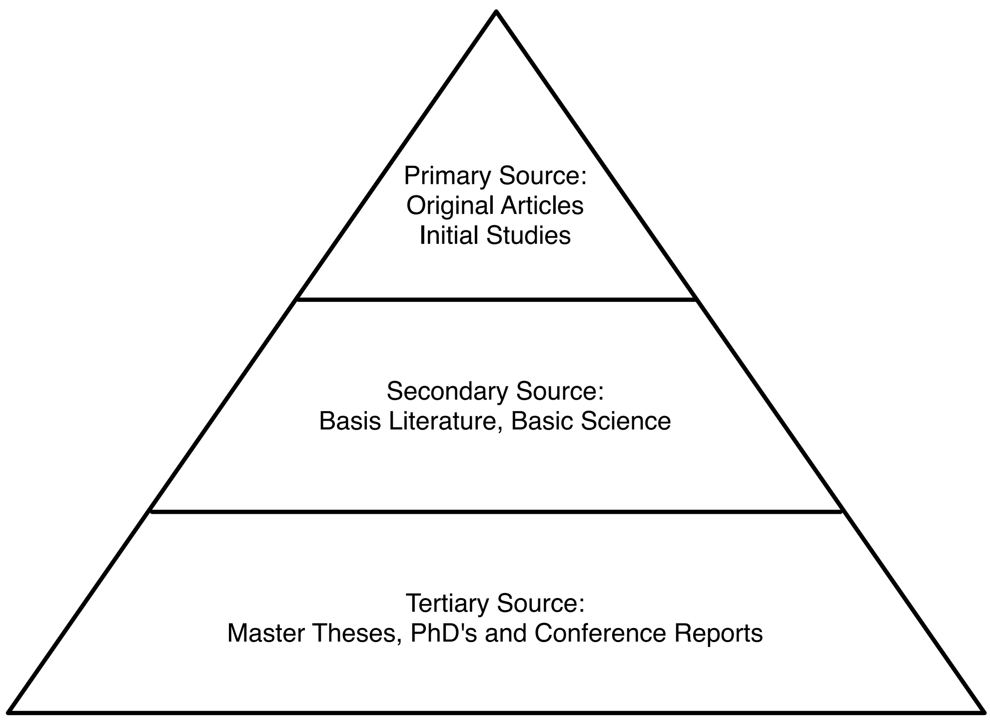

Figure 1.1: The scientific sources in this document is organized in three different categories depending on the grade of direct relationship to the thesis. [20]

This structuring of sources discerns more effectively between important sources of key research and basic widespread knowledge of the system that is being researched [20]. Perhaps more importantly it makes the document easier to read, validate and distinguish from other publications on similar subjects. In this thesis the sources most relevant to this report are placed at the top of the bibliography. Relevance decreases with increasing page numbers.

1.4 Structure Of The Thesis

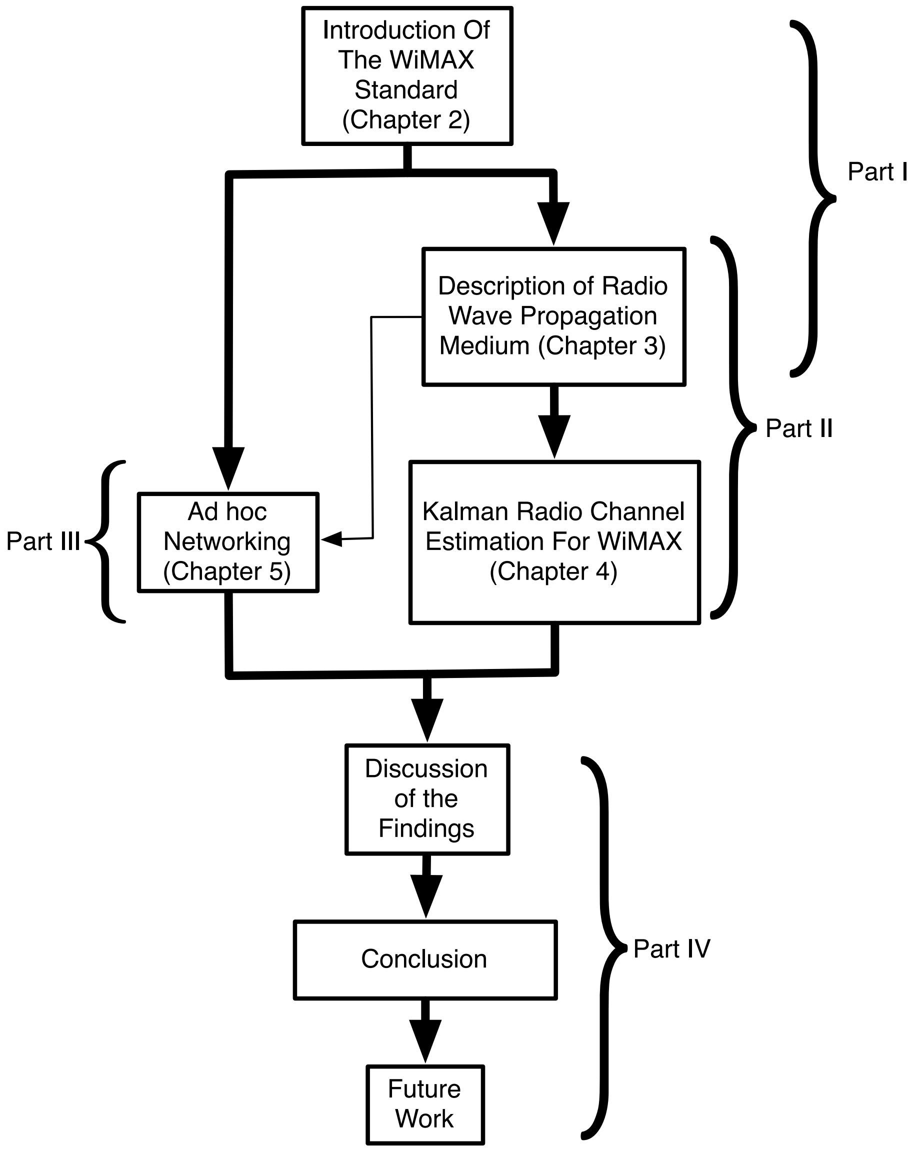

Figure 1.2: The thesis is divided into four parts. To get the most out of the document it is recommended that it is read according to the order of the Parts.

The ultimate goal of studying scientific publications is to provide a good basis for research into new applications. The study of scientific literature is also important for documenting the work that has been done so far on the subject. This provides a perspective on the challenges that exist within the field of research. [20]

Below some brief comments are made regarding the structure of the thesis.

Part I is the introduction to the rest of the document. The first section of Part I describes general characteristics of WiMAX and gives a short explanation of the current state of the WiMAX standard. The second section of Part I is also an introduction but it focuses on the radio wave propagation medium and how meteorological conditions affect the radio channel model.

Part II begins with an explanation on the challenges in developing a high performance wireless network in a fast fading environment. The second section of Part II gives a thorough introduction to the general Digital Kalman Filter. It then explains how Kalman filters may be used to estimate the state of the radio channel and thus counter the effects of fading patterns. It then follows up with an explanation on how to introduce the filter to a WiMAX system.

Part III is somewhat separate from the other parts and sections, although it draws on many of the aspects from Part I, Section I and some from Section II. It explains in detail a model of an Ad hoc network and continues on to illustrating how such a feature may be applied and implemented in WiMAX.

Part IV All the theory, methods and findings are evaluated. Choices of models and references are explained, the method, type of thesis(litterature study, coding, model creation), type of problem description and the specifics of the problem description is discussed. The significance of the work is then discussed. The significance is solidified in the conclusions section. and what could and should have been done differently ends up in the section of future work. Also a prospect f workload is usefull in this last section.

Structure Of The Main body

This thesis, as previously mentioned, discusses three different topics in the context of WiMAX. To provide an overview and facilitate better understanding, a reference model based on [4] is provided. This is a description and implementation of a full scale Simulink WiMAX simulator and therefore provides an excellent framework for this thesis.

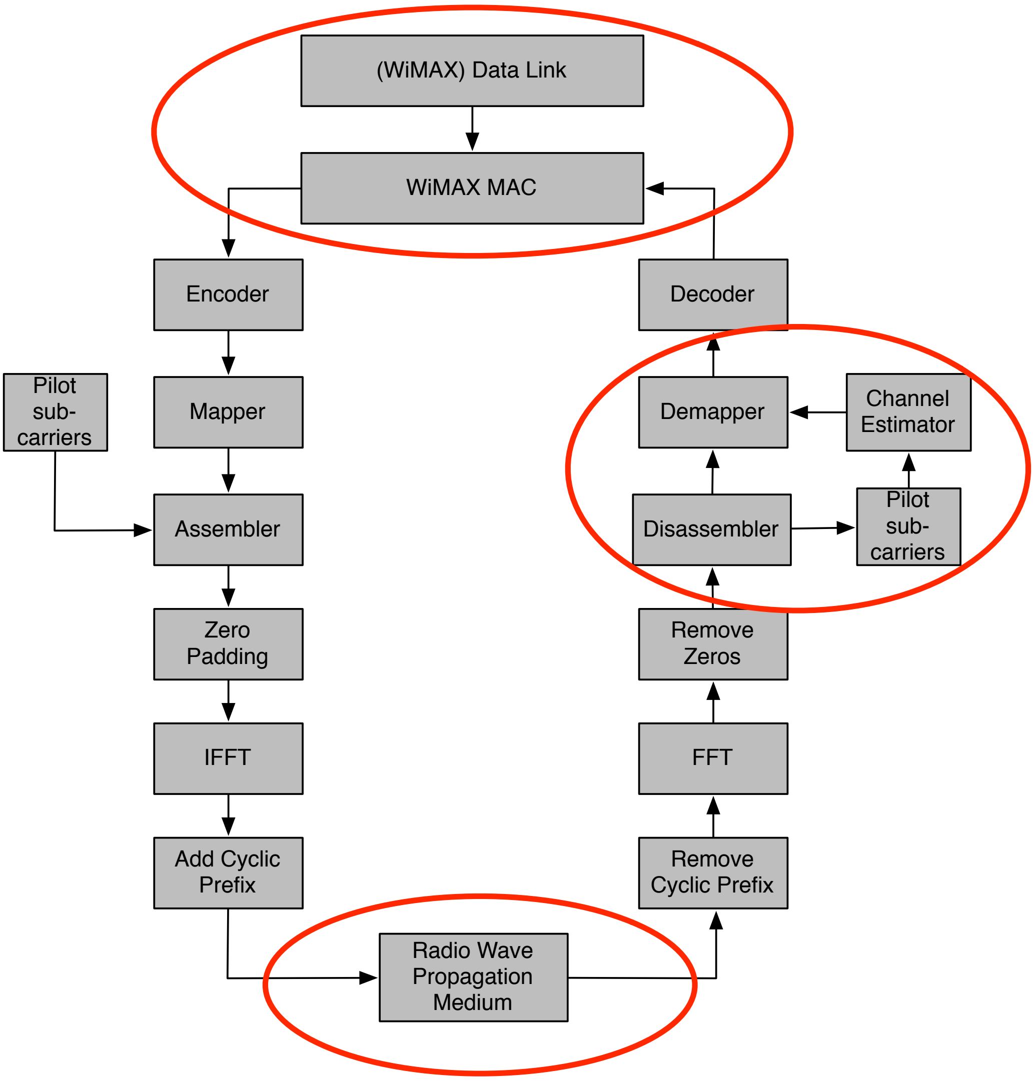

Figure 1.3: The three contributions to the main body of the thesis are marked with a red circle at the beginning of each chapter to identify the parts of the WiMAX standard that are currently being investigated. DEpicted above: All three areas of the WiMAX system that are investigated in this document [4]

Chapter 2

Overview of WiMAX

The sources for this chapter are:[10], [17] , [12], [18], [19], [23]

WiMAX (Worldwide Interoperability for Microwave Access) provides both fixed and nomadic wireless long range broadband connectivity without the need for Line Of Sight. Mobile versions of WiMAX are also in the coming.

The technology is based on the 802.16 standards and the oversight of certification and adoption of WiMAX is supervised by the WiMAX Forum. the WiMAX forum in turn is a non-profit organization formed by some of the largest technology companies in the world [17]. Its goal is to promote the use of wireless broadband technology in general and specifically the use of WiMAX. The WiMAX system can both be point-to-point and point-to-multipoint[10]. The former is a candidate for backhaul for large office buildings without fiber possibilities and last mile broadband delivery to rural areas. The latter is a more likely approach in backbone solutions for Wi-Fi hotspots and cellular networks. Furthermore it can be divided into Fixed, Nomadic and Mobile.

Fixed WiMAX can be both point-to-point and point-to-multipoint. The point-to-point version exemplified by the above mentioned office building. The point-to-multipoint version of Fixed WiMAX can provide private home internet connectivity in suburban areas, with either external and internal antennas. The Wi-Fi example also falls under this category

The nomadic version provides the opportunity to connect to the network at one location, then disconnect and connect again at a different location to the same network only on a different node. Much like how Wi-Fi works today. Examples of areas of usage are laptops and PDA's and location specific services such as automatically updated public transport timetables and traffic information.

Mobile WiMAX is the newest addition to the 802.16 more specifically named IEEE802.16e-2005 [12] and supports different hand-over techniques i order to provide continuous connectivity to the network. The technology is intended to deliver high speed data access to mobile devices and has the potential to compete with the next evolutions of the different 3G networks of today, both in peak and average transfer rates.

WiMAX has already been deployed in several locations. Most notably in Seoul - South Korea under the name WiBro which is fully compatible with the 802.16e-2005 standard, and in Singapore. WiBro is used as a mobile network for high speed data transfers in addition to the already existing CDMA2000 service where it is used for video, multimedia messaging and entertainment services. The frequency used for this is 2,3GHz and data rates range from 512kbps to 3Mbps[5][12]. In Sigapore a nomadic variant of WiMAX has been installed in the harbor area with a 15km radius. It is being offered as a more economical alternative to satellite uplink for ships in and just outside the harbor. The intention is that electronic data exchanges and regulatory filings can be performed offshore as opposed to only when the ships are docked at the harbor. Another important feature is that sailors will through this connection also be able to use services such as video calls and internet applications.

It is claimed by the WiMAX Forum that equipment they certify will have a per channel capacity of up to 40Mbps and even 70Mbps [17]. This however has been challenged by real live tests of the system [14]. Ideal conditions where needed to obtain data rates close 40Mbps.

However much hype is to be expected in the technology business, it is rather the rule than the exception, higher and more stable performance comes along as technologies mature.

2.1 Prominent features of WiMAX

One of the most significant features of WiMAX is that there really is nothing new about it. The 802.16 standards are all - with a few honorable exceptions - based on existing and very well proven techniques and technologies.

There are a lot of promising features in the 802.16 standard that in many respects are on par or often surpass existing technologies. The capacity of WiMAX for *Dynamic User Allocation* is implemented through a TDM scheme that when used in the mobile context is further divided in the frequency domain using the OFDMA-PHY mode. In addition beamforming is possible for further allocation of resources in the spatial domain.

Adaptive Modulation and Coding (AMC) also perhaps more logically called Link Adaption is a set of techniques that allow the transmitter to rapidly change - along with other parameters- the modulation and coding techniques depending on the condition of the link. This increases robustness. In WiMAX the channel used for feedback on the link condition is called *Channel Quality Information Channel* (CQICH).

Through its adaption of OFDMA the 802.16e-2005 standard has the ability to easily *scale bandwidth*. This is performed through changing the length of the FFT. In the negotiation between the MS and the BS, the MS indicates the FFT sizes that it supports. These values range from 128 to 2048 bits in length.

A very interesting feature of WiMAX is its capability to sustain *High Peak Data Rates*, up to 74Mbps given a broad channel of 20MHz, uplink and downlink speeds combined. This is not a common bandwidth however and a more likely data rate is around 25Mbps. Average data rates are already higher for mobile WiMAX than that for 3G in Seoul - South Korea. On a more comparable note the Long Term Evolution (LTE) of 3G under development by the 3rd Generation Partnership Project (3GPP) is intended to support peak data rates of 100Mbps downlink and 50Mbps uplink. These numbers are not attainable i the immediate future, the numbers for WiMAX are however, as the technology has a head start in implementation, standardization and interoperability.

For error control WiMAX supports *Automatic Repeat Request* (ARQ). ARQ is used in many different data transmission solutions. It basically sends a confirmation for each packet that correctly arrives at the receiver (ACK) and a repeat request for each failed package (NACK). As a means to improve performance WiMAX also implements Hybrid ARQ which uses *Forward Error Correction* (FEC) in addition to the standard Error Detection bits. Although more efficient than ARQ, Hybrid ARQ introduces higher implementation complexity and a significantly slows down the data rate under good signal conditions.

Perhaps the most frequently mentioned part of WiMAX is its application of *Orthogonal Frequency Division Multiplexing* or OFDM on which the physical layer of WiMAX is based.

OFDM

The discovery of OFDM started with the challenge of how to overcome the multipath problem without lowering the data rate. The solution, discovered in the sixties by *R. W. Chang*, was sending the signal modulated over several smaller carriers.

Later on it was proven that this multicarrier modulation was possible through Discrete Fourier Transform which simplified the implementation of the technology thus making it more feasible as a commercial solution in the form of the Fast Fourier Transform. OFDM was first adopted in DSL and later on in the Wi-Fi standards. The technology was first seen in a WiMAX context in 1999 when the IEEE 802.16 committee released an OFDM-based standard for metropolitian area network wireless broadband. The key accomplishment of OFDM is the ability to lower the data rate per subcarrier whilst maintaining or increasing the total data rate with respect to single carrier schemes. OFDM, overcoming the multipath problem, also allows WiMAX to operate in NLOS - Non Line Of Sight - conditions.

OFDM being a multiplexing scheme splits a broad carrier signal into several sub-carrier signals. A data frame for instance will be divided over a multiple of partial frames. Each of these sub-carrier signals are orthogonal in order to avoid interference.

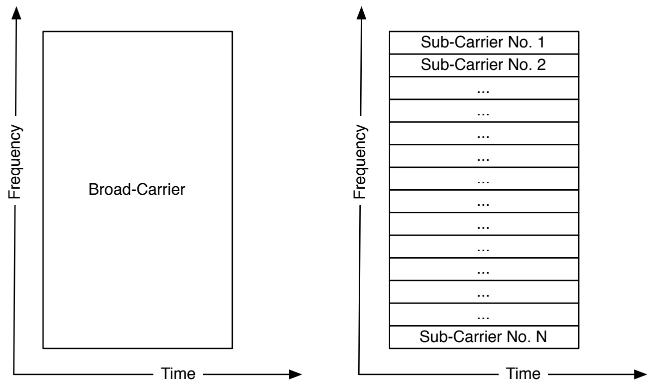

Figure 2.1: Normal Broadband carrier versus OFDM carriers

These subcarriers may be grouped into subchannels in order to simultaneously serve multiple subscriber stations. In the fixed WiMAX solution, subchannelization is only possible for the uplink whereas for mobile WiMAX it can be done for both up- and downlink. For fixed WiMAX the standard has defined that a total of 16 channels is possible of which 1, 2, 4, 8 or all can be assigned to a subscriber station. This allows for the subscriber station to use as little as 1/16 of the total available bandwidth with the power and range improvements this provides.

In the mobile scenario however subchannelization is possible both in the uplink and the downlink, it is based on OFDMA-PHY, *Orthogonal Frequency*

Division Multiple Access Physical Layer. Multiple access can be achieved through the assignment of one or several subchannels per subscriber station. The assignment of subchannels is essentially an optimization problem with SINR in mind.

WiMAX defines the layers of the IEEE 802 reference model corresponding to the two lowest layers in the OSI reference model: The Data Link Layer and the Physical Layer. The last versions of the Physical Layer of WiMAX are based on OFDM in order to provide the system with NLOS capability. This is not always necessary and as such not all of the four versions of the PHY layer of WiMAX uses OFDM. The list of available physical layers for WiMAX is given below:

- WirelessMAN SC

  Essentially intended for backhaul traffic as it is a single carrier PHY layer in need of LOS conditions, suitable for point-to-point. It operates in frequencies over 11GHz.

- WirelessMAN SCa

  Operating between 2GHz ad 11GHz is also a single carrier PHY layer, it is used for point-to-multipoint solutions under LOS conditions.

- WirelessMAN OFDM

  Has OFDM capabilities and can therefore perform in NLOS conditions. It also operates between 2GHz and 11GHz. FFT size is 256. This is the version of WiMAX referred to as *fixed* WiMAX.

- WirelessMAN OFDMA

  The mobile version of the WiMAX standard. referred to as *mobile* WiMAX. Through the application of SOFDMA (scalable OFDMA) it can vary the size of the FFT from the following selection of lengths: 128, 256, 1,024 and 2,048. This allows for adaptable operation given the link conditions and bandwidth.

The process of creating a WiMAX signal is composed of several stages. For the OFDM versions of WiMAX a description is approproate.

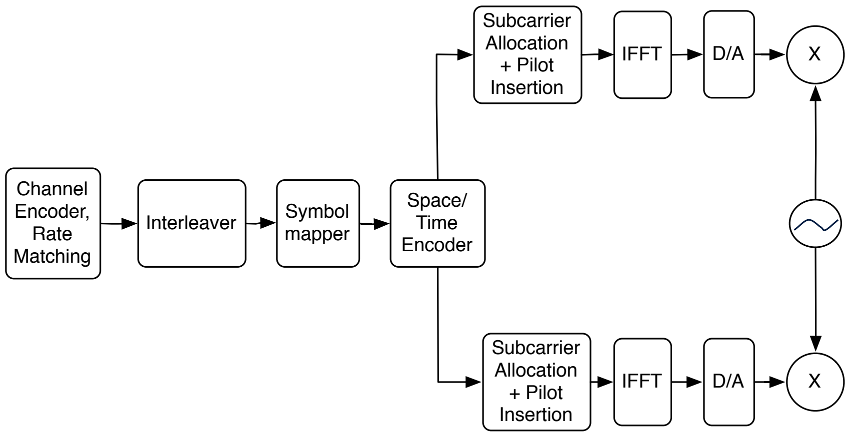

Figure 2.2: The different stages of the WiMAX physical layer

As illustrated in figure 2.2 the process concerning the physical layer starts in the channel coding block. The stages performed here are data randomization, channel coding, rate matching, HARQ (optional) and interleaving. The randomization stage provides a layer 1 encryption. It also assures that subscriber units will not be able to decode data intended for a specific subscriber unit. Given that WiMAX is a wireless transmission standard there is need for forward error correcting codes. This allows the recipient to repair an erroneous data block and free the systems bandwidth from unnecessary retransmissions. The coding scheme used in WiMAX PHY is convolutional coding. Optional coding schemes are Block Turbo Codes, Convolutional Turbo Codes and LDPC (Low Density PArity Check). These optional codes are the codes closest today in reaching the theoretical limit of Shannon's theorem for transmission over a noisy channel.

The interleaver then follows which essentially makes the transmission more robust towards burst errors. The theory of interleaving states that by reorganizing the bits in a seemingly random way, long contiguous parts of bits will not be lost in case of a burst error and the signal will more likely be recoverable. Adjacent coded bits are first placed on non-adjacent subcarriers to ensure frequency diversity. Then, adjacent bits are recoded into more or less significant bit positions. This is done in order to even out the probability for burst error among the bits in a code block.

The symbol mapper transforms sequences of bits into sequences of complex valued symbols. Constellations mandatory in the WiMAX system are QPSK, 16 QAM and 64 QAM. For uplink the 64 QAM is optional. A table of transmission rates for different symbol mappings is given below.

Channel Bandwidth	3,5MHz		1,25MHz		5MHz		10MHz		8,75MHz	
PHY mode	256 OFDM		128 OFDMA		512 OFDMA		1,024 OFDMA		1,024 OFDMA	
Oversampling	8/7		28/25		28/25		28/25		28/25	
Modulation and code rate	PHY-Layer Data Rate (kbps)									
	DL	UL	DL	UL	DL	UL	DL	UL	DL	UL
BPSK, 1/2	946	326	Not Applicable							
QPSK, 1/2	1,882	653	504	154	2,520	653	5,040	1,344	4,464	1,120
QPSK, 3/4	2,822	979	756	230	3,780	979	7,560	2,016	6,696	1,680
16 QAM, 1/2	3,763	1,306	1,008	307	5,040	1,306	10,080	2,688	8,928	2,240
16 QAM, 3/4	5,645	1,958	1,512	461	7,560	1,958	15,120	4,032	13,392	3,360
64 QAM, 1/2	5,645	1,958	1,512	461	7,560	1,958	15,120	4,032	13,392	3,360
64 QAM, 2/3	7,526	2,611	2,016	614	10,080	2,611	20,160	5,376	17,856	4,480
64 QAM, 3/4	8,467	2,938	2,268	691	11,340	2,938	22,680	6,048	20,088	5,040
64 QAM, 5/6	9,408	3,264	2,520	768	12,600	3,264	25,200	6,720	22,320	5,600

Figure 2.3: Data rates for OFDM and OFDMA. Green marks rates for WiBro implemented South Korea. [10]

In OFDM the entire signal is first created in the frequency domain. Then it is inverse fourier transformed into a symbol in the time domain and sent on different subcarriers in parallel over the air. The inverse fourier transformation can be described as:

$$x(t) = \sum_{i=0}^{L-1} s[i]e^{-2\pi j(\Delta f + iB_c)t}, 0 \leq t \leq T'. \tag{2.1}$$

Here s[i] represents the symbol carried o the ith subcarrier, B_c is the separation frequency ad Δf is the frequency of the first subcarrier. T' is the useful symbol duration without the cyclic prefix.

There are three different subcarriers in WiMAX:

- *Data Subcarriers* carry, among other things the net information.
- *Pilot Subcarriers* are used for channel estimation and tracking
- *Null subcarriers* are mainly the outer subcarriers in the frequency band, these are prone to disturbances and are as a result not modulated and/or powered. As such they carry no information. Also the DC subcarriers which are the subcarriers at the transmission frequency carry no information.

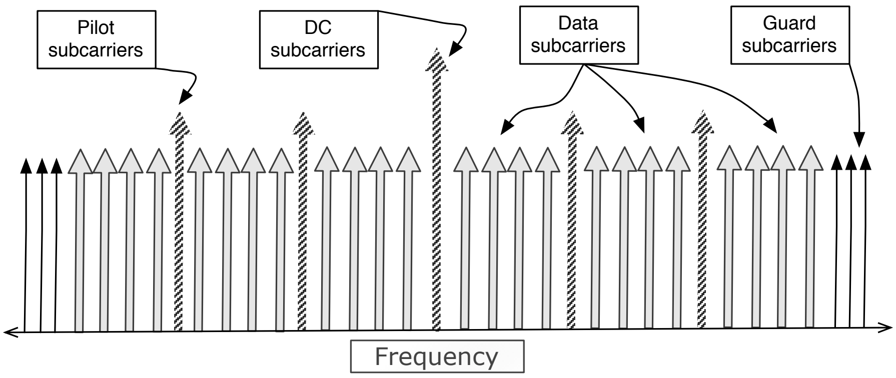

Figure 2.4: Frequency representation of an OFDM symbol

OFDM symbols when received, are retrieved by integrating with the complex conjugate of their subcarrier over the symbol duration T' mentioned above in equation 2.1. For this to work, time and frequency need to bee synchronized between the SU and the BS. Otherwise the system will suffer from intersymbol interference. The doppler effect is often the cause for non-synchronized frequencies, It occurs whenever the SU is in motion relative to the BS. This is important in mobile communications.

2.2 Fixed WiMAX

Fixed WiMAX is as mentioned, intended for last mile broadband for office buildings, housings and Wi-Fi hotspots. Its structure allows it to serve multiple Subscriber Units at the same time. The standard is more correctly referred to as IEEE 802.16-2004. It has an advantage over fiber or copper based broadband in that it is easy to implement. The payoff however is lower speeds.

2.2.1 PHY Layer

FDD and TDD

FDD(Frequency Division Duplexing) and TDD(Time Division Duplexing) are two different techniques for simultaneous uplink and downlink communication. TDD is based on assigning slots in time for uplink and downlink traffic in which the BS and SS take turns in sending each other packets of information. Upload and download packets are intertwined in a 1:1, 1:2 or 1:3

relationship. This is the ratio of data traffic between *upload* : *download* slots respectively. FDD uses different frequencies for uplink and downlink that do not interfere with one another. In the case of WiMAX different subcarriers are use for up- and downlink This means that at the very same instant uplik and downlink transmissions are passing each other on their way to and from the Base Station and the Subscriber Station.

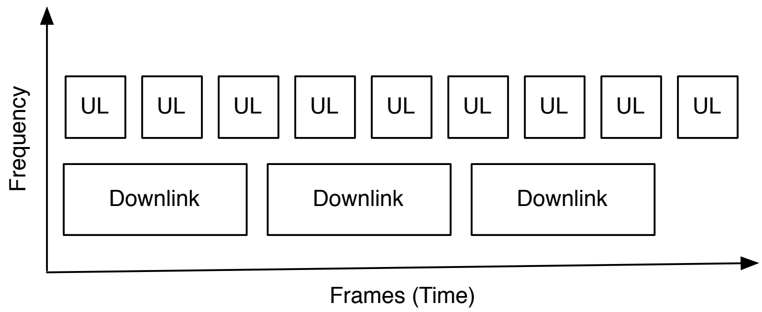

Figure 2.5: A generic FDD scheme (UL - Uplink)

FDD and TDD are available in both fixed and mobile WiMAX. FDD however is only utilized in one profile of fixed WiMAX. Mobile WiMAX on the other hand only uses TDD.

For fixed WiMAX which normally operates at 3.5GHz there is only one possible size for the FFT transform, namely 256. This implies that the frequency spacing between subcarriers will vary with bandwidth. When fixed WiMAX makes use of a larger bandwidth, the spacing also is wider which in turn decreases symbol time. Decreased symbol time means that a larger guard time is needed to counter delay spread. The table below indicates that there are four different cyclic prefixes available to the standard in order to adjust guard time.

Table 2.1: WiMAX OFDM PHY. Some basic, important parameters of Fixed WiMAX

Parameter	
FFT Size	256
Number of Used data subcarriers	192
Number of Pilot subcarriers	8
Number of Null/Guardband subcarriers	56
Cyclic prefix or Guard Time	1/32, 1/16, 1/8, 1/4
Oversampling rate	7/6
Channel Bandwidth (MHz)	3.5

Upon adjusting the cyclic prefix the evaluation stands effectively between increasing robustness towards delay spread and better spectral efficiency.

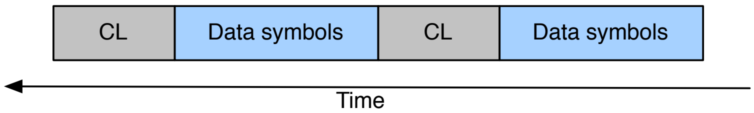

Figure 2.6: Illustration of Cyclic prefix or Guard Time (Gray) together with the payload of the signal (Blue)

The cyclic prefix is as mentioned a technique to overcome the problem of delay spread. This phenomenon is caused by reflections and structures in the way of the signal making multiple versions of a transmission ”echoes” arrive at the receiver at different times. In order to avoid receiving combinations of previously sent signals and the current signal (ISI), the prefix is appended to the beginning of each symbol so that when the payload of the symbol arrives shortly after the prefix, there is no interference.

2.2.2 MAC Layer

The MAC layer’s main function is to provide an interface between the physical layer and the logical link layer of a network [?]. It transforms packets known as service data units into protocol data units and forwards them to the physical layer for transmission. The MAC layer is also responsible for channel access, reserving bandwidth to the different users connected to the base station. In addition to this the WiMAX MAC layer supports Quality of Service.

There are five scheduling services available to WiMAX's MAC layer. The five different modes are intended to service different types of applications as described in Table 2.2

Table 2.2: Service flows supported in WiMAX. [10]

Service Flow Designation	**Defining QoS Parameters**	**Application Examples**
Unsolicited Grant Services (UGS)	- Maximum sustained rate - Maximum latency tolerace - Jitter Tolerance	Voice over IP (VoIP) without silence suppression.
Real-time Polling service (rtPS)	- Minimum reserved rate - Maximum sustained rate - Maximum latency tolerance - Traffic priority	Streaming audio and video, MPEG(Motion Pictures Experts Group) encoded.
Non-real-time Polling service (brtPS)	- Minimum reserved rate - Maximum sustained rate - Traffic priority	File Transfer Protocol (FTP)
Best-effort service (BE)	- Maximum sustained rate - Traffic priority	Web browsing, data transfer
Extended real-time Polling service (ErtPS)	- Minimum reserved rate - Maximum sustained rate - Maximum latency tolerance - Jitter tolerance - Traffic priority	VoIP with silence suppression

The WiMAX MAC layer is divided into three sublayers: The MAC Convergence sublayer, MAC Common part sublayer and the MAC Security sublayer all depicted in figure 2.7

Convergece sublayer

In the convergence sublayer packet suppression is performed for instance source and destination IP addresses for packets destined to one SU are all the same, this redundant information is reduced prior to sending over the air. The redundant header information is correspondingly inserted into each IP packet when sent from the SU to another IP address.

The convergence sublayer maintains a logical connection between the BS and the SUs. This is done by the application of a connection identifier (CID). The CID not only provides an identifier for a connection, its composition also affected by the type of service flow ID (SFID) and source address [**?**] (presented in table 2.2).

Common part sublayer

The common part sublayer is responsible for scheduling, ARQ, bandwidth allocation, modulation and code rate selection [10]. This is also where the SDUs are transformed into PDUs. All MAC PDUs are composed of a header, payload and a CRC i that order. PDUs are sent to the scheduler after assembly where their service flow ID and CID aides the scheduler in determining the optimal physical layer resource allocation.

In bandwidth request allocation the BS determines the bandwidth for downlink connections. For uplink connections the MS makes requests for resource allocations through single purpose MAC PDUs or by piggybacking on a generic MAC

Security sublayer

The security sublayer provides users of WiMAX with privacy and authentication across the fixed broadband wireless network [12]. This is accomplished through the sublayers two component protocols who are: An *encapsulation protocol* for securing packet data on the wireless channel and a *key management protocol* (PKM) for secure transfers of keying data. The Key management protocol makes use of EAP together with an RSA public key encryption algorithm or a sequence starting with RSA authentication followed by EAP authentication. Encryption is applied to the MAC PDU when required by the selected ciphersuite [23].

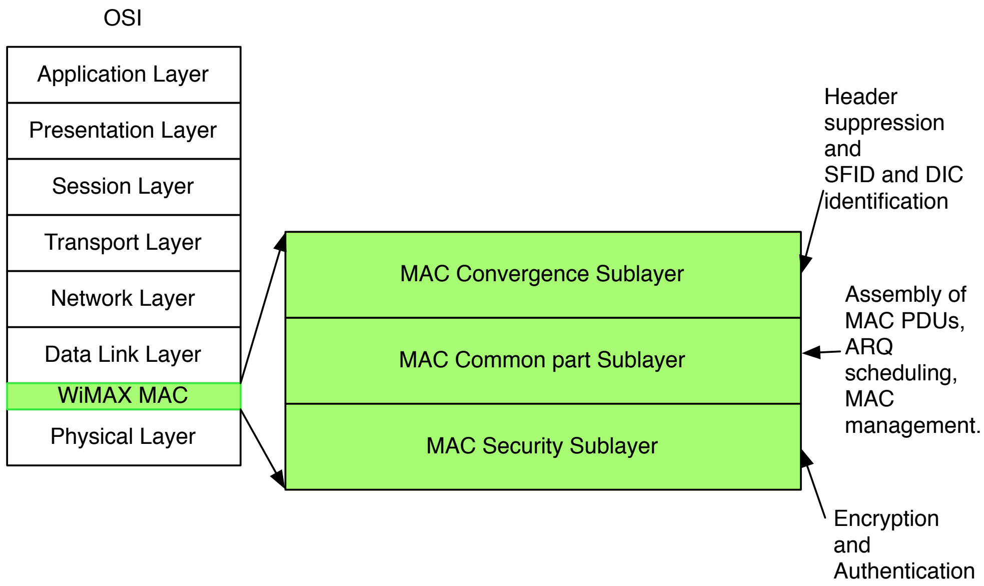

Figure 2.7: The sublayers of the WiMAX MAC layer

2.3 Mobile WiMAX

Mobile WiMAX is for the most part the result of a review of the IEEE 802.16 standard motivated by the increase in mobile data traffic in later years. It is however apparent that the technology lends features outside the scope of the 802.16 as it moves above the MAC layer to define features in the data link layer needed to implement mobility.

2.3.1 PHY Layer

There are several differences between fixed and mobile WiMAX in the physical layer. Some of the most significant differences are seen when comparing tables 4.1 and 2.1. Mobile WiMAX has four FFT sizes available i order to adapt the broadband channels for the multitude of link conditions that mobile devices may cause. Implementations of mobile WiMAX generally operate on frequencies lower than that of fixed WiMAX solutions. This makes the system more robust towards doppler spread and multipath fading which are key challenges to overcome for a network with mobile users [10]

TDD

The duplexing technique of mobile WiMAX is TDD (Time Division Duplexing). It is also the preferred duplexing technique in most of the implementations of WiMAX due to, among other things, the ease of varying the upload:download ratio and a less complex transceiver design. Also the uplink and downlink transmissions are at the same frequency which yields better channel reciprocity.

Mobile WiMAX also supports H-FDD (Half-duplex FDD). It is a basic FDD scheme where the MS is unable to transmit and receive simultaneously. Its main advantage is lower cost and lower implementation complexity [12]

Table 2.3: WiMAX PHY (Mobile). The oversampling rate 8/7 is for bandwidths of multiples of 1.75MHz and 28/25 is for multiples of 1.25 MHz,1.5MHz, 2MHz, or 2.75MHz.

Parameter	OFDMA PHY			
FFT Size	128	512	1,024	2,048
Number of Used data subcarriers	72	360	720	1,440
Number of Pilot subcarriers	12	60	120	240
Number of Null/Guardband subcarriers	44	92	184	368
Cyclic prefix or Guard Time	1/32, 1/16, 1/8, 1/4			
Oversampling rate	8/7, 28/25			
Channel Bandwidth (MHz)	1.25	5	10	20

OFDMA

In mobile WiMAX, the smallest time-frequency resource in WiMAX is a slot. A slot is composed of one subchannel in the frequency domain that span one, two or three symbols in the time domain. Subchannels are discussed earlier in this chapter and to a great extent in [10]. For a model on a frame consisting of several subcarriers and symbols please refer to Figure 2.8. Subchannels can be organized i different *permutation schemes*. The way in which subchannels are distributed is crucial with regard to desired operation and performance. There are two main techniques for organizing subchannels over the broadband channel. One aims at increasing frequency diversity by distributing subcarriers pseudorandomly over the broadband channel. The other organizes the subcarriers in contiguous groups which are each assigned to a distinct user. This in turn allows the system to adjust each channel to each user based on the channel frequency response. Here, frequency diversity is lost, multiuser diversity is gained however, which may improve overall performance [**?**]. The two schemes that are used in WiMAX to accomplish this are called, *Partial Usage of Subcarriers (PUSC)* and *Adaptive Modulation and Coding (AMC)*, respectively. PUSC and AMC use slots in the following way [10]:

- Downlink PUSC: Each slot is 24 subcarriers by two OFDM symbols
- Uplink PUSC: Each slot is 16 subcarriers by three OFDM symbols
- Band AMC: Each slot is 8, 16 or 24 subcarriers by 6, 3 or 2 OFDM symbols

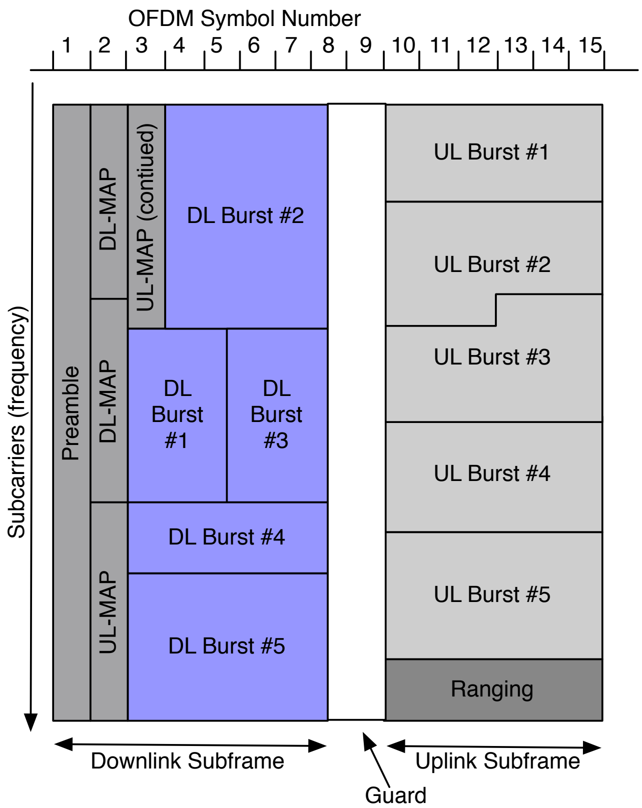

Figure 2.8: Example of a TDD frame in mobile WiMAX [23]

Ranging

The process of ranging depicted in dark grey in the uplink in Figure 2.8 is an uplink procedure aimed at maintaining the quality and reliability of the radio link communication between the BS and the MS. The message is sent from the MS to the BS where the signal is analyzed for channel impulse response, SINR and time of arrival among others. Adjustments to improve the channel accordingly are based on these parameters [10].

2.3.2 MAC Layer

Mobility

In the IEEE 802.16e -2005 support for mobility is introduced into the WiMAX MAC layer. When a mobile device powers up, it starts the acquisition of a nearby network. This is a multi-step procedure referred to as network entry [23]. The process includes determining the available base stations, determining quality of the radio link channel through *ranging*, bandwidth allocation and IP connectivity. in the 802.16 family, mobile WiMAX is the member receiving the most attention due to high activity in mobile communications development lately.

In order to facilitate true mobility the 802.16e-2005 standard must support handover techniques. The three techniques supported in mobile WiMAX are *Hard Handover*, *Macro Diversity Handover* and *Fast Base Station Switching*, of which only the first is mandatory.

Hard Handover means simply that the mobile device cuts off the connection with the current BS before it connects to the target BS. This regime is also known as break-before-make. **Macro Diversity Handover** and **Fast Base Station Switching** both maintain, in contrast to HH, connections with multiple base stations in addition to its current active connection. This group of potential new base stations is called *the active set*. MDHO and FBSS differ in that MDHO both in the uplink and downlink maintain a connection to the base stations in the active set simultaneously.

Power saving

Mobile WiMAX introduces power saving. This is an important feature for small handheld devices. Power management enables the mobile device to preserve power depending its operational status. There are basically two modes for power saving, *Sleep mode* and *Idle mode* Sleep mode makes use of *sleep windows* which essentially are predetermined periods where the BS and MS agree upon to disrupt the connection. In WiMAX sleep mode is divided into three different classes aptly named [12].

- Power saving class 1

- Power saving class 2
- Power saving class 3

In Idle mode, the MS is able to receive downlink transmissions but no effort is made with regard to handover. Handover is not needed for instance when the MS is not engaged in active transmission or reception. The Idle mode allows the MS to switch off certain parts of the hardware entirely and as a consequence, save power.

Multicast and Broadcast

Multicast and Broadcast, abbreviated MBS, is a feature in mobile WiMAX supported in the MAC layer. It is intended for providing "real-time, high quality and interactive multimedia contents" [12] which will differentiate Mobile WiMAX from other Wireless broadband providers.

2.3.3 Summary

WiMAX provides an alternative to the existing and the next generation of wireless broadband communication. Its features provide secure adaptable channels for high speed data transfers both for moving and stationary subscribers. All using the same type infrastructure. There are signs that the new field of interest in the IEEE 802.16 group is mobile networking and that attempts at getting a hold on the market will come from this side

Chapter 3

The Radio Wave Propagation Medium

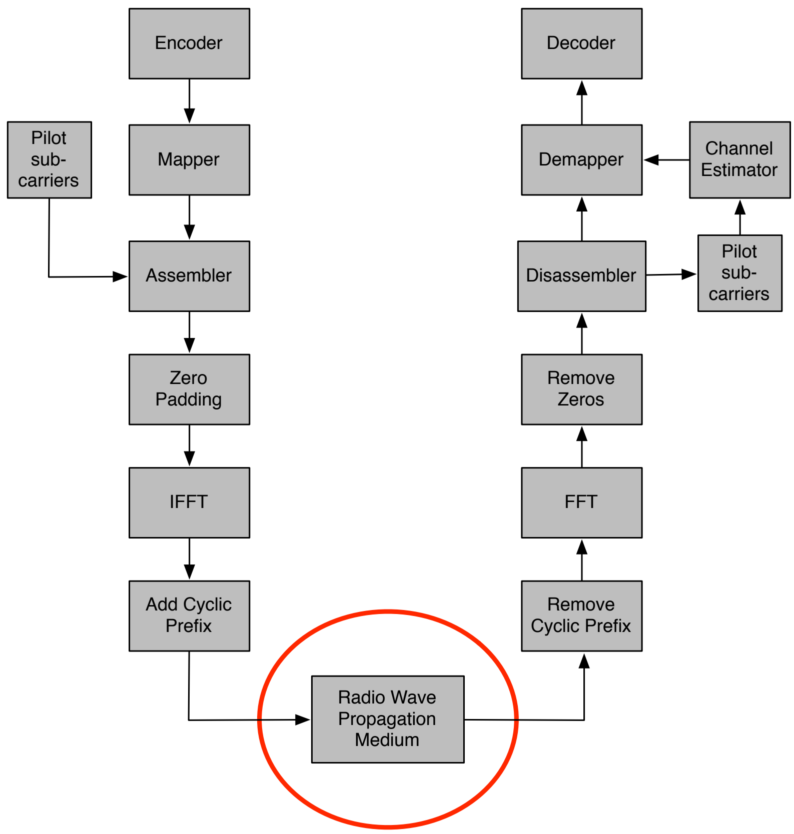

Figure 3.1: Model of a WiMAX simulator according to [4]

3.1 Link Budget

To describe the total of the channel and the conditions influencing the radio signals in an organized manner, a link budget is used. The link budget gathers the average values of amplifications and attenuations of the radio signal and the noise and sums it up to indicate the quality of the channel and to identify challenges in the system. The link budget is based on the transmission equation given in equation 3.1:

$$\frac{E_b}{N_0} = P_{transmit} G_{transmit} * (\frac{\lambda}{4\pi d})^2 * \frac{1}{k} * \frac{G_{receiver}}{T_{receiver}} * \frac{1}{R} * G_c * \frac{1}{L_{misc}} \tag{3.1}$$

Where $\frac{E_b}{N_0}$ is the ratio between the energy per bit E_b and the density of the noise power N_0. $P_{transmit}$ and $G_{transmit}$ are the transmit power and the transmitter antenna gain respectively. Their product gives the EIRP (Equivalent Isotropic Radiated Power) illustrated by figure 3.2

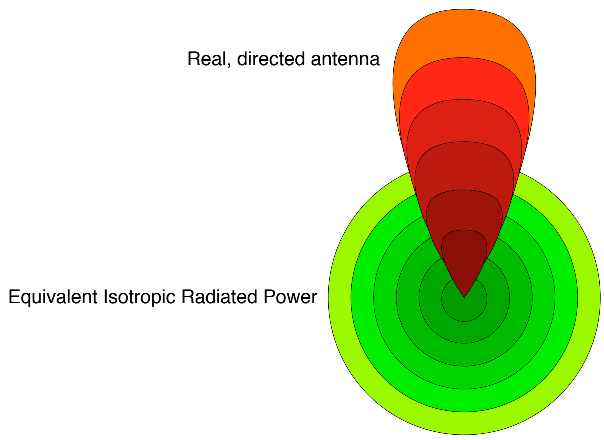

Figure 3.2: A real antenna and its Isotropic Equivalent

Antennas can be omnidirectional or focused depending on the application, when the antennas are focused, the The EIRP is a representation of what the signal would have looked like if distributed in all directions [29] [25]. It is a measure of the effective power emitted from the antenna. It may be looked upon as analogous to the Thevenin equivalent in circuit engineering.

The $(\frac{\lambda}{4\pi d})^2$ often just written as $\frac{1}{L}$ is the free space attenuation, the loss in power density due to the total signal power being divided over the area of an imaginary sphere representing the coverage area of the antenna.

The letter k represents Boltzmann's constant $1.38 * 10^{-23}$

Representing the conditions at the receiver antenna is the expression $\frac{G_{receiver}}{T_{receiver}}$. $G_{receiver}$, the antenna gain, while $T_{receiver}$ is the temperature noise at the antenna. $\frac{1}{R}$ is the data symbol rate $baud/s$. The last gain factor G_c is the improvement of the channel conditions due to efficient coding of the data signal being transmitted.

$\frac{1}{L_{misc}}$ is a collective term for all the other disturbances that cause attenuation. Some of these are discussed in the following chapter.

The major reason for determining the $\frac{E_b}{N_0}$ [1]. is its relationship to the "Bit Error Probability". BEP is an important quality parameter for the radio channel and relates to the $\frac{E_b}{N_0}$ by a curve described in figure 3.3 below:

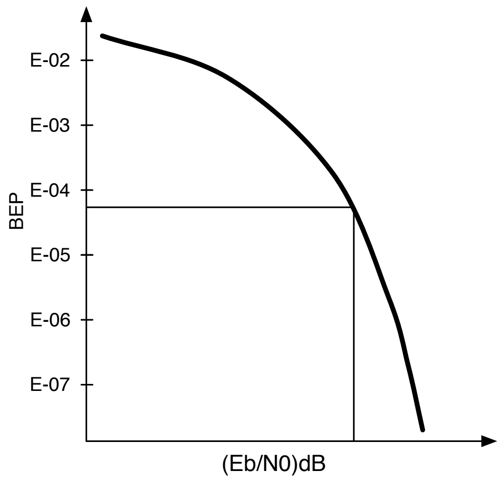

Figure 3.3: *Bit Error Probability* as a function of *Bit Energy* over *Noise Power Density*. It is possible to see from the curve that for fewer bit errors, a greater E_b/N_0 is required.

Based on parameters such as the bove a budget can be made with gains and attenuations (A1, A2, A3 etc. are explained in the Appendix):

[1]The relationship $\frac{E_b}{N_0}$ is also connected to $\frac{C}{N_0}$ (Total signal strength over Noise power density) through the proportionality constant R(bit rate): $\frac{C}{N_0} = R\frac{E_b}{N_0}$

Table 3.1: A proposed link budget for WiMAX [10]

Parameter	**Mobile Handheld In Outdoor Scenario**		**Comments**
	Downlink	Uplink	
Amplifier output power	43,0dB	27,0dB	A1
Number of Tx antennas	2	1	A2
Power amplifier backoff	0dB	0dB	A3; Assumes that amplifier has sufficient linearity for QPSK operation without backoff
Transmit antenna gain	18dBi	0dBi	
Transmitter losses	3,0dB	0dB	A5
EIRP	61dBm	27dBm	$A6 = A1 + 10log_{10}(A2) - A3 + A4 - A5$
Channel Bandwidth	10MHz	10MHz	A7
Number of subchannels	16	16	A8
Receiver noise level	-104dBm	-104dBm	$A9 = -174 + 10log_{10}(A7 * 1e6)$
Receiver noise figure	8dB	4dB	A10
Required SNR	0.8dB	1.8dB	A11; for QPSK, $R1/2$ at 10% BLER in ITU Ped. B channel
Macro diversity gain	0dB	0dB	A12; No Macro diversity assumed
Subchannelization gain	0dB	12dB	$A13 = log_{10}(A8)$
Data rate per subchannel (kbps)	151.2	34.6	A14; using QPSK, R1/2 at 10% BLER
Receiver sensitivity	-95.2(dBm)	-110.2(dBm)	$A15 = A9 + A10 + A11 + A12 - A13$
Receiver antenna gain	0dBi	18dBi	A16
System gain	156.2dB	155.2dB	$A17 = A6 - A15 + A16$
Shadow-fade margin	10dB	10dB	A18
Building penetration loss	0dB	0dB	A19; assume single wall
Link margin	146.2dB	145.2dB	$A20 = A17 - A18 - A19$
Coverage range	1.06km	0.81km	Assuming COST-231 Hata urban model

3.2 The Channel

The channel of the system is the part that is beyond all control for the engineers and scientists. The channel is the medium in which the electromagnetic waves of a radio application travels through. It is both a conductor and often a source of nuisance, full of complications and obstacles. Implementing a radio network without sufficient knowledge about the possible channel conditions is difficult. Instead of adjusting the network parameters after implementation, a model that imitates the states of the channel that affect the signal is used to predict the parameters for the application.

In studying cellular networks, one will find that there are a number of different models for different conditions. The main categories are *Theoretical*, *Empirical and Statistical* and *Semi-Empirical models* [36] [30].

> *Theoretical models* "are based on the laws of physics combined with adequate approximations and atmosphere and land models. These models lead to complex mathematical relations and require the resolution of Maxwell's equations through the use of different methods. The main drawbacks of this method is a relatively high computation time which is often incompatible with operation constraints. Since the variables used in such models are in general deterministic, these models are generally referred to as deterministic models. They may however take into account random variables characterized by their distribution."[30]

> *Empirical and statistical models* "are based on the statistical analysis of a large number of experimental measurements conducted with respect of several different parameters like the frequency, the distance, the effective heights of the base station antenna and of the Mobile Station. The best known such model is the Okumura-Hata model which is based on the statistical analysis of a large number of experimental measurements conducted in the Tokyo area with respect to different parameters like the frequency or the distance. Empirical models can be implemented rapidly without requiring any extremely accurate or expensive geographical databases. These models are robust since they are as a general rule developed from a large number of measurements. However empirical models are unsuited for the study of propagation over short distances." [30] ([10], [36]).

> *Semi-empirical models* ”combine the analytical formulation of physical phenomena like reflection, transmission, diffraction or scattering with a statistical fitting by variables adjustment using experimental measurements. This method is more robust than purely empirical methods since it avoids the improbability of independent variables. The best known such model is the COST model (see table 3.1) which relies on a multiple screen diffraction. The statistical optimization is based on traditional linear regression techniques, but also to more elaborated techniques are used.”[30]

3.2.1 Fast Fading Channel

The kind of model needed to simulate radio applications at sea will need to take into account the rough conditions at the sea surface. Wind, waves, sea spray and fog are all major factors that affect the mobile recipient at sea. The changes are rapid and follow a random pattern of reflections and refractions creating multiple echoes of the signal described as *multipath*.

In assuming such a rapid changing environment for the radio channel and a making a second fair assumption that the transmitter is not always in a LOS path due to the receiver being in a wave low-point, it can be concluded that we have a channel model with many rapid changing NLOS components and no main LOS components for large periods of time. This scenario is common in mobile networks due to the rapid changes in fading that mobile stations experience when moving through its environment. The most popular model for describing such conditions is called *Rayleigh fading*. This model is a statistical representation of how the different rapid changing reflections of a radio signal converge at the receiver. The rapid changes in the channel causes rapid changes between constructive and destructive interference of the multipath components.

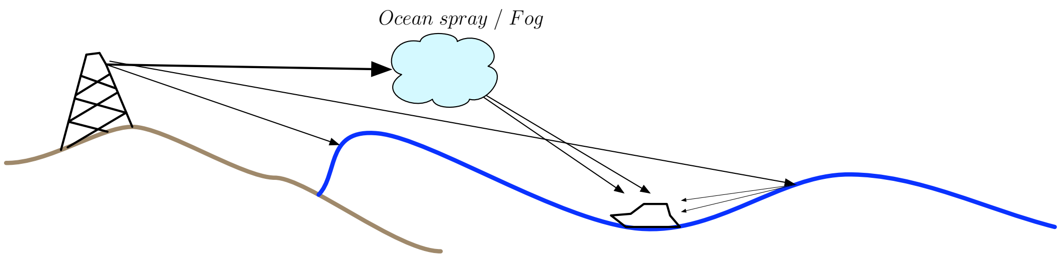

Figure 3.4: Recipients of radio signals at sea will experience rapid changes in position and the physical structure of the environment may also change rapidly(waves). The recipients will also be subject to *Hydrometeor Attenuation* which is clouds of sea spray (essentially aerosol) and fog that attenuate(refract) the signal adding to the multiple path scenario.

The scenario described above is a recipient in bad weather, conditions where waves shadow ships occurs quite frequently off the long norwegian coast [32]. In such weather, ocean spray is also abundant. Fog on the other hand is occurs in still waters.

> In the case of clouds and fogs consisting entirely of very small droplets with diameter smaller than $0,01cm$ on average, the Rayleigh approximation is valid at frequencies lower than $200GHz$, Attenuation can therefore be expressed as a function of the total water content per volume unit (g/m^3). The following equation yields the specific attenuation in clouds or fogs with such characteristics [30]:
>
> $$\gamma_c = K_l M (dB/km) \tag{3.2}$$

The assumption that chaotic weather creates even more dispersion of the signal as a result of higher waves and more ocean spray and also rain is sound. Increasingly chaotic weather thus should create conditions increasingly similar to the Rayleigh model. A representation of the Rayleigh model is thus also a way of describing a common worst-case scenario for receivers at sea.

Rayleigh fading is statistically characterized by a fading amplitude, $\alpha(t)$ modeled with a Rayleigh probability distribution which has zero-mean Gaussian components. Furthermore the phase $\phi(t)$ is uniformly distributed over the interval $(0, 2\pi)$. The fading amplitude is described by the probability density function (pdf)[30]:

$$f_{Ray}(a) = \frac{a}{\sigma^2} exp(-\frac{a^2}{2\sigma^2}) \; for \; a \geq 0, \quad zero \; elswhere \tag{3.3}$$

The Rayleigh fading model is similar to the Ricean distribution which is used to model signals *with* a LOS component. The Ricean distribution is a generalization of the Rayleigh distribution and quite intuitively has a more complicated expression.

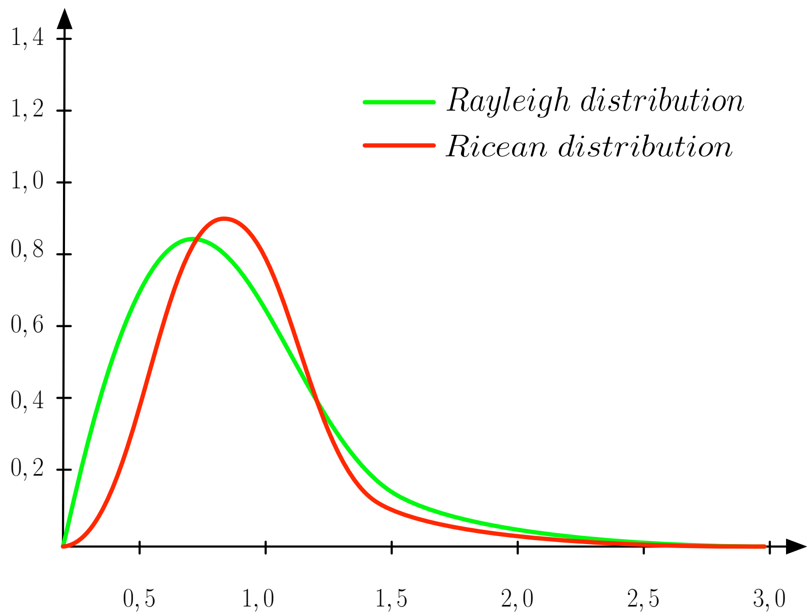

Figure 3.5: Specimen of the Rayleigh and Ricean distribution depicted together. As a result of the LOS component, the Ricean model does not have zero-mean like the Rayleigh model [10][36]

The Rayleigh fading model is implementable in Matlab and many examples are found on *www.mathworks.com*[31]. A sample of small matlab code representing a Rayleigh filter is given below 3.6

The following Matlab function generates a stochastic correlated Rayleigh fading envelope with effective Doppler frequency f_D. See Figure 3.18 for example-generated envelopes.

```
function [Ts, z_dB] = rayleigh_fading(f_D, t, f_s)
% Inputs
%   f_D : [Hz] Doppler frequency
%   t   : simulation time interval length, time interval [0,t]
%   f_s : [Hz] sampling frequency, set to 1000 if smaller.
% Outputs
%   Ts   : [Sec][1xN double] time instances for the Rayleigh signal
%   z_dB : [dB] [1xN double] Rayleigh fading signal
% Required parameters
if f_s < 1000, f_s = 1000; end  % [Hz} Min. required sampling rate
N = ceil(t*f_s);     % Number of samples
Ts = linspace(0,t,N);
if mod(N,2) == 1, N = N+1; end   % Use even number of samples
f = linspace(-f_s,f_s,N);
% Generate I & Q complex Gaussian samples in frequency domain
Gfi_p = randn(2,N/2); Gfq_p = randn(2,N/2);
CGfi_p = Gfi_p(1,:)+i*Gfi_p(2,:); CGfq_p = Gfq_p(1,:)+i*Gfq_p(2,:);
CGfi = [fliplr(CGfi_p)' CGfi_p ]; CGfq = [fliplr(CGfq_p)' CGfq_p ];
% Generate fading spectrum for shaping Gaussian line spectra
P_r = 1;  % normalize average received envelope to 0dB
S_r = P_r/(4*pi)./(f_D*sqrt(1-(f/f_D).^2)); %Doppler spectra
% Set samples outside the Doppler frequency range to 0
idx1 = find(f>f_D); idx2 = find(f<-f_D);
S_r(idx1) = 0; S_r(idx2) = 0;
% Generate r_I(t) and r+Q(t) using inverse FFT:
r_I = N*ifft(CGfi.*sqrt(S_r));
r_Q = -i*N*ifft(CGfq.*sqrt(S_r));
% Finally, generate the Rayleigh distributed signal envelope
z = sqrt(abs(r_I).^2+abs(r_Q).^2);
z_dB = 20*log10(z);
z_dB = z_dB(1:length(Ts)); % Return correct number of points
```

Figure 3.6: An example of elegant implementation of a Rayleigh fading model in matlab. The matlab function generates a stochastic correlated Rayleigh fading envelope with effective doppler frequency f_D [10]

An alternative to matlab code of a Rayleigh fading model i.e. a model implented ion Simulink or LabView could look like the following. The basic idea is to generate two quadrature signals represented by

$$n(t) = x(t)cos(\omega t) - y(t)sin(\omega t). \tag{3.4}$$

These signals are then added together to produce a signal with Rayleigh envelope and uniform phase. The mathematical model leads to the implementation in figure 3.7:

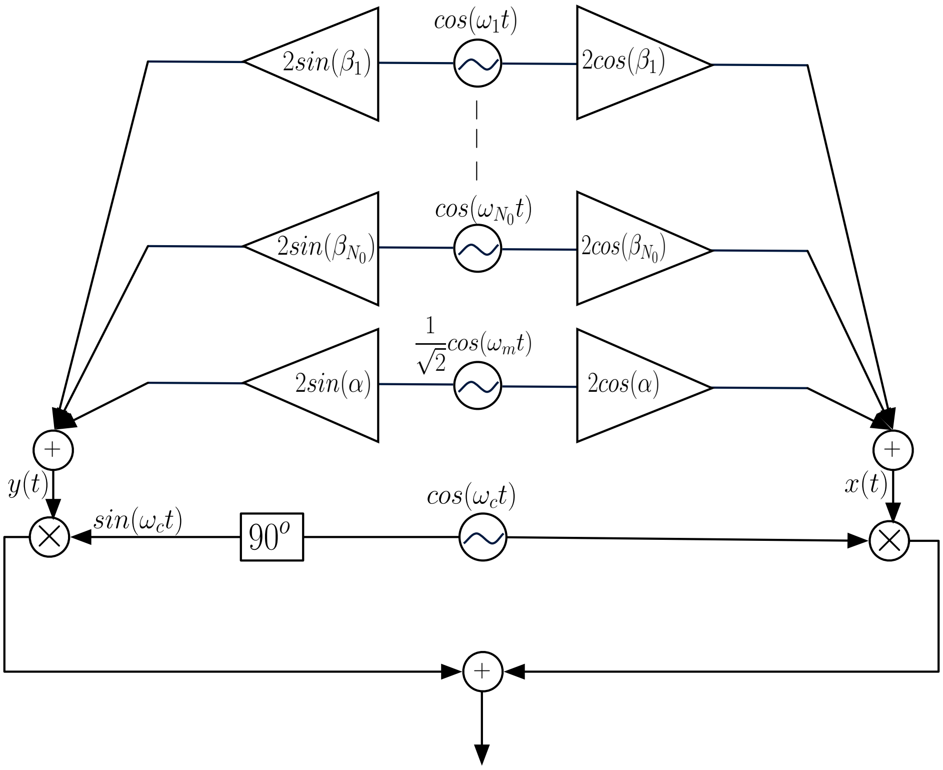

Figure 3.7: Illustration of Rayleigh simulator for implementation in Simulink, LabView etc. [36]

The low frequency oscillators N_0 with angular frequencies equal to the Doppler shifts $\omega_m cos(2\pi n/N)$, $n =, 1, 2, \cdots, N_0$ together with one oscillator at frequency ω_m are used to generate signals that are added together and modulated onto quadrature carriers. The amplitudes of all oscillators are the same with the exception of the oscillator ω_m. The phases β_n are appropriately chosen so that the PDF of the resultant phase approximates to a uniform distribution. The proper amplitude and phase relationships are provided by amplifiers with gains of $2cos(\beta_n)$ or $2sin(\beta_n)$

It is apparent from the diagram that

$$x(t) = 2\sum_{n=1}^{N_0} cos\,\beta_n t\; cos\,\omega_n t \;+\; \sqrt{2}\,cos\,\alpha\; cos\,\omega_m t \tag{3.5}$$

$$y(t) = 2\sum_{n=1}^{N_0} sin\,\beta_n t\; cos\,\omega_n t \;+\; \sqrt{2}\,sin\,\alpha\; cos\,\omega_m t \tag{3.6}$$

where $\beta_n = \pi n/N_0$, $\omega_n = \omega_m cos(2\pi n/N)$, $\omega 2\pi \upsilon/\lambda$ and $N = 2(2N_0 + 1)$ The phase of the output $n(t)$ has to be random and uniformly distributed in the range $(0, 2\pi)$. To achieve this it is necessary to ensure that $x^2 \approx y^2$ and $xy \approx 0$.

3.2.2 Fast Fading With Varying LOS Component

The receiver will not always find itself in rough weather surroundings. For the more calm meteorological states a second model is proposed. For the scenario with moderate wind and waves the assumption of a LOS component in the received total radio signal is sound. The environment in which the receiver would find itself in between waves not reaching higher than itself although sea spray and reflection from the surrounding continuously changing environment would cause components with rapid fade characteristics.

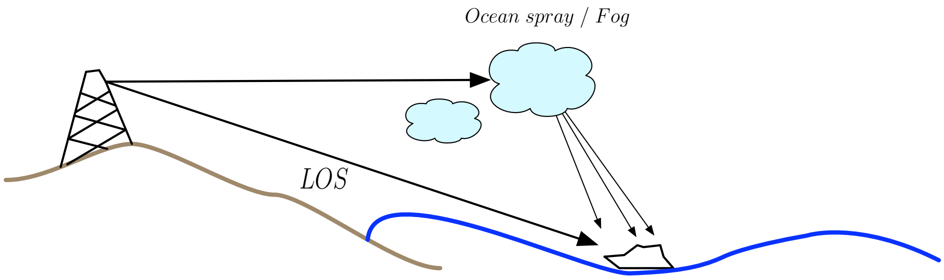

Figure 3.8: While subjected to Hydrometer Attenuation as in the case of the Rayleigh fading model, the Ricean receiver also takes in a LOS component that contributes to a stronger received signal.

The Ricean distribution has the more complicated form[2]:

$$f_{|r|}(x) = \frac{x}{\sigma^2} e^{-(x^2+\mu^2)/2\sigma^2} I_0(\frac{x\mu}{\sigma^2}),\ x \geq 0. \tag{3.7}$$

Where μ^2 is the power of the LOS component and I_0 is the 0th-order modified Bessel function of the first kind Since the Ricean distribution depends on the LOS component's power μ^2, a common way to characterize the channel is by the relative strengths of the LOS and scattered paths. this factor, K, is quantified as:

[2]By letting μ approach 0 it can be seen that the part $I_0 \frac{x\mu}{\sigma^2} = 1$ thus transforming the Rice distribution into the special case of Rayleigh distribution 3.3

$$K = \frac{\mu^2}{2\sigma^2} \tag{3.8}$$

For $K = 0$ the distribution is obviously Rayleigh. As K approaches ∞ The physical interpretation is that the LOS component becomes an increasingly larger part of the total signal until there is only the LOS component and no scattering [10].

By looking at this in the context of meteorology, the K-factor can be interpreted as a collective parameter for the scale of the wind, waves and amount of sea spray. Hence, within the restricted model of waves, wind and water particles in the air, the meteorological conditions from calm to rough weather can be described by a combination of Rayleigh- and Rice distributions.

Chapter 4

Channel estimation and The digital Kalman filter

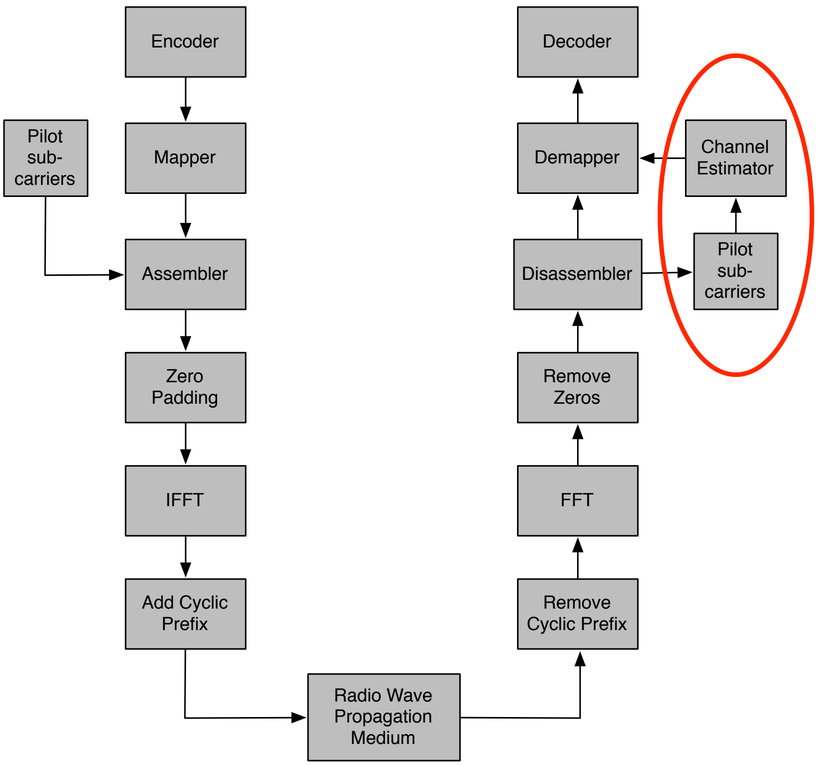

Figure 4.1: Model of a WiMAX simulator according to [4]

The digital Kalman filter is really more of an iterative algorithm than anything else. In many respects it does not resemble a filter at all [1]

The reason for bringing up the Kalman filter in the context of radio transmission is the need to effectively estimate channel conditions. The different physical media in which radio signals propagate have properties that also deteriorate the very same signals, making them unintelligible at the receiver. The effects of this signal fading can be countered by the application of estimators in the receiver. The better the estimate, the better the capabilities of countering the effects of this fading.

The Kalman filter is particularly interesting because of its versatility, accuracy and in the case of radio signal estimation relative efficiency. The algorithm as utilized in [1] is fed data from the training sequences and from a Jakes radio channel model. The novel idea is to use this model of the channel in parallel with the training sequences to improve the estimates. The result is a high performance channel estiamtor. Going back to table 4.1:

Table 4.1: Extract of table 4.1

Parameter	OFDMA PHY			
FFT Size	128	512	1,024	2,048
Number of Pilot subcarriers	12	60	120	240

It is seen that pilot subcarriers make out roughly ten percent or more of the total bandwidth in any of the OFDMA sizes. Pilot subcarriers are part of the adaptive coding and modulation regime of current WiMAX systems. They are the training sequences previously mentioned, taking up bandwidth. Hence to increase performance in channel estimation it is important to look at other solutions than increasing the number of or length of the pilots. The introduction of a channel model in parallel with training sequences allows improvement in channel estimates by as much as 30% without the need for more training sequences. The importance of the Kalman filter thus prompts an introduction of its basic functionality.

4.1 Introduction to the discrete Kalman filter

The following is a derivation from what may be found in [11]

The general assumption is that a process can be modelled as something similar to:

$$x_{k+1} = \Phi_k x_k + w_k \tag{4.1}$$

A discrete model represents the process that the Kalman filter will be subjected to. Measurements of the discrete values are modeled by

$$z_k = H_k x_k + v_k \tag{4.2}$$

The Kalman filter needs a sizable amount of calculations to be performed at each iteration. The number of variables so far gives an indication of this:

- $x_k = (n \times 1)$ process state vector at time t_k
- $\Phi = (n \times n)$ matrix connecting x_k and x_{k+1}. When x_k is a sample of contiuos source Φ_k is the state transition matrix.
- $w_k = (n \times 1)$ white sequence vector with known covariance.
- $z_k = (m \times 1)$ measurement vector
- $H_k = (m \times n)$ matrix connecting the sampled value to the measurement value
- $v_k = (m \times 1)$ vector of noise components affecting the measurement, assumed to be white, with know covariance and no correlation to w_k

From the values v_k and w_k their correlation matrices are constructed according to:

$$E[w_k w_i^T] = \mathbf{Q}_k \; \forall \, i = k, \; 0 \; otherwise. \tag{4.3}$$

$$E[v_k v_i^T] = \mathbf{R}_k \; \forall \, i = k, \; 0 \; otherwise. \tag{4.4}$$

and as previously mentioned the relationship:

[1]The Kalman filter owes its appearance to its function and time of conception. It is a practical solution of sorts of the discrete Wiener problem, conceived in 1960 by the Hungarian-American Rudolph Kalman. The algorithm estimates optimal values based on discrete measurements. The solution has its roots from a time when filters where constructed by consecutive electric elements to form a desired impulse response. [11]

$$E[w_k v_i^T] = 0 \; \forall \; i \; and \; k \tag{4.5}$$

A priori knowledge of the state of the system is assumed available through an estimate and is denoted $\hat{x}_k^-$, the hat meaning *estimate* and the minus indicating that it is *a priori*. The error in the estimate then follows as:

$$e_k^- = x_k - \hat{x}_k^- \tag{4.6}$$

This enables the creation of the covariance of the estimation error:

Assuming that the mean of the estimation error is 0

$$P_k^- = E[e_k^- e_k^{-T}] = E[(x_k - \hat{x}_k^-)(x_k - \hat{x}_k^-)^T] \tag{4.7}$$

This is where the adaptive features of the Kalman filter comes in. With the measurement of the process z_k and the latest estimate $\hat{x}_k^-$ a new estimate of x is produced through the relationship:

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H_k \hat{x}_k^-) \tag{4.8}$$

Where K_k is the *Kalman gain* blending the noise from the system with the prior estimate. The new error covariance matrix is then produced from

$$E[(x_k - \hat{x}_k)(x_k - \hat{x}_k)^T] \tag{4.9}$$

just as in equation 4.7 only with the new state estimates.

By substituting 4.2 into 4.8 and furthermore substituting this into 4.9 a general expression for the updated error covariance

$$P_k = (I - K_k H_k) P_k^- (I - K_k H_k)^T + K_k R_k K_k^T \tag{4.10}$$

is obtained. From this the calculation of any Kalman gain K_k can be done. This covariance matrix is necessary for finding the optimal Kalman gain which again finds the optimal estimates of the next state of the system.

To perform the optimization three rules of matrix derivation are applied:

1. $\frac{d[trace(AB)]}{dA} = B^T$ where A and B must be square
2. $\frac{d[trace(ACA^T)]}{dA} = 2AC$ where C must be symmetric
3. $$\frac{ds}{dA} = \begin{bmatrix} \frac{ds}{da_{11}} & \frac{ds}{da_{12}} & \cdots \\ \frac{ds}{da_{21}} & \frac{ds}{da_{22}} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}$$

The equation 4.10 is prepared for optimization by multiplying out its parts, its new form is:

$$P_k = P_k^- - K_k H_k P_k^- - P_k^- H_k^T K_k^T + K_k (H_k P_k^- H_k^T + R_k) K_k^T \tag{4.11}$$

With regard to the variable K, the second and third term are linear whereas the fourth term is quadratic. According to the rules of derivation the error covariance derivated with respect to K_k is:

$$\frac{d[traceP_k]}{dK_k} = -2(H_k P_k^-)^T + 2K_k (H_k P_k^- H_k^T + R_k) \tag{4.12}$$

To find the optimum K the equation is solved with respect to K:

$$K_k = P_k^- H_k^T (H_k P_k^- H_k^T + R_k)^{-1} \tag{4.13}$$

It is the first step in the digital Kalman algorithm presented by figure 4.2

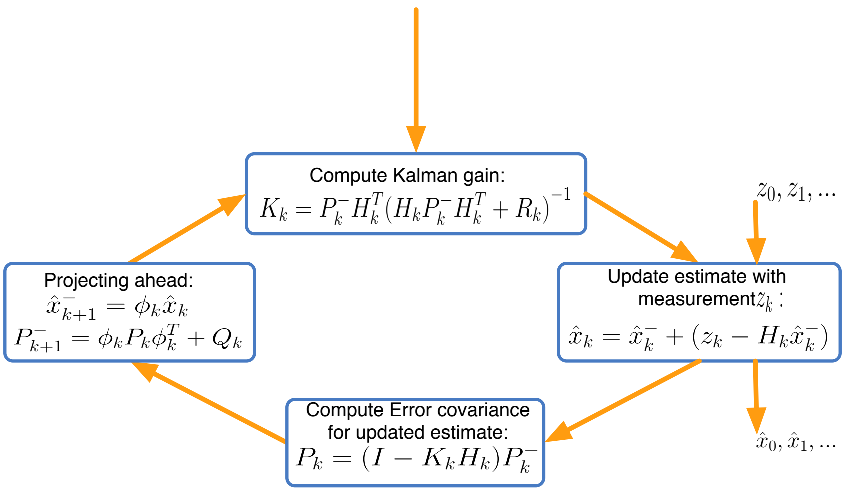

Figure 4.2: Basic graphical representation of a Kalman filter loop [11]

The optimal gain equation 4.13 in combination with the covariance equation 4.11 gives, through various substitutions, the optimal covariance:

$$P_k = (I - K_k H_k) P_k^- \tag{4.14}$$

Under the assumption that w_k is negligible, which is fair considering that it is uncorrelated with previous w and that it has zero mean, the next a priori estimate in the algorithm is given by:

$$\hat{x}_{k+1}^{-} = \Phi_k \hat{x}_k \tag{4.15}$$

Furthermore the Error covariance matrix needed to produce the next Kalman gain is computed from the a priori error:

w_k and e_k have zero crosscorrelation, because w_k is the process noise for the next step ahead of t_k

$$e_{k+1}^{-} = x_{k+1} - \hat{x}_{k+1}^{-} = (\Phi_k x_k + w_k) - \Phi_k \hat{x}_k = \Phi_k e_k + w_k \tag{4.16}$$

The resulting expression for a priori covariance is:

$$P_{k+1}^{-} = E[e_{k+1}^{-} {e_{k+1}^{-}}^T] = \Phi_k P_k \Phi_k^T + Q_k \tag{4.17}$$

Which is the last equation needed to form the iterative digital Kalman filter. It is being used in many applications from ship position control to stock exchange markets and now in recent years as an estimator of radio channels.

4.2 Application of the Kalman filter as a radio channel estimator- multiple path scenario

This section is in large part based on [4] and [1].

The digital Kalman filter has now been introduced. The following will describe how it may benefit WiMAX. The figure below represents the general idea of estimating a signal and finding the error in the estimate afterwards. In this particular case the algorithm is a version of the digital Kalman filter.

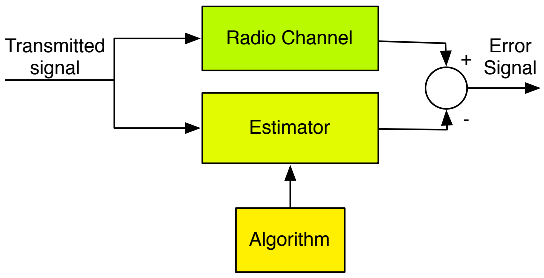

Figure 4.3: Generic model for state estimator [1]

4.2.1 Auto-regressive Estimator

The scenario of interest is where multiple paths of the same radio signal arrives at the receiver. This is a very real situation for most radio channel systems. The model receives training sequences regularly, of these training sequences there are multiple echoes as in a real multipath environment. Each of the echoes are used together with a Jakes tap-gain model in order to arrive at better estimates.

The Jakes tap-gain model is chosen to represent a scenario where the mobile station is moving at constant speed and the receiving omnidirectional antenna ”receives an infinite number of scattered waves at uniformly distributed angles of arrival” [1]. These are conditions for a Jakes shaped received power spectrum.

The Jakes spectrum is modeled as an *Auto-Regressive* process [2] The filters weights may be found by solving the Yule-Walker set or by utilizing a shaping filter. In [1], a shaping filter is used. This closed form shaping filter

[2]The Auto-regressive process may be looked upon as a filter with infinite impulse response consisting of only poles, no zero-points.

$$h_j(t) = 2^{1/4}\Gamma(\frac{3}{4})f_m(2\pi f_m t)^{-1/4}J_{1/4}(2\pi f_m t) \tag{4.18}$$

with the parameters:

- Γ - the gamma function
- f_m - doppler bandwidth [3] of the channel.
- $J_{1/4}$ - the fractional Bessel function [4]

is sampled at a pace 16 times higher than the doppler bandwidth to avoid aliasing and frequency warping. $h_j(n) = h_j(\frac{n}{F_s}) \ \forall\ n = 0...(M-1)$. M is the nubmer of taps in the Jakes filter. The output of the shaping filter when fed with white noise is described by the convolution:

$$S(n) = \sum_{m=0}^{M-1} h_j(m)w(n-m) \tag{4.19}$$

$w(n)$ is white noise

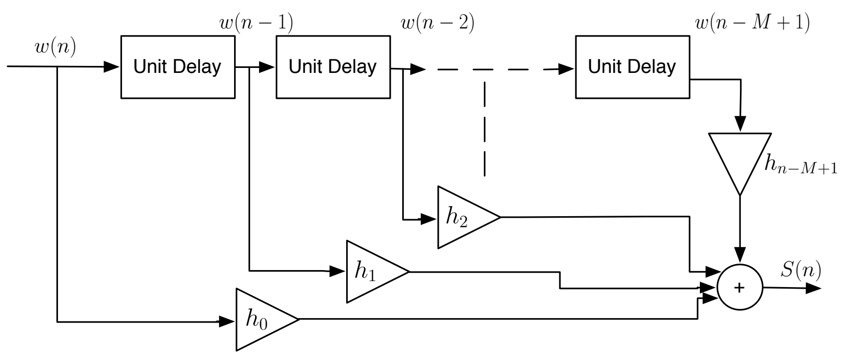

Figure 4.4: Illustration of the convolution process as a weighted moving average [1]

The reason for representing the convolution process as a moving average (fig: 4.4) is to more easily see the transformation into the equivalent Auto-regressive form.

[3] The doppler bandwidth is defined as $f_m = \frac{\nu}{\lambda}$ where ν is the velocity of the mobile station and λ is the wavelength of the carrier

[4] The Bessel functions are solutions of Bessels differential equation: $x^2\frac{d^2y}{dx^2} + x\frac{dy}{dx} + (x^2 - \alpha^2)y$ where $\alpha = 1/4$ in this case.

Using the delay operator:

$$z^{-j}S(n) = S(n-j) \tag{4.20}$$

The equation 4.20 may be transformed into:

$$S(n) = \left(\sum_{m=0}^{M-1} h_j(m) \left(z^{-1}\right)^m \right) w(n) \tag{4.21}$$

Which again may be rewritten

$\Psi(z^{-1})$ may be regarded as a polynomial of z^{-1}.

$$S(n) = \Psi(z^{-1})w(n) \tag{4.22}$$

This permits a transformation of 4.22 expressed as:

$$\frac{S(n)}{\Psi(z^{-1})} = w(n) \tag{4.23}$$

The polynomial term is subjected to more simplification:

$$\frac{1}{\Psi(z^{-1})} = \frac{1}{h_0 + h_1 z^{-1} + h_2 z^{-2} ... h_{M-1}(z^{-1})^{M-1}} \tag{4.24}$$

In [1] this rational function is expanded into

$$\frac{1}{\Psi(z^{-1})} = \frac{r_1}{1-p_1 z^{-1}} + \frac{r_2}{1-p_2 z^{-2}} + \frac{r_{M-1}}{1-p_{M-1}(z^{-1})^{M-1}} \tag{4.25}$$

by convergence of sums it follows that:

$$\frac{1}{1-pz^{-1}} = \sum_{i=0}^{\infty} \left(pz^{-1}\right)^i = \left[1 + pz^{-1} + (pz^{-1})^2 + (pz^{-1})^3 + \ ... \right] \tag{4.26}$$

This allows a transformation of equation 4.25

$$\begin{aligned} \frac{1}{\Psi(z^{-1})} = r_1 \Big[1 + p_1 z^{-1} + (p_1 z^{-1})^2 + (p_1 z^{-1})^3 + \dots \Big] + \\ r_2 \Big[1 + p_2 z^{-1} + (p_2 z^{-1})^2 + (p_2 z^{-1})^3 + ... \Big] + \dots \\ \dots + r_{M-1} \Big[1 + p_{M-1} z^{-1} + (p_{M-1} z^{-1})^2 + (p_{M-1} z^{-1})^3 + \dots \Big] \end{aligned}$$

Simplifying again transforms equation 4.27 into an infinite series sum:

$$\frac{1}{\Psi(z^{-1})} = \sum_{i=1}^{M-1} r_i + z^{-1} \sum_{i=1}^{M-1} r_i p_i + z^{-2} \sum_{i=1}^{M-1} r_i p_i^2 \ \dots \infty \tag{4.27}$$

which in turn is truncated into N+1 terms: Simplifying again transforms equation 4.27 into an infinite series sum:

$$\frac{1}{\Psi(z^{-1})} = \sum_{i=1}^{M-1} r_i + z^{-1}\sum_{i=1}^{M-1} r_i p_i + z^{-2}\sum_{i=1}^{M-1} r_i p_i^2 \; \ldots \; z^{-N}\sum_{i=1}^{M-1} r_i p_i^N \tag{4.28}$$

Substituting $\Pi_n = \sum_{i=1}^{M-1} r_i p_i^n$ gives the equation on the form:

$$\frac{1}{\Psi(z^{-1})} = \Pi_0 + z^{-1}\Pi_1 + z^{-2}\Pi_2 + \ldots + +z^{-N}\Pi_N \tag{4.29}$$

If equation 4.30 is inserted into 4.23 a new equation is produced

$$\Big(\Pi_0 + z^{-1}\Pi_1 + z^{-2}\Pi_2 + \ldots + +z^{-N}\Pi_N\Big)S(n) = w(n) \tag{4.30}$$

Expanding by multiplication gives:

Keeping in mind that $z^{-j}S(n) = S(n-j)$

$$\Pi_0 S(n) = -\Pi_1 S(n-1) - \Pi_2 S(n-2) - \Pi_N S(n-N) + w(n) \tag{4.31}$$

$$S(n) = \frac{1}{\Pi_0}\Big[-\Pi_1 S(n-1) - \Pi_2 S(n-2) - \Pi_N S(n-N) + w(n)\Big] \tag{4.32}$$

When compared to the autoregressive system equation:

$$S(n) = \sum_{i=1}^{N} \Phi_i S(n-i) + w(n) \tag{4.33}$$

$$S(n) = \Phi_1 S(n-1) + \Phi_2 S(n-2) + \ldots + \Phi_N S(n-N) + w(n) \tag{4.34}$$

There is a strong resemblance between the two, the auto-regressive coefficient for the moving average is thus derived to be:

$$\Phi_n = \frac{\Pi_n}{\Pi_0} \tag{4.35}$$

Coincidently, for a "moving average system driven by unity variance gaussian noise is equivalent to an autoregressive process where the plant noise dirving the autoregressive system is given by" [1]:

$$\sigma_w^2 = \left(\frac{1}{\Pi_0}\right)^2 \tag{4.36}$$

Figure 4.5 illustrates the connection between the two models:

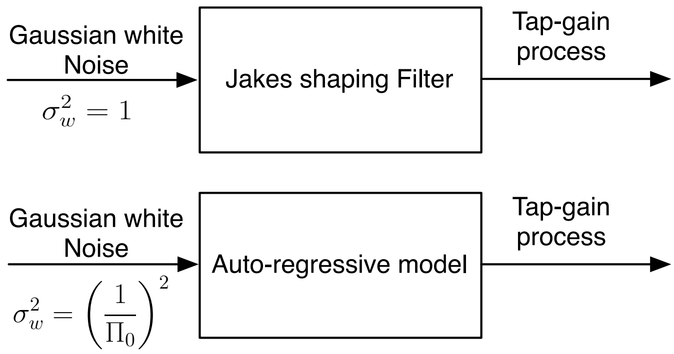

Figure 4.5: Illustration of the two equivalent tap-gain systems: Jakes shaping filter and Auto-regressive model [1]

This is also how the parameters for the autoregressive model is calculated from the Jakes shaping filter. A finite length filter would result in an infinite length AR-model, hence the AR-model is truncated to finite length [1]. For a comparison of the quasi-infinite versus the truncated version see [1]. The comparison concludes that the truncated version is less accurate than the quasi-infinite version. It is preferred however as it is easier to implement, yields a faster start-up and has a smaller computational load.

When tracking a multiple path radio channel the auto-regressive model becomes:

$$
\begin{aligned}
S_1(n) &= \sum_{i=1}^{N} \Phi_i S_1(n-i) + w_1(n) \\
S_2(n) &= \sum_{i=1}^{N} \Phi_i S_2(n-i) + w_2(n) \\
&\quad . \\
&\quad . \\
S_l(n) &= \sum_{i=1}^{N} \Phi_i S_L(n-i) + w_L(n)
\end{aligned}
$$

The matrix describing the multiple path scenario for the auto-regressive model is thus:

$$
\begin{bmatrix}
S_1(n) & S_2(n) & \cdots & S_L(n) \\
S_1(n-1) & S_2(n-1) & \cdots & S_L(n-1) \\
\vdots & \vdots & \ddots & \vdots \\
S_1(n-N+1) & S_2(n-N+1) & \cdots & S_L(n-N+1)
\end{bmatrix} =
$$

$$\begin{bmatrix} \Phi_1 & \Phi_2 & \cdots & \Phi_N \\ 1 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} S_1(n-1) & S_2(n-1) & \cdots & S_L(n-1) \\ S_1(n-2) & S_2(n-2) & \cdots & S_L(n-2) \\ \vdots & \vdots & \ddots & \vdots \\ S_1(n-N) & S_2(n-N) & \cdots & S_L(n-N) \end{bmatrix} \begin{bmatrix} w_1(n) & w_2(n) & \cdots & w_L(n) \\ 0 & \cdots & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & \cdots & 0 \end{bmatrix}$$

This expression can be written on vector form as:

$$\bar{S}(n) = A\bar{S}(n-1) + \bar{W}(n) \tag{4.37}$$

From the noise matrix $\bar{W}(n)$ the plant noise covariance is calculated [5]:

$$Q = E\Big[\bar{W}(n)(\bar{W})^H\Big] = \begin{bmatrix} \sum_{i=1}^{L} s_w^1(l) & \cdots & 0 & \\ 0 & \cdots & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & \cdots & 0 \end{bmatrix} \tag{4.38}$$

4.2.2 Data estimation

The *Observation model* predicts the next state of the channel based on the *training sequences*. In [1] the proposition is to augment this training sequence scheme with the above introduced auto-regressive channel model. The motive being to improve the estimates.

In the case of WiMAX the training sequences are pilot subcarriers.

The training sequences are modeled in vector form as [6]:

$$\bar{x} = \Big[x_0, x_1, \cdots, x_{M-1}\Big]^T \tag{4.39}$$

The sequence is simulating BPSK modulation via the mapping:

$$bit\ 0 = +1\ ,\ bit\ 1 = -1 \tag{4.40}$$

When sent over the channel the impulse response of the sequence is:

L is the number of processes to be tracked

$$\bar{h} = \Big[\tilde{h}_0\tilde{h}_1\tilde{h}_2\cdots\tilde{h}_{L-1}\Big]^T \tag{4.41}$$

When received the signal will be the convolution sum of the output from the transmitter and the impulse response under influence of channel noise:

$$\bar{y} = \bar{x} * \bar{h} + n_c \tag{4.42}$$

---

[5] The exponent ^{H} is the Hermetian matrix transpose. The Hermetian transpose is the complex conjugate of the common matrix transpose ^{T}

[6] It is assumed that "the channel does not change over the period of one training sequence" [1]

The same signal represented in matrix form:

$$y = \begin{bmatrix} x_0 & 0 & \cdots & 0 \\ x_1 & x_0 & \cdots & \cdots \\ \cdots & x_1 & \ddots & 0 \\ \cdots & \ddots & \ddots & x_0 \\ x_{M-1} & \ddots & \ddots & x_1 \\ 0 & x_{M-1} & \ddots & \cdots \\ \cdots & 0 & \ddots & \cdots \\ 0 & 0 & \cdots & x_{M-1} \end{bmatrix} \begin{bmatrix} h_0 \\ h_1 \\ \vdots \\ \vdots \\ h_{L-1} \end{bmatrix} + \begin{bmatrix} n_{c_0} \\ n_{c_1} \\ \vdots \\ \vdots \\ \vdots \\ n_{c_{L+M-2\times 1}} \end{bmatrix}$$

Also represented in vector form as [7]:

$$\bar{Y} = \bar{X} * \bar{h} + \bar{n}_c \tag{4.43}$$

The $\bar{h}$ is the channel's impulse response and the $\bar{n}_c$ is the additive white gaussian noise with zero mean and variance σ_c^2. SNR is then calculated given an $E_b = 1$:

$$\frac{E_b}{N_0} = \frac{1}{2\sigma_c^2} \tag{4.44}$$

In [1] a linear regression is proposed to estimate this data, it has the form of:

$$\hat{\bar{h}} = (\bar{X}^T \bar{X})^{-1} (\bar{X}^T \bar{Y}) \tag{4.45}$$

From this the error of the data based (training sequence based) estimator can be calculated by insertion of equation 4.43 into equation 4.45:

$$\begin{aligned} \hat{\bar{h}} &= (\bar{X}^T \bar{X})^{-1} (\bar{X}^T (\bar{X} * \bar{h} + \bar{n}_c)) \\ = (\bar{X}^T \bar{X})^{-1} &(\bar{X}^T \bar{X}) \bar{h} + (\bar{X}^T \bar{X})^{-1} (\bar{X}^T \bar{n}_c) \\ &\bar{h} + (\bar{X}^T \bar{X})^{-1} (\bar{X}^T \bar{n}_c) \end{aligned}$$

The error between the two then being:

$$\tilde{\bar{h}} = \hat{\bar{h}} - \bar{h} = (\bar{X}^T \bar{X})^{-1} (\bar{X}^T \bar{n}_c) \tag{4.46}$$

The mean of which is: $E[\tilde{\bar{h}}] = 0$. The covariance of the error is then calculated:

$$P_D = E\Big[\tilde{\bar{h}} (\tilde{\bar{h}})^H\Big] = \sigma_c^2 (\bar{X}^T \bar{X})^{-1} \tag{4.47}$$

[7] The $\bar{X}$-vector having constant diagonals is called a Toeplitz matrix. The $\bar{X}$-vector contains the delayed versions of the training sequence

The term $(\bar{X}^T\bar{X})^{-1}$ being a matrix of *normalized* training sequence autocorrelation is represented as[8]:

$$(\bar{X}^T\bar{X})^{-1} = \frac{1}{M}\begin{bmatrix} 1 & r_{xx}(1) & \cdots & r_{xx}(L-1) \\ x_1 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ r_{xx}(L-1) & \cdots & r_{xx}(1) & 1 \end{bmatrix}^{-1} \tag{4.48}$$

With the training sequence autocorrelation denoted:

$$r_{xx}(k) = \frac{1}{R_{xx}(0)}\sum_{i=0}^{M-1} x_i x_{i-k} = \frac{1}{M}\sum_{i=0}^{M-1} x_i x_{i-k} \tag{4.49}$$

The error covariance matrix looking at equation 4.47 then becomes:

$$\frac{\sigma_c^2}{M}\begin{bmatrix} 1 & r_{xx}(1) & \cdots & r_{xx}(L-1) \\ x_1 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ r_{xx}(L-1) & \cdots & r_{xx}(1) & 1 \end{bmatrix}^{-1} = \frac{\sigma_c^2}{M}(\bar{X}^T\bar{X})^{-1} \tag{4.50}$$

The conclusion is that the *data estimate covariance* and the length of the *training sequences* are *inverse proportional*. Furthermore the data estimate deteriorates according to the amount of noise in the channel.

4.2.3 The Kalman filter according to [1]

The Kalman filter proposed is a vector Kalman filter with initial conditions:

$$\hat{S}(0) = E\{S(n)\} = \begin{bmatrix} 0 \\ \vdots \\ \vdots \\ 0 \end{bmatrix} \tag{4.51}$$

and [9]:

$$P(1) \geq \{\sigma_w^2[I] \;\&\; \sigma_v^2[I]\} \tag{4.52}$$

The parameters for the Kalman filter mid-process are as follows:

[8] $(\sum_{i=0}^{M-1} x_i x_{i-k} = M \;, \forall\, k = 0.)$

[9] the I is the $L \times L$ Identity matrix

1. The contemporary estimate of the process, with the data estimate:

$$\hat{S}_{cont}(n) = \hat{S}(n) + K(n)[X(n) - H\hat{S}(n)] \tag{4.53}$$

2. The predicted estimate of the process:

$$\hat{S}(n+1) = A\{\hat{S}_{cont}(n)\} \tag{4.54}$$

3. Current error covariance:

$$P(n+1) = A\{P_{cont}\} \tag{4.55}$$

4. Predicted error covariance:

$$P(n+1) = A\{\hat{P}_{cont}(n)\}A^T + Q \tag{4.56}$$

These equations share some similar traits with equations 4.14 to 4.17 in the introduction of the Kalman filter, thus implying a Kalman filter structured algorithm. An illustration of the total channel estimating process is given in figure 4.6[10]:

[10]The figure 4.6 is based on description in [1]

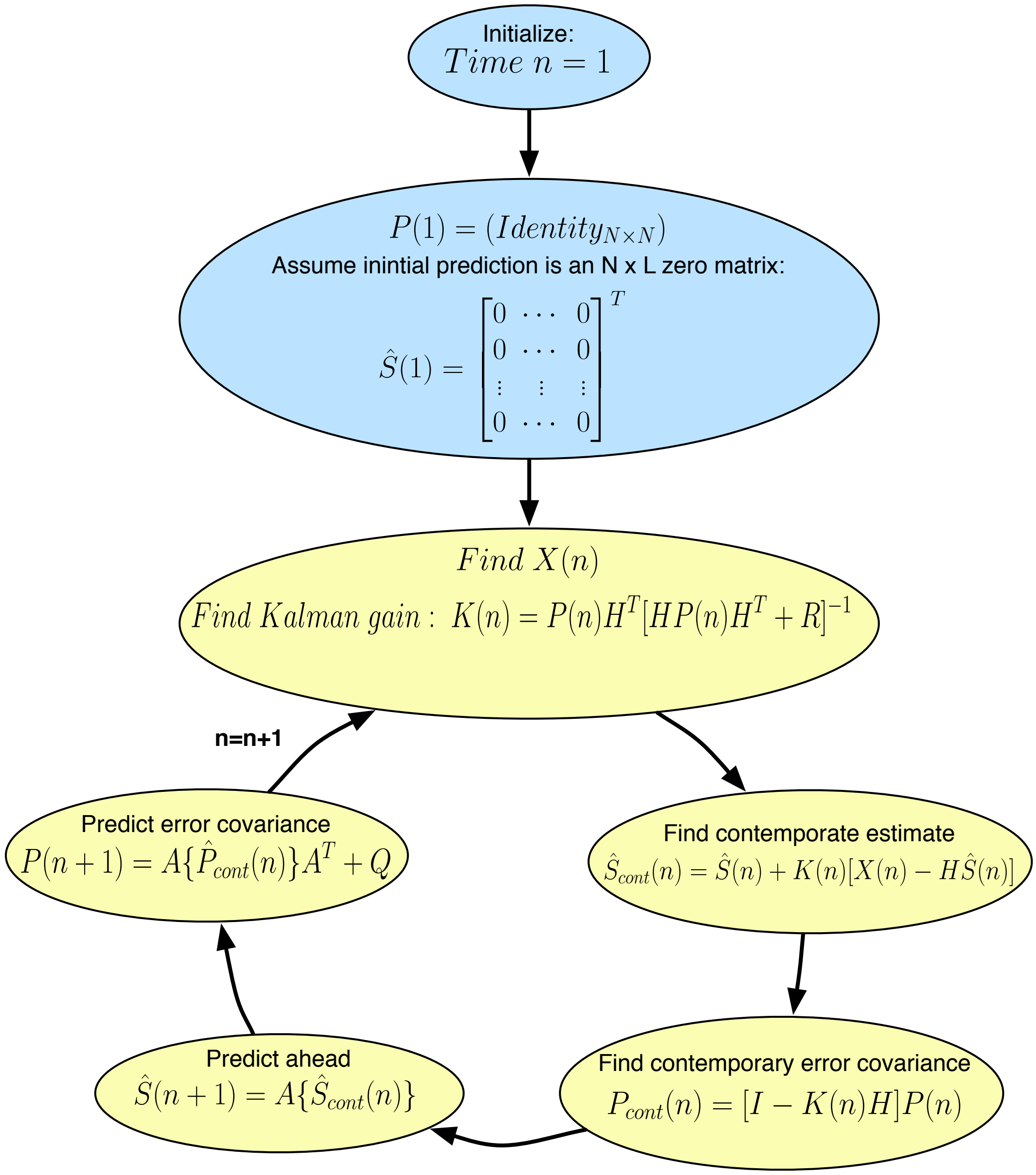

Figure 4.6: Channel estimator algorithm for multiple path signals.

4.2.4 Estimating WiMAX signals

In [4] a model for OFDM a model for a complete WiMAX simulator is proposed. The implementation of the model is constructed in Matlab Simulink. The report describes in detail a 256 point FFT OFDM PHY layer. In this case the ratio of pilot subcarriers to the other subcarriers is smaller than for the mobile WiMAX setup:

$$pilot\ subcarrier\ ratio : \frac{\#pilot\ subcarriers}{FFT - size} = \frac{8}{256} = \frac{1}{32} => \underline{3.125\%} \quad (4.57)$$

The model is however a good foundation for an OFDMA model. It contains the traditional channel estimation and AMC functions. The goal is to improve the channel estimation of the WiMAX system through an adaptation of the method proposed by [1]. The model used as basis for this preliminary step is the one presented in [4]. More specifically the part of interest is the "Channel Estimation" block in figure 4.7

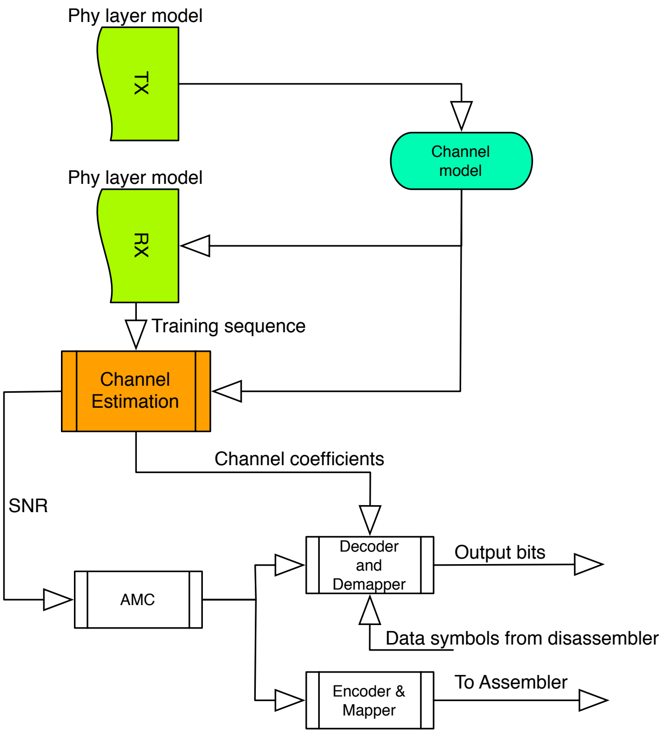

Figure 4.7: The Channel estimation and AMC modules as proposed by [4]. Above this a rudimentary layout of the Transmitter-Channel-Receiver relationship is illustrated to give perspective.

There are a number of transformations needed to fit the two models together. Looking at figure 4.7 the part in the WiMAX model that will be changed is the channel estimation algorithm.

In the case of OFDM there are two different methods for implementation of training sequences. One adds the training sequence as a preamble in the signal. This is the model adopted by [4]. The other, which has been tacitly assumed default until now, uses some of the subcarriers for training sequences. To accommodate both approaches they should both be implemented. This implies, when looking at the model from [4], that the As for the estimator algorithm from [1] the model needs to be able to handle different signal modulations, not just BPSK. Also, the training sequences of [1] are not compatible with the ones of a WiMAX system thus prompting an adaptation. The issue of the training sequences affects the length of the vector 4.39 in the data estimator:

$$\bar{x} = \left[x_0, x_1, \cdots, x_{M-1}\right]^T \tag{4.58}$$

further affecting the size of the matrix:

$$\begin{bmatrix} x_0 & 0 & \cdots & 0 \\ x_1 & x_0 & \cdots & \cdots \\ \cdots & x_1 & \ddots & 0 \\ \cdots & \ddots & \ddots & x_0 \\ x_{M-1} & \ddots & \ddots & x_1 \\ 0 & x_{M-1} & \ddots & \cdots \\ \cdots & 0 & \ddots & \cdots \\ 0 & 0 & \cdots & x_{M-1} \end{bmatrix} \tag{4.59}$$

of the equation 4.43:

$$\bar{Y} = \bar{X} * \bar{h} + \bar{n}_c \tag{4.60}$$

The error covariance remains the same size as it is determined by the number of processes tracked. The length of the training sequences will vary with the size of the WiMAX symbols. A small 256 OFDM symbol will make a small training sequence because of smaller size and fever pilot carriers in the fixed WiMAX protocols. A large 1024 OFDMA symbol will make a much larger sequence.

The SNR produced by the channel estimator is used in WiMAX to decide which modulation and coding scheme that best fits the current channel conditions. These thresholds are decided by the relationships between SNR and BER shown in figure 4.8

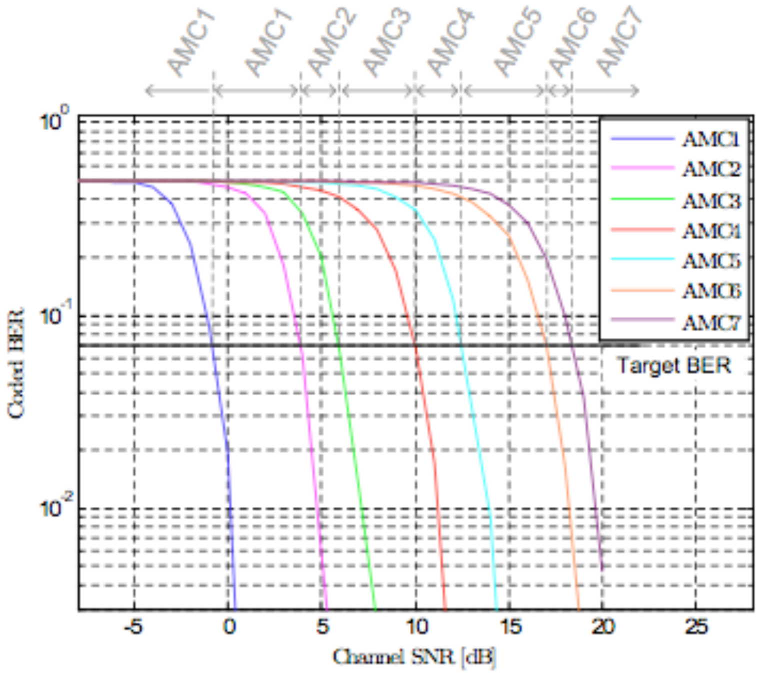

Figure 4.8: SNR-BER curves for the different modulations in WiMAX [4]

These AMC levels are described in modulation and coding rate as follows:

AMC Mode	Modulation scheme	Overall coding rate
AMC1	2-PAM	1/2
AMC2	4-QAM	1/2
AMC3	4-QAM	3/4
AMC4	16-QAM	1/2
AMC5	16-QAM	3/4
AMC6	64-QAM	2/3
AMC7	64-QAM	3/4

Figure 4.9: Parameters for the different AMC schemes[4]

The different modulations have different energy efficiency. The low spectral efficiency modulations (2-PAM, 4-QAM) require lower bit energy to noise rate $\frac{E_b}{N_0}$. They are described as energy efficient. High spectral efficiency modulations are accordingly less efficient in energy. Each modulation has a corresponding SNR-BER curve. The output SNR from the signal estimator is converted to BER and the appropriate modulation and coding scheme for the next sequence to be sent is then chosen. With a better estimate it is possible to more accurately decide the best modulation for the current channel conditions, this is the key to better throughput of WiMAX via enhanced channel estimation.

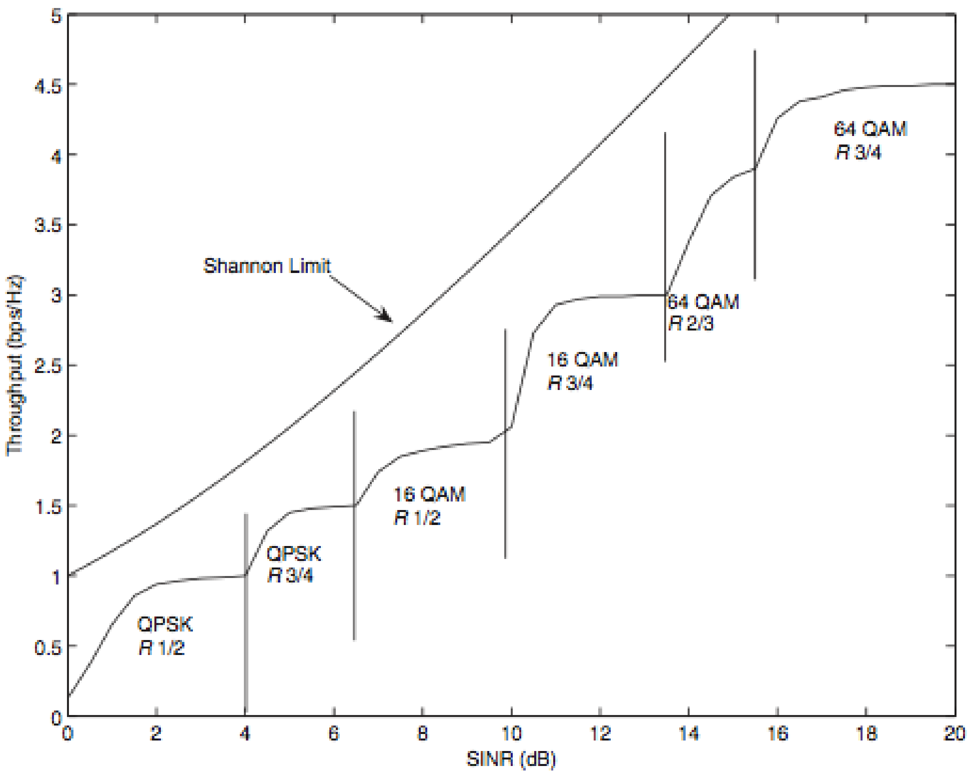

Figure 4.10: The figure describes throughput versus SINR, assuming that the best available constellation and coding configuration are chosen for each SINR. Only six configurations are used in this figure. [10]

The improvement of the new estimator algorithm is determined by comparing the MSE of the error in the *data only* estimate scenario 'v' to the MSE of the *data and model* estimate scenario. The expression for comparing the relationship is given below in equation 4.61

$$\frac{\sigma_v^2 - diag(P_{cont_{sim}})[1,1]}{\sigma_v^2} \tag{4.61}$$

Where

$$\sigma_v^2 \tag{4.62}$$

is the MSE for the data only scenario and

$$diag(P_{cont_{sim}})[1,1] \tag{4.63}$$

Is the MSE for one of the paths in the data and model scenario.

In [2] a simulation run with three paths is presented. The improvements according to the relationship 4.61 for path one, two and three are respectively 28.66%, 30.57% and 32.48%.

The extent and degree of improvement of a WiMAX system will be revealed by model simulations and live testing.

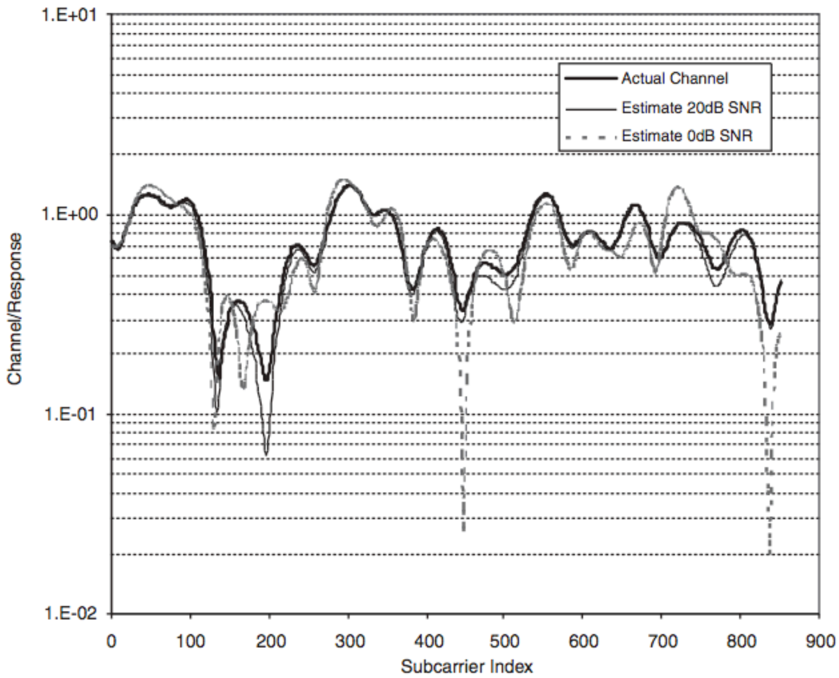

Figure 4.11: Simulation run of an LMMSE channel estimator. The algorithm performs badly below an SNR of 0dB.[10]

Chapter 5

Ad hoc networking

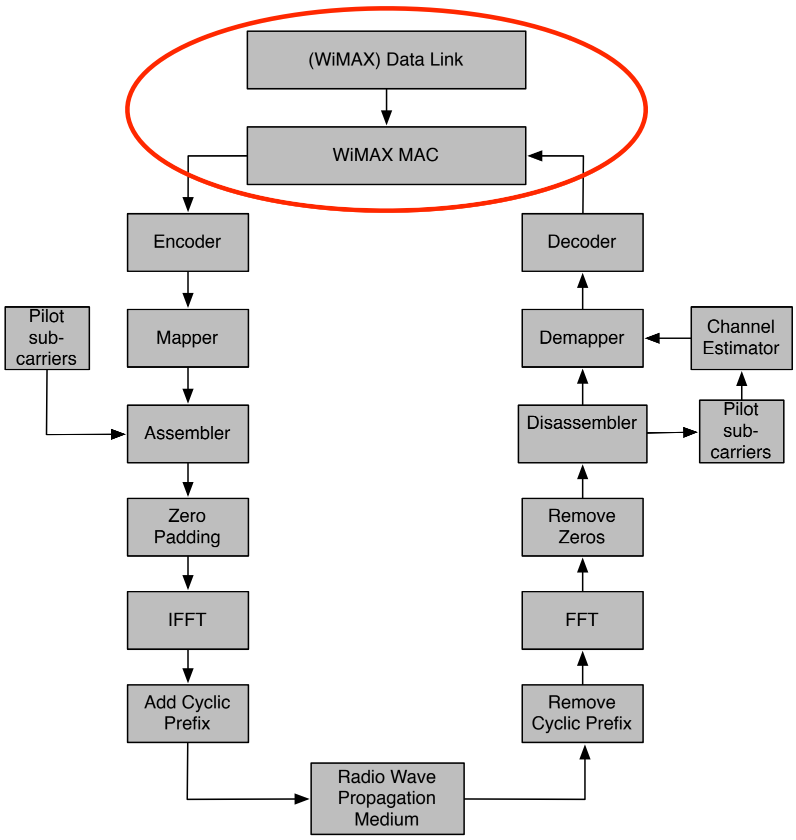

Figure 5.1: Model of a WiMAX simulator according to [4]

Ad hoc networks are versatile and resilient to rapid changes in the network structure. This is a technology that enables untethered, wireless networking in environments where there is no wired or cellular infrastructure. The term *"ad hoc"* implies that the network is created for a special purpose, a particular service or application. [16]. Such a purpose is clear in situations like rescue operations and natural disasters where coordination is key to safe and effective operation. In the event of an emergency situation the local infrastructure could experience overload and as a result a severe loss in service quality. Such situations are to a certain extent preventable with ad hoc network solutions.

A scenario is illustrated in figure 5.2. The situation is ameliorated by the redundancy in network nodes. With node C broken the connection between A and E is still active via other network nodes. This is not special for Adhoc networking but the lack of centralized control to obtain this result is a distinguishing feature.

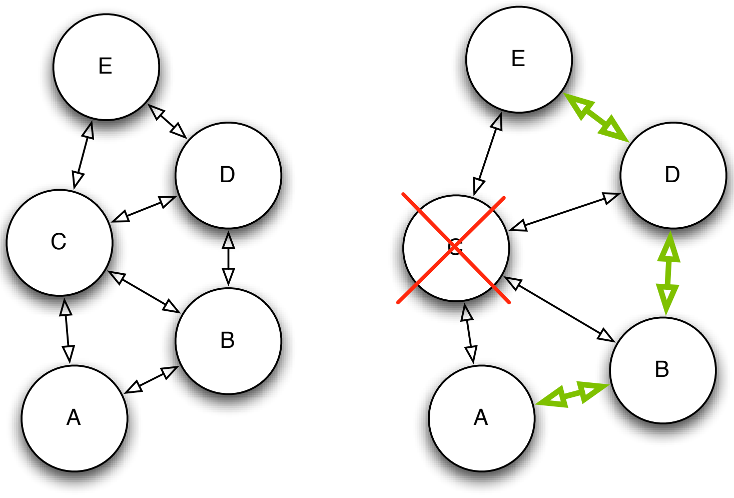

Figure 5.2: Robust ad hoc network

The nodes have rearranged the stream of data from A to E without the use of a supervising process and maintained connection with all the other nodes through direct or indirect connections.

An important application of ad hoc networking is the connection of networks. By placing nodes between two networks otherwise unreachable the two networks may communicate. As mentioned in chapter one, a major challenge in the northern norwegian controlled waters is lack of communication capacity. This potentially leaves vessels at sea in emergency situations with little or no means of communication. With the capability of deploying one or several network nodes to connect to the mainland this can be redeemed.

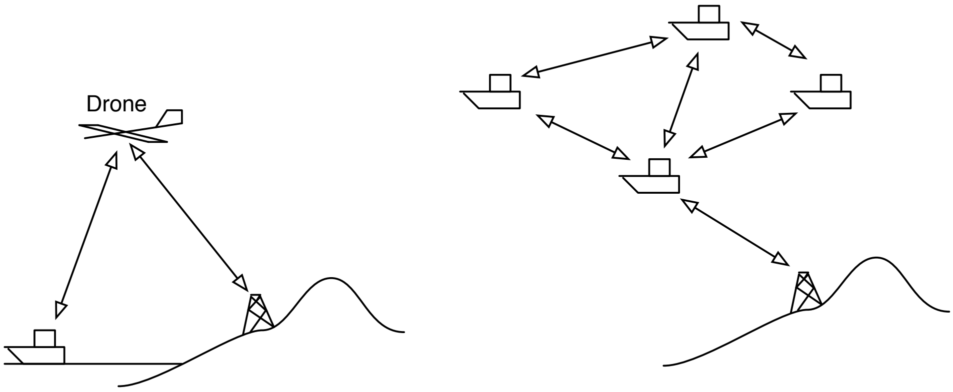

Figure 5.3: Extended network through ad hoc network nodes

Figure 5.12 illustrates the situation where vessels, airborne or at sea level, act as relay stations to temporarily expand the range of a network. Enabling broadband wireless capacities in ad hoc solutions would provide good connectivity even in remote locations. Evolving the WiMAX standard to include such capabilities prompts the investigation of ad hoc networking.

Ad hoc networks really has not seen a lot of deployment outside military applications [16]. The technology is still to a large extent unused. In [7] A model based on the random access algorithms ALOHA[1] and CSMA[2] is created to measure their performance in an ad hoc context. The main parameter of the simulations is probability of outage.[3]. It makes sense to look at outage as an important metric in the context of critical situations such as search and rescue operations.
CSMA is vastly more efficient than ALOHA as it actually waits on a vacant

[1]ALOHA is a simple random access communication protocol where data is sent over the medium and if collision occurs the data is sent again [18]

[2]CSMA is, like ALOHA, a random access protocol. It is called *Carrier Sense* because it senses after other carrier waves before sending its own message in order to avoid collision from other transmitters.[18]

[3]Outage occurs when the received SINR is below a threshold β [7]

channel to send, whereas the ALOHA protocol sends regardless of traffic. Hence CSMA obtains a much larger throughput than ALOHA.

5.1 The Ad hoc model according to [7]

The model described by [7] is built up by transmitters and receivers arranged in pairs with fixed distance and random position with respect to each other. The transmitters are assigned to random positions within an area A. All transmitters emit the same amount of power. Packets for transmission are then assigned to each transmitter according to a one-dimensionsional *Poisson Point Process*. The channel model is only considering path loss attenuation effects. Shadowing and fast fades are not part of the model design. However, as in any cellular network all nodes in the model experience interference from other transmitters which add to the total SINR at the receivers.

Packets received at a time when the SINR is below the threshold β are regarded ass *received in outage*.

With an upper limit of ϵ.

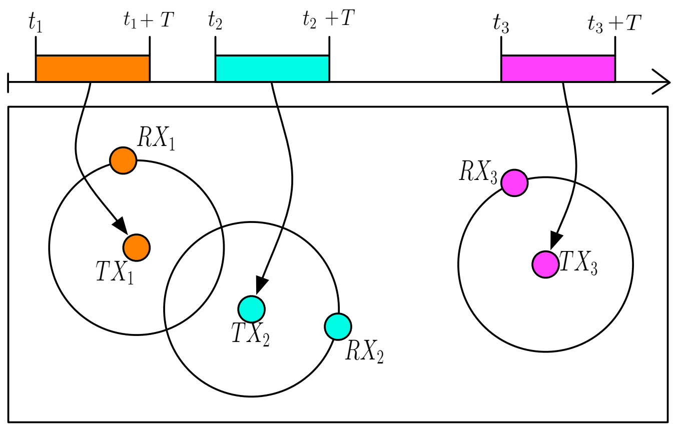

Figure 5.4: The packets are assigned to a transmitter-receiver pair, randomly placed on the plane A [7]

The Poisson Point Process:

Point processes provide a useful and convenient way of looking at processes with jumps, particularly processes with independent increments that lead to Poisson point processes. The simplest example of a Poisson Point Process is the random set of times at which a Poisson process $N(t)$ has jumps. Here X is $\mathbb{R}^+$ and $d\mu = \rho dt$ where ρ i the intensity. The number of jumps in an interval $[a,b] \subset [0,\infty]$ is the increment of N(t) over that interval and has the poisson distribution with parameter $\rho(b-a)$. The increments are mutually independent if the intervalls are disjoint. The definition of Poisson random measure is therefore satisfied when the sets in question are intervals [26].

A *Poisson Random Measure* or *Poisson Point Process* with intensity μ is a random measure $\lambda(A,\omega)$ such that for any $A \in \mathbb{B}$ it has a Poisson distribution with parameter $\mu(A)$ and $\lambda(A_j,\omega)$ are mutually independent for any finite collection of disjoint sets $\{A_j\} \in \mathbb{B}$ [26].

Table 5.1: Parameters of the Ad hoc model

Description	Parameter	Value	Unit
Path loss exponent	α	3	-
Length of each side of an $L \times L$ plane	L	40	Meters
Distance between TX and designated RX	R	1	Meters
Transmission power for each transmitter	ρ	1	Watts
Length of each data packet transmitted	T	[1, 100]	Seconds
Required threshold for received SINR	β	0	dB
Spatial density of nodes	λ^s	$[10^{-5}, 10]$	Nodes/m^2
Temporal density of transmission packets	λ^t	0,1	Packets/sec

As far as the ad hoc network model [7] is concerned the arrival rate is $\lambda^{temporal} = (A\lambda/T)$, where A is the area of the plane. The parameter for the Poisson distribution is described by the equation:

$$\lambda^{temporal} = \frac{A\lambda}{T} = A\lambda^s\lambda^t \tag{5.1}$$

This is the density of packet arrivals and λ^s represents the spatial density of nodes on the plane. Also, the total number of nodes on the plane is given by:

$$AT\lambda^s\lambda^t \tag{5.2}$$

The model is assuming AWGN[4] between all nodes in the network. The transmitter receiver distance is designed so that the emitted power from

[4]Additive White Gaussian Noise

a transmitter is unity at unity distance to the receiver. Active nodes start transmitting their packets immediately after they are positioned on the plane.

The SINR threshold for the simulations is set to 0dB meaning that the signal to interference and noise ratio ($\frac{signal}{interference+noise}$) is unity.

The simulations are run for the slotted ALOHA[5], unslotted ALOHA and CSMA protocols. During the two latter simulations three different approaches are considered, the RX-RX, TX-RX and the TX-TX approach.

5.1.1 Slotted ALOHA

This prompts the introduction of *guard zones*, a word known from cellular network solutions and radar applications [6]. Specifically, in the context of the model at hand, a Guard zone is a theoretical circular border around a receiver. Within the circle, the SINR ratio is high enough to avoid packets arriving in outage. Essentially if two transmitters exist within the same guard zone, SINR will drop to a level $\leq \beta$.

The size of guard zones affects throughput in an Ad hoc network because nodes are inhibited within the guard zones [7]. Furthermore, the size of the guard zone is determined by setting the expression for SINR equal to β and solving for s, thus obtaining:

$$s = \left(\frac{R^{-\alpha}}{\beta} - \frac{\eta}{\rho} \right)^{-1/\alpha} \tag{5.3}$$

The area of the circle with radius s for the Receiver RX_1 is denoted $B(R_1, s)$

[5] Slotted ALOHA is an improvement of the ALOHA protocol that reduces the number of packet collisions. It introduces discrete time periods in which packets are either sent or not sent. Packet transmission may only occur at the beginning of the time period.

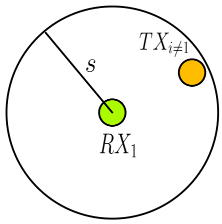

Figure 5.5: The guard zone of RX_1 depicted together with a transmitter not paired with the receiver, thus causing destructive interference according to the model of [7]

Denoting the distance from the transmitter $TX_{i\neq 1}$ as r the power at that distance can be written $p(r)$. With the intended receiver of the signal from $TX_{i\neq 1}$ a distance R away, the power at $RX_{TX_{i\neq 1}}$ equals:

$$p(r) = \rho r^{-\alpha} \mid r = R \tag{5.4}$$

The lower bound for the probability of outage for the slotted version of ALOHA, P_{outage} is the situation where *at least one* non-paired transmitter exists within the area $B(R_1, s)$. A theorem is stated for this lower bound and also proven, for the proof please refer to [7]

$$P_{out}^{LB}(Slotted\ ALOHA) = 1 - e^{-\lambda\pi s^2} \tag{5.5}$$

5.1.2 Unslotted ALOHA

Guard zones of the receiver are studied in the RX-RX approach of. The motivation is, as in the latter section, to find the lower bound. In the case of unslotted ALOHA, transmitters $TX_{...}$ send packets regardless of it being in outage or if it causes outage [7]. Outage is caused in this scenario by a second transmitter entering the confines of the guard zone ($B(R_1, s)$) of the first receiver .

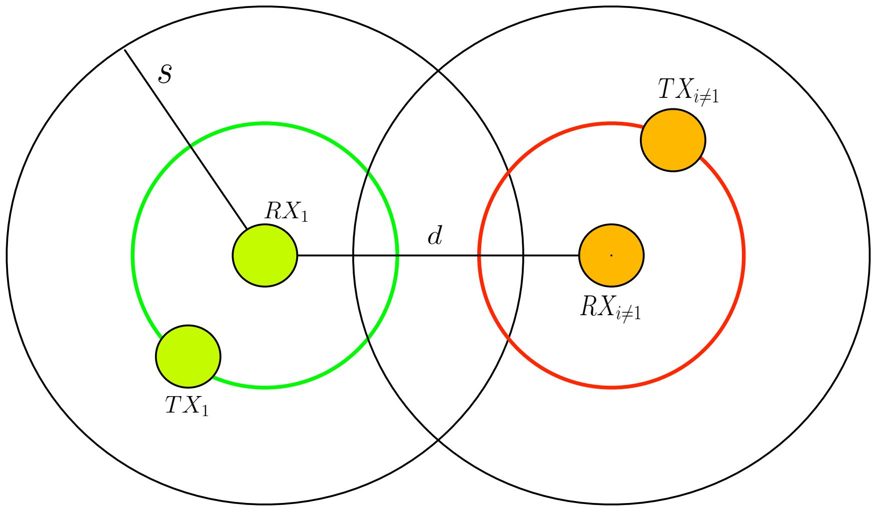

Figure 5.6: Outage scenario for the RX-RX approach with unslotted ALOHA [7]

Referring to the illustration of figure 5.6 this can be expressed as $TX_{i\neq 1} \exists \left(B(R_1, s) \cap C_{red\ circle}\right)$ [6].

The lower bound on the probability of outage in the RX-RX approach, i.e. the probability that RX_1 experiences outage as a result of the transmitter of $RX_{i\neq 1}$ entering the area $B(R_1, s)$ is:

$$P_{out}^{LB}(Unslotted\ ALOHA \mid d) = \frac{1}{\pi}cos^{-1}\left(\frac{d^2 + R^2 - s^2}{2Rd}\right) \tag{5.6}$$

This is the probability conditioned on the distance d 5.6. The total probability is achieved through integration of d over its distribution [7].

$$P_{out}^{LB}(Unslotted\ ALOHA) = \int_0^{(s+R)^2} \frac{1}{\pi}cos^{-1}\left(\frac{d^2 + R^2 - s^2}{2Rd}\right)\left(\pi\lambda e^{-\pi\lambda d^2}\right)d(d^2) \tag{5.7}$$

The corresponding probability function for the RX-TX and TX-TX approach (the function is the same for the two approaches) is stated as a Theorem 2:

[6] $C_{red\ circle}$ is the circumference of the the red circle

$$P_{out}^{LB}(Unslotted\ ALOHA) = 1 - e^{-2\lambda\pi s^2} \tag{5.8}$$

5.1.3 CSMA

In the case of CSMA a new term *backoff* is introduced. This is not the backoff from amplifier theory [25] but a characteristic in the behavior of the CSMA protocol. If the measured SINR at the beginning of the packet is found to be below the predetermined SINR threshold β, the transmitter backs off. The probability that the packet is in outage at the start of the packet is therefore called *backoff probability*[7] The approximate backoff probability is stated as Theorem 3:

$$P_{backoff} = 1 - e^{-\pi\lambda(1-P_{backoff})s^2} \tag{5.9}$$

The theorem further states that the approximation can be stated, via the Lambert function [7], as:

$$P_{backoff} = 1 - \frac{1}{\pi\lambda s^2} W_0(\pi\lambda s^2) \tag{5.10}$$
$$= 1 - \frac{1}{\pi\lambda s^2} \sum_{n=1}^{\infty} \frac{(-n)^{n-1}}{n!} \left(\pi\lambda s^2\right)^n \tag{5.11}$$

As for the unslotted ALOHA the CSMA protocol is tested with the three approaches RX-RX, RX-TX and TX-TX.

The probability of outage is now concerned with the scenario where an ongoing packet transmission is received in outage given that it was not in outage initially. For the particular case of RX-RX, receivers are placed randomly on a plane according to PPP [7]

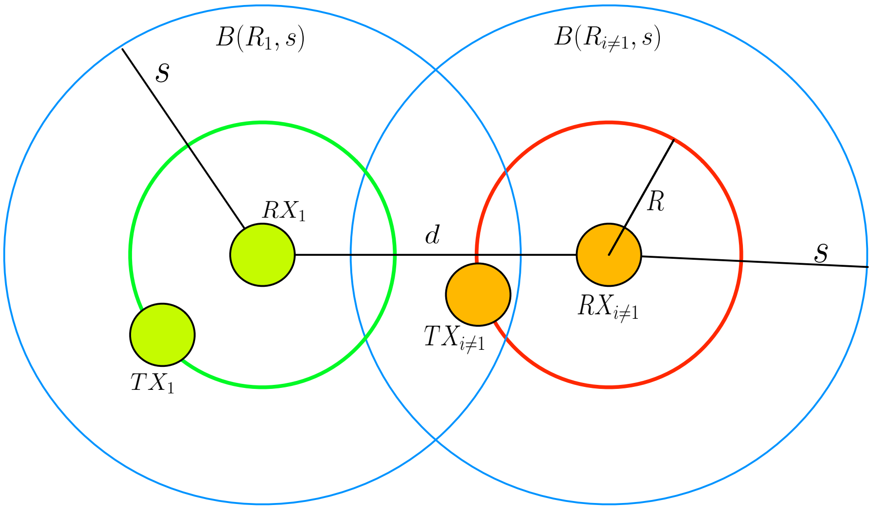

Figure 5.7: RX-RX for the CSMA protocol[7]

If during a packet transmission between TX_1 and RX_1 a packet arrives at $TX_{i\neq 1}$, the transmission from TX_1 to RX_1 will be in outage if:

$$\left(TX_1 \notin B(R_{i\neq 1}, s)\right) \;\&\; \left(TX_{i\neq 1} \in B(R_1, s)\right) \tag{5.12}$$

[7]The Lambert function is defined as the inverse of the function $f(W) = We^W$ [21]

The utilization of mathematical sets to describe the positions of the nodes is natural since the illustrations (5.7, 5.6) essentially act as Venn diagrams. The lower bound for outage given that the transmitter did not back off initially in the RX-RX approach is then stated as [7]:

$$P_{out}^{LB}(CSMA|no\,backoff) = \int_0^{(s+R)^2} \frac{1}{\pi}cos^{-1}\Big(\frac{d^2+R^2-s^2}{2Rd}\Big)\Big[1-\frac{1}{\pi}cos^{-1}\Big(\frac{d^2+R^2-s^2}{2Rd}\Big)\Big]\pi\lambda e^{-\pi\lambda d^2} d(d^2) \tag{5.13}$$

In the TX-TX and the RX-TX approaches are concerned with the distances TX_1-$TX - i \neq 1$ and RX_1-$TX - i \neq 1$ The condition for outage in the TX-TX case is:

$$\Big(TX_{i\neq 1} \in \Big(B(R_1, s)\backslash A_{C-TX_1}\Big)\Big) \;\&\; \Big(RX_{i\neq 1}\backslash B(T_1, s)\Big) \tag{5.14}$$

For which the probability for outage is:

$$P(TX_2 \in B(R_1, s)) = \frac{1}{\pi}cos^{-1}\Big(\frac{d^2+R^2-s^2}{2Rd}\Big) \tag{5.15}$$

Similarily, but not identically, the condition for the RX-TX case is:

$$\Big(TX_{i\neq 1} \in B(R_1, s)\Big) \;\&\; \Big(RX_{i\neq 1}\backslash B(T_1, s)\Big) \tag{5.16}$$

Note that the condition $TX_{i\neq 1} \in \Big(B(R_1, s)\backslash A_{C-TX_1}$ is altered to simply $TX_{i\neq 1} \in B(R_1, s)$. Making it possible for the intruder transmitter to be very close to TX_1. [8]

[8] In both approaches no backoff is tacitly assumed.

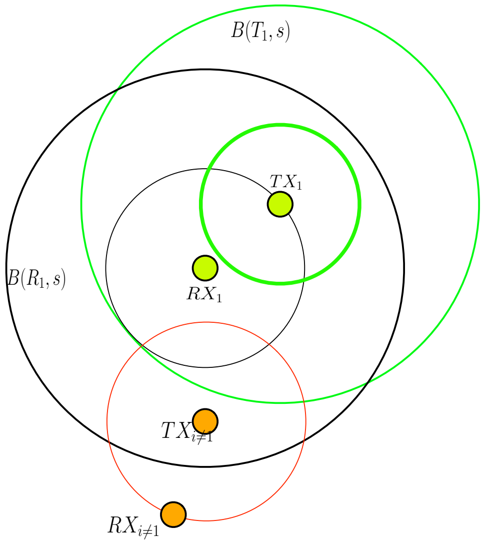

Figure 5.8: The distance between the two transmitters is PPP distributed in the TX-TX case. For the RX-TX case the distance between RX and TX is regarded as PPP distributed[7].

The probability for packets received in outage for the RX-TX case is stated as theorem 4 [7]:

$$P_{out}^{LB}(CSMA|no\ backoff) = \int_0^{s^2}\int_{\upsilon(d)}^{\omega(d)} \frac{1}{2\pi} P(transmit|d,\phi)\pi\lambda e^{-\pi\lambda d^2} d\phi\, d(d^2) \tag{5.17}$$

Where ϕ is the angle $(TX_1\ , RX_1\ , TX_{i\neq 1})$ and its integration limmits are:

$$\upsilon(d) = cos^{-1}\Big(\frac{d^2 - s^2 + 2Rs}{2Rd}\Big)\ \ and\ \ \omega(d) = 2\pi - \upsilon(d) \tag{5.18}$$

5.2 WiMAX and the Ad hoc network solution

In studying outage as a performance parameter the network node density is implicitly studied as well. The number of transmitting nodes in a given area is directly attached to the lower bound for probability of outage. Outage is determined by a threshold in SINR, β. Currently the Ad hoc network model presented in [8] does not take fading into account.

Introducing fading complicates the Ad hoc network model a great deal. Both fast fading and shadow fading will provide different channel conditions depending on the positioning and velocity of the network nodes. An increase in the frequency of packets received in outage will in some cases render the network paralyzed.

The mobile WiMAX standard contains interesting adaptive techniques to counter the effects of strong interference and to increase the range and directionality of transmission and reception.

> Multiple antennas at the receiver and the transmitter can provide diversity gain as well as increased data rates through space-time signal processing. Alternatively, sectorization or smart (adaptive) antenna array techniques can be used to provide directional antenna gain at the transmitter or at the receiver. This directionality can increase the cell range, reduce channel

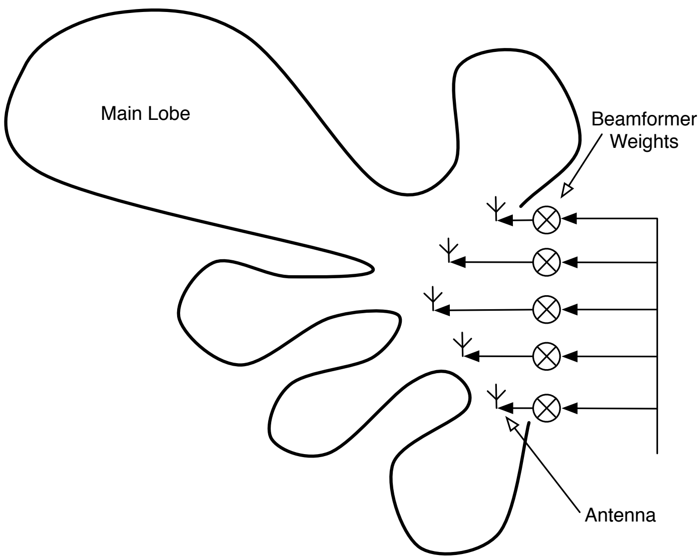

Figure 5.9: Phase array antennas typically use phased-array techniques to provide directional gain, which can be tightly controlled with a sufficient number of antenna elements. Phased array techniques work by adapting the phase of each element in the array, which changes the angular locations of the antenna beam through destructive and constructive interference.[12][10].

> delay spread and flat-fading and suppress intereference between users. Whether it is best to use multiple antennas to increase data rates through multiplexing, increase robustness to fading through diversity or reduce channel delay spread and interference through directionality is a complex tradeoff decision that depends on the overall system design as well as on the environment.

[12]

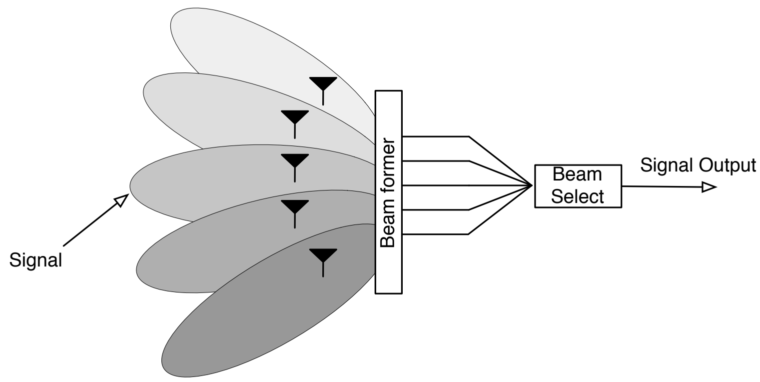

Figure 5.10: Switched beam antennas are designed to provide high gain across a range of signal arrival angles, and can also be used at base stations to cut down interference [12][10].

An array with N_t transmit antennas and $N_r$receiver antennas may provide an average SNR gain of $N_t + N_r$ and a diversity gain (BER slope reduction) of $N_t N_r$. A four element antenna can provide up to a 13dB SNR gain (7dB array gain and 6dB diversity gain).

The WiMAX Forum has selected two different multiple antenna pro?les for use on the downlink. One of them is based on the space?time code (STC) proposed by Alamouti for transmit diversity, and the other is a simple 2x2 spatial multiplexing scheme.

In order to investigate the optimal weighting for the antenna arrays a set of equations are presented to explain the example of MRC[9], the received signal vector $\bar{r}$:

$$\bar{r} = H_D w_t b_(s) + \sum_{i=1}^{L} \sqrt{\Omega_i} h_i b_i + \bar{n} \tag{5.19}$$

[9]Maximal Ratio Combining

Where:

- $H - D$ - the vector of receive antenna channel gains for
- w_t - the vector of wieghts at the transmitter
- b_s - transmitted symbol of interest
- b_i - symbol of th ith interfering signal
- h_i - the gain of the ith interfering signal
- Ω_i - the power of th ith interference signal realtive to the desired signal

the combined output then stated as:

$$y = w_r^H \bar{r} \tag{5.20}$$

where w_r are the antenna weights at the receiver. In this case it is shown that the SINR of y assuming weights associated with MRC is given by:

$$\gamma = \frac{\Omega_D \lambda}{\sum_{i=1}^{L} \chi_i + \sigma^2} \tag{5.21}$$

Furthermore the outage probability of γ is obtained based on the Moment Generating Function of the sum of interferers $\chi = \sum_i \Omega \chi_i$. For example i the case of OC[10] the received signal is given by

$$y_r = \bar{w}^H \bar{c}_s b_s + \sqrt{P_I} \sum_{i=1}^{L} w^H c_i b_i \tag{5.22}$$

where c_s is the fading of the symbol b_s of interest, c_i is the fading on the symbol b_i of the ith interferer, and P_I is the weighted power of the interferes. Concluding the search for the optimal combination is the equation:

$$\bar{w} = g R^{-1} c_s \tag{5.23}$$

The variables are: g - an arbitrary constant and $R = \sum_i c_i c_i^H$ is a Wishart matrix. This is the optimal setup of the antenna array.

[10]Optimal Combining

Discussion

The decision to make a study of existing literature on the subject of WiMAX was made for a couple of reasons. A study into scientific literature is often a stepping stone for new ideas within a certain field of research [20]. In order to promote WiMAX as a viable alternative telecom technology, it appears necessary to consider adding features to the standard. A lot of literature exists on WiMAX and each book, paper and article present a unique view on how to model or simulate a separate feature of the standard. This thesis is based on the work in these documents.

Being a study of scientific literature this thesis is subject to a set of specific rules. The document produced shall give an overview of existing knowledge about the subject. The content of a study like this one is composed of the data presented in the sources and first upon analyzing the data, results are produced. Finally a literature study should be focusing a single topic allow for an in-depth study[20].

This thesis takes the reader through a background on the WiMAX standard and the radio wave propagation environment. The content presented afterwards in chapters 4 and 5 result in comparing ideas from other fields of radio communication technology to see to what extent they are viable as WiMAX augmentations.

Although being specialized in the sense that the thesis considers application of outside technology, this is not likely what is meant by *specialized* in [20]. The thesis has a main focus on channel conditions and estimation of channel conditions, but it also considers Ad hoc networking which is not directly related to channel estimation thus perhaps sacrificing some depth to gain a little width.

The chapters 4 and 5 present promising results in the analysis of the systems. This opens up to deeper future investigation of the two approaches described.

The new Kalman filter based data- & channel-model estimation algorithm is likely to perform in a similar manner for WiMAX compared to how it performed in its original model. Having said this, it is also likely to need much more computation power. The key to its success as a channel estimator for WiMAX will therefore be to ensure that the estimate improvements perform well enough to make deployment of additional base stations unattractive. Here, the logic that more cells-/base stations within a finite area increases capacity and thus make the capacity abundant and therefore cheap is followed.

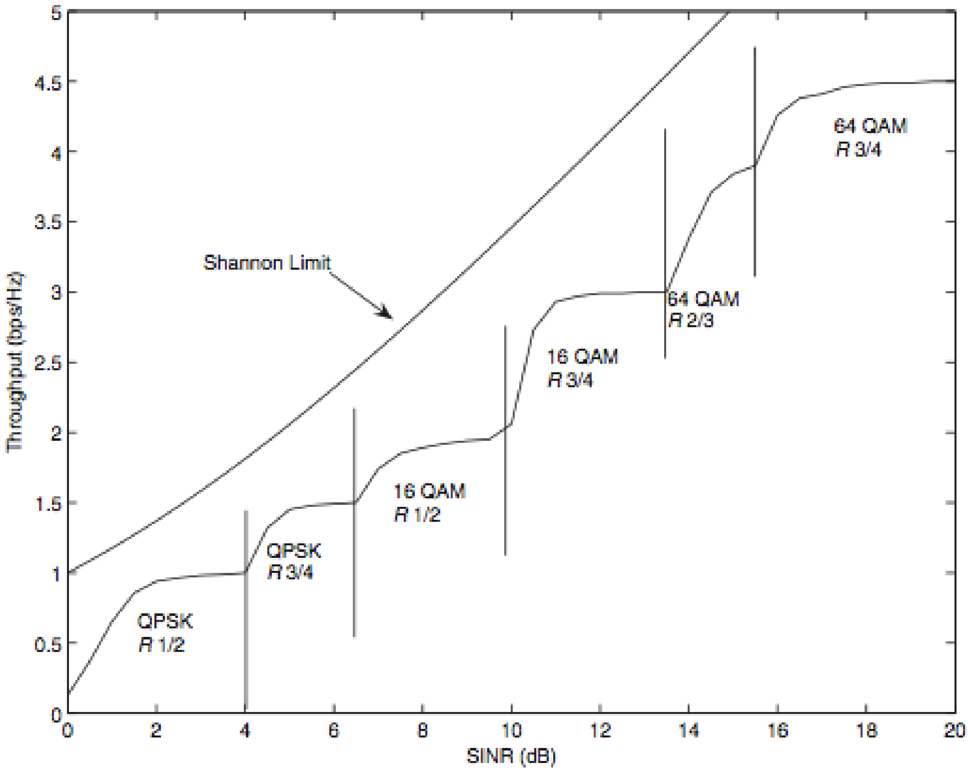

Figure 5.11: [10]

In light of this, the Kalman filter solution will likely have more appeal in building out networks in rural areas where network deployment costs more per square kilometer than in cities where the infrastructure and research is already in place and ready for application.

Also, WiMAX seems to have the right tools available to handle the challenges of ad hoc networking. The directional antenna solutions that are supported by mobile WiMAX may provide up to 13 dB of SINR gain in a given direction which makes it very resistant to fading effects. The ability to adjust the direction of its main lobes for transmission and reception also increases range sacrificing area coverage thus accommodating the application of a fast deployable network for extraordinary situations in areas with little or no infrastructure. Like the models described in the introduction to chapter 5.

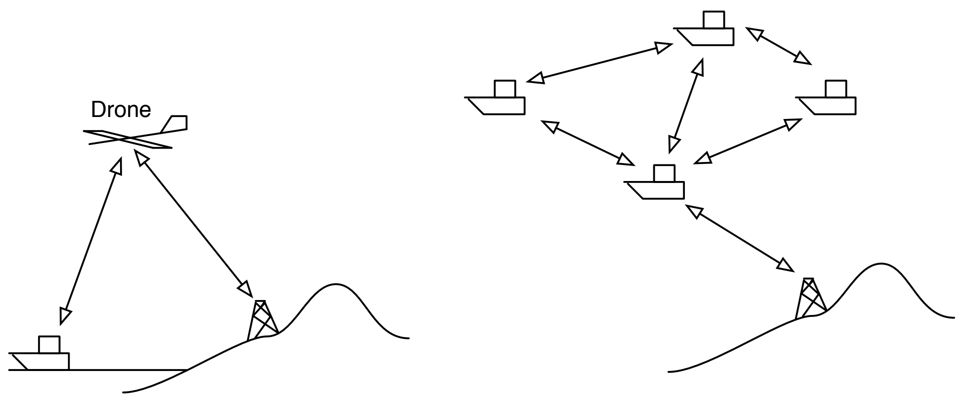

Figure 5.12:

Conclusion

The Contributions of this thesis are the introduction of two new technologies to the WiMAX standard to make it more applicable in rural areas. In particular with regard to a coastal WiMAX network for ships regularly traveling the the busy leads of norwegian controlled waters.

Also, that very same coastal network is the application niche that WiMAX needs to get ahead of the competition. By finding such niches, the WiMAX standard may get a foothold in areas from which it can start to mature into a successful application of technology.

WiMAX is a comparatively young standard and as such it should be open for suggestions and alterations, thus making it adaptable and sought after. However there is also a need for WiMAX to establish itself as a unified well established standard for high speed data transfers over large distances. These two facts are somewhat in contradiction. Establishment on the one hand and dynamic progress on the other. Both seem to lead to the same goal which is success for the standard, but as of now it seems that WiMAX is somewhere in between these two paradigms. As a result it seems to be making little progress.

Main Findings

The main findings in this thesis are identification of and the discovery of the feasibility of incorporating two network solutions (Improved channel estimation, and Ad hoc network capabilities) into the large standard that is WiMAX. This has been carried out through studying available technical solutions and the standard of WiMAX. The thesis has been carried out following the guidelines for the studies of scientific literature. [20]

Future Work

Due to the drastic increase in data traffic on cellular networks there is apparently a need to develop solutions that increase the capacity of such networks. The intention of this study of scientific literature was to create a stepping stone from which new research may be done. This is one of the key purposes of such studies -To establish an overview of the current state of development and on the basis of this create new ideas and inspiration for research.

In the following, a list of potential research topics is presented.

- In-depth research on implementation of a Kalman filter based estimation algorithm for channel estimation in WiMAX

  Type: Preliminary/Preparatory work (Student project)

  Load: 10 weeks

- In-depth research on the possibility of incorporating Ad hoc capabilities in WiMAX

  Type: Preliminary/Preparatory work (Student project)

  Load: 10 weeks

- Implementation of a simulation of the Kalman filter based estimation algorithm into a model of mobile WiMAX for performance verification.

  Type: Master thesis/diploma

  Load: 20 weeks

- Implementation of an Ad hoc network model for verification of the performance of WiMAX's antenna configurations.

  Type: Master thesis/diploma

  Load: 20 weeks

Definitions

- *Channel Coherence Time* - The time period during which the channel impulse response remains invariant [15].

  -The coherence time depends on how quickly the transmitter and the receiver are moving relative to each other [10].

- *Channel Delay Spread* - Also known as multipath spread is the range of values of excess time delay τ, over which $\Phi_c(\tau)$ is essentially nonzero [15].

  -The approximate value of the channel duration [10].

  - Intuitively, the delay spread is the amount of time that elapses between the first arriving path and the last arriving (non-negligible) path. [10].

- *Power Delay Profile* - $\Phi_c(\tau)$ This is the average output signal power of the channel as a function of excess time delay τ. In practice $\Phi_c(\tau)$ is measured by transmitting very narrow pulses, or equivalently a wide band signal and cross-correlating the received signal with a delayed version of itself. Also known as: *Multipath Intensity Profile* and *Delay Power Spectrum.* [15]

- *Channel Coherence Bandwidth* B_c - The frequency component in which all the spectral components of the transmitted signal pass through a channel with equal gain and linear phase is known as coherence bandwidth of that channel. [15]

  - The Coherence Bandwidth is related to the Delay Spread via the relationship: $B_c \approx \frac{1}{5\tau_{RMS}} \approx \frac{1}{\tau_{max}}$. The Channel Coherence Bandwidth B_c gives a rough measure for the maximum separation between a frequency f_1 and a frequency f_2 where the channel frequency response is correlated. [10]

- *Angular Spread* θ - Refers to the statistical distribution of the angle of arriving energy. A large θ_{RMS} implies that channel energy is coming from many directions, a small θ_{RMS} implies a more focused channel energy. [10]

- *Fading* is caused by the reception of multiple versions of the same signal. The multiple received versions are caused by reflections that are referred to as *multipath*. [10].

- *Doppler Spread* is defined by the formula: $f_D = \frac{vf_c}{c}$. Where v is the maximum speed between the transmitter and the receiver, f_c is the carrier frequency and c is the speed of light. [10]

- *Coherence Distance,* D_c - Is the dual of the angular spread. As the angular spread increases, the coherence distance decreases, and vice versa. A coherence distance of d means that any physical positions separated by d have essentially uncorrelated received signal amplitude ad phase. Approximate rule of thumb is $D_c \approx \frac{0.2\lambda}{\theta_{RMS}}$. [10]

- *Symbol* - The smallest unit in the *Baud*, related to *Bit Rate*. If the number of *Bits* per *Symbol* is b_S and the total *Bit Rate* is b_{Tot}, then the *Baud* is represented by $Baud = \frac{b_{Tot}}{b_S}$. [24]

Acronyms

FFT Fast Fourier Transform
3G Third Generation
3GPP Third Generation Partnership Project
4G Fourth Generation
AMC Adaptive Modulation and Coding
ARQ Automatic Retransmission Request
AWGN Additive White Gaussian Noise
BER Bit Error Rate
BS Base Station
CC Convolutional Coding
CIR Channel Impulse Response
CP Cyclic Pre?x
CSMA Carrier Sense Multiple Access
CSMA/CA Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD Carrier Sense Multiple Access with Collision Detection
CTC Convolutional Turbo Coding
dB deciBel
DL DownLink
DSL Digital Subscriber Line
FCH Frame Control Header
FDD Frequency Division Duplexing
FDM Frequency Division Multiplexing
FEC Forward Error Correction
HSDPA High Speed Downlink Packet Access
ICI Inter-Carrier Interference
i.i.d. Independent Identically Distributed
IEEE Institute of Electrical and Electronics Engineers
IFFT Inverse Fast Fourier Transform
IP Internet Protocol
ISI Inter-Symbol Interference

LLR Log-Likelihood Ratio
LOS Line of Sight
LSE Least Squares Estimation
MAC Medium Access Control
MAN Metropolitan Area Network
MEA Multi-Element Antenna
MIMO Multiple-Input Multiple-Output
MISO Multiple-Input Simple-Output
MRC Maximum Ratio Combining
MS Mobile Station
MSS Mobile Subscriber Station
NLOS Non Line of Sight
NTNU Norwegian University of Science and Technology
OFDM Orthogonal Frequency Division Multiplexing
OFDMA Orthogonal Frequency Division Multiple Access
PDA Personal Digital Assistant
pdf Probability Density Function
PDP Power Delay Pro?le
QAM Quadrature Amplitude Modulation
QOS Quality of Service
RRC Root-Raised Cosine
RF Radio Frequency
RMS Root Mean Square
RS Reed-Solomon
RX Receiver
SC Single Carrier
SINR Signal-to-Interference-plus-Noise Ratio
SISO Single-Input Single-Output
SNR Signal-to-Noise Ratio
SS Subscriber Station
TDD Time Division Duplexing
TDM Time Division Multiplexing
TDMA Time Division Multiple Access
TX Transmitter
UL UpLink
UMTS Universal Mobile Telecommunications System
VoIP Voice over IP
Wi-Fi Wireless-Fidelity
WiMAX Worldwide Interoperability for Microwave Access
WLAN Wireless Local Area Network
WMAN Wireless Metropolitan Area Network

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