



# Radio system for reliable data transfer

Master Thesis  
in  
Information and Communication Technology

*Submitted to  
Agder University College  
Faculty of Engineering and Science*

By

Jim Hultgreen  
Rolf Inge Sivertsen

Grimstad, May 2002

## Abstract

This thesis is a study of a radio system for reliable data transfer in the 433 MHz ISM frequency band. The objective was to express propagation models for two different topologies, and compare these to actual channel behavior by transmitting data in these two scenarios. In addition, different parameters' relevance for the radio transmission have been looked at in order to make conclusions about the channel's and the communication system's reliability.

By testing on a radio kit, this project has shown that the propagation models found are in varying accordance with the natural behavior of the channel. The open area tests showed that the channel was relatively reliable up to a distance of 40 meters. This result was in accordance to the propagation model. In the forest area the bit error rate was acceptable up to a distance of 30 meters, whereas the propagation model for that area gave a range of 22 meters. An improved loss factor was included to correct this gap. Other parameters, such as the polarization of the antennas, the bit pattern and the block size were also tested to see the influence these had on the performance of the system.

## Preface

This thesis is the result of an assignment from Kitron Development AS in Oslo, Norway, and is a part of the master degree "Sivilingeniør" in Information and Communication Technology (ICT) at Agder University College.

We would like to thank our supervisors Rune Fensli, associate professor at Agder University College, and project manager Erik Hardeng at Kitron Development AS for their help and inspiration during the work of this thesis. In addition we would like to thank 'høgskolelektor' Magne Arild Haglund at Agder University College for his help.

Grimstad, May 2002

Jim Hultgreen

Rolf Inge Sivertsen

## Table of contents

Abstract .....	ii
Preface .....	iii
Table of contents .....	iv
1 Introduction .....	1
1.1 Background and general description of the project .....	1
1.1.1 Background .....	1
1.1.2 General description .....	1
1.1.3 The nRF401 module .....	2
1.2 Theoretical approach .....	2
1.2.1 Why the propagation models are tested .....	2
2 Theoretical references .....	4
2.1 Introduction .....	4
2.2 Main problems .....	4
2.2.1 Theoretical part .....	4
2.2.2 Practical part .....	4
2.3 Limitations .....	5
2.3.1 Noise .....	5
2.3.2 Output power .....	5
2.3.3 Antenna size .....	5
2.3.4 Bit patterns .....	6
2.3.5 Block size .....	6
2.3.6 Block delay .....	6
2.3.7 Baud rate .....	6
2.3.8 Forest area tests .....	6
3 Transmission theory .....	7
3.1 Introduction .....	7
3.2 General radio communication .....	7
3.2.1 The communication system .....	7
3.2.2 Modulation .....	8
3.2.3 The antenna .....	9
3.2.4 The frequency band .....	9
3.2.5 Important radio communication parameters .....	10
3.3 Signal modulation .....	11
3.3.1 General .....	11
3.3.2 Frequency shift keying .....	11
3.4 Antenna theory .....	12
3.4.1 General description .....	12
3.4.2 Resonance and tuned antennas .....	13
3.4.3 Antenna efficiency factors .....	13
3.4.4 Polarization .....	14
3.4.5 Radio wave reflection .....	14
3.4.6 Restrictions in the 433 MHz band .....	14
3.4.7 Antenna gain .....	15
3.4.8 Antenna location .....	15
3.4.9 Transmission problems .....	15
3.4.10 Loss of signal strength .....	16
3.4.11 nRF401 antenna: The aerial loop antenna .....	17
3.5 Noise theory .....	18
3.5.1 Noise sources .....	18
3.5.2 Electrical equipment generated noise .....	18
3.5.3 External noise .....	18

3.5.4	Jamming of the signal .....	19
3.5.5	Noise sources .....	19
3.5.6	EMC .....	20
3.6	Propagation .....	20
3.6.1	Electromagnetic Fields .....	20
3.7	Propagation in free space .....	22
3.8	Propagation close to the earth's surface .....	23
3.9	Propagation over plane earth .....	24
3.10	Reflections .....	26
3.11	Ground Wave Propagation .....	28
3.12	Diffraction .....	28
3.12.1	ITU-R method .....	30
3.13	A propagation model by Nordic VLSI .....	30
3.13.1	Range calculations .....	31
3.13.2	Loop antenna electrical equivalent circuit .....	32
3.14	Attenuation in forest environment .....	34
4	Description of the channel models .....	36
4.1	Introduction .....	36
4.2	The Wireless Link .....	36
4.3	The open area scenery .....	36
4.3.1	Diffraction Loss .....	38
4.4	The forest scenery .....	39
5	Measuring methodologies .....	41
5.1	Introduction .....	41
5.2	Schematic sketch of the test setup .....	41
5.3	Test procedures .....	41
5.4	Test parameters .....	44
5.5	LabVIEW .....	44
5.5.1	The serial output program .....	45
5.5.2	The serial input program .....	46
5.6	RS-232 converter circuit .....	47
5.7	Noise and attenuation measurements .....	47
6	Measuring results .....	48
6.1	Introduction .....	48
6.2	Lab test .....	48
6.3	Frequency analyzing .....	48
6.4	Open area tests .....	50
6.5	Forest area tests .....	54
6.5.1	Real loss factor .....	55
7	Discussion .....	56
7.1	Introduction .....	56
7.2	Distance .....	56
7.3	Variation in data .....	57
7.3.1	Code value .....	57
7.3.2	Message Length .....	57
7.4	Antenna influence .....	58
7.4.1	Polarization .....	58
7.4.2	Angle of turning .....	58
7.4.3	Height above ground .....	59
7.5	Other variations .....	59
7.5.1	Noise sources .....	59
7.5.2	Daytime's influence on the test results .....	60
7.6	BER .....	60
7.7	Frequency analysis .....	60
7.8	Propagation model .....	61

7.9	Suggestions to improve the overall performance of the system.....	61
7.10	Proposals to further work.....	62
8	Conclusion .....	64
	References .....	65
	Appendix A - LabVIEW diagrams .....	66
	Appendix A.1 - LabVIEW serial out 8 bit diagram.....	66
	Appendix A.2 - LabVIEW serial in 8 bit diagram.....	67
	Appendix A.3 - LabVIEW serial out 16 bit diagram .....	69
	Appendix A.4 - LabVIEW serial in 16 bit diagram .....	70
	Appendix B – RS 232 converter.....	72
	Appendix C – Complete measurement series .....	73
	Appendix abbreviations .....	73
	Appendix C.1 - School ICT-lab test .....	73
	Appendix C.2 - Signal strength measured in the open area .....	74
	Appendix C.3.1 - Bit pattern test 2 meters in the open area.....	74
	Appendix C.3.2 - Bit pattern test 30 meters in the open area.....	74
	Appendix C.4 - Polarization test in the open area.....	75
	Appendix C.5 - Block size test in the open area .....	76
	Appendix C.6 - Distance and polarization test in the open area .....	77
	Appendix C.7 - Different time a day in the open area .....	79
	Appendix C.8 - Distance and polarization test in the forest area .....	79
	Appendix D - Mail from Bent Andre Støyva, dated 12.03.2002 .....	81

# 1 Introduction

## 1.1 Background and general description of the project

### 1.1.1 Background

This assignment is given by Kitron Development in Oslo. Kitron Development wishes to explore the possibility of making a system for tracking animals, which can be used in the farming industry and other similar areas of use.

It is desirable for many farmers to be able to keep track of their animals kept outside, whether it being dogs, reindeer or sheep. A system that could do this would help them to maintain control over the whereabouts of the animals at all times which, among other things, will make it a lot easier to collect them. A tracker system should also be able to detect instances where, for instance, a sheep hasn't moved for a long time, which might indicate that it is ill, or if one of the sheep has been separated from the rest of the flock. Acting on this, the system should notify the farmer so that he can make the right decision about what to do in this situation. Such a tracker system would be possible to implement by having a radio transmitter with GPS (Global Positioning System), and a radio receiver. Having these positioning data, the receiver can make out a map with relevant information which can be presented for the user.

### 1.1.2 General description

In the past few years some frequency bands (among others 433MHz and 869MHz) have been approved/released for free use by radios with limited output power (10-500mW) and range. Communication systems such as these are becoming more and more popular, and there are circuits and complete modules for sale. Examples are electronic car keys and simple radio controllers. Due to the fact that the bands are free, anarchy rules, and there are no guarantees that the signals reach the destinations we want them to. It is therefore vital to know more about causes of errors, and probability of errors when transferring information. If a car key doesn't work, we just push the button until the doors open. However if the signal is meant for a burglar alarm, or a control for an engine, it is more important that the communication works properly the first time. The more one knows about a channel, the easier it is to prevent errors by choosing suitable parameters and error-correcting code, when transmitting the data.

This project contains the following tasks:

- Learn from relevant theory concerning radio-communication and antennas.
- Express channel models for the radio channel, and describe the consequences of changing the model's parameters according to the theory.
- Compare these models with practical measurements.
- Make suggestions of, and connect a simple test circuit with a transmitter and a receiver (Nordic VLSI nRF401) and test it in various environments. A familiar data-sequence will be sent. The receiver will analyze the probability of errors as a function of effect, different antenna parameters

(size, placing), distance and placing of the transmitter – receiver, outer conditions, and interruption from controlled noise sources.

### 1.1.3 The nRF401 module

The module used for the radio communication in this project is the nRF401. This module was chosen because Kitron Development wanted to test the performance of this module in particular. The nRF401 is a single chip transceiver produced by Nordic VLSI, which operates in the 433MHz ISM (Industrial, Scientific and Medical) frequency band. The chip can handle data rates up to 20kbit/s and has a maximum output power of 10mW. The modulation type used is frequency shift keying (FSK), and the chip handles both modulation and demodulation. The loop kit we use is developed to give the users an experience of the functionality of the chip. It is equipped with a loop antenna, and has 10 soldering points making it easy to connect to other devices. It also holds all the necessary electronics to make it work, such as a crystal, resistors and capacitors. The modules in the nRF401 loop kit have three different antenna sizes; 35x20mm, 25x15mm and 18x10mm. The nRF401 is intended for UHF radio equipment, and is made in compliance with the European Telecommunication Standard Institute (ETSI) specification EN 300 220-1 V1.2.1. [Nordic VLSI (2), 2002]

## 1.2 Theoretical approach

The goal with this project is to derive propagation models that describe the channel behavior, and later compare them to practical measurement results. If there are gaps that can be covered in the models, these will be attempted updated after the measurements have been performed.

The models will be derived by studying different aspects of radio communication, and by looking at existing models and if possible adding parameters that are relevant for this thesis. There will be expressed more than one propagation model in order to make the model as realistic as possible for different types of environments and topologies.

After developing these channel models, the next step will be to compare them with the actual behavior of the channel. This will be done by transmitting a known signal from the transmitter to the receiver. The receiver will then analyze the signal to find the bit error rate (BER). These measurements will be made in the different environments that the propagation models are meant to cover.

Depending on the results, the models will, if possible, be modified to simulate the real channel as accurately as possible.

### 1.2.1 Why the propagation models are tested

The reason for testing these models is to know whether or not they can be used to predict the behavior of such a type of communication. It is also important to know how well the models describe the different channels. If these models weren't to be tested, no assumptions about the models' accuracy, or even overall



credibility, could be made. If this was the case, the risk of ending up with models that could be full of errors, and therefore partly useless, would be present.

## 2 Theoretical references

### 2.1 Introduction

This chapter describes the main problems we are facing in this project, and how we plan to overcome these problems. In addition, the different limitations we have made during the work are described closer in this chapter.

### 2.2 Main problems

This thesis has two main parts; the theoretical part which will start out with general radio communication theory and conclude with derived channel models for the actual channel, and the practical part which will show the real behavior of the channel and how the different parameters actually influence the transmissions.

#### 2.2.1 Theoretical part

The theoretical part of this thesis begins with theory on basic radio communication. Important elements that are described are, among other things, signal modulation, antennas and noise.

In the project we take aim at deriving two different propagation models, one for open areas and one for more vegetated areas such as woods. The propagation models will include several parameters which will influence the behavior of these models. These parameters are the distance the data has to travel, the antenna gain and the module's output power. In addition, some other parameters which the channel models do not cover, and that influence such types of transmitting, will be looked at. These parameters are the message code value, the message length, the data rate, division of the data into data blocks, the antenna polarization and the noise sources of different kinds.

#### 2.2.2 Practical part

This part of the project includes building an application that can generate and handle bits of data. It will be necessary for us to be able to control which data the modules are to send. In order to get the data from the computer to the modules, a converter circuit (RS232 to TTL) must be built. This equipment will be used to perform tests consisting of transmitting data in the two different sceneries. The tests will include altering the mentioned parameters to derive the behavior of the actual channel.

The results from all these tests will be compared to the results from the theoretical part of the project. A discussion and a conclusion of the comparison will then be made, in order to evaluate the channel models this project has resulted in.

## 2.3 Limitations

### 2.3.1 Noise

It would have been helpful to be able to log background noise in the 433 MHz band. However, the college did not have the equipment this type of measurement requires, and this part of the project was therefore skipped. How vital such a type of measurement would have been, can be discussed. It would have given a certain idea of what type and how strong the signals in this frequency band are, but this would not have been a faultless target. This is because the noise will vary according to where the measurement is made. However, by using a spectrum analyzer we were able to see the instantaneous values of the different signals present. The use of this analyzer is described closer in chapter 7.7.

An interesting aspect of the testing phase would have been testing in different and known noise surroundings. This was limited to the college's ICT-lab, an open area field outside college and a forest not far from campus. The noise properties of these different surroundings are unfortunately unknown to us other than the obvious; the ICT-lab's noise from all computers and electronic equipments and lights, the outdoors' noise from cars and other background noise. We have therefore not treated the noise surroundings as a test parameter beyond this.

### 2.3.2 Output power

The modules allow the possibility of altering the output power. Originally the output is 10mW at its peak, but by applying a resistor on the modules, this output can be reduced.

The 433 MHz band allows a maximum output of 10mW [Post- og teletilsynet, 2002]. This is a low effect which limits the range of devices used in this frequency band considerably. Reducing the output to less than 10mW will result in even shorter range and therefore a link of poorer quality. The usefulness of a system solution with this output will be more expensive since it will require more buffer stations that just forward data. 10mW output will require more power use of every module, but this will be a better solution than reducing the output power. Because of this we chose to test the modules only with the output of 10mW.

### 2.3.3 Antenna size

The modules in the nRF401 Loop Kit came with three different antenna sizes. Originally we wanted to test all the different antennas in order to see the different results these led to. However, we soon discovered, after performing a lot of tests with the largest antenna module, that there would not be time enough to perform all the tests we wanted to.

#### 2.3.4 Bit patterns

As we found it necessary to have at least five, and preferably ten, series of measurements on each setting of the test parameters, we had to limit the number of total parameters. Because of this we decided to only test two different bit patterns for each block size.

#### 2.3.5 Block size

Another parameter that we limited the number of variations in, was the block size. We ended up with two different applications, one for eight bit block size, and one for 16 bit block size. Having smaller blocks than eight bits is not of much relevance due to the reduced amount of information sent in each block. Blocks larger than 16 bits would have been interesting to test with, but this would have required a much larger application and more work with bit setting for each measurement series.

#### 2.3.6 Block delay

Testing different block delays, we found that the applications' communication with the COM-port had certain limitations. The block delay could not be less than 70 ms. Lower values of the block delay only led to severe data loss. To make sure that the block delay didn't obstruct the data transmissions, we decided to use a block delay of 100 ms. We did not wish to use a block delay of larger value because it would have led to very time-consuming measurement series.

#### 2.3.7 Baud rate

We tested the communication with a baud rate of 9600 bps (the Windows default value), 14400 bps and 19200 bps. All of these worked fine with the LabVIEW applications, so we decided to use 19200 bps in all of the tests. In this manner the COM-ports would not be the restricting parameter for the system's transmitting speed. A baud rate of 19200 bps is also the closest value to the nRF401 module's maximum bit rate of 20kbit/s.

#### 2.3.8 Forest area tests

Due to all the tests that were performed on the open field area, and all the time this took, we decided we had enough test material to discuss most of the parameters' influence on the transmissions. In the forest area tests we therefore concentrated on altering only the distance between the antennas and the polarization of the radio waves.

## 3 Transmission theory

### 3.1 Introduction

Radio communication is a complex area of research. This chapter describes general radio communication, and the different parts and terminologies that make up this form of communication. The most important parts are regarding the antenna, noise and propagation.

### 3.2 General radio communication

The knowledge that energy could be transported without wires dates back to the late 19th century. Heinrich Hertz managed in 1888 to demonstrate that his 60 MHz transmitter was able to produce a spark in his simple reception device over a few meters across his laboratory. It was however the Italian engineer Guillermo Marconi who first successfully applied the "Hertzian waves" in communications. After his first experiments on his father's estate in 1895, his wireless devices became a commercial success around the world. From bridging a few hundreds meters in his original experiments, he communicated successfully over the Atlantic from Cornwall to Massachusetts in 1901. [Ahlin et al, 1998]

#### 3.2.1 The communication system

A communication system consists of a transmitter, a receiver and a transferring medium. Radio communication means transmitting information through the air with radio waves (electromagnetic radiation) from a transmitter to one or several receivers (figure 3.1). [Hollen, 1990]

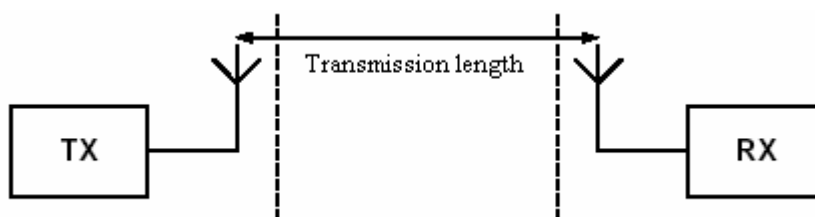


Figure 3.1: Simple wireless/radio link [simplified from figure 3 in Karlsen, 2001]

The transferring medium, which in radio communication is the air or vacuum, is exposed to noise and disturbance. The radio waves are transferred at a certain frequency which is called the nominal channel frequency.

Radio connections are either simplex or duplex. Simplex means that information must be sent and read separately. These channels often use only one frequency. Duplex, on the other hand, means that these two operations can be made simultaneously, however this requires the use of two different frequencies.

A channel is a given frequency for transmitting or receiving information. [Hollen, 1990]

The parameters that are the most important, are the transmit power and the sensitivity. The definition of sensitivity is how low signal power the receiver can receive, and still have a satisfactory Bit Error Rate (BER, for instance  $1 \times 10^{-3}$ ). The resulting difference between the actual signal power and the sensitivity is called the transmission link margin or the 'headroom' (see figure 3.2). There are several factors that reduce the headroom. Such factors are antenna efficiency, transmission path length carrier frequency and physical characteristics of obstructions in the transmission path. [Karlsen, 2001]

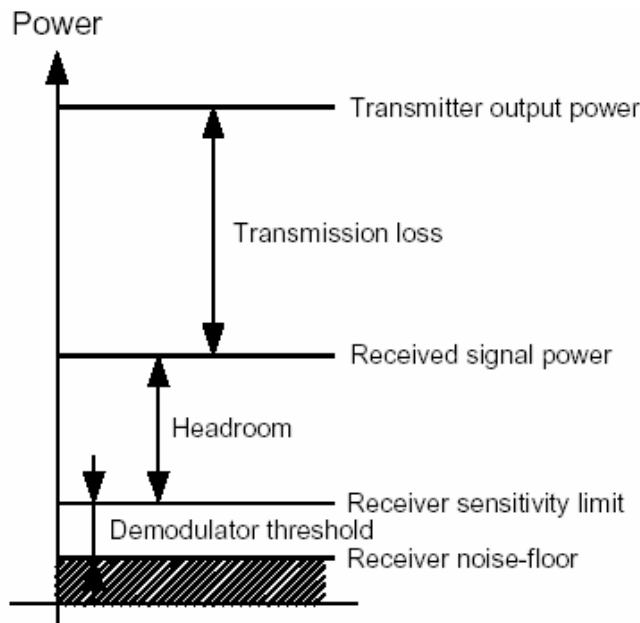


Figure 3.2: Transmission link margin; headroom [figure 4 in Karlsen, 2001]

There is both an electric and a magnetic field in electromagnetic radiation. A current through the antenna makes a magnetic field, while a charge on it makes an electric field. [Svanes, 1995]

### 3.2.2 Modulation

The following section is collected from [Svanes, 1995], and describes general signal modulation.

A low frequency signal cannot be submitted directly from the transmitting antenna. For radio signals to be able to beam from an antenna, the frequency must be higher than approximately 10 kHz. This is because at this frequency, the wave length is relatively long and would require a huge antenna, in order for the antenna to be able to transmit and receive the signal. It is therefore necessary to use a high frequency signal to carry the low frequency information from the transmitter to the receiver. Such a signal is produced in the transmitter's oscillator.

In the transmitter, the high frequency signal is manipulated in such a way that it varies in time with the low frequency signal. The low frequency signal is *modulated* into the high frequency signal with the nominal channel frequency. The result is a modulated signal. The modulated signal is amplified in a high

frequency amplifier, and is fed to the transmitter's antenna through a power amplifier (figure 3.3).

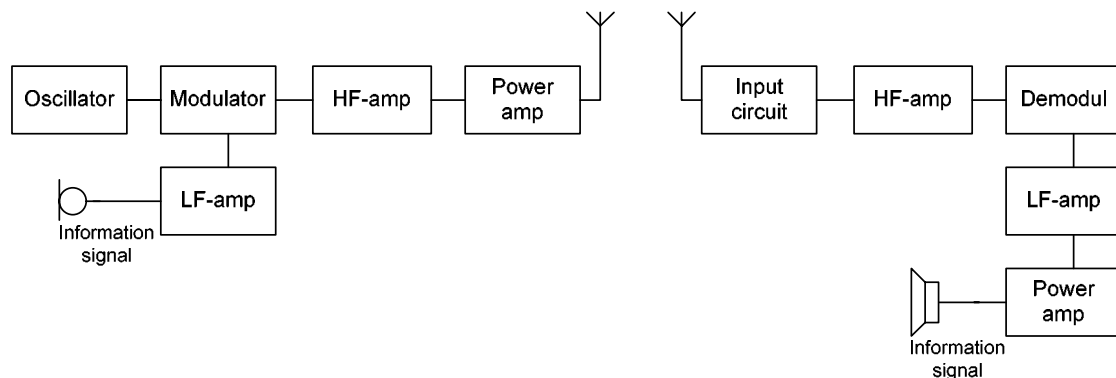


Figure 3.3: Block scheme for a simple transmitter and receiver

The modulated signal's carrying wave is called the oscillator voltage. The new high frequent voltages, that contain the low frequency information, are called side waves. Every transmitter that wants to transmit a modulated signal must have a certain frequency band in possession to transmit in. The receiver must then be able to choose the desired frequency band, and amplify it. This is done by first filtering the signal with a band pass filter. It is also desirable to amplify the received signal prior to getting the low frequency information out of the signal. The input circuit and the high frequency amplifier provide for this job. The demodulator retrieves the low frequency information signal from the modulated signal. This process is called demodulation. The information signal is then amplified by a low frequency amplifier and a power amplifier before it is sent to the output device, such as a speaker. Modulation is explained further in chapter 3.3.

### 3.2.3 The antenna

The antenna radiates the modulated signal from the transmitter as electromagnetic waves. The radio waves move wirelessly from the transmitter to the receiver. The wave propagation takes place either along the earth's surface, or through the ionosphere, as space waves.

The electromagnetic radio waves propagate with the velocity of light. In the receiving antenna, the radio waves are transformed into signal voltage that is fed to the receiver's input circuit.

How great the signal voltage must be in order to make a usable receipt of the signal, depends a lot on the local noise. More antenna theory is explained in chapter 3.4. [Svanes, 1995]

### 3.2.4 The frequency band

433 MHz, which is the frequency the modules in this project use, is in the UHF (Ultra High Frequency) band. The propagation is mostly limited to free sight, and

the main mechanism for the spread of the signals is direct transmission. [Stette, 2001]

The frequency band 433,050 – 434,790 MHz is allowed for free use in a lot of countries. These frequencies are not allowed for safety alarm, social alarm or any medical telemetry. The maximum allowed output power is 10 mW. The channel bandwidth, however, is optional. [Post- og teletilsynet, 2002]

There is always a risk of jamming when two or more devices operate at the same frequency. To reduce this risk there has been set a maximum allowed transmit duty-cycle which equals transmit-time percentage of the system over an hour period. In the 433MHz band this value is 10% or 6 minutes. The transmit time can be spread over multiple time slots. [Karlsen, 2001]

### 3.2.5 Important radio communication parameters

The following section is collected from [Karlsen, 2001], and describes some important radio parameters.

In addition to transmit power and receiver sensitivity, there are also other important parameters that influence the transmission reliability, even though these parameters do not enter the transmission link budget directly.

#### *Receiver dynamic range*

The receiver's dynamic range is the maximum variation in received power that leads to correct demodulation of the signal. In other words, the receiver tolerates signals that vary within the boundaries of the sensitivity limit and the sensitivity limit plus the dynamic range.

#### *Co-channel rejection*

The co-channel rejection tells us how much higher, in dB, the wanted signal's strength has to be compared to a co-existing unwanted signal and its signal strength (with the same nominal frequency) for the receiver to be able to demodulate the wanted signal correctly. Typical co-channel rejection is approximately 12-14 dB.

#### *Adjacent channel selectivity (ACS)*

A receiver's ACS is how much higher, in signal strength, a sine component centered in the adjacent channel can be compared to a wanted signal (at the sensitivity limit), and still not prevent the receiver from demodulating the wanted signal correctly. However, the system ACS is often lower because the adjacent channel is seldom a sine component, but rather a modulated spectrum.

#### *Reference frequency stability*

A parameter that influences the ACS is the reference frequency stability which means how steady the frequency offset is compared to the ideal crystal frequency. Offset in the crystal reference frequency also leads to deviation of the transmitted frequency.

#### *Blocking performance*

A receiver's blocking performance is the receiver's ability to demodulate wanted signals with high power RF-signals interfering in near by frequency bands (10-200 MHz from the wanted channel).



## 3.3 Signal modulation

### 3.3.1 General

The process where the information signal is converted into a radio signal with a nominal channel frequency, is called modulation. The nominal channel frequency is the carrier wave's frequency before it is modulated. Modulation can be divided into two main categories:

- Amplitude modulation/shift keying
- Frequency and phase modulation/shift keying

[Hollen, 1990]

### 3.3.2 Frequency shift keying

The following section is collected from [Svanes, 1995], and describes frequency shift keying.

The modules that are used in this project operate in the 433 MHz ISM (Industrial, Scientific and Medical) frequency band, and feature Frequency Shift Keying (FSK) modulation and demodulation capabilities. Because of this, ASK will not be explained any further. [Nordic VLSI (2), 2002]

In contrast to amplitude modulation, where the amplitude is altered, frequency modulation implies constant amplitude of the modulated signal. However, the frequency varies in time with the modulation frequency in a certain frequency range over and under the nominal carrier wave frequency. The logical values are represented as follows:

$$\begin{aligned} \text{DATA}_{\text{FSK}} = '1' &\rightarrow f_{1'} = f_{\text{centre}} + \Delta f \\ \text{DATA}_{\text{FSK}} = '0' &\rightarrow f_{0'} = f_{\text{centre}} - \Delta f \end{aligned}$$

The frequency range, in which the modulated signal varies, is determined by the strength or amplitude of the information signal. How many times per second the frequency is altered from minimum till maximum is determined by the frequency of the information signal.

The phase angle of a signal that hasn't been modulated increases evenly with time. However, in case of a frequency modulated signal the phase angle in one moment increases faster, and in the next moment slower, than a yet not modulated signal. The change of the phase angle gets bigger the bigger the frequency swing is and the lower the modulation frequency is. The distance in frequency from the carrier wave signal to the highest or the lowest frequency in the modulated signal is called the frequency deviation  $\delta$ . The frequency swing is always equal on both sides of the carrier wave frequency.

A frequency modulated signal is made up by a carrier wave and an infinite number of side waves. In practice, only the side waves that are relatively close to the carrier wave frequency are relevant to the quality of the signal. The amplitudes of the side waves that are far away from the carrier wave frequency are also very small.

The relation between the frequency deviation and the modulation signal's frequency is called the modulation index  $m_f$ . See equation 3.1.

$$m_f = \frac{\delta}{f_L} \quad (3.1)$$

$\delta$ : The frequency deviation  
 $f_L$ : The modulation frequency

When frequency modulation is used, the transmitted energy is always constant. If there is a carrier wave that hasn't been modulated ( $m_f = 0$ ), the only frequency component present is the carrier wave frequency. All of the effect is then found in the carrier wave component. When the carrier wave is modulated, side wave components come into being, and energy is transferred to these. However, the total amount of energy is constant.

Solutions using Amplitude Shift Keying (ASK) have dominated the license free LPRD bands until now. The reason for this is that these solutions are simple and relatively cheap. However the quality and reliability this technology offers is poor when it is influenced by in-band interference. If even a very weak signal is present in the channel, it may still be interpreted as logic '1' if the receiver's sensitivity is low enough. FSK is therefore preferable, also because the dynamics range is a lot bigger. [Karlsen, 2001]

### 3.4 Antenna theory

#### 3.4.1 General description

In order to communicate by radio, one needs a part that is able to transmit and receive radio waves. These parts are called antennas. [Hollen, 1990]

An equivalent scheme for an antenna consists of a generator, a coil, a capacitor and a resistance (figure 3.4). [Svanes, 1995]

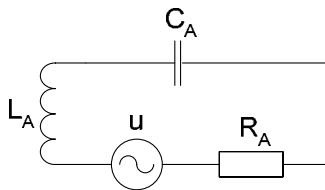


Figure 3.4: Equivalent scheme for an antenna [figure 18.1 in Svanes, 1995]

Energy with a very high frequency is in radio connections generated as electromagnetic oscillations, and led to the transmitting antenna by a transmission line. When energy is led into this feeding spot of the antenna, it influences the charge and current distribution in the antenna. The transmitting antenna then radiates the energy as transversal electromagnetic waves, which

propagate with the speed of light. Ideally an antenna is supposed to transmit all the energy it is provided with. The receiving antenna is supposed to absorb as much of the emitted energy as possible, and transfer the received waves to the receiver through the transmission line. Both transmitter and receiver antennas can be reciprocal elements, which means that they have the same qualities when both transmitting and receiving. An antenna is a linear element, which implies that there is a constant ratio between current and voltage in the antenna. Antennas are also described as passive elements. This means that an antenna cannot emit more energy than it is fed with. Another fact about antennas is that they can radiate in either all directions, so called isotropic antennas, or just in certain directions. [Hollen, 1990]

### 3.4.2 Resonance and tuned antennas

The antenna length has to be a certain value in proportion to the wavelength, in order to make the antenna able to transmit and receive energy with maximum efficiency. Different parameters of several set values make the antenna go into the state of resonance. In these cases, both current and voltage reach the maximum value, and transmitted/received energy also has its peak. Antennas are often given names by their length in proportion to the wavelength, for example the half wave antenna and the quarter wave antenna. [Hollen, 1990]

There are both tuned and not tuned antennas. The first have a length that equals exactly a number (integer) of quarter wavelengths. Such an antenna's impedance equals a pure resistance. The latter, on the other hand, which hasn't got a length that equals a number of quarter wavelengths, is either inductive or capacitive depending on the actual length. An antenna that is shorter than  $\frac{1}{4} \lambda$  (wavelength), or is between  $\frac{1}{4}$  and  $\frac{1}{2} \lambda$ , is too short and is therefore capacitive. By making a series circuit of a coil and the antenna, the resonance frequency is reduced. Such a coil is called a lengthening coil, and can be used to achieve resonance in the antenna even though it is shorter than  $\frac{1}{4} \lambda$ . A series circuit of a capacitor and the antenna has the opposite effect; it makes the antenna seem shorter than it really is. Such a capacitor is called a shortening capacitor. [Svanes, 1995]

### 3.4.3 Antenna efficiency factors

The following is collected from [Svanes, 1995], and describes different antenna efficiency factors.

An antenna has a specific impedance. How large this impedance is depends on the antenna's length, its thread's thickness and how high from the ground the antenna is placed. The impedance is also affected by where (on the antenna) the signal is collected. If maximum effect is to be transferred from the antenna to the receiver, the impedance of which the antenna is loaded with must be equal to the antenna's impedance. Maladjusted circuits lead to stationary waves in the antenna cable. This causes that the transmitter's effect won't be changed into electromagnetic waves, and the radio waves are returned.

It is important that antennas for long wave, medium wave and short wave radio connections have a good ground connection to make the losses as small as possible. This earth must provide good reflections. If a direct wire down into the

ground is difficult, it is common to use a “counterweight”. This counterweight must be at least the same size as the antenna, preferably bigger.

Other important factors that determine the amount of signal voltage that is induced in an antenna:

- The strength of the electromagnetic field that the antenna is placed in
- How the antenna is placed in proportion to the electromagnetic field
- If there are any pieces of metal near by

#### 3.4.4 Polarization

The radio waves are usually divided into vertically or horizontally polarized waves. An antenna that is placed horizontally (the electrical field is horizontal compared to the earth level) transmits or receives horizontally polarized waves. A vertically placed antenna, on the other hand, beams and receives vertically polarized radio waves. [Svanes, 1995]

When there are problems with interference, vertical waves have several advantages compared to horizontal waves. However, vertical obstructions in the terrain such as trees, cause problems for vertically polarized waves. This phenomenon is not a problem for horizontally polarized waves. [Hollen, 1990]

Noise sources such as ignition noise and other “human-made” noise sources are often vertically polarized. At frequencies where this type of noise can be disturbing, horizontally polarized waves are preferable. However, in general neither of the polarizations can be proclaimed as better than the other. [Hollen, 1990]

#### 3.4.5 Radio wave reflection

When a radio wave hits the earth’s surface, one part of it is reflected, and one part is absorbed by the surface. The reflection is described by Snell’s law which says that the angle of incidence equals the angle of the resulting beam. The beam that reaches the receiving antenna in the field is made up by a direct wave and a wave reflected from the earth’s surface. When the reflected wave’s difference in distance of travel, compared to the direct wave, is added, the resulting field strength varies quite a lot when the receiving antenna is mobile. This phenomenon is called fast fading. [Hollen, 1990]

#### 3.4.6 Restrictions in the 433 MHz band

The 433MHz band is a LPRD (Low Power Radio Device) band and it has a maximum allowed output power (restricted by ETSI) of 10 mW EIRP (Effective Isotropic Radiated Power). The radiation of an isotropic radiator is equal in all directions. This doesn’t mean that an antenna is allowed higher output if it just radiates in one direction. These restrictions are only for transmitting, and not for receiving antennas. [Karlsen, 2001]

### 3.4.7 Antenna gain

The following section is collected from [Karlsen, 2001], and contains a description of the antenna gain.

The antenna gain is one of the main characteristics of an antenna. An antenna's gain is its ability to transform the output power into radiated energy. The definition is as shown in equation 3.2.

$$G_{\text{ant}} = \frac{4 \cdot \pi \cdot A_e}{\lambda^2} \quad (3.2)$$

$A_e$  is the effective area of the antenna, and  $\lambda$  is the wavelength of the carrier frequency. For the 433MHz LPRD band, the wavelength is approximately 0.69m.

In order to achieve an antenna gain of 1 (0 dB) in the 433MHz band, the area has to be 0.0038m<sup>2</sup> (0.19m x 0.19m). However it is seldom practical with such a big antenna, and therefore smaller ones are often used. Settling for smaller antennas will introduce loss in the transmission budget.

It is usually quite complex to work out radiation patterns and antenna gain. Often the practical radiation pattern differs from these calculations due to conducting surfaces in the antenna environment. However, this phenomenon is hard to avoid in most practical applications.

### 3.4.8 Antenna location

The following section is collected from [Karlsen, 2001], and contains a description of the impact of different antenna locations.

The location of the antenna when transmitting will be of great importance to the result. According to the location, the signal from the antenna will most often be either horizontally or vertically polarized.

First of all the difference between placing antennas indoors and outdoors is important to explain. Placing such low output power transmitting and receiving antennas either indoors or, which in this case is the natural choice, outdoors is vital. If the receiving antenna for an outdoor transmitting antenna, is placed indoors, a lot of energy is lost when the waves penetrate the walls to reach the antenna.

For the open area we assume that the placing won't be too significant. However, in the woods and other heavily vegetated areas, the polarization will be quite vital. Due to all the trees, any vertically polarized waves will be attenuated and maybe stopped quite effectively. It is therefore advantageous that the waves that are sent are horizontally polarized.

### 3.4.9 Transmission problems

The following section is collected from [Karlsen, 2001], and contains a description of several transmission problems.

As the distance between the transmitter and the receiver increases, the headroom decreases. When this happens, the probability of communication loss due to multipath phenomenon and environmental obstacles increases.

Fading may vary if one or both radio modules are mobile, due to the short wavelength of only 0.69 meters. Also moving objects near by, such as vehicles and people, will influence the extent of the fading, even if the modules are stationary.

If the transmitted signal has to travel multiple paths in order to get to the receiver, the signal will be faded (see figure 3.5). The combined signals might reach the receiver out of phase, due to the different lengths of the different paths. This leads to signal attenuation, and also inter-symbol interference.

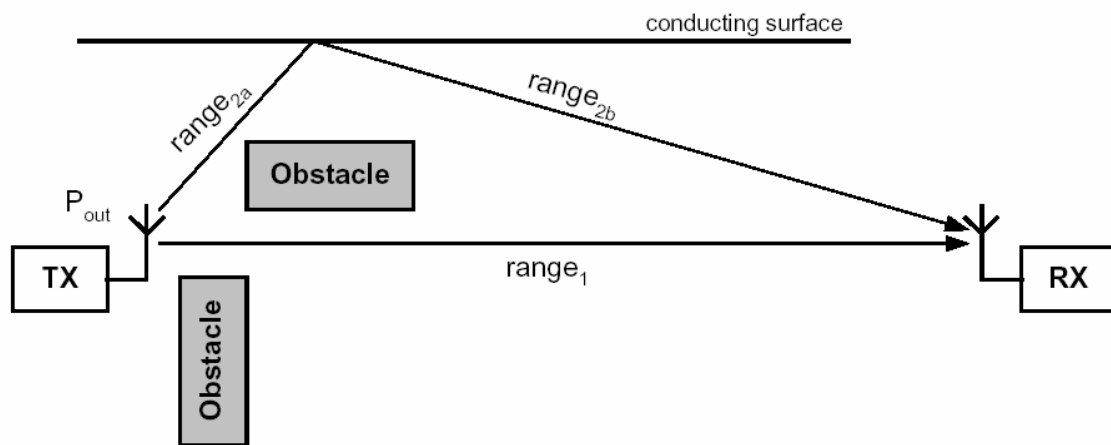


Figure 3.5: Multipath signals [figure 8 in Karlsen, 2001]

Reflection, scattering and diffraction cause what is called the multipath phenomenon, which among other things causes the headroom to vary.

- *Reflection* occurs when a radio wave strikes an object with large dimensions compared to the wavelength of the propagation wave. Reflection can occur from buildings or from the surface of the earth.
- *Diffraction* occurs when a radio path is obstructed by a surface with irregularities. Secondary waves occur from the obstructing surface, giving rise to a bending of waves around and behind the obstacle.
- *Scattering* occurs when the radio wave travels through a medium containing a lot of small (compared to the wavelength) objects, which influence the propagation. Scattered waves are produced by irregularities in the media or rough surfaces.

### 3.4.10 Loss of signal strength

The obstacles that the radio waves hit, or in other ways are influenced by, cause loss in the signal strength. Typical obstacles are floors, buildings, walls and windows. Depending on the physical characteristics of the object, the loss in dB

varies. For example iron causes more loss than wood. See table 3.1 for typical losses in the 433 MHz frequency band. [Karlsen, 2001]

Obstacle	Typical loss [dB]
Wall (indoor)	10-15
Wall (exterior)	2-38 (percentage of windows and height important)
Floor	12-27
Window	2-30 (metal tinted windows cause high loss)

Table 3.1: Typical losses due to objects [table 2 from Karlsen, 2001]

### 3.4.11 nRF401 antenna: The aerial loop antenna

The modules in the test kit nRF401 have aerial loop antennas. The principle of the aerial loop antenna is that the diameter, or the length of the sides, must be small compared to the wavelength. These types of antennas are most often used in electronic bearing equipment. [Hollen, 1990]

The loop antennas are tuned to approximately  $400\Omega$  with a T-match. The loop conductor's width is 1mm. There is no ground plane beneath the antennas. Applied on the antenna, a T-matching method is used to match the impedance of the antenna to a transmitter or a receiver. See figure 3.6. [Nordic VLSI (1), 2002]

The antenna's physical dimensions are used to calculate the required components for the equivalent, and the antenna efficiency. In order to calculate the antenna's electrical parameters, the rectangular loop antenna has to be modeled as an equivalent quadratic loop, and the planar loop conductor must be modeled as a wire conductor with an equivalent circular radius. These calculations are described more closely in chapter 3.13.2.

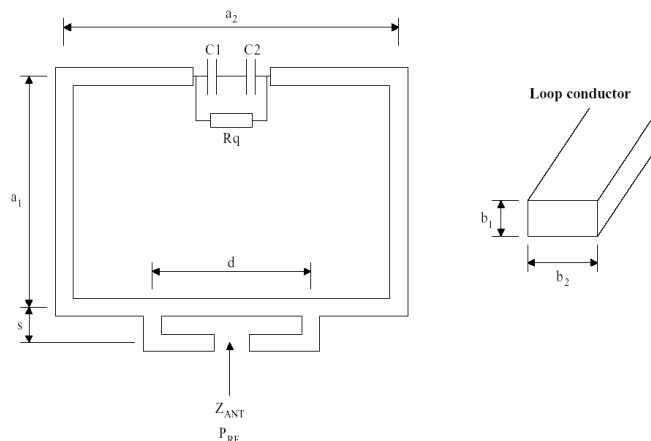


Figure 3.6: Geometry of rectangular loop antenna [figure 5 in Nordic VLSI (1), 2002]

## 3.5 Noise theory

The noise level is one of the most important parameters that decide the transmitting capacity and quality of a radio system.

### 3.5.1 Noise sources

Noise comes from a lot of different sources. Examples are electronic circuits, thermal noise in cables with loss, noise from amplifiers and frequency mixers. Specific radio noise may be caused by

- Atmospherical discharge, lightning
- Electrical equipment, engines, welding devices
- Atmospherical gases and rain-/snowfall
- The ground and other obstructions in the antenna beam
- Radio sources in space

Another type of noise is intermodulation noise which is generated when more than one signal is transferred simultaneously through an unlinear channel.

### 3.5.2 Electrical equipment generated noise

The following three types of noise are the main types of noise that are generated in circuits and equipment.

Thermal noise is caused by casual movement of free electrons in an electrical conductive material. The resulting current, which is made up by many small contributions, is then a stochastic process with a mean value of zero.

Grain noise appears when a relatively small number of electrons move at great speeds, as in electron tubes and in semi-conductors. Every electron that lands on the anode in an electron pipe has generated a characteristic waveform with a broad effect spectrum. The sum of all these waveforms has a noise characteristic.

At very low frequencies, some kHz for semi-conductors and some hundred Hz for vacuum tubes, the noise density is inverse proportional with the frequency. This noise is called the  $1/f$  noise, or the scintillation noise. We haven't found any theory that describes this noise satisfactory.

### 3.5.3 External noise

There are several types of external noise. For instance an antenna will always contribute to some noise. There is also atmospherical noise; the radio signals are attenuated due to the oxygen, water vapour, rain, snow etc. The body absorbing the radio waves, also contributes to the noise the antenna receives. In addition, the earth's surface also contributes to antenna noise. However, considering the impact this has on an actual system is quite complex. [Stette, 2001]



### 3.5.4 Jamming of the signal

The following section is collected from [Karlsen, 2001], and describes jamming of radio signals.

More than one module transmitting in the same frequency range interfere with one another. For example, in case of two transmitters with equal antenna gain and output power, and a co-channel rejection of 12dB, there has to be a certain difference in the distance the transmitters are located from the receiver. The ratio between  $range_1$  and  $range_2$  (see figure 3.7) has to be at least 4. If not, the receiver will not be able to demodulate the wanted  $TX_2$  signal correctly without interference from  $TX_1$ ; the signal is jammed by  $TX_1$ .

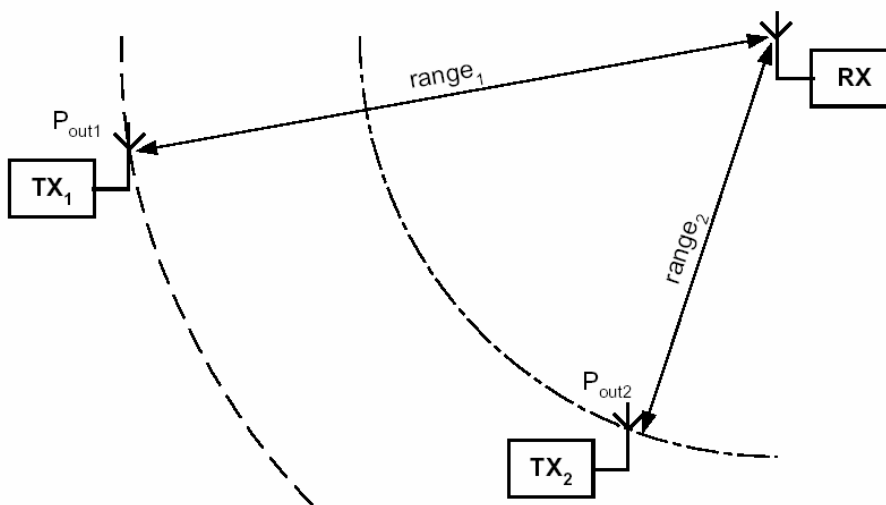


Figure 3.7: Range for multiple transmitters [figure 9 in Karlsen, 2001]

Another problem is jamming caused by other systems. One of these systems is the Tetra communication system, which operates in the 410-430MHz frequency band. The output power of this system is 25W (44dBm), and might therefore jam the signal from the nRF401 (433MHz) modules completely.

### 3.5.5 Noise sources

It is very difficult to assume much about the background noise, due to the variations in the electromagnetic field depending on the whereabouts of transmitter and receiver. However, some noise sources can be expected, for instance the Tetra communication system as described above in chapter 3.5.4. [Karlsen, 2001]

The Norwegian "Post- og teletilsynet" could not give any description of which sources for different types of noise that could be expected in this frequency band. [Post- og teletilsynet, 2002]

### 3.5.6 EMC

More and more devices use radio signals to communicate. All of these contribute to more radio traffic, and the possibilities for new devices to be able to communicate with high quality, is reduced. This is because the noise floor, the level of constant background noise, becomes higher. This is a growing problem in the world of radio communication. This also makes EMC increasingly vital. EMC stands for ElectroMagnetic Compability and has come into being to better achieve electromagnetic co-existence. Most countries follow international directives which require that all types of equipment or electronic components must be made in such a manner that they do not cause more powerful electromagnetic disturbances than what radio communication devices can tolerate in order for them to function as purposed. However, this doesn't help too much for low output devices in released frequency bands, such as the nRF401 modules.  
[Wisler, 1996]

## 3.6 Propagation

### 3.6.1 Electromagnetic Fields

The following section is collected from [Ahlin et al, 1998], and describes some basic electromagnetic properties.

The electromagnetic fields were discovered late in the 19<sup>th</sup> century. James C Maxwell introduced and developed a completely new theory in 1873 - the "Maxwell equations". By the time Maxwell died in 1879, there had been no experimental proof that his theory was correct. That all changed in 1888, when Heinrich Hertz managed to show that energy can be transferred through the air.

The Maxwell equations combined with the wave equation are a set of equations that in principle provides us with a thorough solution to all problems in electromagnetic fields and propagation. Due to these equations complexity, they are only of practical use in certain simple and idealized cases. In most practical cases, the requirement of detailed knowledge hampers us from being able to predict the propagation phenomena by directly applying Maxwell's equations. Instead, we should tend to use rather simple models that only give a coarse description of the physical phenomena.

An electromagnetic (EM) field arises around a conductor (antennas) that are fed with an alternating current. The EM field consists of an electrical field  $E(x,y,z,t)$  that varies in time and space, and a corresponding magnetic field  $H(x,y,z,t)$ . These fields are orthogonal. The field propagates with the speed of light, and transports energy both in the E and H plane. The energy flow is described by *Poyntings vector*:

$$\mathbf{P} = \mathbf{E} \times \mathbf{H}. \quad (3.3)$$

The average magnitude of this vector  $S$ , is denoted the intensity, or *power density*, of this field. For sinusoidal fields this becomes

$$S = \frac{1}{2}|\mathbf{P}| = \frac{1}{2}|\mathbf{E}| \times |\mathbf{H}| \quad [\text{W/m}^2]. \quad (3.4)$$

By the *field strength* we usually mean the RMS-value of the electrical field, given by:

$$E_{RMS} = \frac{1}{\sqrt{2}} |E|.$$

The spatial orientation of the electrical field is usually called the polarization of the field. If the electrical field has a constant direction, we say that the field is linearly polarized. Often the terms *horizontal* and *vertical polarization* are used when discussing propagation close to the surface of the earth. By this we mean electrical fields that are parallel or perpendicular to the earth's surface. A vertically polarized wave is shown in figure 3.8. If the direction of the polarization changes with time, we have a field with elliptical polarization. If, in this case, the magnitude  $|E(x_0, y_0, z_0, t_0)|$  is constant for  $t$ , we have a circular polarized field.

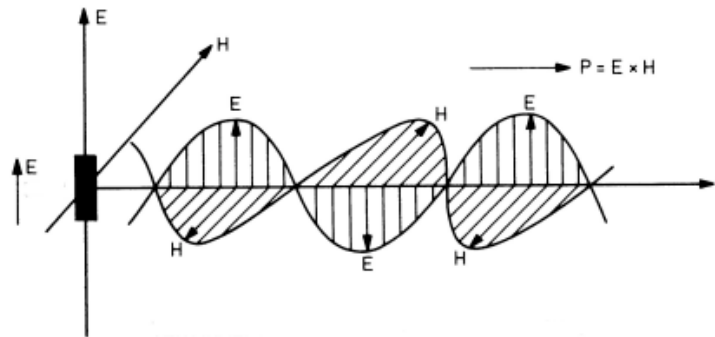


Figure 3.8: Vertically polarized wave. [Figure 4.7 in Hollen, 1990]

The relationship between power density and field strength is given by the energy equations. The energy  $dW$  in a volume element  $dV$  in free space (vacuum) carried by the electrical and magnetic field is given by:

$$\begin{aligned} dW_E &= \frac{1}{2} \epsilon_0 |E|^2 dV \\ dW_H &= \frac{1}{2} \mu_0 |H|^2 dV \end{aligned}$$

where  $\epsilon_0$  and  $\mu_0$  are the constant of permittivity and permeability respectively for the medium, in this case vacuum. In free space (propagation without any external disturbances) both fields carry the same amount of energy:

$$\epsilon_0 |E|^2 = \mu_0 |H|^2. \quad (3.5)$$

The quantity  $Z_0$  is defined as

$$Z_0 = \frac{|E|}{|H|} = \sqrt{\frac{\mu_0}{\epsilon_0}} \approx 120\pi \approx 377 (\Omega). \quad (3.6)$$

This constant is interpreted as the *impedance of vacuum*. This expression has a striking similarity to Ohms law relating current and voltage. In free space we may now express the power density as:

$$\begin{aligned} S &= \frac{1}{2} |E| \cdot |H| = E_{RMS} \cdot H_{RMS} = \frac{E_{RMS}^2}{Z_0} \\ &= \frac{1}{2} \frac{|E|^2}{Z_0} = \frac{1}{2} Z_0 |H|^2 = Z_0 H_{RMS}^2. \end{aligned} \quad (3.7)$$

Propagation in free space is the most ideal situation. When propagation takes place close to obstacles or in an atmosphere with gases, different propagation mechanisms occur. The propagation mechanisms are reflection, diffraction and scattering. These are described in chapter 3.4.9.

With these basic facts about EM-fields, we can study some radio propagation situations in detail. Depending on the situation, different models can be used.

As the frequency increases, the propagation properties of transmitted waves do more and more resemble to the properties of light. At lower frequencies, when the wave length of the radio signal becomes larger, or of the same order of magnitude as the obstacles it encounters, diffraction and surface phenomena tend to dominate. Waves may propagate beyond the horizon or in behind obstacles. If the wavelength is short, we are basically confined to line-of-sight type communications. At very high frequencies (>10 GHz), the wave length may even be smaller than a typical water drop which means that rain or even fog may block a communication path.

### 3.7 Propagation in free space

The following section is collected from [Ahlin et al, 1998], and describes propagation in free space.

In the simplest of all propagation models, we disregard all obstacles that may affect the field. We call this the *free space* propagation model. We assume that the radiator of energy (the transmitting antenna) is placed in such a manner that the influence of obstacles may be neglected. This model does an excellent job in providing rough estimates of field strengths and received powers. For simplicity, let us assume the transmitting antenna is isotropic, meaning it generates a field with equal strength in all directions. Assume this antenna emits a total power of  $P_t$ . Since the antenna is isotropic, the power will be uniformly distributed over the entire surface of a sphere. The power density of the sphere can then be computed as

$$S_r = \frac{P_t}{4\pi r^2} \quad (\text{W/m}^2), \quad (3.8)$$

since the area of the surface of the sphere is  $4\pi r^2$ .  $r$  denotes the distance from the emitting antenna to the receiving antenna. The received power will depend on the area of the receiving antenna that is able to collect the energy in the field, and on the matching of the antenna to the receiver. The *effective aperture*, as the area of an equivalent perfectly absorbing loss less antenna, can be defined as  $A_e$ . The total received power can then be written as

$$P_r = S_r A_e = \frac{P_t A_e}{4\pi r^2}. \quad (3.9)$$

It is well worth mentioning that the maximum electrical aperture may be considerably less than the actual, "physical" area of the antenna. We see that the received power decays with the square of the distance between the antennas, and that the received power is independent of the frequency of the radiated field. Equation (3.9) therefore holds for all kinds of EM-fields propagating in free space, including light waves.

### 3.8 Propagation close to the earth's surface

The following section is collected from [Ahlin et al, 1998], and describes propagation close to the earth's surface.

When transmitting and receiving antennas are in the earth's atmosphere, close to the ground, the free space model can only give a crude approximation to the actual propagation. The field is influenced by the ground and by different obstacles on the ground as well as by the properties of the medium (i.e. the gases of the atmosphere). The surface of the earth is a partly conducting surface and will influence the field and the energy transport in several ways.

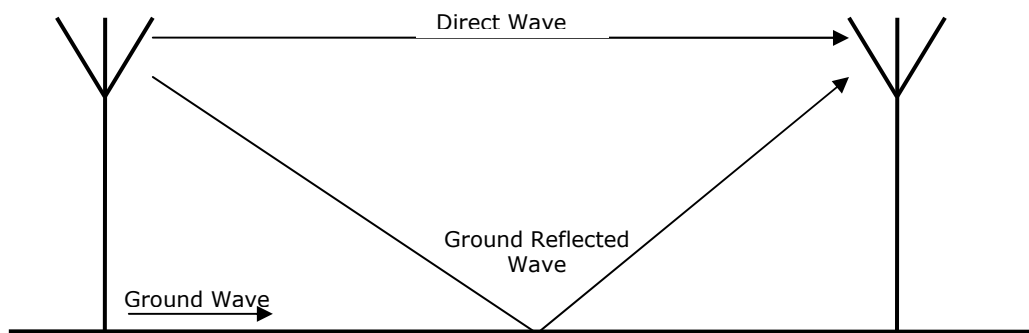


Figure 3.9: Wave components propagation close to the earth surface [figure 2.2 in Ahlin et al, 1998]

Simplifying somewhat we may decompose the field at the receiver into the following three components, according to figure 3.9:

- *Direct wave* components propagating on the line-of-sight path between the transmitter and receiver.
- *Ground reflected wave* components propagating by means of one or more reflections at the ground.
- *Ground waves* that are conducted in the electrical border between air and ground.

The direct wave and the ground reflected wave are the two components of the *atmospheric wave*. The direct wave can sometimes be treated simply with the free-space propagation model of the previous section. The other propagation component, the ground wave, requires a more detailed investigation, including

knowledge of the electrical properties of the ground and reflecting surfaces. The ground wave can only exist close to the surface and is of importance only if the height of the transmitting antenna is small compared to the wavelength.

### 3.9 Propagation over plane earth

The following section is collected from [Ahlin et al, 1998], and describes propagation over plane earth.

A typical communication link can be described as the geometry in figure 3.10. A transmitting antenna is located at the altitude  $h_1$  above the ground. At the distance  $r$  and with the altitude  $h_2$  we find the receiving antenna. The EM-field at the receiver will at reasonably high frequencies be dominated by the direct wave and the wave component reflected by the ground. This is a phenomenon called *multipath propagation*. Since the reflected wave have a longer distance to travel than the direct wave, this component arrives at the receiver with a slight time delay,  $\Delta t$ . At the reflection point the wave interacts electrically with the ground. This results in the wave being both phase shifted and attenuated. The reflected wave may also be depolarized.

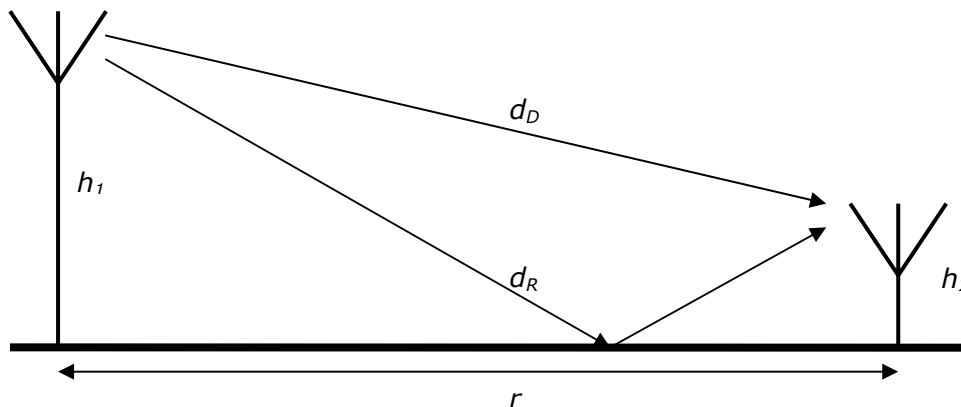


Figure 3.10: Plane-earth model geometry [figure 2.3 in Ahlin et al, 1998]

If we assume that the signal we transmit has a reasonably narrow bandwidth, the EM-field will be roughly sinusoidal. The electrical field at the receiver will be the sum of the field caused by the direct (free space) field and the reflected field component. The magnitude of the field component of interest to the receiver,  $E(t)$ , varies according to

$$E(t) = E_0 \cos(\omega t) + \rho E_0 \cos(\omega(t-\Delta t) + \Phi), \quad (3.10)$$

where  $\rho$  and  $\Phi$  describes the attenuation factor and the phase shift caused by the ground reflection, including possible depolarization effects.  $E_0$  denotes the field strength (i.e. the amplitude) of the direct wave according to the free space model. We assume that the difference in path lengths between the two components is considerably less than the distance  $r$  between the antennas. We may therefore neglect the additional free space attenuation for the reflected wave due to the excess path length of this component. If we have  $\rho = 1$  and  $\Phi = \pi$ , corresponding to perfect, loss-free mirror reflection, we may write equation (3.10) as

$$E(t) = E \cos(\omega t + \psi),$$

where we with trigonometric calculations may derive the resulting field amplitude as

$$E = 2E_0 \sin\left(\frac{\omega \Delta t}{2}\right). \quad (3.11)$$

From figure 3.10 we may now derive the difference in distance traversed by the two wave components. Letting  $d_D$  and  $d_R$  denote the path lengths for the direct and reflected components, we get

$$d_D = \sqrt{r^2 + (h_2 - h_1)^2} \approx r \left( 1 + \frac{1}{2} \left( \frac{h_2 - h_1}{r} \right)^2 \right)$$

$$d_R = \sqrt{r^2 + (h_2 + h_1)^2} \approx r \left( 1 + \frac{1}{2} \left( \frac{h_2 + h_1}{r} \right)^2 \right).$$

This approximation holds if  $h_1, h_2 \ll r$ . The path length difference  $\Delta d$  may thus be approximated by

$$\Delta d = d_R - d_D \approx \frac{2h_1 h_2}{r}. \quad (3.12)$$

Now by using the relations  $\Delta t = \Delta d/c$ ,  $\omega = 2\pi f = 2\pi c/\lambda$  in (3.11), we get

$$|E| = 2E_0 \left| \sin\left(\frac{\omega \Delta t}{2}\right) \right| = 2E_0 \left| \sin\left(\frac{2\pi h_1 h_2}{\lambda r}\right) \right|. \quad (3.13)$$

As we can see in expression (3.13), the field strength will be periodic and dependent on the antenna elevation, the distance between the antennas and the wavelength. By combining (3.9) with (3.13) we get the received signal power

$$P_r = 4P_{fs} \sin^2\left(\frac{2\pi h_1 h_2}{\lambda r}\right) = 4 \cdot \frac{P_t A_e}{4\pi r^2} \sin^2\left(\frac{2\pi h_1 h_2}{\lambda r}\right), \quad (3.14)$$

where  $P_{fs}$  denotes the received power if only the free space component would have been present.

The *propagation factor*  $F$  (in dB) is defined as the ratio between the actual received power in a certain propagation situation and the corresponding received power for free space propagation, at a certain distance from the transmitter. That is

$$F = 10 \log\left(\frac{P_r}{P_{fs}}\right). \quad (3.15)$$

For the plane earth model, the propagation factor will be

$$F = 10 \log 4 \sin^2 \left( \frac{2\pi h_1 h_2}{\lambda r} \right). \quad (3.16)$$

For antenna elevations that are small compared to the distance between antennas, i.e. for  $h_1 h_2 \ll \lambda r/4$ , we may use the approximation  $\sin x \approx x$  which gives us

$$P_r \approx 4\pi \frac{P_t A_e (h_1 h_2)^2}{\lambda^2 r^4}. \quad (3.17)$$

This means that for large distances  $r$ , the received signal power decays with the fourth power of distance. The simplified model should be used with care because of the conditions that have to be fulfilled.

The plane earth model is usually well suited to describe propagation path losses from about 50 MHz and above, in particular at comparatively low grazing angles (relatively low antenna elevations).

### 3.10 Reflections

The following section is collected from [Ahlin et al, 1998], and describes wave reflection theory.

The plane earth model is also useful under less ideal conditions, such as for higher antenna elevations. In this case, the complex reflection coefficient  $\rho$  (in formula (3.10)) has to be taken into account, which is a function of the material properties, and generally depends on the wave polarization, angle of incidence and the frequency of the propagating wave. The ground is electrically characterized by its conductivity  $\sigma$  and its constant of relative permittivity  $\epsilon_r$ . In a partially conducting medium, the current density caused by an electrical field of field strength  $E$  is described by the complex quantity

$$J = \sigma E + j\omega \epsilon E, \quad (3.18)$$

where  $\epsilon = \epsilon_0 \cdot \epsilon_r$ , and  $\epsilon_0$  is the permittivity in vacuum,

$$\epsilon_0 = 8,85419 \cdot 10^{-12} \approx \frac{10^{-9}}{36\pi}.$$

We see from (3.18) that at high frequencies the complex term will dominate, whereas at lower frequencies the resistive part is the larger one. The ratio between the real part and the imaginary part of the current density is denoted the *relative conductivity* of the material. This quantity is denoted by  $q$  and is defined as

$$q = \frac{\sigma}{\omega \epsilon} = \frac{\sigma}{\omega \epsilon_0 \epsilon_r}. \quad (3.19)$$



Whenever  $q \gg 1$  the real resistive part dominates and the material (the ground) may be considered as a good conductor. On the other hand, if  $q \ll 1$ , the ground may be considered as an insulator or dielectric. Since  $q$  is clearly frequency dependent, the frequency where  $q$  becomes unity is a parameter of interest. This frequency is usually called the *cross-over frequency* and is denoted by  $f_q$ . Using  $q=1$ , we may from (3.19) compute the following simple expression

$$f_q = \frac{18\sigma}{\epsilon_r} \quad (3.20)$$

To get the result in MHz we have to express  $\sigma$  in mS/m. Table 3.2 shows some of these parameters for some typical ground conditions.

Ground Conditions	$\sigma$ (mS/m)	$\epsilon_r$	$q$ (1,5 MHz)	$f_q$ MHz
Sea Water	4000	80	600,0	900,0
Fresh Water	5	80	0,8	1,1
Typical Ground	5	15	5,0	6,0
Wet Ground	20	30	8,0	12,0
Rocky Terrain	5	7	8,6	12,9
Dry Land	1	7	1,7	2,6
	1	4	3,0	4,5
	10	4	30,0	45,0

Table 3.2: Electrical characteristic for some typical ground conditions [table 2.1 in Ahlin et al, 1998]

The received envelope power can be written as [Parsons, 1992]

$$P_r = 4P_t \left( \frac{\lambda}{4r\pi} \right)^2 G_T G_R \sin^2 \left( \frac{2\pi h_1 h_2}{r\lambda} \right), \quad (3.21)$$

where  $G_T$  and  $G_R$  are the transmitter and receiver antenna gains.

Under the condition that  $r \gg h_1 h_2$ , (3.21) can be reduced to

$$P_r = P_t G_T G_R \left( \frac{h_1 h_2}{r^2} \right)^2, \quad (3.22)$$

where we have invoked the approximation  $\sin x \approx x$  for small  $x$ . When  $r \gg h_1 h_2$  the propagation over a flat reflecting surface differs from free space propagation in two ways; first, the path loss is not frequency dependent and second, the envelope power decays with the forth power rather than the square of the distance.

In dB, we get

$$\begin{aligned}
 L_{p(dB)} &= 10 \log \left\{ \frac{P_t G_T G_R}{P_r} \right\} \\
 &= -10 \log \left\{ 4 \left( \frac{\lambda}{4r\pi} \right)^2 \sin^2 \left( \frac{2\pi h_1 h_2}{r\lambda} \right) \right\} dB
 \end{aligned} \tag{3.23}$$

### 3.11 Ground Wave Propagation

When a wave is propagating horizontally and close to the surface of the earth, the wave interacts electrically with the ground. Some of the energy in the wave is absorbed by the ground, causing a slight downward shift in energy flow. If the surface is reasonably conducting, the wave may under proper conditions follow the ground over potentially long distances. The field strength of the ground wave will strongly depend on the relative conductivity. If the frequency is well below  $f_q$  (cf. (3.20)), the ground will be a good conductor and we may expect a high field strength in the ground wave component. If, on the other hand, the frequency is well above  $f_q$ , the ground wave is strongly attenuated. Ground wave propagation primary dominates at low frequencies, typically for  $f < 2$  MHz. [Ahlin et al, 1998]

Since our assignment covers the frequency domain around 433 MHz, ground wave propagation will have very little influence, and is thus not discussed any further.

### 3.12 Diffraction

The following section is collected from [Ahlin et al, 1998], and describes diffraction theory.

For a more detailed analysis of rougher terrains, we need to take different diffraction phenomena into consideration. Propagation of waves with short wavelengths is basically limited to line-of sight conditions. On the other hand, if the wavelength is much larger than the object that block the way, the wave passes them virtually unaffected.

Diffraction allows radio signals to propagate around the curved surface of the earth and to propagate behind obstacles. Although the received field strength decreases rapidly in the obstructed region, the diffraction field often has sufficient strength to produce a useful signal. The phenomena of diffraction can be explained by Huygen's principle, which states that all points on a wave front can be considered as point sources producing secondary wavelets, and that these wavelets combine to produce a new wave front in the direction of the propagation.

In figure 3.11 we have a transmitter and a receiver located at a distance of  $d_1 + d_2$  apart. The direct line of sight path is obstructed by an obstacle of height  $h$  over the direct path. Assuming that the object at its tip can be modeled as a sharp "knife edge", we know from optics that we will not only have a direct wave along

the line A-K-C, but there will also be some rather weak field components that illuminate the shadow region behind the obstacle.

Assuming  $h \ll d_1, d_2$  and  $h \gg \lambda$ , the *excess path length*  $\Delta$  (the difference between the direct path and the diffracted path) can be obtained from the geometry in figure 3.11, as

$$\Delta \approx \frac{h^2(d_1 + d_2)}{2d_1d_2}. \quad (3.24)$$

The corresponding phase difference is given by

$$\phi = \frac{2\pi\Delta}{\lambda} = \frac{2\pi}{\lambda} \frac{h^2(d_1 + d_2)}{2d_1d_2}. \quad (3.25)$$

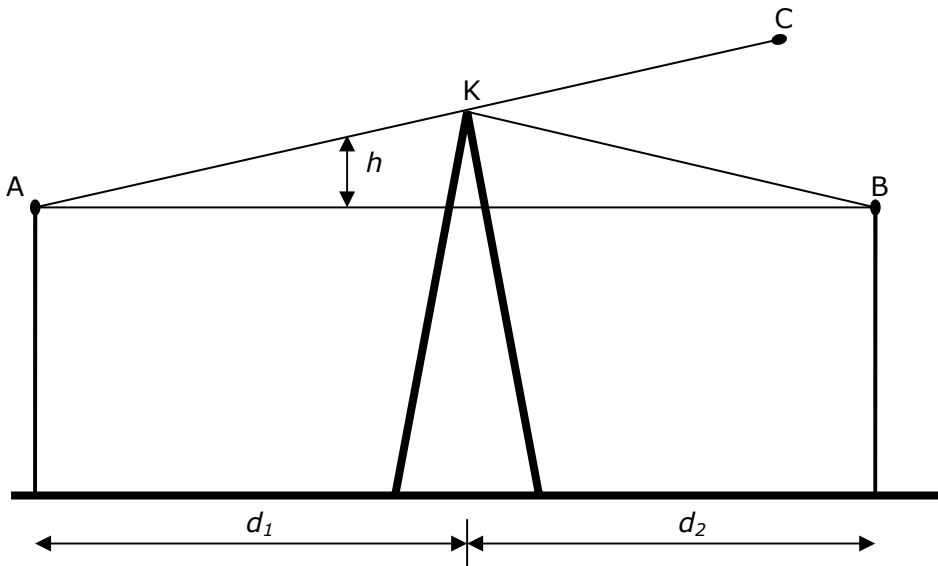


Figure 3.11: Knife edge diffraction model [figure 2.8 in Ahlin et al, 1998]

Equation (3.25) can be normalized by using the *diffraction parameter*  $v$ , given by

$$v = -h \sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}}. \quad (3.26)$$

Hence the phase difference can be expressed as

$$\phi = \frac{\pi}{2} v^2. \quad (3.27)$$

The estimation of the loss caused by diffraction is a difficult process of theoretical approximation and empirical corrections. Briefly, the total path loss from A to B can be computed as

$$(L_{tot})_{dB} = (L_{fs})_{dB} + (L_d)_{dB},$$

where  $L_{fs}$  is the free space loss between A and B (if no obstacles had been present) and  $L_d$  is the excess diffraction loss.

The last section is collected from [Stette, 2001], and describes equations for diffraction calculations.

The diffraction loss  $(L_d)_{dB}$  can be written as

$$(L_d)_{dB} = 20 \cdot \log L_d \quad (3.28)$$

The expression to obtain  $L_d$  is mathematically complicated by the very fact that it includes Fresnel integrals. The different expressions are given below

$$L_d = \frac{S + 0,5}{\sqrt{2} \cdot \sin\left(\Delta\phi + \frac{\pi}{4}\right)}, \quad (3.29)$$

where

$$\Delta\phi = \arctan\left(\frac{S + \frac{1}{2}}{C + \frac{1}{2}}\right) - \frac{\pi}{4}. \quad (3.30)$$

S and C are Fresnel integrals, given as:

$$S = \int_0^v \cos\left(\frac{\pi}{2} x^2\right) dx \quad (3.31)$$

$$C = \int_0^v \sin\left(\frac{\pi}{2} x^2\right) dx \quad (3.32)$$

### 3.12.1 ITU-R method

An easier way to calculate the terrain diffraction loss without including Fresnel integrals, is using the ITU-R method. The factor  $v$  is calculated from

$$v = h \sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}}.$$

The diffraction loss can then be found from the formula

$$J(v) = 6.4 + 20 \log\left(\sqrt{v^2 + 1} + v\right) dB$$

The adaptability of this method is proven by a investigation made by Rao, T. Rama and S. Vijaya Bhaskara. [Rao, 1999]

## 3.13 A propagation model by Nordic VLSI

### 3.13.1 Range calculations

The following section is collected from [Nordic VLSI (3), 2000], and describes a propagation model.

RF systems that operate in the UHF band are not restricted to the line-of-sight coverage of optical systems (IR systems) due to diffraction and reflection of radio waves at edges and conductive surfaces as well as their capability to penetrate dielectric materials.

Range calculation parameters are

- transmitter output power,  $P_{RF}$  [dBm]
- transmitter and receiver antenna efficiency,  $\eta$
- antenna separation,  $R$  [m]
- free-space loss,  $L_p$  [dB]
- additional propagation losses other than free-space loss,  $L_x$  [dB]
- receiver sensitivity,  $S$  [dBm]

The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear, unobstructed line-of-sight path between them. The free-space loss factor  $L_p$  is given by

$$L_p = \left( \frac{\lambda}{4\pi \cdot R} \right)^2$$

$$L_p [dB] = 20 \cdot \log \left( \frac{\lambda}{4\pi \cdot R} \right)$$

The free-space loss factor takes into account the losses due to the spherical spreading of the energy by the antenna. The equation shows that the received power will decrease as the square of the transmitter-receiver separation distance. This implies that the received power decays with distance  $R$  at a rate of 20 dB/decade, (i.e. 6dB extra loss for doubling of the distance).

Assuming reflection and polarization-matched antennas, aligned for maximum directional radiation and reception, it can be shown that the communication range with given output power  $P_{RF}$ , sensitivity  $S$  and equal TX/RX antennas is given by

$$R = \frac{\lambda}{4\pi \sqrt{\eta^2 P_{RF} S}} \quad [m]$$

This equation is based on the assumption that the two antennas are separated by a distance  $R > \frac{2D^2}{\lambda}$ .  $D$  is the largest dimension of either antenna. Wave guidance occurring along conductive surfaces may increase the operation range as well.

The free-space path analysis applies to line-of-sight propagation, which means you have to correct for other various propagation losses  $L_x$  such as signal reflection, diffraction, scattering and polarization losses. When these losses are included, the communication range is given by

$$R = \frac{\lambda}{4\pi \sqrt{\frac{S}{L_X \cdot \eta^2 \cdot P_{RF}}}} \quad [m]$$

Given the required range  $R$ , assumed losses  $L_X$ , sensitivity  $S$  and equal TX/RX antennas, the necessary output power  $P_{RF}$  is given by

$$P_{RF} = \frac{S}{L_X L_p \eta^2} \quad [W]$$

### 3.13.2 Loop antenna electrical equivalent circuit

According to [Balanis, 1997] the equivalent circuit for the input impedance of a small loop, when the loop is used as a transmitting antenna, is shown in figure 3.12.

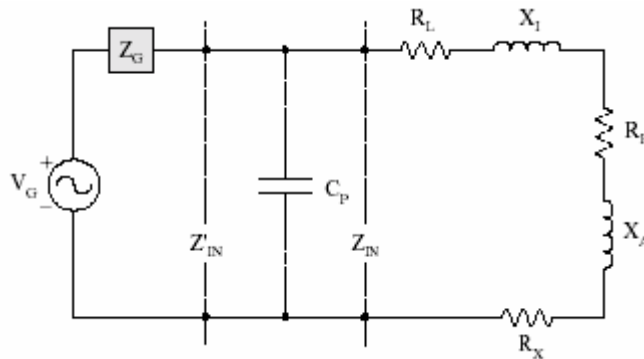


Figure 3.12: Loop antenna equivalent circuit (transmit mode) [figure 2 in Nordic VLSI (3), 2000]

The following selection is collected from [Nordic VLSI (3), 2000].

To calculate the efficiency of the receiver, we first need to calculate some electrical coefficients.

The loop antenna impedance  $Z_{IN}$  is given by:

$$Z_{IN} = (R_R + R_L + R_X) + j2\pi f_0(L_A + L_I) \quad [\Omega]$$

Where

- $R_R$  = radiation resistance  $[\Omega]$
- $R_L$  = loss resistance of loop conductor  $[\Omega]$
- $R_X$  = additional ohmic losses (ESR in capacitor CP etc.)  $[\Omega]$
- $L_A$  = inductance of loop antenna  $[H]$
- $L_I$  = inductance of loop conductor  $[H]$

The radiation resistance is given by

$$R_R \approx 31171 \cdot \left( \frac{A^2}{\lambda^4} \right) \quad [\Omega]$$

where

$$\lambda = \frac{c}{f_0} \quad [m]$$

where

$c$  is the speed of light equal to  $3 \cdot 10^8$  m/s  
 $f_0$  is the resonance frequency in Hz.

The loss resistance of the loop inductor is given by

$$R_L = \frac{l}{P} R_S = \frac{a_1 + a_2}{b_1 + b_2} \sqrt{\frac{\pi f_0 \mu_0}{\sigma}} \quad [\Omega]$$

where

$l$  = length of the metal loop conductor  
 $P$  = perimeter of the cross section of the loop conductor  
 $R_S$  = conductor surface resistance  
 $\mu_0 = 4\pi \cdot 10^{-7}$  H/m  
 $\sigma$  = conductivity of the conductor equal to  $5.8 \times 10^7$  S/m for copper.

The additional ohmic losses that is introduced mainly because of ESR (Equivalent Series Resistance) of the capacitor  $C_p$  is given by

$$R_X = R_{ESR} = \frac{2\pi f_0 (L_A + L_I)}{Q} - R_R - R_L \quad [\Omega]$$

As can be seen from the expression above, the maximum possible quality factor  $Q$  of a loop antenna is mainly determined by the ESR (i.e. the quality factor) of the capacitor  $C_p$ . A resistor  $R_Q$  in parallel with  $C_p$  can be used to control the  $Q$ -value of the antenna. The insertion of this parallel resistor will reduce the antenna input impedance.

In figure 3.12 the capacitor  $C_p$  is used in parallel to  $Z_{IN}$  to resonate the antenna, that is to cancel out the imaginary part of the input impedance  $Z_{IN}$  at the operating frequency.  $C_p$  can also be used to represent distributed stray capacitances. It can be shown that the parallel capacitor  $C_p$  at resonance is given by

$$C_P = \frac{L_A + L_I}{(R_R + R_L + R_X)^2 + [2\pi f(L_A + L_I)]^2} \quad [F]$$

During resonance the input impedance  $Z_{IN}$  can be shown to be equal to

$$Z_{IN} = R_R + R_L + R_X + \frac{[2\pi f(L_A + L_I)]^2}{R_R + R_L + R_X} \quad [\Omega]$$

The inductive reactance  $X_A$  of the loop is computed using the inductance  $L_A$  of, [Balanis, 1997]

Circular loop of radius  $a$  and wire radius  $b$ :

$$L_A = \mu_0 a \left[ \ln \left( \frac{8a}{b} \right) - 2 \right] \quad [H]$$

Square loop with sides  $a$  and wire radius  $b$ :

$$L_A = 2\mu_0 \frac{a}{\pi} \left[ \ln \left( \frac{a}{b} \right) - 0.774 \right] \quad [H]$$

The reactance  $X_I$  of the loop conductor can be computed using the inductance  $L_I$  of the loop. For a single turn this can be approximated by [Kraus, 1992]

$$L_I = \mu_0 \frac{A}{2a} \quad [H]$$

where  $A$  is the area of the loop.

The antenna efficiency can then be expressed as

$$\eta = \frac{R_R}{R_R + R_L + R_{ESR}}$$

alternatively

$$\eta = \frac{QR_R}{2\pi f_0(L_A + L_I)}$$

### 3.14 Attenuation in forest environment.

It is difficult and complex to estimate the attenuation in forest like environment. A paper by Kulemin Gennady [Gennady, 1999] describes an investigation to map the attenuation by conducting different experiments in such areas. The mean density of trees was 10-20 trees per 100m<sup>2</sup>, and the field attenuation was measured in comparison to the free space level. The dependencies between the attenuation and the range at 430MHz for horizontal polarization are given in the table 3.3.

Distance	Path Loss (approximately)
25m	15dB



50m	17dB
75m	21dB
100m	25dB
125m	27dB
150m	32dB
175m	32dB
200m	33dB

Table 3.3: Path loss due to scattering in woodland [extracted from figure 15 in Gennady, 1999]

The attenuation increases with higher frequencies, and it is greater for vertically polarized waves than for horizontal polarized waves. The polarization difference decreases with rising frequency. There are also some seasonal changes in the attenuation of the signal, with a decrease of attenuation during autumn and winter time. The difference between the summer and autumn values are approximately 0.02 dB/m.

## 4 Description of the channel models

### 4.1 Introduction

This chapter contains a description of the specific propagation model chosen as the theoretical basis for the further data transmission tests. Also included are calculations on the different antennas and ranges.

### 4.2 The Wireless Link

The wireless link is made up of 3 major parts - the transmitter with antenna, the transmission path and the receiver with antenna. Parameters of interest are the output power of the transmitter and the sensitivity of the receiver. Figure 4.1 illustrates a typical wireless link.

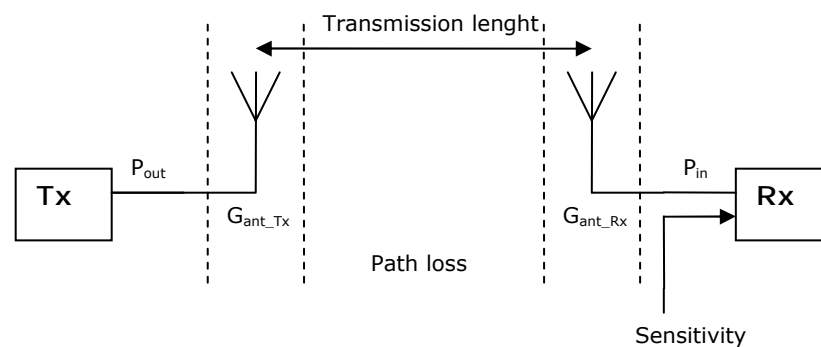


Figure 4.1: The wireless link [figure 3 in Karlsten, 2002]

The sensitivity of the receiver can be found in the documentation provided with the chip. In our case the sensitivity of the nRF401 is  $-105\text{dBm}$ , or  $31.62\text{fW}$ . The path loss depends on the environment the wireless link operates in. Different propagation models are made to best describe these different environments. Some of these are described in chapter 3.7 – 3.14. To choose a model for our case, we need to look at our environment, and choose from that. We choose to focus on an open area scenery, with few or none obstacles, and a forest landscape with a lot of diffraction and scattering.

### 4.3 The open area scenery

By open area we mean an area that is flat and with few or none obstacles that are similar or smaller in size compared to the wavelength, resulting in few scattered components. Reflections are on the other hand a common phenomena. The base station antenna is relatively high elevated; in the region 50 – 250 m above the ground, and the mobile transmitter have a typical elevation of 0.5 - 1.0 m. A suitable propagation model for this case is the reflection model (from chapter 3.10), which has the following structure

$$P_r = 4P_t \left( \frac{\lambda}{4r\pi} \right)^2 G_T G_R \sin^2 \left( \frac{2\pi h_1 h_2}{r\lambda} \right)$$

where  $P_r$  is the received power,  $P_t$  is the transmitted power (in our case 10mW),  $r$  is the distance between the two communicating nodes,  $G_T$  is the antenna gain for the transmitter,  $G_R$  is the antenna gain for the receiver,  $h_1$  and  $h_2$  is the heights of respectively the base node and the mobile node and  $\lambda$  is the wavelength of the signal (0.6928m in our case). Due to the difficulties in testing with an elevated base station antenna, we chose to use the same elevation (one meter) on both the antennas during the testing.

If  $P_r$  is set to be equal to the receivers' sensitivity, we can calculate the *maximum theoretically communication range*. The sensitivity can be found in the product specification, and is in our case equal to -105dBm or 31.62fW. Finding a value for  $h_1$  and  $h_2$  must be based on assumption about the environment. Since  $h_1$  is the base station, it typically has an elevation in the region of 50-200m, but is, as described above, set to 1m. It is on the other hand easier to assign a value to  $h_2$  since this module is in our case situated in a necklace worn by a sheep. A typical value for  $h_2$  must therefore be 0.5 - 1.0 m.

We have divided the calculations into three groups, one for each antenna size. The common parameters are:

$$P_r = 31.62fW.$$

$$P_t = 10mW.$$

$$h_1 = 1.0m.$$

$$h_2 = 1.0m.$$

$$f = 433MHz.$$

$$\lambda = \frac{c}{f} = \frac{3 \cdot 10^8 m/s}{433MHz} = 0.6912m.$$

To calculate the range  $r$  from the formula, we first need to find the gain  $G$  of the antenna. The gain is dependent of the area to the antenna and the wavelength the antenna is operating at. From Nordic VLSI the antenna attenuations are given as -26.5dB (18x10mm), -22dB (25x15mm) and -17.7dB (35x20mm).

#### Calculations for the 18x10mm sized antenna

$$20 \log G = -26.5dB$$

$$\Rightarrow G = 10^{\left( \frac{-26.5dB}{20} \right)} = \underline{0.0473}$$

By inserting this into the formula we get

$$31.62fW = 4 \cdot 10mW \left( \frac{0.6912m}{4\pi \cdot r} \right)^2 \cdot (0.0473)^2 \cdot \sin^2 \left( \frac{2\pi \cdot 1m \cdot 1m}{0.6912 \cdot r} \right)$$

giving us  $r \approx \underline{21m}$ .

#### Calculations for the 25x15mm sized antenna

$$20 \log G = -22.0dB$$

$$\Rightarrow G = 10^{\left(\frac{-22.0dB}{20}\right)} = \underline{0.0794}$$

Inserting this gives us

$$31.62fW = 4 \cdot 10mW \left(\frac{0.6912m}{4\pi \cdot r}\right)^2 \cdot (0.0794)^2 \cdot \sin^2\left(\frac{2\pi \cdot 1m \cdot 1m}{0.6912 \cdot r}\right)$$

giving us  $r \approx 27m$ .

#### Calculations for the 35x20mm sized antenna

$$20 \log G = -17.7dB$$

$$\Rightarrow G = 10^{\left(\frac{-17.7dB}{20}\right)} = \underline{0.1303}$$

Inserting this gives us

$$31.62fW = 4 \cdot 10mW \left(\frac{0.6912m}{4\pi \cdot r}\right)^2 \cdot (0.1303)^2 \cdot \sin^2\left(\frac{2\pi \cdot 1m \cdot 1m}{0.6912 \cdot r}\right)$$

which gives a distance of  $r \approx 36m$ .

### 4.3.1 Diffraction Loss

All the calculations above are based on the fact that there is no loss due to diffraction, which is not very likely in rural areas. The diffraction can vary very much from location to location, and it is therefore difficult to find a value that can be used as a common parameter.

An example of such a calculation is given below. We here assume we have a contour that matches a single knife edge, and thus use the single knife edge calculation method. See figure 3.11.

We can assume the receiving antenna A is elevated 150m and the transmitting antenna B is elevated 1m. Between these two there is an obstacle that obstructs the signal, and has a height of 3 m above the signal path. The obstacle is situated exactly halfway between the two antennas, and the distance between the antennas is 500 meters. This gives us the following parameters:

$$A = 150m$$

$$B = 1m$$

$$h = 3m$$

$$d_1 = d_2 = 250m$$

$$\lambda = 0.6912m$$

The diffraction parameter can then be calculated by using

$$v = -h \sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}}$$

This gives us

$$v = -3 \sqrt{\frac{2(250 + 250)}{0.6912 \cdot 250^2}} = -456.43 \cdot 10^{-3}$$

Extracting the absolute value gives us  $v = 456.43 \cdot 10^{-3}$

Using the ITU-R method to calculate the terrain diffraction loss, we get a loss of

$$\begin{aligned} J(v) &= 6.4 + 20 \log(\sqrt{v^2 + 1} + v) \text{ dB} \\ &= 6.4 + 20 \log(\sqrt{456.43 \cdot 10^{-3} + 1} + 456.45 \cdot 10^{-3}) \text{ dB} \\ &= \underline{10.82 \text{ dB}} \end{aligned}$$

Another parameter that is neglected in the range calculations is the noise attenuation, which also will shorten the communication range. The problems surrounding noise are discussed in chapter 3.5.

## 4.4 The forest scenery

The forest scenery is dominated by trees and bushes, giving us additional losses in signal strength due to scattering.

The range is dependant of the polarization of the signal. A horizontal polarized signal is best suited to penetrate vertical obstacles in the signal path, due to the fact that the trees and other obstacles are perpendicular on the electrical field emitted from the antenna.

We can base the forest range calculations on the same model as the model used in the rural areas, i.e the reflection model. The only addition is the path loss due to the vegetation. Based on a paper from Kulemin Gennady [Gennady, 1999] we can assume a loss in the region of 30 – 35 dB over a distance of 200m with trees, using horizontal polarization and a frequency of 430MHz (compare with table 3.3 in chapter 3.14).

The forest calculations are based on this equation (extended from equation 3.21):

$$P_r = 4P_t \left( \frac{\lambda}{4r\pi} \right)^2 G_T \cdot G_R \cdot F_L \cdot \sin^2 \left( \frac{2\pi h_1 h_2}{r\lambda} \right)$$

where  $F_L$  is the forest loss factor.

Using a forest range of 50 meters, the loss factor is

$$20 \log X = -17 \text{ dB}$$
$$X = 10^{\frac{-17}{20}} = 0.1412$$

Calculations for the 35x20mm sized antenna

Including this in the reflection model gives us, for the largest antenna, a range of

$$31.62 \text{ fW} = 4 \cdot 10 \text{ mW} \left( \frac{0.6912 \text{ m}}{4\pi \cdot r} \right)^2 \cdot (0.1303)^2 \cdot 0.1412 \cdot \sin^2 \left( \frac{2\pi \cdot 1 \text{ m} \cdot 1 \text{ m}}{0.6912 \cdot r} \right)$$
$$\Rightarrow \underline{r = 22 \text{ m}}$$

Calculations for the 25x15mm sized antenna

The mid-sized antenna has a range of

$$31.62 \text{ fW} = 4 \cdot 10 \text{ mW} \left( \frac{0.6912 \text{ m}}{4\pi \cdot r} \right)^2 \cdot (0.0794)^2 \cdot 0.1412 \cdot \sin^2 \left( \frac{2\pi \cdot 1 \text{ m} \cdot 1 \text{ m}}{0.6912 \cdot r} \right)$$
$$\Rightarrow \underline{r = 17 \text{ m}}$$

Calculations for the 18x10mm sized antenna

The smallest antenna have a theoretically communication range of

$$31.62 \text{ fW} = 4 \cdot 10 \text{ mW} \left( \frac{0.6912 \text{ m}}{4\pi \cdot r} \right)^2 \cdot (0.0473)^2 \cdot 0.1412 \cdot \sin^2 \left( \frac{2\pi \cdot 1 \text{ m} \cdot 1 \text{ m}}{0.6912 \cdot r} \right)$$
$$\Rightarrow \underline{r = 13 \text{ m}}$$

## 5 Measuring methodologies

### 5.1 Introduction

This chapter describes the data transmission test set up and how the tests were performed. Also the different test parameters, and the PC applications used are described here.

### 5.2 Schematic sketch of the test setup

Figure 5.1 shows the test setup used in our measurements. Both the transmitter and the receiver were set up as shown in the figure.

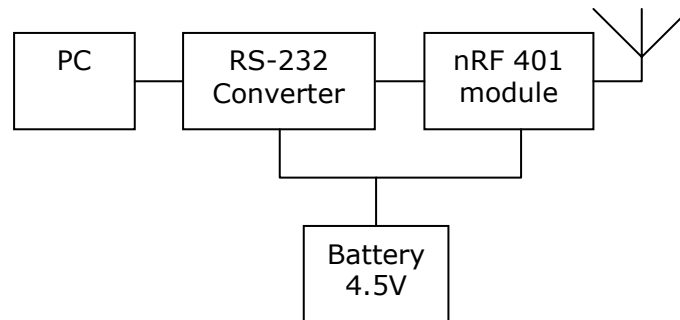


Figure 5.1 – Schematic sketch of the test setup.

### 5.3 Test procedures

We chose to test the radio system in two different topological areas. These were an open area and a forest area. The tests were performed by using two portable laptops, each having the LabVIEW software installed. To control the transmitter side we used the 'Serial Output' programs, and at the receiver we used the 'Serial Input' programs. These programs are described in further detail in chapter 5.5.

The open area we used was a lawn just outside our university college. An image of the area is given in picture 5.1.



Picture 5.1: Open area environment.

The forest we tested in is also located near campus. The tree density was not very thick, and at the time of the measurements the trees held very little leaf. An image of the location is given below in picture 5.2. The exact locations are plotted into a map in figure 5.1 to give a better overview; where 1 refers to the open area, and 2 to the forest area. [Map-data provided by [www.maponweb.com](http://www.maponweb.com)]



Picture 5.2: Forest area environment.



We measured the bit error rate (BER) at the ranges 2, 10, 20, 30 and 40 meters between the two modules. The BER was adopted as a quality measure because it is simple to implement in a software program, and it also gives a good indication of the performance of the system. It is the most widely used method to measure the quality of a data channel. The calculation of BER is simply the number of bits received with errors divided by the total number of bits received.

The height of the antennas were in the region 30-50 cm above ground. We varied the bit pattern and polarization to see if this had any impact on the performance. The block size was also varied between data blocks of 8 and 16 bits to see if that had any influence on the BER. The total number of bits sent was in each case 8000. A 50 meter long tape-measure, as shown in picture 5.1, was used to measure the distance between the two communicating nodes.

To get a qualitative result, the tests were performed at least 10 times at every distance. The number of bits and the number of errors were then averaged respectively to calculate a final BER. This was done for each parameter we changed. The results of these measurements are given in chapter 6, and are discussed in chapter 7.



Figure 5.1: Map overview of the test areas.

The verbal communication between the two test stations was maintained by using two walkie-talkies. These were very helpful in the executions of the measurements, but due to the fact that they could affect the result of the tests by introducing bit errors, they were only used between the different test runs.

To solve the problem of a portable power supply, we used 3 AA alkaline batteries of 1.5V each, giving us a total of 4.5V. This is sufficient to power both the nRF module and the RS232 converter circuit (see chapter 5.6 for a description of the circuit).

## 5.4 Test parameters

Due to the number of test parameters, the order in which these different parameters were altered and the according results were measured, was important. The parameters that were the easiest to alter would be most suitable to alter most often. The ones that required more work and time to be altered would, on the other hand, only be altered as seldom as possible. We limited the tests of some parameters. These limitations are described in chapter 2.3.

The different parameters, and reasons for the chosen order, are described below:

1. Message length (the division of data blocks, referred to as block size) and message value (referred to as bit pattern). These are the easiest parameters to vary, because they can both be altered from the PC application that transmits the data.
2. Antenna polarization. This is an easy procedure; it only requires changing the angle/position of the transmitting and receiving antenna.
3. Distance. The distance that the data has to travel between the transmitting and the receiving antenna is a parameter that requires a bit more time to be altered. The transmitter and the receiver has to be moved geographically a number of measured meters.
4. Topology. This might require moving relatively far, and a change of topology will because of this only be performed a couple of times.

We decided to use two different topologies, according to the two channel models, for the tests. Parameters 1-3 above will be altered while transmitting data within an area that is equivalent to one of the propagation models. Then the same tests will be performed for the other propagation model.

## 5.5 LabVIEW

To build the application that communicates with the nRF401 module, we chose to use a program from National Instruments called LabVIEW. It is a graphical programming software that allows us to build our own specialized virtual instruments, so-called VI's. We chose to use this software because of its simplicity together with the fact that there are several people here at the college with knowledge to the software, and therefore could assist us if we had any questions or problems.

The LabVIEW program is divided into two main parts; the front panel and the diagram part. The front panel is the interface the VI presents to the user. It can contain several items such as graph displays, switches, knobs and other controls. The diagram is the area where the behavior of the VI is implemented. Using different symbols and items, the program is "wired" together using a programming method called G programming (graphical programming). The diagram is hidden for the user during execution since all the adjustments can be done from the front panel.

Our data exchange software is split into two different applications. One that writes to the serial port on the computer, and one that reads from the serial port and calculates the Bit Error Rate. These applications are discussed individually below. To be able to vary the block size of the transmitted message, we built one

set of programs for both 8 bit and 16 bit message length. The different diagrams can be found in appendix A.

### 5.5.1 The serial output program.

The program is split into two modes of operation; one where the bit pattern written to the port is selected by a random algorithm, and one mode where the user can select the bit pattern manually. The number of bits written to the port is in both cases 8 bits or 16 bits. The selection of manual/automatic mode is controlled by a vertical slide switch. The slider has the boolean values 'true' and 'false'. The value is 'true' if automatic is chosen, and 'false' else. The random selection process is repeated until we get a total of 8/16 bits generated by the use of a while loop, and the bits are stored in an indexed byte array.

The manual bit pattern can be selected by using 8/16 vertically toggle switches. These 8/16 values are the elements used to build an array. The array is then presented in a display, so the user can see the actual bit pattern on the screen. The array is then delayed for 100ms before it is converted to a string and written to the serial port. The delay is needed because there is a limit of how fast the COM port can write a message to the module. To prevent an uncontrolled build up of data in the buffer, a break in the bit flow is needed to regularly empty the buffer. The duration of this delay can be adjusted from the front panel. To write to the serial port we use a VI that is included in the LabVIEW package called "Serial Port Write.vi".

From the front panel the user can also change the port number to write to, and the number of bytes to be written to the port. A screenshot of the front panel is shown in figure 5.2, and shows the transmission of the bit pattern '10110110'.

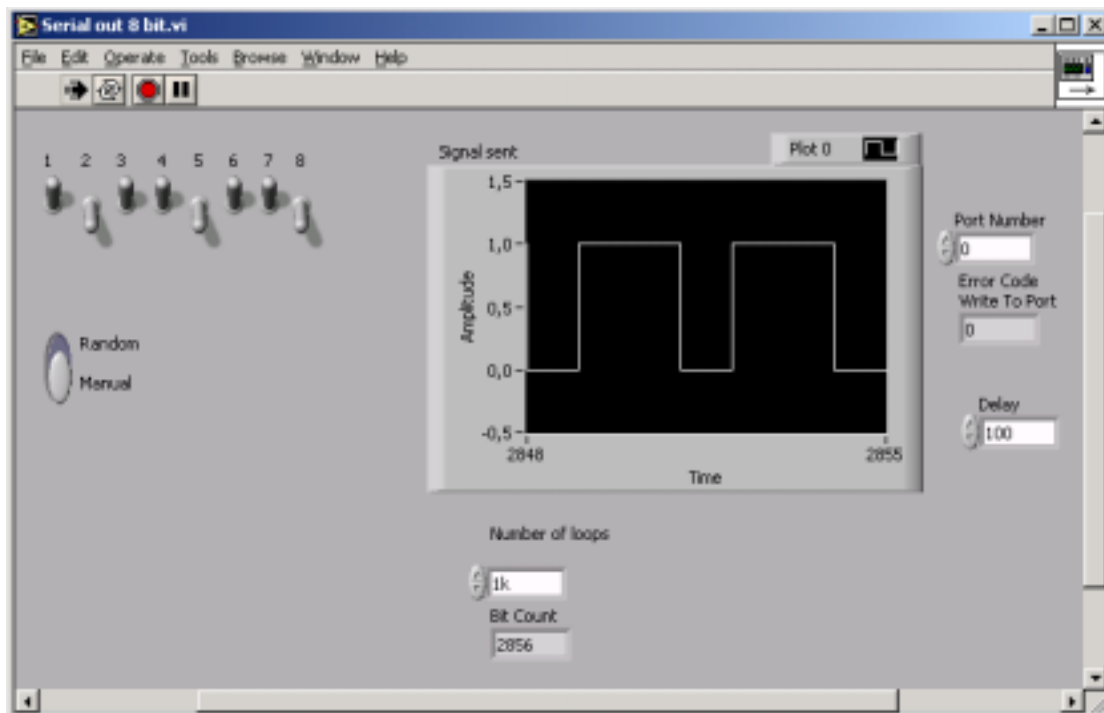


Figure 5.2: Screenshot of the LabVIEW program in transmit mode.

## 5.5.2 The serial input program

The purpose of the input program is to compare the received bit pattern to a pre-defined pattern, and then calculate the BER by counting the number of errors and the number of bits received. The correct bit pattern is set in the same way as in the output program by using 8/16 toggle switches. These are then put into an indexed array, and are compared to the bits read from the serial port. This comparison is done bit wise, meaning we are examining one bit at the time, and not the whole array.

To read from the port we use a VI that comes with the LabVIEW program called "Serial Port Read.vi". We also use another predefined VI, the "Bytes At Serial Port.vi" to count the number of bytes available at the port. The number of bytes at the serial port is used to control a case loop that ensures that we only read from the port when there is anything in the buffer to read. The comparison of the two arrays is done by a 'for' loop. Each time the 'for' loop runs, the "No. Of Bits" counter is incremented. If the two bits compared are dissimilar, the "No. Of Errors" counter is incremented. The BER is computed by dividing "No. Of Errors" with "No. Of Bits". The results are presented to the user via the front panel. Figure 5.3 shows the reception of the bit pattern '10100110'.

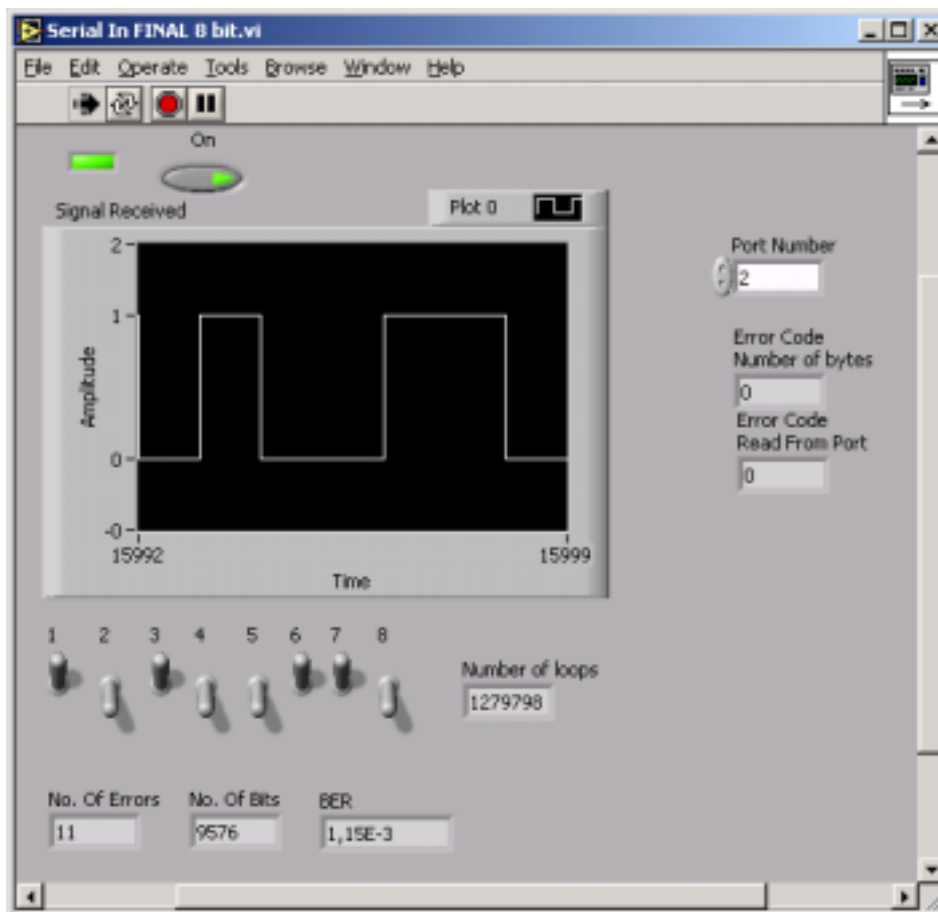


Figure 5.3: Screenshot of the LabVIEW program in reception mode.

## 5.6 RS-232 converter circuit.

The next step was to get the signal from the COM-port to the nRF modules. The modules require 0 and 5 volts as logical zero and one (TTL). However the RS-232 signal uses -10 and +10 volts as the corresponding values. This made it necessary to build a converter circuit that could give the modules the right voltage. Maxim's integrated circuit MAX232 is one of many IC's that can do this job.

A small printed circuit board was made according to the specifications for such a converter circuit (see appendix B). The circuit converts both incoming and outgoing signals to the corresponding correct values. In the specification of the MAX232, it is stated that it needs a power supply of 5 Volts  $\pm$  10%, meaning 4.5V is sufficient.

## 5.7 Noise and attenuation measurements.

To get an impression of how the background noise level in our frequency domain was, we performed some measurements to find out more about this. We also wanted to see how the field strength of our transmitter attenuated with distance. To perform these measurements we used a spectrum analyzer (HP 8558B OPT 002) and a reference antenna. The spectrum analyzer covers the frequencies from 0MHz to 1.5GHz. We focused on the frequency range 400 - 460MHz. The tests were performed in the open area (area denoted 1 in figure 5.1) due to the need of a power outlet.

The field strength measurements were performed by observing how the signal attenuated when the transmitting distance increased. The attenuation was measured every 10 meters up to a distance of 110 meters, with both vertical and horizontal polarization. The reference antenna was rotated in the horizontal plane to find strongest field at every distance and polarization.

The results of these measurements are presented in chapter 6, and they are discussed in chapter 7.

## 6 Measuring results

### 6.1 Introduction

This chapter contains all the results from the data transmission tests and the frequency analysis. All the data in the different tables are mean values. The accurate measurement series are given in the referred appendixes.

### 6.2 Lab test

Our first tests took place in the college ICT-lab. Contact between the transmitter and the receiver was established without any problems, and we performed the tests as planned. We tested at a distance of approximately 20 meters, and with the other parameters set to the following values:

Bit pattern sent	10001000
Polarization transmitter	Horizontal
Polarization receiver	Horizontal
Block delay	100 ms
Number of bits sent	8000 bits
Baud rate	19200 bps
Block size	8 bits

The result of this test was a total bit error rate (BER) of  $3,46 \cdot 10^{-3}$ . See appendix C.1 for all the results.

### 6.3 Frequency analyzing

An HP 8558B OPT 002 Spectrum Analyzer was used to look at the existing radio signals as described in chapter 5.7.

We tested by using one of the nRF401 modules set to transmit data. The HP Spectrum Analyzer showed the transmitted signal from the nRF401 module as a spike with varying intensity (in dBmV), depending on the distance between the antennas and the polarization of the reference antenna. Also the direction of the antenna was quite significant to register the signal effectively. By turning the reference antenna slowly around in the horizontal plane (when the module's transmitting antenna was horizontally polarized and pointing towards the reference antenna) approximately 2 meters away from the module, the following variations in the signal intensity are shown in table 6.1.

Vertically polarized reference antenna	-20 ⇔ +15 dBmV
Horizontally polarized reference antenna	-15 ⇔ +20 dBmV

Table 6.1: Signal strength whilst turning reference antenna

After this we wanted to find the signal intensity at certain distances from the transmitting module. The same polarization on both the nRF401 module antenna

and the reference antenna was used to compare these two separate ways of transmitting data. The results (mean values of signal strengths, given in dBmV) are shown in table 6.2 and plotted in figure 6.1. See appendix C.2 for all the results.

Distance (m)	Horizontal polarization intensity	Vertical polarization intensity
2	21	19
10	6	8
20	6	1
30	2	-5
40	-5	-10
50	-9	-16
60	-12	-17
70	-17	-19
80	-17	-24
90	-20	-24
100	-22	-27
110	-22	-22

Table 6.2: Signal strength at different distances

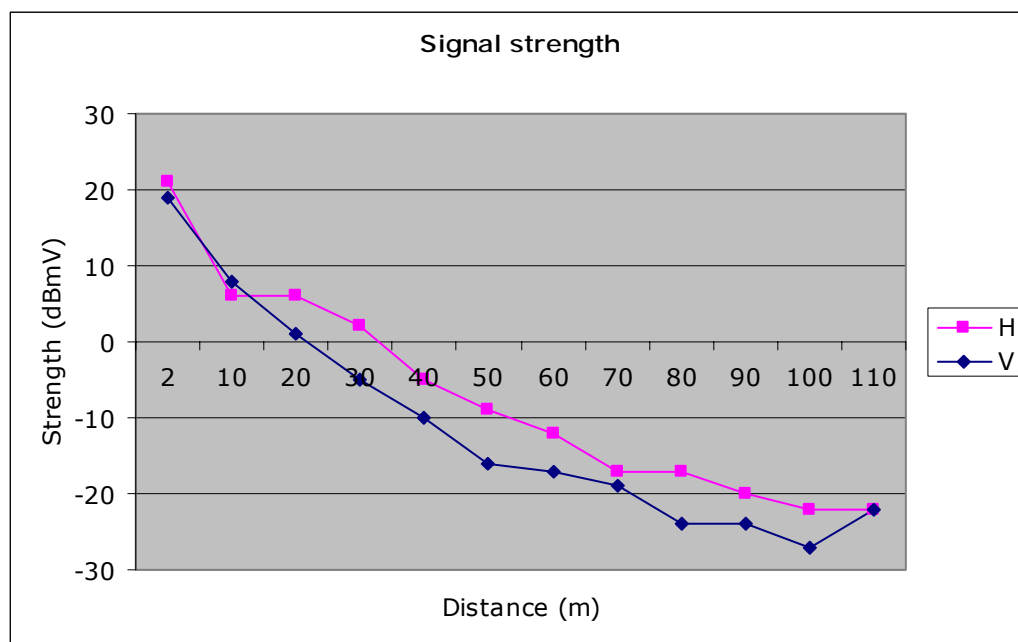


Figure 6.1: Signal strength at different distances

Performing the measurements from 70 meters and up to 110, we found that turning the reference antenna just a few degrees in the horizontal plane improved the level of the intensity at most 8 dBmV.

The test also gave us a good idea of which other types of radio signals were present. Most importantly we found that there were no other signals interfering at the exact same frequency as the nRF401 modules. The closest signal, that is the one nearest by in distance of frequency, was a spike that occurred for a few

seconds twice during the whole test approximately 5 MHz away from the nRF signal spike. The source of this signal is unknown to us.

Another objective that was covered was finding the white noise level. This level was constant all the time we used the frequency analyzer. The level was measured to be approximately -35 dBmV.

## 6.4 Open area tests

The outdoors tests were performed in the two different sceneries (according to the channel models). Almost all the tests were performed in series of 5 or 10, each transmitting 8000 bits. The values given in this chapter is a total bit error rate based on total number of errors and total number of received bits in each series. In this presentation of the results we ignore some of the worst cases, that is the series with bit error rates that are a lot higher than the median value. However, in the appendix section all the measurements are given accurately. The results that are skipped in this chapter are marked as 'Ignored' in the appendixes because of the measurement's rather extreme values compared to the other measurements.

Some of the parameters were set at constant values for all the measurement series. These are:

Baud rate	19200 bps
Block delay	100 ms
Number of bits sent	8000 bits

A change of bit pattern was the first thing that was tested. The two different bit patterns were tested at a distance of 2 and 30 meters, and horizontal polarization was used on both transmitter and receiver. The results of this test are shown in table 6.3 and plotted in figure 6.2 with a logarithmic y-axis. See appendix C.3 for the complete measurement series.

Bit pattern	BER, 2 m	BER, 30 m
10100010	1,73E-02	4,50E-03
10110110	8,20E-03	3,59E-03

Table 6.3: Different bit patterns



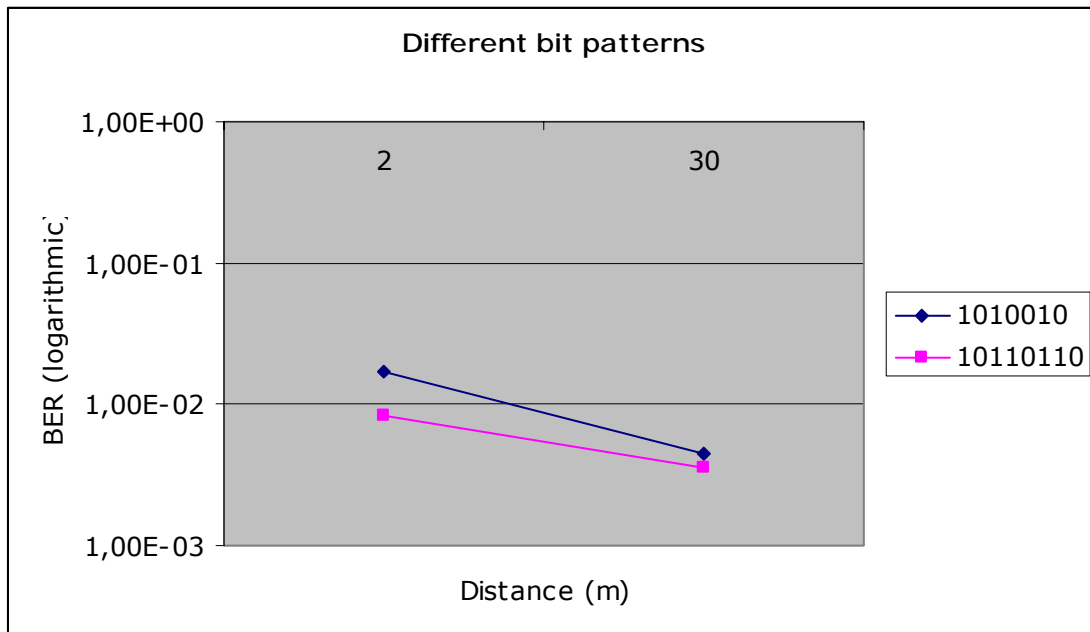


Figure 6.2: Different bit patterns

After this the same bit pattern ('10110110') was used for all the other measurement series. The next parameter we tested was the polarization. First we used the same polarization on both transmitter and receiver. H stands for horizontal, and V stands for vertical polarization. The transmitter's polarization is the first letter, for example "HV" which means that the transmitter is horizontally polarized whilst the receiver is vertically polarized. The results of this test are shown in table 6.4 and plotted in figure 6.3 with a logarithmic y-axis. See appendix C.4 for the complete measurement series.

Polarization	BER, 2 m	BER, 10 m
HH	8,20E-03	6,71E-03
VV	9,79E-04	1,50E-03

Table 6.4: Different polarizations

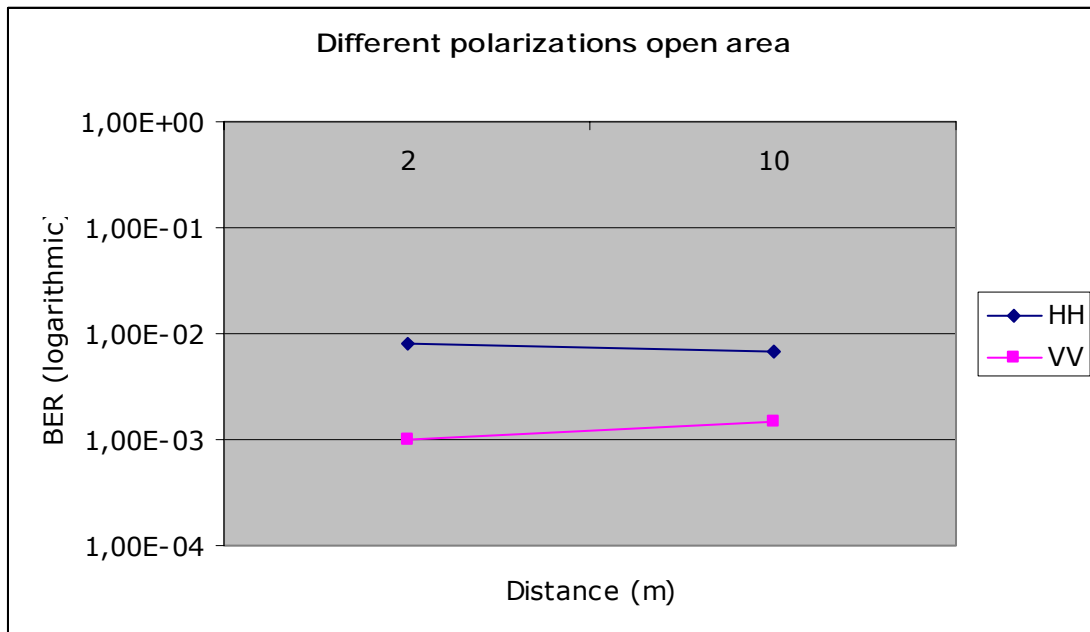


Figure 6.3: Different polarizations in open area

These BER measurements were performed when the antennas were facing each other. In addition, we tested how much the transmitting antenna could be turned in degrees in the horizontal plane compared to the receiver, and still maintain contact. In the case of HH the carrier was lost at approximately 30 degrees. For VV the corresponding value was approximately 45 degrees. Both these values were found at the distance of 22 meters.

By applying different polarization to the transmitter and the receiver, we tested the maximum distance with an adequately strong carrier wave present. For HV polarization the distance was 22 meters, and for VH polarization the maximum distance was 15 meters. These results were only possible when the antennas were facing straight towards one another.

The importance of the block size in order to achieve the best possible BER, was also tested. Blocks of 8 bits and 16 bits were transmitted. The results are given in table 6.5 and plotted in figure 6.4 with a logarithmic y-axis. See appendix C.5 for the complete measurement series.

Distance (m)	BER, 8 bit	BER, 16 bit
20	4,33E-03	1,93E-02
30	3,59E-03	1,75E-02
40	8,04E-03	6,87E-02

Table 6.5: Block size influence

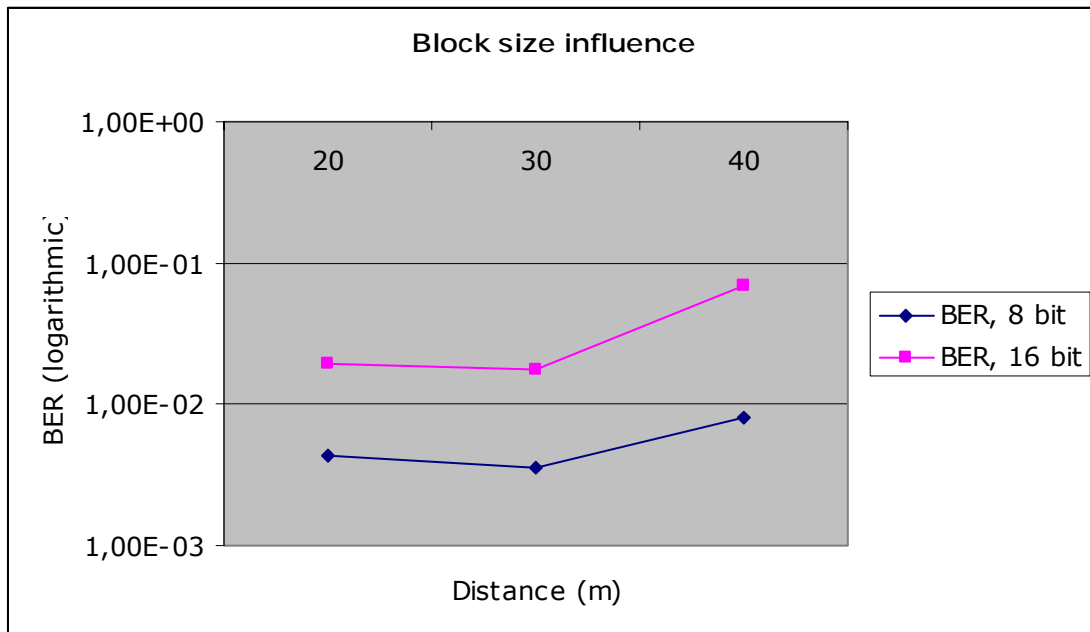


Figure 6.4: Block size influence

The last parameter that was altered to see its relevance was the distance. We here show the results of the measurements performed with both HH and VV polarization, from 2 meters till the signal faded away just after 30 meters for VV, and 40 meters for HH. We have stated the BER at 40 meters for VV to be  $4.02 \cdot 10^{-1}$ , but at that distance we only partly had the carrier wave present, so we were able to conduct only 3 measurements. See table 6.6 for the results. The results are also plotted in figure 6.5 with a logarithmic y-axis. See appendix C.6 for the complete measurement series.

Distance (m)	BER, HH	BER, VV
2	8,20E-03	9,79E-04
10	6,71E-03	1,50E-03
20	4,33E-03	6,46E-04
30	3,59E-03	3,75E-04
40	8,04E-03	4,02E-01

Table 6.6: BER in open area

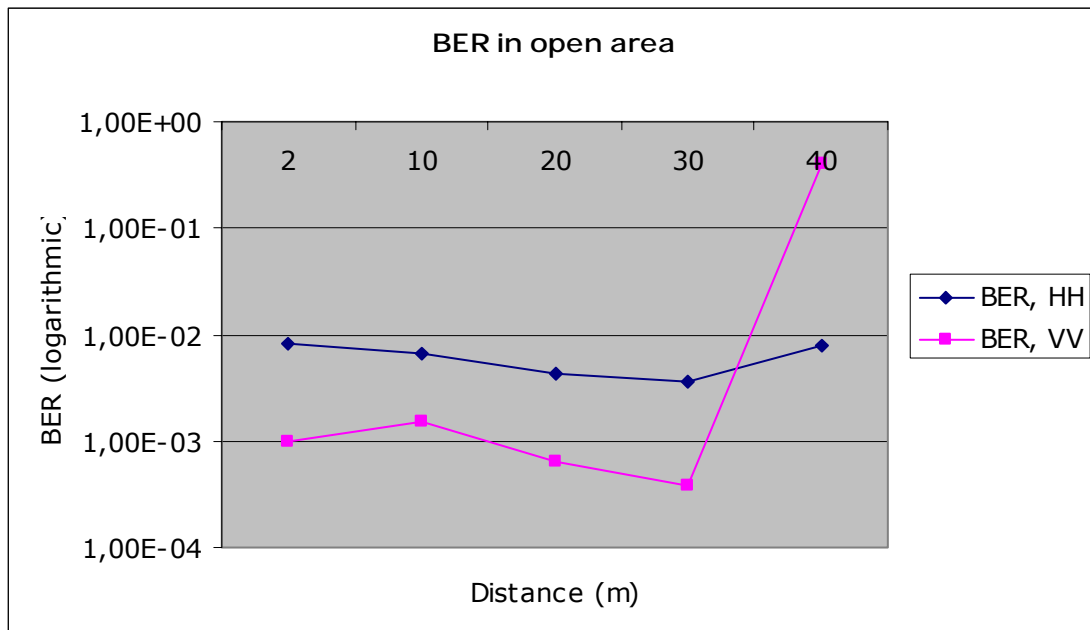


Figure 6.5: BER in open area

In addition, we found that the time the tests were performed had an impact on the results. The tests took place around noon and around seven pm. The results are given in table 6.7. See appendix C.7 for the complete measurement series.

Time	BER
Noon	8,04E-03
Evening	3,75E-04

Table 6.7: BER according to time

## 6.5 Forest area tests

In the forest we only altered the polarization of the antennas and the distance between the transmitter and the receiver. All the other parameters were set as the final measurements in the open area. Table 6.8 below shows the different BER. The results are also plotted in figure 6.6 with a logarithmic y-axis. See appendix C.8 for complete measurement series.

Distance (m)	BER, HH	BER, VV
10	6,09E-02	2,14E-01
20	7,64E-02	1,06E-01
30	9,45E-03	5,34E-02
35	1,35E-01	2,54E-02
40	2,77E-01	3,79E-01

Table 6.8: BER in forest area

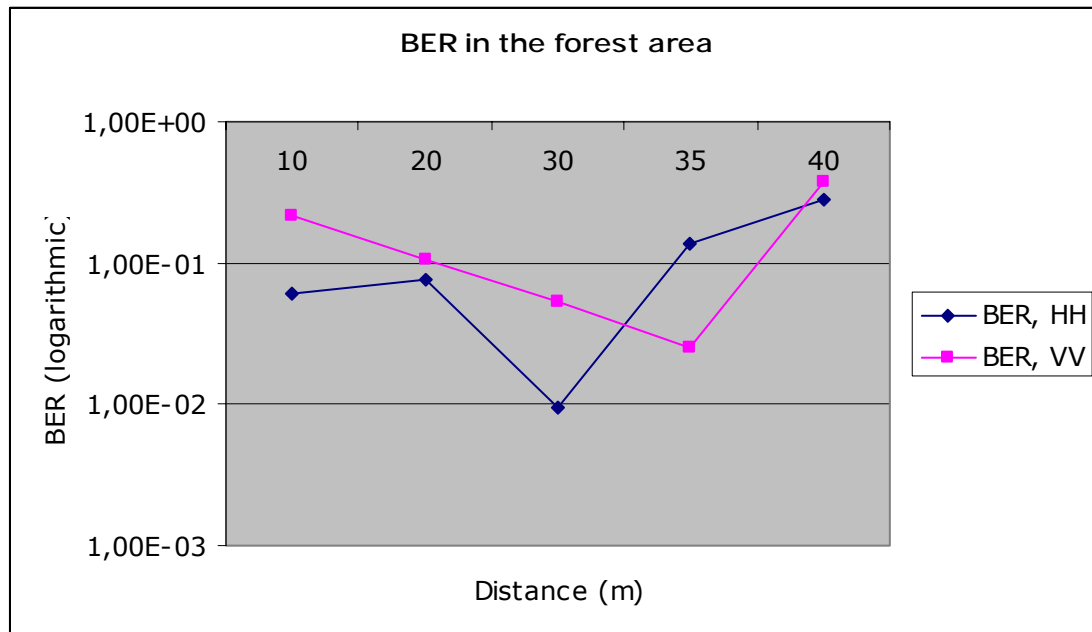


Figure 6.6: BER in forest area

### 6.5.1 Real loss factor

Based on the results from the measurements, we here calculate a loss factor that corresponds to the attenuation in the forest used for our measurements. Based on the forest propagation model, we can find the loss factor that is correct in our measurements.

$$31.62fW = 4 \cdot 10mW \left( \frac{0.6912m}{4\pi \cdot r} \right)^2 \cdot (0.1303)^2 \cdot 0.1412 \cdot \sin^2 \left( \frac{2\pi \cdot 1m \cdot 1m}{0.6912 \cdot r} \right)$$

Substituting  $r$  with 30 meters, and 0,1412 (the loss factor) with  $X$ , enables us to find the correct loss factor for our measurements. This gives us a loss factor of

$$31.62fW = 4 \cdot 10mW \left( \frac{0.6912m}{4\pi \cdot 30m} \right)^2 \cdot (0.1303)^2 \cdot X \cdot \sin^2 \left( \frac{2\pi \cdot 1m \cdot 1m}{0.6912 \cdot 30m} \right)$$

$$\Rightarrow X = \frac{31.62fW}{4 \cdot 10mW \cdot \left( \frac{0.6912}{4\pi \cdot 30m} \right)^2 \cdot (0.1303)^2 \cdot \sin^2 \left( \frac{2\pi \cdot 1m \cdot 1m}{0.6912 \cdot 30m} \right)}$$

$$\Rightarrow X = 0.49523 \Rightarrow 20 \cdot \log(0.49523) = \underline{\underline{-6.1dB}}$$

## 7 Discussion

### 7.1 Introduction

In this chapter the results from all the measurement series are discussed. We propose explanations for the different observed behaviour based on the theory of this thesis. Discussed elements are variation in data, the antenna and other parameters that have influence on the measurements. In addition, we introduce ideas we have regarding further work on this project.

### 7.2 Distance

From our measurements we see that it is possible to reach a distance of 40 meters in open area with horizontally polarized antennas. The bit error rate was in this case  $8.04 \cdot 10^{-3}$ . This was the longest possible range achievable without losing the carrier wave, which would result in a BER close to one. In chapter 4.3 of the theory section we calculated a range of 36 meters, meaning that after this distance the signal strength falls below the receiver's sensitivity limit. This gap of approximately 10% must be considered acceptable. This result shows that the choice of propagation model in this case was adequate.

Studying the results from the forest measurements, we see a decrease in the range, in which the BER was acceptable. In this case we have a range of 30 meters and a BER of  $9.45 \cdot 10^{-3}$ . However, the maximum range was still 40 meters but at that range the system was on the verge of breakdown. Comparing this with the theory, we see a rather significant gap. The forest model has a theoretical range of 22 meters. This difference may be the result of the forest model's loss factor, since this factor is the only thing that differs in the two models. The value of this factor represents the attenuation in a relatively heavy vegetated forest (20 trees pr.  $100\text{m}^2$ ). The vegetation density is in our case not as high as it is in the paper presented by Kulemin Gennady [Gennady, 1999]. In our case, the trees were smaller, stood further apart and hardly any of the trees had grown leaves yet. Therefore the attenuation used in the model is too high compared to the real attenuation in our forest test area. Based on this, we calculated a new forest loss factor, see chapter 6.5.1.

Comparing the results from the open area and the forest area, we notice that the BER found at a distance of 40 meters in open area corresponds to the BER found at the range of 30 meters in the forest. Moving further away we partly lost the carrier wave in the open area, while we in the forest better maintained contact up to 40 meters. It must be stressed that the quality of the link (BER) on verge of breakdown was a lot worse in the forest area, more precisely the forest BER was 35 times worse than the open area BER, most likely due to scattering.

The tests in the forest area showed a performance that was a bit particular. The data link was rather poor at short ranges and long ranges, while the link was best in the mid-range (approximately at 30 meters). This behaviour is closer described in chapter 7.4.1.

## 7.3 Variation in data

### 7.3.1 Code value

Prior to the tests we believed that the code value most probably would not influence the result and quality of the data transmissions much. There was no particular reason to believe that one of the two frequencies (each representing the logic value zero or one) should be more susceptible to noise than the other.

The influence of the bit pattern was tested at the ranges of 2 meters and 30 meters. The results at 30 meters were rather clear. We got almost exactly the same BER with the different bit patterns. At 2 meters the results were a little bit different. At this latter distance, the series with one of the bit patterns contained twice as many errors as the other series. The reason for the gap between the BER at 2 meters might be that there is a lot more reflections at close ranges that can jam the signal. This causes the receiver problems with correct demodulation. This phenomenon is described further in chapter 7.4.1. We therefore consider the measurement series performed at 30 meters to be of higher significance than the other series. Based on this we mean that the bit pattern has very little influence on the performance of the system.

### 7.3.2 Message Length

The message length, or data block size, in the data transmissions is also a parameter that influences the system performance. Short messages are preferable because changes in the electromagnetic field might occur suddenly and at random. By short messages we mean that the time it takes to transmit the message is a lot shorter than the time between each noise occurrence. Considering this phenomenon of sudden noise, short messages will have bigger chance of reaching the receiver without being influenced by various noise sources. Division into data blocks will provide a better link, which contributes to fewer errors per time unit. Such a division also means that shorter messages are sent, and this has the same advantages as short messages; there is less chance of influence from sudden noise.

By varying the block size we got different test results. We tested both blocks of 8 and 16 bits, and the results were relatively clear. As shown in table 6.5, the series containing blocks of 16 bits were more receptive to errors. Increasing the distance led to an even bigger ratio of errors in the bigger block series compared to the smaller block series. This relation between the BER for 16 bit and the BER for 8 bit increased from approximately 4.5:1 to 8.5:1 by increasing the distance from 20 to 40 meters. The reason for 16 bit block series having more errors than 8 bit block series is that sudden external changes in the electromagnetic field have a better chance of jamming a data block when the size of it increases. Longer data blocks require more transmission time to transmit the entire block, and therefore the probability of being influenced by burst noise increases. There is shorter time between the transmitter's active phases (transmitting data) when the data blocks are longer, and the transmitter's active phases are also longer (in seconds) in the latter case. This means the probability of influence from burst noise increases. Even though the total number of bits transmitted, and the duty-

cycle per test series, are the same for both block sizes, bigger blocks still lead to more noise influence.

## 7.4 Antenna influence

### 7.4.1 Polarization

Testing transmissions with different antenna polarizations, we found that this was a parameter that influenced the test results quite a lot. In the open area measurements, the tests with vertically polarized waves gave the best results. The relation BER for vertically polarized waves vs. the BER for horizontally polarized waves was here from 4.5 (at 10 meters) to 9.6 (at 30 meters) times better. At 40 meters the connection was lost for the vertically polarized waves, but there was still contact with horizontally polarized waves with a fair BER.

In the forest area the situation was quite different. Here the horizontally polarized waves had the better resistance against noise influence. The relation BER for horizontally polarized waves vs. the BER for vertically polarized waves was here from 1.4 (at 20 meters) to 5.7 (at 30 meters) times better. However, at the distance of 35 meters the BER for the vertically polarized waves was 5 times better than for horizontal polarization. This is generally pretty much what could be expected from the theory, with the exception of the test at 35 meters. The reason for the particularly bad transmissions for the vertically polarized radio waves at short ranges is most likely because of reflections from the surrounding environment. The transmitted waves are reflected by trees and bushes near by, and cause fading at the receiver. Vertically polarized waves are more exposed to fading because of the majority of vertical obstacles. Also the horizontally polarized waves suffered some fading at short ranges. It is likely that also this is caused by reflections from near by obstacles. Increasing the distance led to less fading at the receiver. This is because the reflected waves are weakened due to the distance they have to travel compared to the direct waves, and because reflections, caused by trees and other vegetation, result in some energy loss. This energy loss is absorbed by the reflecting obstacles.

By using different polarization on the transmitter and receiver, we tested what the maximum ranges for these two configurations were in the open area. When using a horizontal polarization at the transmitter antenna and a vertical polarization at the receiver, we found that the maximum distance was 22 meters. The other way around the corresponding range was 15 meters. This shows us that it is important that the two antennas have the same polarization to achieve the best possible transmission link because two equally polarized antennas communicate more easily and with better result.

### 7.4.2 Angle of turning

By turning the direction of the transmitter's antenna, we measured the maximum angle of rotation in the horizontal plane we could apply without losing the connection completely. These measurements were performed with both HH and VV polarized antennas. We noticed that in the case of the HH polarization, we lost the connection at an angle of approximately 30 degrees. With VV polarization, the



corresponding angle was 45 degrees. The most likely explanation to this behaviour is the beam characteristics of the loop antenna.

### 7.4.3 Height above ground

An observation we made during the tests, but without making any further documentation of the phenomenon, was that the antenna height above the ground was of great significance to the maximum range, even if the height was altered only by i.e. 10 cm. All our measurements were therefore performed with the same antenna height of 50 cm. We chose not to test with different heights due to the number of parameters we already had decided to find the significance of. Now, after all the measurements have been performed, we can see that investigating the influence of the height would have been preferable. Since we can not perform tests on all the desirable parameters, a selection had to be done early on, and at that time of the project this parameter was not being considered.

## 7.5 Other variations

### 7.5.1 Noise sources

During the test phase we found several sources of noise that could influence the performance of our system, if the sources were close enough to the receiver. These sources were walkie-talkies, GSM cell phones and other electronic equipment that produces electromagnetic waves. This type of noise has an influence on the modules' electronics, i.e. making the oscillators malfunction. We tried to shield the receiver's electronics by wrapping aluminium foil around it, but without any improvement in the test results. Another influence on the performance was when a human hand was close to, or in contact with, the receiver or the receiver's antenna. The module then behaved like it received a lot of noise. We have two theories that can explain this odd behaviour. First, the hand may function as an external antenna, intercepting signals and passing them to the receiver. The other theory describes the behaviour as a result of the hand shielding the receiver's ability to receive the signal, and also the carrier. We have experienced when the carrier disappears, the receiver seems to behave like it is only receiving a lot of noise. We believe the latter is the most probable cause, since the antenna effect of the human body decreases at higher frequencies, and since there aren't any other signals in the module's frequency band.

Holding the receiver close to the ground, in the region of 0 – 5 cm above, we experienced that the receiver was very susceptible to noise. In relation to the wavelength, the receiver was then too close to the ground to be able to receive the carrier. Holding the receiver at the usual height, but laying the transmitter on the ground also produced the same behaviour at the receiver. To further investigate this behaviour, tests with the spectrum analyzer could have been performed. Placing the reference antenna e.g. 5 meters away from the transmitter, values of the signal strength could be found as a function of the reference antenna's height above ground.

## 7.5.2 Daytime's influence on the test results

The data transmission tests were mainly performed between 10 a.m. and 3 p.m. However, performing some tests later on the day, we found that this change of test time also had influence on the results of the tests. The series performed in the evening proved to have better results than the series performed in the middle of the day. The first had an average BER of  $8.04 \cdot 10^{-3}$  while the latter averaged  $3.75 \cdot 10^{-4}$ , giving a relation factor of 21:1 in favour of the tests performed in the evening. This result is probably caused by the level of electromagnetic activity in the test area, which naturally is a lot lower in the evening when there are fewer people at school, and therefore not as many computers and other electronic devices in use. Another factor that may explain this result, is the sun spot phenomenon. However, the extent of this phenomenon, and its influence on the tests, is difficult to determine.

## 7.6 BER

The value of an acceptable BER is dependent on the system investigated. Since we in this project use no error correction in the transmissions, a BER in the region of approximately  $1 \cdot 10^{-3}$  should be sufficient to establish an acceptable channel. Nordic VLSI, the producer of the transceivers used in this project, also claims that a BER in this region is satisfactory. The BER value of  $1 \cdot 10^{-3}$  was used as a foundation in the evaluation of the performance of the system.

## 7.7 Frequency analysis

The frequency analysis showed us that there are no signals in the same frequency band as the nRF401 module uses. Neither were there many signals close by. As described in the measurement results chapter, only a couple of times a spike occurred approximately 5MHz away from our signal. There was for instance no sign of the Tetra communication system, which we earlier considered a possible noise source for our modules. The reason for this may be that this system is not yet deployed at a full scale in this region. However, the Tetra system may still be a possible threat to future use of this ISM frequency band. Other than this, we could see some traffic in the 450MHz band, which is the NMT450 mobile phone system. This means that there isn't much noise that jams our 433MHz signal. However, we can't know for sure if any other signals, with other frequencies, in some way influence either our signals or our modules in such a manner that our transmissions are threatened. In addition, radio amateurs can cause some problems for the 433MHz ISM frequency band, in spite of us not seeing any traffic of this kind during the frequency analysis.

Measuring the signal strength from our active module (transmitting a carrier wave) at different distances with the spectrum analyzer, we got slight variations in the results of the different measurement series. The reference antenna used with the analyzer was very directional, and if the two antennas weren't facing each other exactly at the time of the measurement, the signal strength would appear slightly faded. This may explain some of the small variations in the different measurement series. Another reason for this variation may be that the height of the antennas varied from test to test since they were held by hand, and

since we in that phase of the project didn't realize the impact this factor had on the performance of the system.

The measured background noise level appeared relatively constant during the frequency analysis. The value was measured to be approximately -35dBmV in intensity. This value is most likely an adequate value, due to the constantly varying character of the background noise.

## 7.8 Propagation model

From the different propagation models presented in the theory, we chose to use the reflection model as the base for the calculations in our investigation. Looking at the results from the measurements compared with the calculated values, the choice of propagation model was suitable. The reason for choosing the reflection model was based on the planned environments the communication should take place. On a flat open area, the best suitable model is the reflection model, since the only addition to the direct wave component are reflections from the ground. We were not able to obtain a specialized model for such a wooden area, so by introducing another loss factor in the model, it was also capable of handling an area like this. The loss factor we used was a loss of 17 dB, which should simulate a forest length of 50 meters. Looking at the conformity between the measured results and the computed length, we see there is a gap of approximately 18 meters. This indicates that the value of the loss factor we used in the calculation may be a bit too high. The reason for this difference may be that the forest we performed our measurements in was not as dense in terms of trees and vegetation as the forest used in the investigation by Kulemin Gennady [Gennady, 1999]. The loss factor in our case is -6.1 dB at a distance of 40 meters.

A weakness in the model is that it states that an antenna height of less than one meter makes it impossible to receive the transmitted signal with the nRF401's sensitivity. Applying an antenna height of 50 cm in the tests gave us approximately the same results as using an antenna height of one meter in the calculations. This indicates that the model used is not particularly suited for relatively low antenna elevations.

## 7.9 Suggestions to improve the overall performance of the system.

In order to make a tracking system, it is necessary to consider some changes in the part of the system that we have tested; the transmitter and receiver communication part. A maximum range of 40 meters with top conditions will not be adequate considering that a sheep moves further than this. It also moves in different topological areas, which makes it crucial that the system works satisfactory in different environments. We here present a few methods to achieve a better system performance.

The performance of the current antenna is not optimal. The attenuation of the signal caused by the antenna can be bettered by using another antenna with a better gain. This will provide a stronger transmitted signal, and will make the receiver able to demodulate weaker signals. The result of this is a better communication range. It is also important to consider the use of the antenna, and

in particular the transmitting antenna. Obviously, a big antenna can't be mounted on a sheep. This would just cause the antenna to brake, or make the sheep get stuck or injured. However, the receiving antenna can basically be as big as necessary. This antenna will be placed stationary, and will not be the limiting factor of the system.

Lowering the carrier frequency will also result in a better range, with the same use of power as earlier, due to the propagating nature of such signals. They can easier propagate in all types of areas because they are not so easily influenced by the surrounding environment.

Applying higher output power would also improve the system range due to the power's direct relation with the range. However, this has to be done in accordance with the regulations in the respective frequency band. Also the battery capacity of the transmitter has to be considered in the choice of output power, since the power supply needs to be relatively light weighted and small.

Adding error correction in the data transmissions is another way of improving the system performance with less data loss and fewer errors. The range would not have been increased by this, but the data would have been transferred close to perfectly all the time until breakdown would occur when losing the carrier wave. This would require a lot of overhead error handling data causing the total effective data rate to decrease. This is not really too much of a problem due to the small amount of information originally sent. A faultless data transmission is preferable rather than having a quicker data rate with errors. This is an area of interest that can be investigated further, but it is outside the boundaries of our assignment.

## 7.10 *Proposals to further work*

Due to the time limit we did not have the opportunity to investigate all the areas of the assignment we found relevant. To further investigate problems and parameters of interest, we here present areas that we would have continued exploring if we were to work on this project longer.

The maximum range that can be achieved when transmitting data across water, is one of the tests that would have been of great interest to see the results of. Water may in some conditions function as a perfect reflector, and may have a very good effect on the maximum range.

By looking at different antennas and antenna types, an investigation to find an antenna that is preferable, in terms of antenna gain, would have been interesting. Using an antenna at the receiver that differs from the one situated at the transmitter, is also a variation that should be studied. Since the receiver antenna is stationary, it is possible to use a bigger and better antenna at this end. In addition, the influence the antenna's height above the ground has on the quality of the link is also an area that would be interesting to have a closer look at.

The impact the block size has on the performance of the system is another interesting issue. One task could be finding the optimal block size to improve the system performance.

Investigating the influence reflections occurring along walls have on the strength of the received signal is also a natural way of continuing the project. Also looking at the signal strength when transmitting signals around corners, to find the grade of attenuation, and to find out whether this has the same effect as diffraction would be interesting.

We would also have liked to use the spectrum analyzer to investigate how much the signal from the transmitter attenuates when shielding the receiver with a hand, and when shielding the transmitter in the same manner.

Another area of great interest is finding a proper frequency, with according output power. The power use and the corresponding propagation range must in this case be considered in order to make the system as practical as possible.

To look at different error handling mechanisms, and to find an error correction that can be implemented in a system as the one described in this thesis, could also be an important area to explore. In a fully developed system, error correction would most likely be both preferable and vital for the different parts of the communication system to be able to perform a best possible job for the user.

## 8 Conclusion

We have during this project worked on wireless communication between two transceivers from NVLSI working in the ISM frequency band of 433 MHz. We have during the work come up with two different propagation models, one for transmissions of signals in open areas, and one for transmissions in forest areas.

In this report we have presented theory that gives the reader an introduction to general radio communication. We have covered the areas of signal modulation, antenna theory, noise theory and propagation theory. This work resulted in a presentation of some actual propagation models that cover the areas of open terrain and woodland. These two models were the basis for the practical measurements.

Tests have been performed to map the real behavior of the system, and the results have been compared with the theoretical propagation models to see how well these models describe the actual behavior of the channel. During the tests, different parameters have been altered to see the impact this would have on the system's performance. These parameters were the distance, antenna polarization, message block size and the bit pattern. In the forest area only the distance and polarization were altered. We saw that the polarization was an important parameter in terms of achieving the maximum distance. In both areas a horizontal polarization was preferable since this gave the longest range. We also altered the bit pattern in the transmissions without seeing that it led to any difference in the bit error rate. One parameter that did have an influence on the bit error rate, was the length of the messages sent. We tried to transmit blocks with the size of both 16 and 8 bits, and saw that the larger block size was more receptive for errors than the smaller one.

We found that the propagation model presented seemed to reflect the actual behavior of the channel rather accurately in open areas. The model representing the forest area differed from the true behavior of the channel. An improved loss factor is presented to better adapt the latter propagation model to more precisely fit the environment. The maximum distance achievable in open areas, was approximately the same as in the forest. We managed to communicate up to a distance of 40 meters, but we had a poorer bit error rate in the forest than in the open field.

A possible area of use for this system is tracking of sheep. However, the results have shown that the current system is not suitable for such use. Based on this, we have described some proposals to improve the performance of the system. This includes a change of antenna, use of a different and lower frequency band, higher output power and use of error handling and correction.

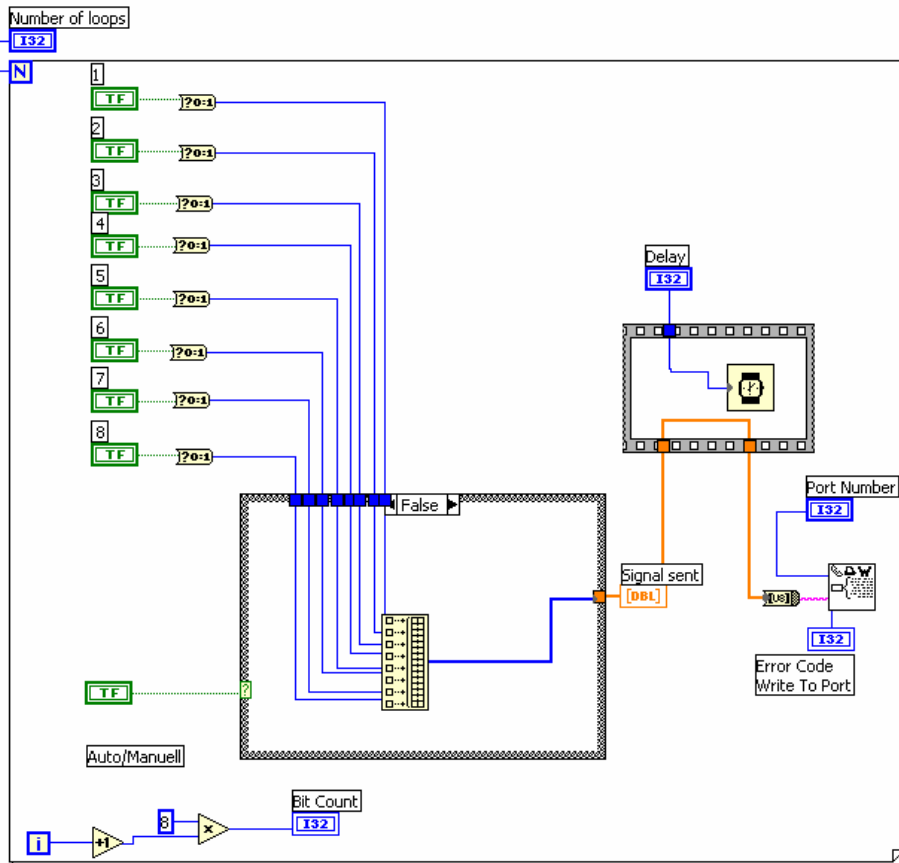
Further work in this field of interest should include a study on how the waves propagate across water, how reflections occurring along walls influence the received signal, and how well the signal can be received when there is a building corner shielding the receiver from the transmitter. Work on finding a preferable block size is also of great relevance. Another parameter's influence that should be studied further, is the antenna's height above ground. Also, the results of using another antenna type or size at the receiver, should be investigated.

## References

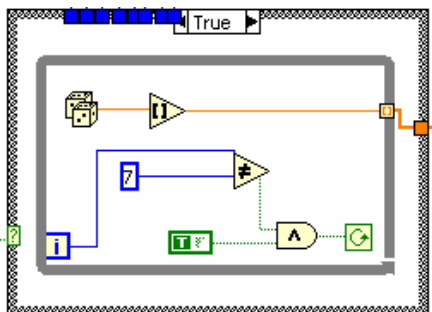
- Ahlin, Lars and Zander, Jens. Principles of wireless communications, Studentlitteratur, Sweden 1998.
- Balanis, C. A. Antenna Theory, Analysis and Design, second edition, John Wiley & sons, Inc., 1997]
- Gennady, Kulemin. Propagation of UHF radio waves in town and forest and park areas, Institute of radio physics and electronics, National Academy of Science, Krakow 1999.
- Haaheim, Nils. Digital transmisjon, Institutt for teleteknikk, transmisjonsteknikk, NTH 1982.
- Hollen, Sverre. Radiokommunikasjon systemteori, ElektronikkBransjens Forlag as, Oslo 1990.
- Karlsen, Frank. Guidelines to low cost wireless system design, Nordic VLSI ASA, Trondheim 2001.
- Kraus, J. D. Electromagnetics, 4th ed., McGraw-Hill Book Co., New York, 1992.
- Nordic VLSI (1). nRF401 RF and antenna layout, Application Note order code: 280202-nAN400-05, Trondheim 2002.
- Nordic VLSI (2). Product specification, Datasheet order code: 280202nRF401, Trondheim 2002.
- Nordic VLSI (3). Small loop antennas, Application Note order code : 290200-nAN400-03, Trondheim 2000.
- Parsons, J. D. The Mobile Radio Propagation Channel. NY: Wiley, New York, 1992.
- Rao, T. Rama and S. Vijaya Bhaskara. Single Knife edge diffraction propagation studies over a hilly terrain, IEEE Transactions on Broadcasting, Vol 45. No.1, 1999.
- Svanes, Edmund. Radiokommunikasjon, Universitetsforlaget, Oslo 1995.
- Stette, Gunnar. Radiokommunikasjon, Institutt for teleteknikk NTNU, NTNU 2001.
- Wisler, Freddy. EMC-teknik, Elektronikforlaget, Århus 1996.
- Owner: Post- og teletilsynet  
Title: FOR 2000-12-20 nr 1399: Forskrift om tillatt bruk av frekvenser  
Date: 01.02.2002  
URL: <http://www.lovddata.no/for/sf/sd/sd-20001220-1399.html>  
URL: <http://www.ero.dk/doc98/Official/Pdf/Rec7003e.pdf>

## Appendix A - LabVIEW diagrams

### Appendix A.1 - LabVIEW serial out 8 bit diagram



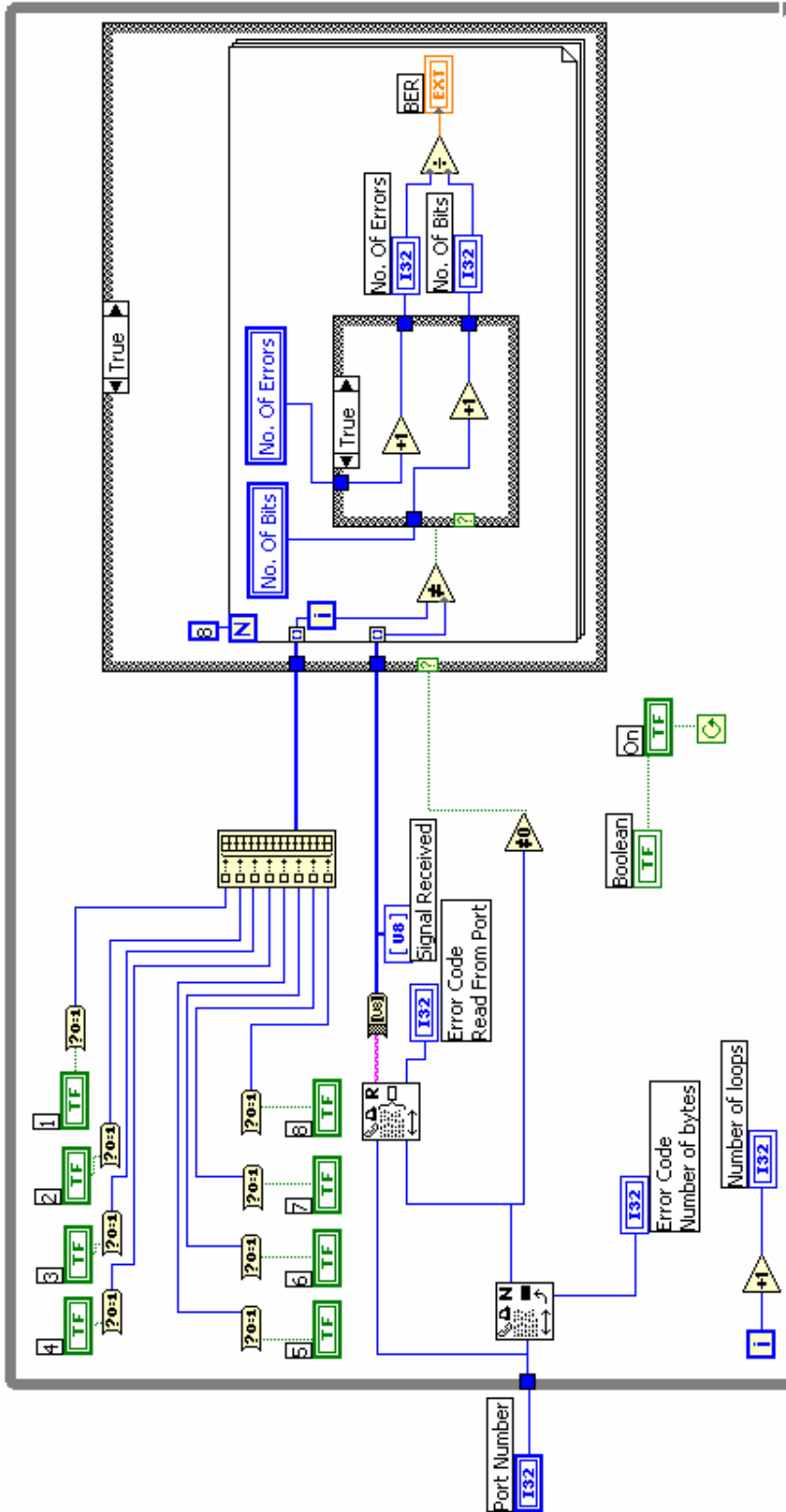
Serial out 8 bit with case loop 'false'



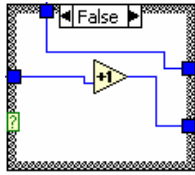
Case loop: Serial out 8 bit with case 'true'



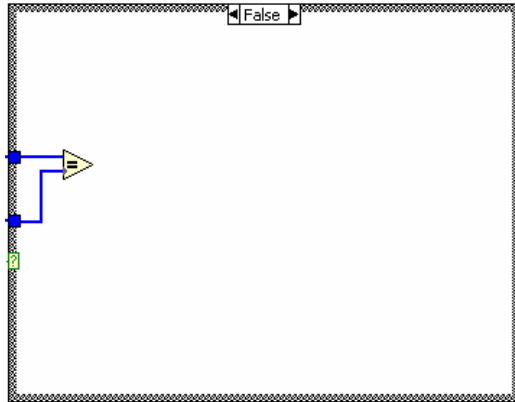
### Appendix A.2 - LabVIEW serial in 8 bit diagram



Serial in 8 bit, both case loops 'true'

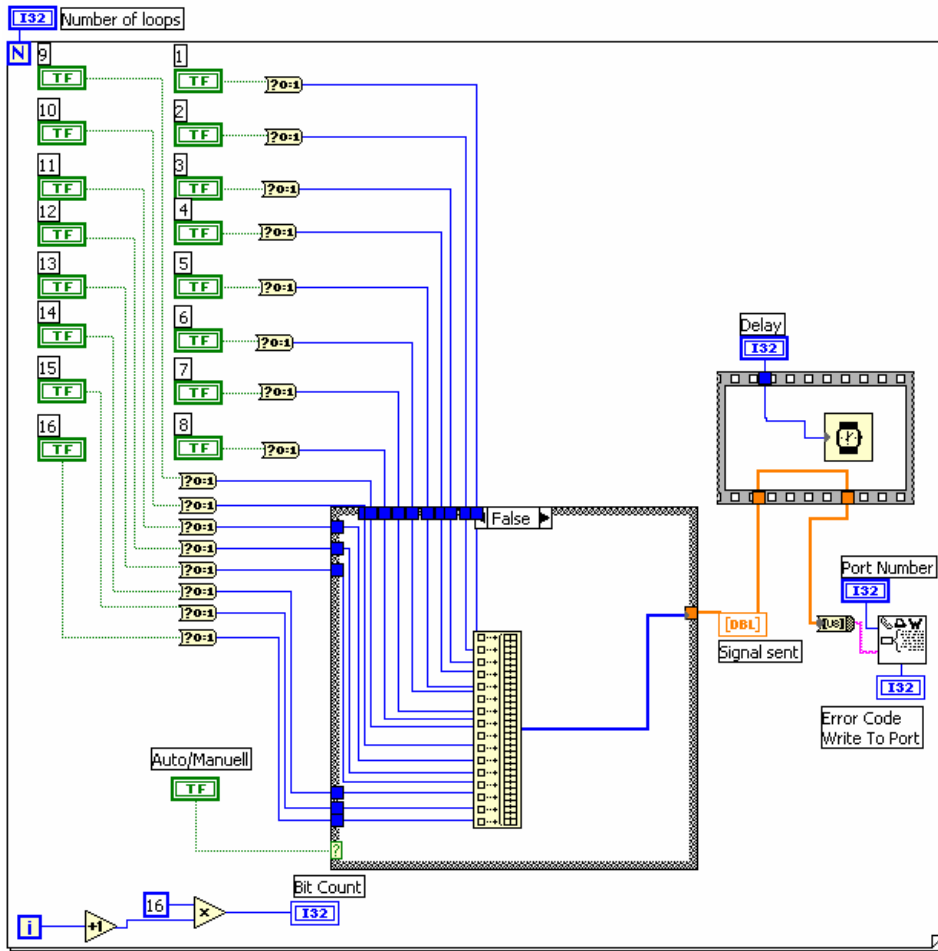


Case loop: Serial in 8 bit, inner case loop 'false'

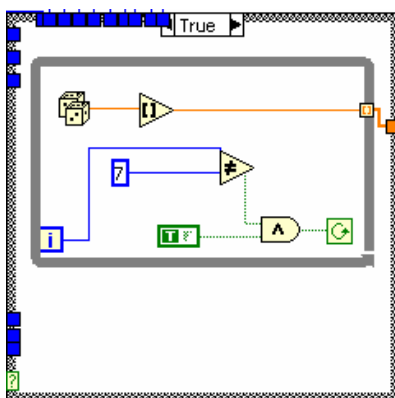


Case loop: Serial in 8 bit, outer case loop 'false'

### Appendix A.3 - LabVIEW serial out 16 bit diagram

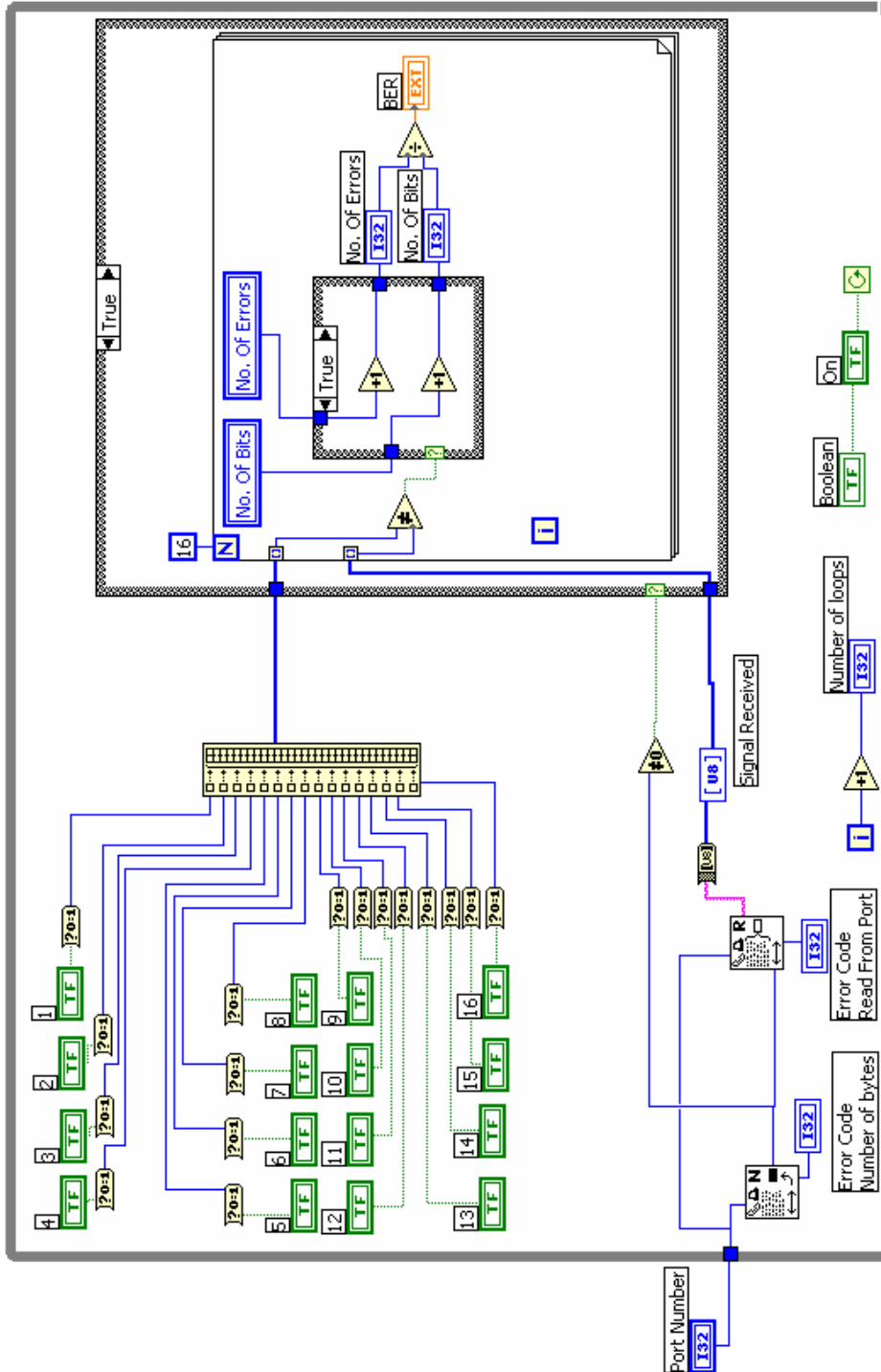


Serial out 16 bit, case loop 'false'

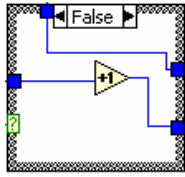


Case loop: Serial in 16 bit, case loop 'true'

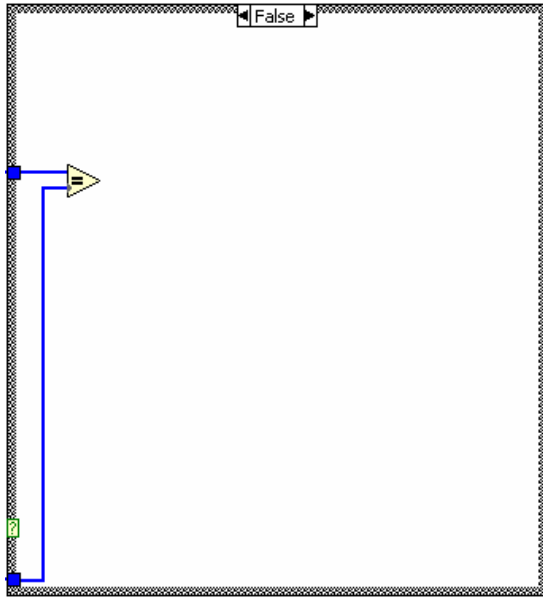
### Appendix A.4 - LabVIEW serial in 16 bit diagram



Serial in 16 bit, both case loops 'true'



Case loop: Serial in 16 bit, inner case loop 'false'



Case loop: Serial in 16 bit, outer case loop 'false'

## Appendix B – RS 232 converter

The pin position of the Maxim MAX232 is shown in figure B.1.

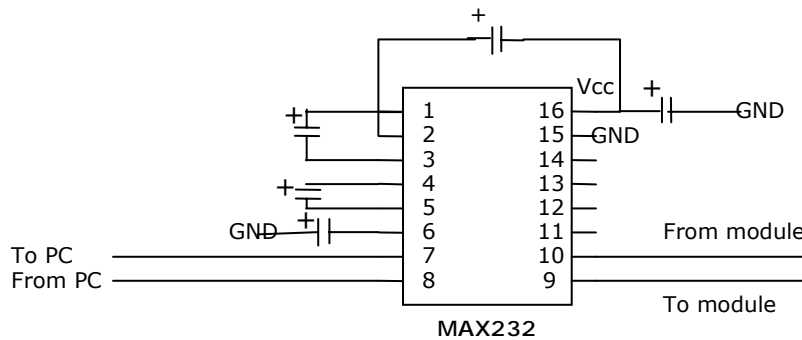


Figure B.1: RS232 converter

All the capacitors have a value of 1  $\mu$ F.

The 'To PC' wire is connected to pin 2 at a 9 PIN COM-port connector. The 'From PC' wire is connected to pin 3. Pin 5 at the connector is coupled to signal ground and pin 6, 7 and 8 are wired together.

The assignments to the different pins of the MAX232 are shown below.

Pin1	Capasitor1 +
Pin2	Voltage +
Pin3	Capasitor1 -
Pin4	Capasitor2 +
Pin5	Capasitor2 -
Pin6	Voltage -
Pin7	Transmit2 OUT (RS232 level)
Pin8	Receive2 IN (RS232 level)
Pin9	Receive2 OUT (TTL level)
Pin10	Transmit2 IN (TTL level)
Pin11	Transmit1 IN (TTL level)
Pin12	Receive1 OUT (TTL level)
Pin13	Receive1 IN (RS232 level)
Pin14	Transmit1 OUT ( RS232 level)
Pin15	Ground
Pin16	Vcc

## Appendix C – Complete measurement series

### *Appendix abbreviations*

BER: Bit error rate

Pol: The antenna polarization (transmitter's polarization first)

H: Horizontal polarization

V: Vertical polarization

Err: Number of errors

Dis: The distance between the antennas

BS: Block size

Rec: Number of bits received

Note: Measurement series comment. Ignored means that the series result is ignored in chapter 6 because of its rather extreme result compared to the other series.

### *Appendix C.1 - School ICT-lab test*

Bit pattern	BER	Pol	Err	Dis
10100010	6,88E-03	HH	55	19,6
10001000	5,50E-03	HH	44	19,6
10001000	3,63E-03	HH	29	19,6
10001000	7,88E-03	HH	63	19,6
10001000	1,25E-04	HH	1	19,6
10001000	2,50E-04	HH	2	19,6
10001000	0,00E+00	HH	0	19,6
Total	3,46E-03		194	

## Appendix C.2 - Signal strength measured in the open area

Intensities of the nRF signal given as dBmV

Distance in meters	First series		Second series		Third series		Total	
	H	V	H	V	H	V	H	V
2	22	17	20	20	20	19	21	19
10	5	8	10	8	4	8	6	8
20	6	0	7	1	5	1	6	1
30	2	-5	2	-6	1	-3	2	-5
40	-6	-12	-6	-7	-3	-10	-5	-10
50	-10	-16	-8	-18	-8	-14	-9	-16
60	-8	-16	-16	-19	-11	-16	-12	-17
70	-16	-22	-18	-18	-16	-16	-17	-19
80			-14	-28	-19	-19	-17	-24
90			-19	-24	-21	-23	-20	-24
100			-26	-30	-18	-23	-22	-27
110			-22	-22	-22	-21	-22	-22

### Appendix C.3.1 - Bit pattern test 2 meters in the open area

Bit pattern	BER	Pol	Err	Dis	Rec	Note
10100010	3,23E-01	HH	2398	2	7421	Ignored
10100010	5,79E-01	HH	4261	2	7360	Ignored
10100010	1,30E-02	HH	104	2	7974	
10100010	2,88E-03	HH	23	2	7992	
10100010	8,53E-03	HH	68	2	7975	
10100010	4,50E-02	HH	356	2	7904	
Total	1,73E-02		551		31845	
10110110	1,91E-01	HH	1465	2	7676	Ignored
10110110	6,26E-03	HH	50	2	7982	
10110110	1,02E-02	HH	43	2	4220	
10110110	1,52E-02	HH	119	2	7839	
10110110	2,25E-03	HH	18	2	7995	
Total	8,20E-03		230		28036	

### Appendix C.3.2 - Bit pattern test 30 meters in the open area

Bit pattern	BER	Pol	Err	Dis	Rec	Note
10110110	2,98E-01	HH	1691	30	5676	Ignored
10110110	3,47E-01	HH	2641	30	7602	Ignored
10110110	1,41E-01	HH	1200	30	8485	Ignored
10110110	7,50E-04	HH	6	30	7999	
10110110	1,25E-04	HH	1	30	8000	
10110110	1,12E-03	HH	9	30	8001	



10110110	2,50E-04	HH	2	30	8000	
10110110	6,25E-04	HH	5	30	7999	
10110110	8,12E-03	HH	65	30	8003	
10110110	1,41E-02	HH	113	30	8004	
Total	3,59E-03		201		56006	
10100010	0,00E+00	HH	0	30	8000	
10100010	0,00E+00	HH	0	30	8000	
10100010	0,00E+00	HH	0	30	8002	
10100010	0,00E+00	HH	0	30	8000	
10100010	0,00E+00	HH	0	30	8000	
10100010	4,87E-03	HH	39	30	8003	
10100010	2,66E-02	HH	213	30	8020	
10100010	7,84E-02	HH	651	30	8300	Ignored
Total	4,50E-03		252		56025	

### Appendix C.4 - Polarization test in the open area

Bit pattern	BER	Pol	Err	Dis	Rec	Note
10110110	1,91E-01	HH	1465	2	7676	Ignored
10110110	6,26E-03	HH	50	2	7982	
10110110	1,02E-02	HH	43	2	4220	
10110110	1,52E-02	HH	119	2	7839	
10110110	2,25E-03	HH	18	2	7995	
Total	8,20E-03		230		28036	
10110110	2,50E-04	VV	2	2	8000	
10110110	6,25E-04	VV	5	2	7999	
10110110	0,00E+00	VV	0	2	8000	
10110110	1,25E-04	VV	1	2	8000	
10110110	1,00E-03	VV	8	2	7989	
10110110	3,87E-03	VV	31	2	8001	
Total	9,79E-04		47		47989	
10110110	3,40E-02	HH	277	10	8153	
10110110	1,25E-04	HH	1	10	8001	
10110110	0,00E+00	HH	0	10	8000	
10110110	0,00E+00	HH	0	10	8000	
10110110	6,25E-04	HH	5	10	7999	
10110110	5,01E-03	HH	40	10	7992	
Total	6,71E-03		323		48145	
10110110	2,12E-03	VV	17	10	8002	
10110110	2,75E-03	VV	22	10	7994	
10110110	5,51E-03	VV	44	10	7989	
10110110	1,25E-04	VV	1	10	7999	
10110110	1,50E-03	VV	12	10	8004	
10110110	0,00E+00	VV	0	10	8000	
10110110	0,00E+00	VV	0	10	7992	
10110110	0,00E+00	VV	0	10	8000	
Total	1,50E-03		96		63980	

### Appendix C.5 - Block size test in the open area

Bit pattern	BER	Pol	Err	BS	Dis	Rec	Note
10110110	4,88E-03	HH	39	8	20	7989	
10110110	2,50E-03	HH	20	8	20	7996	
10110110	3,75E-04	HH	3	8	20	7999	
10110110	0,00E+00	HH	0	8	20	8000	
10110110	1,21E-03	HH	9	8	20	7414	
10110110	3,75E-04	HH	3	8	20	7999	
10110110	1,25E-03	HH	10	8	20	7995	
10110110	4,13E-03	HH	33	8	20	7990	
10110110	2,88E-03	HH	23	8	20	7999	
10110110	2,88E-03	HH	23	8	20	7993	
10110110	1,78E-02	HH	142	8	20	7962	
10110110	1,35E-02	HH	108	8	20	7975	
Total	4,33E-03		413			95311	
1011011010110110	0,00E+00	HH	0	16	20	8000	
1011011010110110	0,00E+00	HH	0	16	20	8000	
1011011010110110	2,50E-03	HH	20	16	20	8001	
1011011010110110	2,50E-04	HH	2	16	20	8002	
1011011010110110	1,50E-03	HH	12	16	20	8000	
1011011010110110	4,01E-02	HH	317	16	20	7896	
1011011010110110	6,74E-02	HH	532	16	20	7895	
1011011010110110	4,40E-02	HH	348	16	20	7918	
1011011010110110	2,90E-01	HH	2215	16	20	7646	Ignored
Total	1,93E-02		1231			63712	
10110110	2,98E-01	HH	1691	8	30	5676	Ignored
10110110	3,47E-01	HH	2641	8	30	7602	Ignored
10110110	1,41E-01	HH	1200	8	30	8485	Ignored
10110110	7,50E-04	HH	6	8	30	7999	
10110110	1,25E-04	HH	1	8	30	8000	
10110110	1,12E-03	HH	9	8	30	8001	
10110110	2,50E-04	HH	2	8	30	8000	
10110110	6,25E-04	HH	5	8	30	7999	
10110110	8,12E-03	HH	65	8	30	8003	
10110110	1,41E-02	HH	113	8	30	8004	
Total	3,59E-03		201			56006	
1010011010100110	1,81E-02	HH	145	16	30	8002	
1010011010100110	3,58E-02	HH	288	16	30	8044	
1010011010100110	2,33E-02	HH	187	16	30	8024	
1010011010100110	5,00E-03	HH	40	16	30	8008	
1010011010100110	5,12E-03	HH	41	16	30	8002	
Total	1,75E-02		701			40080	
10110110	4,62E-03	HH	37	8	40	8004	
10110110	4,64E-03	HH	37	8	40	7972	
10110110	6,12E-03	HH	49	8	40	8003	
10110110	1,12E-02	HH	90	8	40	8006	
10110110	1,64E-02	HH	132	8	40	8047	
10110110	6,87E-03	HH	55	8	40	8002	
10110110	1,76E-02	HH	141	8	40	8012	
10110110	2,63E-03	HH	21	8	40	7999	

10110110	2,12E-03	HH	17	8	40	8002	
Total	8,04E-03		579			72047	
1010011010100110	1,77E-01	HH	1511	16	40	8550	
1010011010100110	4,05E-02	HH	323	16	40	7974	
1010011010100110	1,48E-01	HH	1216	16	40	8238	
1010011010100110	3,52E-02	HH	285	16	40	8091	
1010011010100110	4,50E-02	HH	363	16	40	8065	
1010011010100110	3,75E-03	HH	30	16	40	8010	
1010011010100110	2,27E-02	HH	182	16	40	8024	
Total	6,87E-02		3910			56952	

### Appendix C.6 - Distance and polarization test in the open area

Bit pattern	BER	Pol	Err	Dis	Rec	Note
10110110	6,26E-03	HH	50	2	7982	
10110110	1,02E-02	HH	43	2	4220	
10110110	1,52E-02	HH	119	2	7839	
10110110	2,25E-03	HH	18	2	7995	
Total	8,20E-03		230		28036	
10110110	2,50E-04	VV	2	2	8000	
10110110	6,25E-04	VV	5	2	7999	
10110110	0,00E+00	VV	0	2	8000	
10110110	1,25E-04	VV	1	2	8000	
10110110	1,00E-03	VV	8	2	7989	
10110110	3,87E-03	VV	31	2	8001	
Total	9,79E-04		47		47989	
10110110	3,40E-02	HH	277	10	8153	
10110110	1,25E-04	HH	1	10	8001	
10110110	0,00E+00	HH	0	10	8000	
10110110	0,00E+00	HH	0	10	8000	
10110110	6,25E-04	HH	5	10	7999	
10110110	5,01E-03	HH	40	10	7992	
Total	6,71E-03		323		48145	
10110110	2,12E-03	VV	17	10	8002	
10110110	2,75E-03	VV	22	10	7994	
10110110	5,51E-03	VV	44	10	7989	
10110110	1,25E-04	VV	1	10	7999	
10110110	1,50E-03	VV	12	10	8004	
10110110	0,00E+00	VV	0	10	8000	
10110110	0,00E+00	VV	0	10	7992	
10110110	0,00E+00	VV	0	10	8000	
Total	1,50E-03		96		63980	
10110110	4,88E-03	HH	39	20	7989	
10110110	2,50E-03	HH	20	20	7996	
10110110	3,75E-04	HH	3	20	7999	

10110110	0,00E+00	HH	0	20	8000	
10110110	1,21E-03	HH	9	20	7414	
10110110	3,75E-04	HH	3	20	7999	
10110110	1,25E-03	HH	10	20	7995	
10110110	4,13E-03	HH	33	20	7990	
10110110	2,88E-03	HH	23	20	7999	
10110110	2,88E-03	HH	23	20	7993	
10110110	1,78E-02	HH	142	20	7962	
10110110	1,35E-02	HH	108	20	7975	
Total	4,33E-03		413		95311	
10100010	2,72E-02	VV	221	20	8134	Ignored
10100010	3,61E-03	VV	29	20	8031	
10100010	1,25E-04	VV	1	20	7985	
10100010	0,00E+00	VV	0	20	8000	
10100010	1,25E-04	VV	1	20	8001	
10100010	0,00E+00	VV	0	20	8000	
10100010	0,00E+00	VV	0	20	7992	
Total	6,46E-04		31		48009	
10110110	7,50E-04	HH	6	30	7999	
10110110	1,25E-04	HH	1	30	8000	
10110110	1,12E-03	HH	9	30	8001	
10110110	2,50E-04	HH	2	30	8000	
10110110	6,25E-04	HH	5	30	7999	
10110110	8,12E-03	HH	65	30	8003	
10110110	1,41E-02	HH	113	30	8004	
Total	3,59E-03		201		56006	
10100010	6,26E-04	VV	5	30	7991	
10100010	0,00E+00	VV	0	30	8000	
10100010	0,00E+00	VV	0	30	7992	
10100010	1,25E-04	VV	1	30	8000	
10100010	1,38E-03	VV	11	30	7998	
10100010	1,25E-04	VV	1	30	7998	
Total	3,75E-04		18		47979	
10110110	4,62E-03	HH	37	40	8004	
10110110	4,64E-03	HH	37	40	7972	
10110110	6,12E-03	HH	49	40	8003	
10110110	1,12E-02	HH	90	40	8006	
10110110	1,64E-02	HH	132	40	8047	
10110110	6,87E-03	HH	55	40	8002	
10110110	1,76E-02	HH	141	40	8012	
10110110	2,63E-03	HH	21	40	7999	
10110110	2,12E-03	HH	17	40	8002	
Total	8,04E-03		579		72047	
10100010	2,20E-01	VV	1930	40	8790	
10100010	3,36E-01	VV	2930	40	8725	
10100010	6,11E-01	VV	6378	40	10441	
Total	4,02E-01		11238		27956	

### Appendix C.7 - Different time a day in the open area

Bit pattern	BER	Pol	Err	Dis	Rec	Time
10110110	4,62E-03	HH	37	40	8004	Noon
10110110	4,64E-03	HH	37	40	7972	Noon
10110110	6,12E-03	HH	49	40	8003	Noon
10110110	1,12E-02	HH	90	40	8006	Noon
10110110	1,64E-02	HH	132	40	8047	Noon
10110110	6,87E-03	HH	55	40	8002	Noon
10110110	1,76E-02	HH	141	40	8012	Noon
10110110	2,63E-03	HH	21	40	7999	Noon
10110110	2,12E-03	HH	17	40	8002	Noon
Total	8,04E-03		579		72047	
10110110	1,25E-04	HH	1	40	8000	Evening
10110110	2,50E-04	HH	2	40	8000	Evening
10110110	1,00E-03	HH	8	40	8000	Evening
10110110	5,00E-04	HH	4	40	8000	Evening
10110110	0,00E+00	HH	0	40	8000	Evening
10110110	2,50E-04	HH	2	40	8000	Evening
10110110	5,00E-04	HH	4	40	8000	Evening
Total	3,75E-04		21		56000	

### Appendix C.8 - Distance and polarization test in the forest area

Bit pattern	BER	Pol	Err	Dis	Rec
10110110	2,12E-01	HH	1664	10	7834
10110110	2,92E-02	HH	232	10	7935
10110110	2,77E-02	HH	220	10	7933
10110110	2,43E-02	HH	193	10	7950
10110110	3,71E-02	HH	294	10	7914
10110110	3,65E-02	HH	289	10	7913
Total	6,09E-02		2892		47479
10110110	3,31E-02	VV	266	10	8039
10110110	3,51E-01	VV	3072	10	8740
10110110	1,59E-01	VV	1339	10	8417
10110110	8,89E-02	VV	731	10	8225
10110110	4,09E-01	VV	3653	10	8923
Total	2,14E-01		9061		42344
10110110	1,12E-02	HH	90	20	8017
10110110	9,98E-03	HH	80	20	8013
10110110	5,75E-03	HH	46	20	7994
10110110	2,67E-01	HH	2305	20	8636
10110110	7,34E-02	HH	595	20	8109
Total	7,64E-02		3116		40769

10110110	1,24E-01	VV	1026	20	8290
10110110	1,71E-01	VV	1394	20	8149
10110110	8,66E-02	VV	704	20	8134
10110110	7,82E-02	VV	633	20	8091
10110110	7,16E-02	VV	579	20	8084
Total	1,06E-01		4336		40748
10110110	1,87E-03	HH	15	30	8001
10110110	1,99E-02	HH	159	30	8000
10110110	1,25E-02	HH	100	30	8016
10110110	9,75E-03	HH	78	30	8002
10110110	3,25E-03	HH	26	30	8001
Total	9,45E-03		378		40020
10110110	6,64E-02	VV	535	30	8060
10110110	8,22E-02	VV	573	30	6970
10110110	2,04E-02	VV	164	30	8020
10110110	3,64E-02	VV	292	30	8024
10110110	6,53E-02	VV	527	30	8070
Total	5,34E-02		2091		39144
10110110	7,37E-03	HH	59	35	8003
10110110	1,36E-01	HH	1110	35	8182
10110110	1,73E-01	HH	1435	35	8304
10110110	1,03E-01	HH	876	35	8466
10110110	3,26E-01	HH	2786	35	8547
10110110	5,18E-02	HH	417	35	8047
Total	1,35E-01		6683		49549
10110110	4,30E-02	VV	346	35	8039
10110110	2,85E-02	VV	228	35	8014
10110110	2,88E-02	VV	231	35	8017
10110110	1,76E-02	VV	134	35	7625
10110110	8,74E-03	VV	70	35	8006
Total	2,54E-02		1009		39701
10110110	1,43E-01	HH	1173	40	8219
10110110	9,05E-02	HH	735	40	8120
10110110	3,91E-01	HH	3417	40	8745
10110110	1,78E-01	HH	1537	40	8642
10110110	5,34E-01	HH	5142	40	9634
Total	2,77E-01		12004		43360
10110110	4,25E-01	VV	3940	40	9265
10110110	3,35E-01	VV	2992	40	8934
10110110	2,96E-01	VV	2604	40	8784
10110110	4,58E-01	VV	3977	40	8677
Total	3,79E-01		13513		35660

## Appendix D - Mail from Bent Andre Støyva, dated 12.03.2002

Hei,

Når det gjelder laveffekts utstyr som har 10 mW sendeeffekt er det ikke lett å gi noen oversikt, da dette er lisensfritt og vi ikke fører noen register over hvor sånt utstyr blir brukt, eller hva slags utstyr som blir brukt. Bruken av slikt utstyr er regulert i "FOR 2000-12-20 nr 1399: Forskrift om tillatt bruk av frekvenser"

<http://www.lovdatab.no/for/sf/sd/sd-20001220-1399.html>

Her kan eg nevne at vi jobber med å revidere denne forskriften, og at det muligens vil skje forandringer i 433 MHz. Dette for å komme på linje med resten av Europa. Vi bruker ERC/REC 70-03 som grunnlag når vi ser på forskriften. Denne kan dere finne på ERO sine hjemmesider. Se Annex 1. Stikkord: Sendetid (Duty Cycle)

<http://www.ero.dk/>

I frekvensbåndet 432 MHz - 438 MHz er radioamatørene primærbrukere. Det vil si at brukere av båndet 433,050 MHz - 434,790 MHz (ISM-bånd) er sekundærbrukere og kan ikke kreve noen form for beskyttelse.

Jeg er ikke sikker på om dette var den informasjonen dere var ut etter, men skulle det ikke være det må dere gjerne ta kontakt. Det hadde også vært veldig interessant å se oppgaven deres når den er ferdig, dersom det er mulig.

Med vennlig hilsen

Bent Andre Støyva  
Overingeniør  
Post- og teletilsynet  
Nettavdelingen/Private mobile radiotjenester  
Tlf: +47 22 82 48 33  
Fax: +47 22 82 47 90  
e-mail: bent.stoyva@npt.no