Evaluating Wireless Communication Performance at Quarries

Eleni Kalpaxidou & Susanne Vernersson

Department of Computer Science & Engineering
Computer Systems & Networks
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2013
Master's Thesis

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Susanne Vernersson
Eleni Kalpaxidou

Examiner: *Assistant Professor* Olaf Landsiedel

Chalmers University of Technology
University of Gothenburg
Department of Computer Science and Engineering
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000

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Department of Computer Science and Engineering
Göteborg, Sweden June 2013

Abstract

The quarry industry and the material it provides such as sand, gravel and hard rock are often an overlooked resource to our modern society. Nevertheless, aggregates are found everywhere in our buildings and roads. In Europe alone there are over 24 000 quarries with an annual demand of 3 billion tonnes translating into a 20 billion Euro turnover.

The quarry industry has an increasing potential in improving productivity and safety with the introduction of wireless communication technologies. This may however be a difficult task due to the harsh and constantly changing environment of the quarry with high EMC, vibrations, dust and solid materials. One of the major challenges will be to provide efficiency and reliability to applications based on the wireless communication.

In recent years, great efforts have been made to increase road safety with vehicle-to-vehicle and vehicle-to-infrastructure (V2V/V2I) communication in highly dense traffic scenarios. The proposed communication standard has so far been IEEE 802.11p for communicating vehicles with the use of a vehicular ad hoc network (VANET).

Although large actors such as Volvo, Honda, Daimler and BMW are actively participating in the car-to-car communication (C2C) consortium, little time has been spent in investigating the possibilities of bringing intelligent transport systems (ITS) to the quarry industry. The main focus of this master thesis has therefore been to evaluate a set of suitable wireless technologies that successfully can be used in V2V/V2I communication in quarries. The technologies used in the evaluation included IEEE 802.15.4, ZigBee RF, IEEE 802.11g and IEEE 802.11p that is commonly used in V2V communication.

Keywords: ITS, VANET, V2V/V2I, WAVE, DSRC, 802.11g, 802.11p, 802.15.4, ZigBee

Acknowledgements

I would like to express my gratitude to Volvo for giving me this opportunity to work on such a compelling topic for my master thesis. Every day has been a continuos learning experience where my interest in vehicle-to-vehicle communication and telematics has grown increasingly. I feel very fortunate and would first of all like to thank our supervisor at Volvo, David Rylander, who gave us the chance to work on this master thesis project.

I am also very happy to have had Olaf Landsiedel as an examiner who provided us with extra support and feedback from Chalmers. I greatly appreciate your positive energy, guidance and understanding. Furthermore, this thesis could not have been completed without the extensive help from Jakob Fryk and Edvin Valtersson. Thanks to you and the many hours you spent on providing your expertise during the planning and setting up the testing equipment, we were finally able to conduct our measurements quickly and efficiently. I also like to give special thanks to Katrin Sjöberg whose impressive knowledge about networks and wireless technologies still amazes me. Furthermore, I am very happy to have been surrounded by the welcoming team at Volvo.

Last of all I have to thank Eleni Kalpaxidou, not only for asking me to participate in this master thesis but also for being my hard working colleague during this time. In addition, I am very happy to have had a supporting family and partner during this thesis work. It would not have been possible without you.

Susanne Vernersson, Gothenburg 10/6/13

First of all, I would like to thank all the people that participated during this thesis that took place in Volvo. First and foremost, Edvin Valtersson, developer of the COSMO platform, who provided us with the COSMO platform so as to fulfill our scope and guided us accordingly when we were facing problems. Also, many thanks to Jakob Fryk for being a great support and a key person to this project and without his participation, it would have been really difficult to reach our goal. Katrin Sjöberg, who expanded my knowledge in wireless communication systems. Last but not least, my supervisor David Rylander, who gave me the opportunity to work in Volvo and have a first contact with vehicle-to-vehicle communication.

Of course, I would like to offer my special thanks to my supervisor in Chalmers University, Olaf Landsiedel, for his assistance through the whole period, but also for the understanding he showed when things did not go as we expected to.

Finally, my partner Susanne Vernersson, for the great interest she showed through the whole time, her hard work and professional collaboration. I wish you all the best in your personal and professional life.

Eleni Kalpaxidou, Gothenburg 31/5/13

Contents

List of Abbreviations

C2C	car-to-car
DSRC	dedicated short-range communications
DSSS	direct-sequence spread spectrum
EMC	electromagnetic compatibility
EMI	electromagnetic interference
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
GPS	global positioning system
IEEE	Institute of Electrical and Electronics Engineers
ISM	industrial, scientific and medical
ISO	International Organization for Standardization
ITS	intelligent transportation systems
LAN	local area network
LLC	logical link control
LOS	line-of-sight
LR-WPAN	low-rate wireless personal area network
M2M	machine-to-machine
MAC	media access control
MAN	metropolitan area networks
MANET	mobile ad-hoc network
MIMO	multiple-input multiple-output
NLOS	non line-of-sight
OBU	on-board unit
OFDM	orthogonal frequency division multiplexing
OSI	open systems interconnection
PAN	personal area network
PHY	physical
PRR	packet reception ratio
QPSK	quadrature phase shift keyring
RF	radio frequency
RSU	road-side unit
SDK	software development kit
V2V	vehicle-to-vehicle
V2I	vehicle-to-infrastructure
VCDC	Volvo Cars Demo Center
VANET	vehicular ad-hoc network
WAVE	wireless access in vehicular environments

1

Introduction

This master thesis has been produced in collaboration with Volvo where engineers, developers and researchers are currently working towards a common goal to continue to bring wireless technology into the vehicle industry. Some of the major areas of interest are road safety, quality of service as well as transport and traffic management that all can benefit from vehicle communication. Vehicular ad hoc networks (VANETs) are mainly utilized together with its intended IEEE 802.11p standard for communication between vehicles in dense traffic scenarios. This thesis work aims at an entirely different environment where a set of wireless technologies will be evaluated and exposed to challenges presented by the quarry.

1.1 Thesis Background

The quarry industry is an important part of the construction industry. Quarries supply sand, gravel and asphalt to all sorts of roads, buildings and other infrastructure construction sites. More than 24 000 quarries and aggregate sites can be found only in Europe with a demand of 3 billion tonnes per year, translating into a turnover of approximately 20 billion Euro [1]. The quarry industry has an emerging potential in improving productivity and safety by introducing wireless communication technologies. However, the environment is harsh for wireless communication due to dust, high EMC/EMI and vibrations from machines.

Furthermore, the environment and topology consist of solid materials, which change in position and size over time. This dynamic harsh environment is very challenging for wireless communication-based applications and their ability to be efficient and reliable.

1.2 Purpose

During the last couple of years, the vehicle industry has paid a lot of attention to vehicle-to-vehicle and vehicle-to-infrastructure (V2V/V2I) communication mainly focusing on road traffic safety in highly dense scenarios. IEEE 802.11p has so far been the proposed standard for communicating vehicles using a vehicular ad hoc network.

Despite of the large interest from major actors such as Volvo, Honda, Daimler and BMW in car-to-car (C2C) communication [2], little effort has been made to bring intelligent transport systems (ITS) to the quarry industry. The main purpose of this thesis is therefore to evaluate a set of suitable wireless technologies that may successfully be used in V2V/V2I communication at quarry sites. The selected standards for the evaluation were, apart from 802.11p, ZigBee, 802.15.4 and 802.11g.

1.3 Problem Description

Several research questions were defined for this master thesis that allowed us to investigate how 802.11g, 802.11p, 802.15.4 and ZigBee performed in the quarry environment. We first intended to find out how far apart two vehicles were able to communicate with each other with an acceptable link quality. What was meant by acceptable communication quality was measured in terms of packet loss and range.

A major point of interest for this thesis was to find possible differences in maximum reachable range between the evaluated technologies. We therefore wanted to see if and how the results from the quarry differed from the data that was obtained during the outdoor measurements. Another aim for this work was to discover how the quarry environment affected the packet loss ratio for the evaluated technologies 802.11g, 802.11p, 802.15.4 and ZigBee. These results were then compared to the values received while testing in an outdoor environment not represented by the quarry.

A final goal was to point out the main environmental parameters that influenced the communication performance in the quarry. The intention here was to see the impact on the communication quality and what this may mean to future quarry applications.

1.4 Scope

During this thesis work, a subset of the existing wireless communication standards were assessed at the quarry site. As previously stated, we limited ourselves to investigate the protocols 802.15.4/ZigBee and 802.11g/p that operate in the 868.0-868.6 MHz, the 2.4-2.4835 GHz and the 5855-5925 MHz frequency bands. These technologies were mainly selected due to their range capabilities. However, the fact that the protocols operate in different frequency bands also presented an interesting point of comparison to this study. Subscription-based communication standards that e.g. needs 3G/4G were not considered since these solutions are neither free of charge nor available worldwide. In order to support the given technologies, two platforms were selected that could provide communication for the protocols in the specified frequency ranges.

1.5 Method and Resources

To fulfill the above-mentioned objectives, the thesis work had to include not only theoretical studies and practical software implementation but also hands-on outdoor measurements at the quarry site. The thesis was initially started with a literature study, followed by a platform investigation and purchase of equipment that allowed us to measure according to the specified test cases used to assess the wireless technologies.

When the platform had been chosen, the actual design and implementation could start that enabled us to setup the equipment used during our measurements. At this point, the test cases had to be somewhat rewritten to fit the constraints of the purchased hardware but also the restrictions presented by the two testing locations. After we had finished collecting all measurement data, we could move on with parsing, visualizing and evaluating the results with the help of the produced software. The analysis allowed us to present the measurement data that can be found in this report.

1.6 Report Structure

Chapter 1 serves as a motivation for our thesis and gives a reason to why this work is needed for Volvo and the ITS industry. It consists of a thesis background, an outline of the stated problem, research questions, limitations, but also resources and work strategy that enabled us to complete the project. Chapter 2 presents a background of the IEEE 802.11 protocol suite, the IEEE 802.15.4 and ZigBee standards to provide the reader with an initial understanding of the topic at hand. This section also gives a thorough overview of V2V communication.

In chapter 3, we explain what has been done so far in the ITS industry where we mainly see efforts invested in communication between vehicles in a dense traffic situation to increase road safety. Chapter 4 describes how the measurements where conducted and introduces the test cases that were followed during the evaluation. In chapter 5, we cover the design and implementation of the software produced that was used during the evaluation. Chapter 6 presents the results that were gathered during our tests from the outdoor and quarry measurements.

Chapter 7 discusses the obtained results and observations made during the testing evaluation. In this section, the most important findings are highlighted and compared to our initial predictions. Drawbacks of our methodology and future work are also a part of the chapter. Finally, chapter 8 concludes our findings and aims at giving answers to our research questions stated in the problem description.

2

Background

This chapter presents the IEEE 802.11 and 802.15 protocol suites where we find standards such as 802.11g, ZigBee and 802.15.4. The chapter further describes intelligent transport systems, vehicle ad hoc networks as well as vehicle-to-vehicle and vehicle-to-infrastructure communication. As a final note, we give a short description of modulation schemes, telematics and geonetworking.

2.1 IEEE 802 Overview

The IEEE 802 family consists of a large set of protocols created for a variety of purposes such as ethernet, bluetooth, metropolitan area networks (MAN), token bus and ring networks as well as wireless local area networks (LANs). The services provided by the 802 protocols are mapped to the lower layers of the seven-layered open systems interconnection (OSI) model named data link and physical. The data link layer is further divided into two sub-layers: the media access control (MAC) layer and the logical link control (LLC) layer. An overview of IEEE 802 can be seen in Figure 2.1.

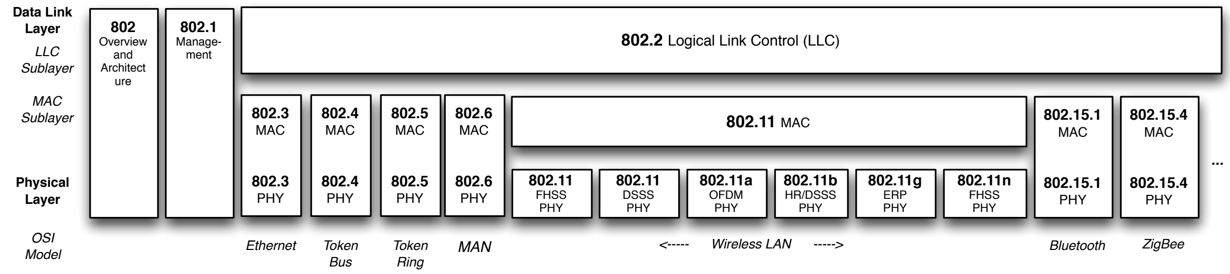


Figure 2.1: The many protocols that together form the IEEE 802 suite

2.1.1 Wi-Fi

According to the Wi-Fi Alliance, Wi-Fi is defined as any wireless local area network (WLAN) product that complies with the IEEE 802.11 standard. The transmission of data in a WLAN is designed in a way to provide network access to computer devices using radio waves instead of cabling infrastructure [3]. The protocol architecture of IEEE 802.11 consists of three layers: the physical, the media access control (MAC) and the logical link control (LLC) layer [4]. The physical layer is responsible for transmitting and receiving data frames over the shared medium. The first level refers to the exchange of frames between the MAC and PHY. The second is the use of the signal carrier and spread spectrum modulation for transmitting data frames. The third functionality is carrier sense of the medium access where an indication is sent back to the MAC for verification of media activity. The MAC layer ensures that all computer devices can cooperate in the LAN [5]. Finally, the LLC layer performs error and flow control while it provides an interface to the layers above [6].

2.1.2 802.11a

The 802.11a specification is an amendment to the IEEE 802.11 family operating in the 5 GHz band that was issued in 1999, two years after the original standard. The specification uses orthogonal frequency division multiplexing (OFDM) where multiple carrier signals at different frequencies are used to send out bits from a single data source on each sub channel. It can achieve a theoretical maximum data rate of 54 Mbps falling back on data rates of 48, 36, 24, 18, 12, 9 and 6 Mbps as the quality of the signal decreases due to factors such as distance, radio interference, physical obstructions and transmitter/receiver power [6][7]. The advantage of 802.11a is the use of the 5 GHz frequency instead of the crowded 2.4 GHz ISM band, where interference from other devices often can be found.

2.1.3 802.11b

802.11b is an another amendment of IEEE 802.11 that extends the direct-sequence spread spectrum (DSSS) with data rates of 5.5 and 11 Mbps to the already existing rates of 1 and 2 Mbps from the original standard. This amendment operates in the 2.4 GHz band and was retained in 1999 around the same time as 802.11a [6]. One disadvantage is the use of the 2.4 GHz frequency where many other devices operate such as microwave ovens, baby monitors and bluetooth devices that may cause interference.

2.1.4 802.11g

Another standard of IEEE 802.11 is the g amendment extending the 802.11b to data rates of 12 up to 54 Mbps. It operates in the 2.4 GHz band and is thus compatible with 802.11b. The key difference between these two amendments is that the 802.11g standard uses OFDM and DSSS whereas 802.11b only uses DSSS [6]. Just like its predecessor, 802.11g suffers from interference from products operating in the same frequency band.

2.1.5 802.11n

The n amendment improves the previous 802.11 standards by using multiple-input multiple-output (MIMO) antennas. It is able to operate in both 2.4 GHz and 5 GHz bands and supports high speed connections with at least 100 Mbps data throughput if measured in the MAC layer [8]. The 802.11n draft was released by IEEE in 2009 [9] and can easily be found in contemporary network devices for home and office use. When measuring at the PHY layer, this standard can reach data rates up to 600 Mbps [10].

2.1.6 802.11p

The 802.11p supports wireless access in vehicular environments (WAVE) and defines all enhancements to the 802.11 standard that are required to support ITS applications. The standard uses the 5.9 GHz ISM band and enables car-to-car or vehicle-to-vehicle communication. Available data rates for this standard are 3, 4.5, 6, 9, 12, 18, 24 and 27 Mbps. With the exception of the sample rate, the physical layer of 802.11p is identical to the one that can be found in 802.11a and the two amendments also use the same modulation scheme OFDM. Since 802.11p is used for C2C communication, high demands on reliability and security are requested for this standard [11].

2.2 IEEE 802.15

IEEE 802.15 is a working group consisting of seven task groups including the well-known bluetooth standard. It further contains ZigBee as well as high and low rate wireless personal area networks (WPAN). 802.15 WPAN aims to develop standards for short distance wireless networks to support interoperability among wireless devices [12].

2.2.1 ZigBee

ZigBee is a standard that defines a set of communication protocols for reliable, cost-effective, low-data and short-range networking operating at 868 MHz (in EU), 902-928 MHz (in America) and 2.4 GHz (worldwide) [13]. ZigBee provides low cost and low power consumption to equipment that is required to function for several months or even years in often isolated conditions without the need for high data rates. ZigBee is preferably used in home automation, consumer electronics, industrial controls and games [14].

The technical characteristics of ZigBee are low power consumption, reliability and high expansibility. The low power consumption is maintained in both working and non-working mode. When a node is in working mode, the amount of exchanged data is small while the rate of transmission is low. When the node is in a non-working mode, it is put into a dormant state. The reliability of a ZigBee node is provided by adopting the collision mechanism talk-when-ready. In this case, the node sends data and subsequently awaits a confirmation from the recipient. If no confirmation is received, a collision has occurred and the node will have to retransmit its packet. As for the expansibility, ZigBee can support 255 nodes where one is the master and the rest function as slaves [14].

2.2.2 802.15.4

ZigBee is based on the 802.15.4 standard. IEEE 802.15.4 defines the physical and MAC layers for Low-Rate Wireless Personal Area Networks (LR-WPAN) while the network layer is defined by ZigBee. 802.15.4 provides the specifications for peer-to-peer, star and mesh topologies as well as the framework for the applications running on the application layer. Some advantages here are ease of installation, low cost, reliability in transmission of data, short-range operation and long battery life [15].

2.3 Intelligent Transport Systems

Recently, more attention has been directed at intelligent transportation systems (ITS). When we use the term ITS, we refer to systems that make the transportation of people or products more efficient, economic and safer, thus "intelligent". These systems supply information and communication technologies to the transportation sector to improve safety, efficiency and coordination. Nowadays, vehicles have evolved into sophisticated computer systems with the aid of embedded computers and sensors, each being responsible for the operational functionality of a specific car component. The main innovation provided by ITS is the integration of existing technologies to create new services [16].

2.3.1 ITS Protocol Architecture

In this section, a brief description of the ITS protocol stack is presented that is based on the OSI model by the International Organization for Standardization (ISO). The stack is defined by two vertical entities and four horizontal layers as seen in figure 2.2 below.

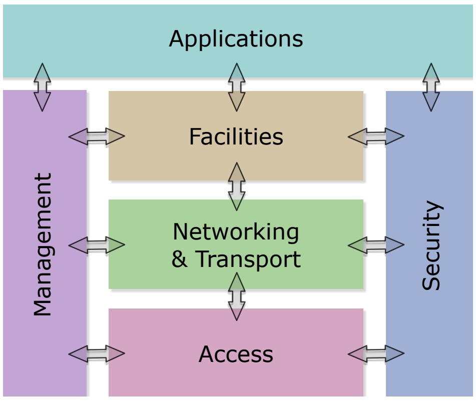


Figure 2.2: The ITS station reference protocol stack

The access layer represents the first two layers of the OSI model, the physical and the data link layer. It covers various communication media and the related protocols. Furthermore, it also includes the MAC layer that controls the medium access. The networking and transport layer refers to the network and transport layers of the OSI model respectively. These layers provide the means to transfer information from sender to receiver. The facilities layer corresponds to the session and presentation layers to support ITS applications. The application layer refers to applications and use cases for traffic efficiency and road safety. The two vertical entities are responsible for exchanging data between the layers and can also assist with security and privacy services [17].

2.3.2 Vehicular Ad-Hoc Networks

Transportation has so far been assisted and managed by a number of technologies that are present in and around our vehicles today. Some examples are traffic information broadcasted via the radio to warn about hazardous situations. Other warning messages are displayed on signs along the highway to make the driver aware of changing road conditions such as traffic jams or slippery surface due to rain and snow. In recent years, a paradigm shift can be seen in industry and academia that points to a major leap forward for ITS. Vehicles are now carrying communication and computing platforms and have the ability to sense their surroundings. Vehicular ad hoc networks (VANETs) are an upcoming technology, which consolidate the abilities of wireless networks and vehicles [18]. A VANET is a special category of mobile ad hoc networks (MANETs) [19] - a network formed between wireless-equipped vehicles that communicate with each other or roadside units without the use of additional equipment [20].

For a vehicle to participate in a VANET, it needs to be equipped with wireless transceivers and modules responsible for the control of the vehicle to let it act as a network node. The range between two communicating vehicles can be no more than a few hundred meters; thus for long distances, the messages need to be able to hop through several nodes for end-to-end communication [21]. The objective of VANETs is to allow omni-present connectivity to the mobile users while traveling, thereby enabling effective V2V communication. Figure 2.3 shows the many future uses of vehicle ad hoc networks.

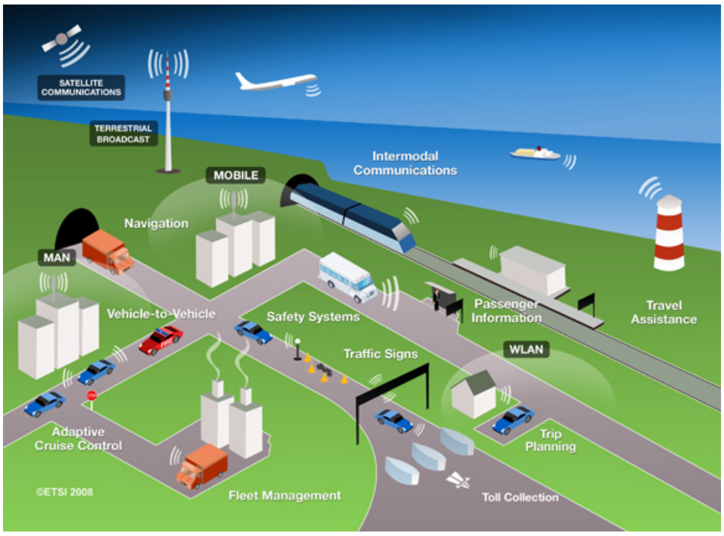


Figure 2.3: Vehicle ad hoc networks in a nearby future [22]

Applications that run on VANETs can be divided into two groups: intelligent transportation applications and comfort applications. Components of ITS applications belong to the first category and include control flow of traffic, on-board navigation and analysis of traffic congestion on the fly. The second group consists of applications allowing passengers to communicate with either Internet or other nearby vehicles [20]. Some common characteristics that can summarize vehicular ad-hoc networks are the following [18]:

- interaction with on-board sensors
- frequently disconnected network
- highly dynamic topology
- geographical type of communication
- mobility modeling and predication
- sufficient energy and storage
- hard delay constraints
- various communication environments

2.3.3 Vehicle-to-Vehicle

In the vehicle-to-vehicle (V2V) communication, the vehicles dynamically exchange data in a wireless fashion with their nearby nodes. The communication is performed anonymously, where the vehicle nodes send and receive messages regarding road and traffic condition information. In matters of safety, the communication between the vehicles gives them the opportunity to sense any threats and hazards that may arise within a 360 degree position range from other vehicles. Great benefits can be acheived with V2V communication in case of emergency situations where cellular base stations many times are overloaded with calls. Distributed vehicle-to-vehicle communication on the other hand can load balance the traffic and thus help avoid a congested cellular network [21].

2.3.4 Vehicle-to-Infrastructure

In the vehicle-to-infrastructure (V2I) communication, the vehicles and the road side infrastructure exchange data with each other directly without the need of using intermediate nodes or equipment. The installation of fixed infrastructure along the roads will naturally lead to large expenses. It is therefore imperative to expand the effective range of the vehicles belonging to the V2V communication network [21]. Figure 2.4 displays V2V/V2I communication scenarios that e.g. can enable traffic warnings to the driver.

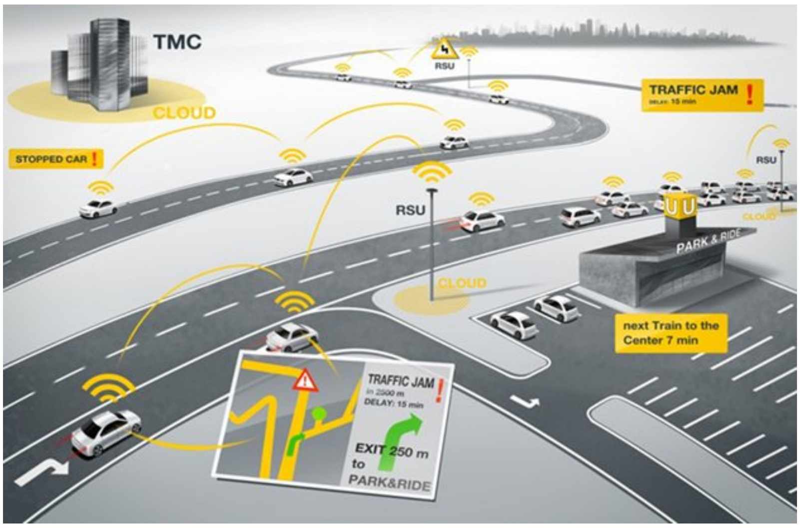


Figure 2.4: Vehicle-to-vehicle and vehicle-to-infrastructure communication [23]

2.4 Modulation Schemes

Modulation can be described as the manipulation of a carrier signal in order to allow the representation of intelligent information. The 802.11 standard originally defined three physical layer technologies intended for WLAN use in 1997: DSSS, FHSS and infrared PHY. Since 1997, OFDM, HR/DSSS, ERP and HT-OFDM have been added to the protocol suite. All 802.11 modulation schemes are described in the list below [6][24]:

- Direct sequence spread spectrum (DSSS). This physical layer technology operates in the 2.4 GHz band with data rates of 1 and 2 Mbps. The available channels to use depend on the bandwidth allocated by the various national regulatory agencies. One channel is available in Japan and 13 in most of the EU countries.
- Frequency hopping spread spectrum (FHSS). In similarity to DSSS, FHSS also defines the medium that operates in 2.4 GHz band with data rates of 1 and 2 Mbps. In Japan, 23 channels are available while 70 can be used in the U.S.
- Infrared physical (IR). Again, the data rates are the same as for DSSS and FHSS. The difference lies in the frequency band where infrared operates in the 850 and 950 MHz ISM bands. Since the data rates are limited for IR together with the fact that the technology requires direct LOS, it did not gain much market support.
- Orthogonal frequency division multiplex (OFDM). The OFDM scheme is able to provide high data rates and can also give excellent resistance to interference that otherwise could disrupt the communication link. OFDM is not an actual spread spectrum technology as stated by FCC but rather a digital modulation method. It was first used in 802.11a and can additionally be found in 802.11g, which indicates that it is able to function both in the 2.4 and the 5 GHz band.

- High-rate DSSS (HR/DSSS). This is the modulation technique used in the 802.11b amendment from 1999. The main objective with HR/DSSS was to enable higher data rates for the 2.4 GHz frequency band that at the same time was compatible with DSSS. The result was an addition of the data rates 5.5, and 11 Mbps to the already existing 1 and 2 Mbps that all can be found in 802.11b.
- Enhanced rate physical (ERP). The scheme was first released together with the 802.11g amendment and is now used in the g standard in combination with OFDM (ERP–OFDM) for communication in the 2.4 GHz frequency band.
- High-throughput OFDM (HT-OFDM). The more recent amendment 802.11n uses this modulation technology that can offer very high data rates up to 600 Mbps.

2.5 Telematics

Vehicle telematics can be described as any application that integrates informatics with telecommunications with the purpose to improve functionality, productivity and security of the vehicle itself and the driver. It may also refer to automobile systems that combine GPS tracking and wireless telecommunication systems. Some uses of telematics are [25]:

- Vehicle tracking or fleet management, which can be explained by the tracking of a vehicle's trailer unit in terms of movement and position. This is performed by the use of a GPS tracking device that contains a GPS locator and GPRS modem. The tracking device is installed in the vehicle that subsequently can be viewed on a computer with GPS tracking software through a PC or Web interface.
- Fuel saving telematics. Onboard engine diagnostics can obtain data directly from the communication network of the vehicle to inform the driver about efficient driving techniques. The system can, for example, let the driver know that he/she is not using the gears optimally, is driving too fast or is over revving.

2.6 Geonetworking

According to [17], geonetworking is defined as:

"A network service that utilizes geographical positions and provides ad hoc communication without the need for a coordination communication infrastructure."

In other words, geonetworking enables communication to specific geographic areas. The transmitter sends a message to the sender, which is in its communication range, by using IP routing. The message is then forwarded until it reaches the desired geographical area. In order to obtain the message, the receiver needs to be in the desired region. The message is sent by broadcast from anyone located within its coverage area. If the message has been received at a previous point in time or if it is received by a node outside the coverage area, it is simply ignored. Geonetworking is important to ITS due to its ad hoc, multi-hop communication characteristics using short-range wireless technologies.

3

Related Work

In this chapter, we will have a quick look at previous research projects that have investigated the wireless communication protocols evaluated during this master thesis. In many of the projects, the evaluation criteria differ from the ones outlined for this project due to our specific target environment and purpose of the evaluation. Since the quarry is still a relatively new area for wireless communication, we had difficulties finding research work that had been conducted in this type of environment. Furthermore, limitations caused by used hardware did not allow us to test e.g. throughput or delay that have been investigated in some of the mentioned projects.

3.1 Throughput Performance of 802.11b

The 802.11b and 802.11g standard using 2.4 GHz frequency band is divided into 13 channels following ETSI in Europe (11 channels according to FCC in the U.S.). These channels are partly overlapping but when using frequency bands that are four channels apart or more, it should be possible to avoid interference. The maximum range that 802.11b/802.11g can reach is approximately 152 meters (500 feet). As a comparison, 802.11a that operates in the 5 GHz band only reaches a maximum distance of 45 meters (150 feet) but can at the same time offer higher data rates of up to 54 Mbps.

The experimental study conducted by Fadhah et al. in [26] present the relation between the throughput and distance. The experiment took place in an empty parking lot so as to avoid any interference. Two laptops were used as nodes and every 15 meters, the experiment was repeated. The results can be seen in figure 3.1. In a distance of 0 meters, the measured throughput was approximately 17 Mbps. However, when reaching a distance of 60 meters, the authors noticed a decrease in throughput of more than 50%.

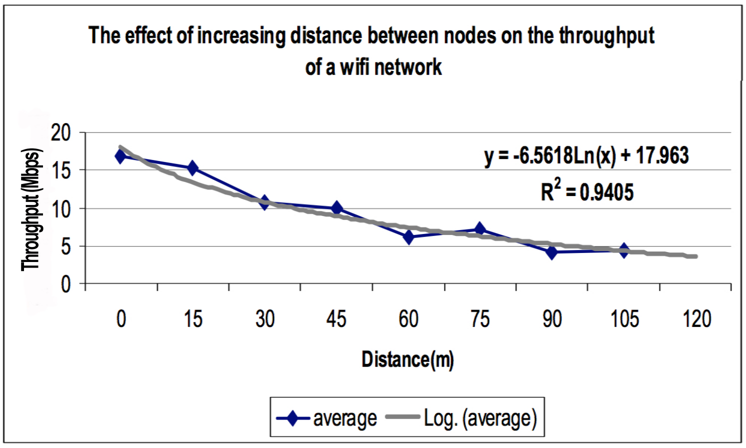


Figure 3.1: Throughput versus distance for 802.11b [26]

The authors were further able to show a great correlation given by the correlation coefficient $R^2 = 0.940$ with the following logarithmic function:

Throughput (d) = -6.5618 Ln (d) + 17.963

Where *d* is the distance meters and *throughput* is given in megabits per second. Another interesting finding was that interference still could be found among two adjacent access points (AP) although these used frequency bands that were more than four channels apart (one AP used channel 1 while the other used channel 6). Following Fadhah et al., the APs had to be 25 meters apart to avoid any interference and channel overlapping.

3.2 A Study of 802.11b/802.11g

The study of Athanasopoulos et al. was performed by using the two simulation tools OPNET and the wireless C++ simulator. In [27], the authors performed simulations between 10 nodes within 150 seconds using packets of 1024 bytes and an RTS threshold of a quarter of the packet length. The testing was performed between the 802.11b and 802.11g technologies where 802.11b used the RTC/CTS mechanism while 802.11g used the CTS-to-self technique. The coverage area of each node was 300 meters. The criteria of evaluation were throughput and media access delay that was measured from the time when the packet was sent via the transmitter until it reached the receiver.

The simulation results showed a poor throughput performance of 802.11b compared to 802.11g (see figure 3.2). The difference in terms of mean network throughput between these two was 30.5%. 802.11b was also the protocol that experienced the longest delays due to the RTS/CTS signaling exchange that added extra network overhead. The only time 802.11b performed better than 802.11g was when the hidden node problem occurred. This could be explained by the fact that the RTS/CTS signaling exchange is able to avoid packet collisions better than the CTS-to-self MAC mechanism used in 802.11g.

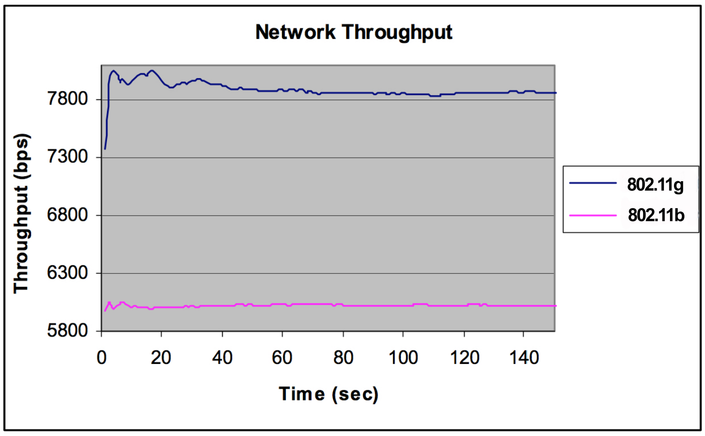


Figure 3.2: Mean network throughput of 802.11b and 802.11g [27]

Observing the performance of the standards in a LOS situation between the nodes, the outcome proved that 802.11g performed better than 802.11b. The results containing network throughput and delay can be seen in figure 3.3 and 3.4. Meanwhile, in a NLOS situation where the hidden node problem existed, 802.11g experienced longer delays than 802.11b that seemed unaffected by this problem thanks to the RTS/CTS protection technique. The conclusion of Athanasopoulos et al. was therefore that 802.11b could provide for more stable performance and quality of service in comparison to 802.11g.

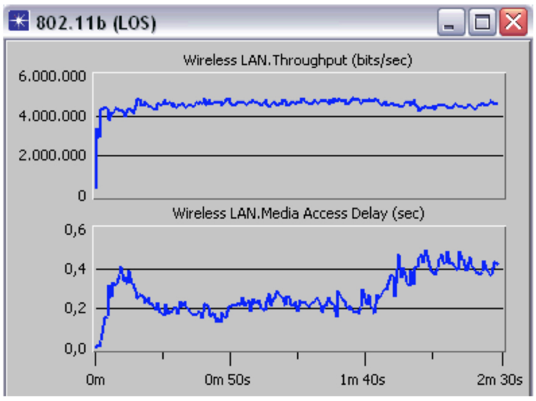


Figure 3.3: 802.11b network throughput and delay during simulated LOS [27]

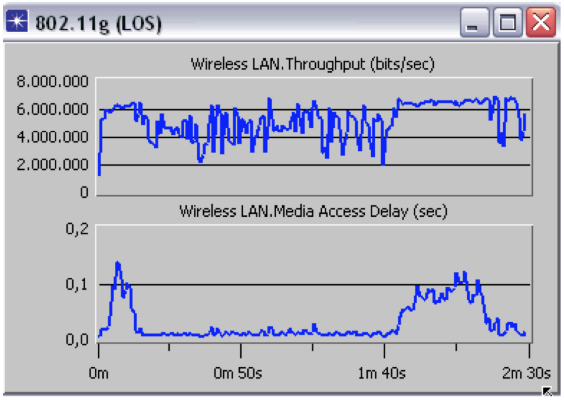


Figure 3.4: 802.11g network throughput and media access delay during LOS [27]

3.3 802.11n in Vehicular Networks

The design and implementation of the 802.11n amendment was triggered by the need for a high performance protocol suitable in a variety of different environments. The maximum 802.11n throughput can reach 600 Mbps with the use of four spatial MIMO streams. 802.11n is above all effective in indoor environments due to its MIMO technology where reflections from walls and ceiling lead to multi-path propagation that increases throughput and range [28]. Multi-path propagation appears when signals scatter on different obstacles to finally reach the receiver at various times [29].

In [28], the authors evaluated the standard in an indoor and outdoor environment. The indoor experiment focused on measuring throughput and signal strength in the MAC layer between two nodes. One node was sending UDP traffic while the other was receiving. As expected, an increase in distance lead to a decrease of both signal strength and throughput. The average throughput was 240 Mbps at 1 meters distance and 90 Mbps at 100 meters. A small increase in throughput was noticed around 35 meters due to reflections from the walls of the corridor. Figure 3.5 and 3.6 show the results in detail.

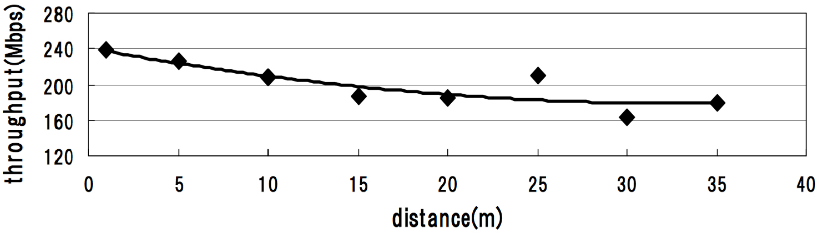


Figure 3.5: Indoor and LOS throughput performance versus distance [28]

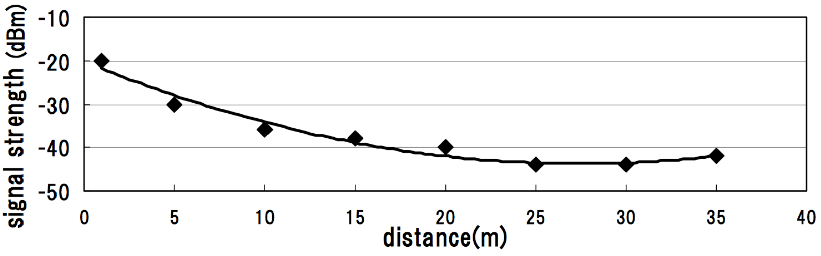


Figure 3.6: Signal strength average versus distance, indoors with LOS [28]

The outdoor experiment consisted of two cars, one remained parked while the other was driving on the road receiving ICMP echo packets. The results showed that by using 1 MIMO stream at a fixed rate of 15 Mbps, the coverage range could reach 850 meters. When using 2 streams at 30 Mbps, the maximum range was only 290 meters. The results showed that 1 stream can be used in a vehicular network over large areas while 2 streams can provide higher throughput at near distances. The 802.11n device was also used in 802.11g mode with a 6 Mbps rate, which gave the best coverage range (1170 meters).

Of course, to be able to achieve high throughput and longer distances, the output power should consequently be increased. That can be accomplished by using special power amplifiers to increase the signal strength from, for example, the typical output power of 23 dBm to a more uncommon 30 dBm. According to Cohen in [30], the 4x4 MIMO technology can have significantly longer ranges than the 3x3 reference design.

In Figure 3.7, we can see in a worldwide legal output power of 23 dBm that the 3x3 system reached up to 60 feet (18.28 m) while 4x4 had a range of 100 feet (30.48 m). When raising the output power to 30 dBm, the distance increased to 95 feet (28.95 m) and 158 feet (48.15 m) respectively. It is necessary to mention that, by increasing the output power, battery life will be reduced while generated heat and power consumption is increased along with more interference in adjacent channels.

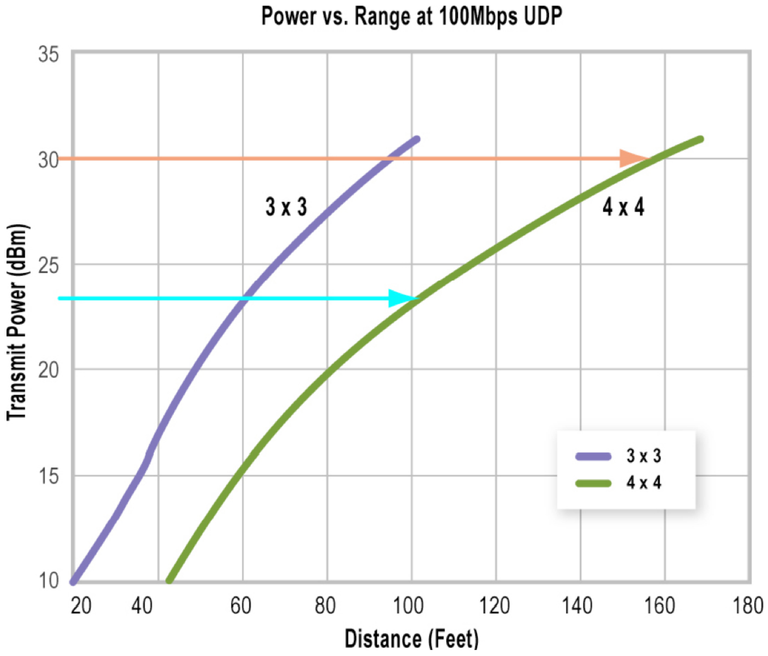


Figure 3.7: Output power versus range at a rate of 100 Mbps [30]

In a similar test that compared the two MIMO systems based on throughput while using normal power (23 dBm) and higher power (30 dBm), the 3x3 technology achieved the same throughput as the 4x4 in a shorter distance. The two scenarios are displayed in figure 3.8 and 3.9 showing an output power of 23 dBm and 30 dBm respectively.

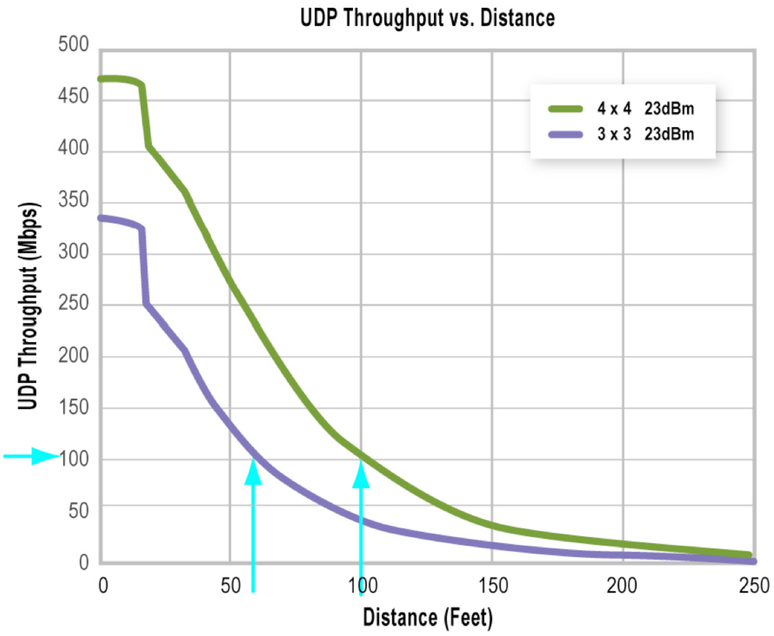


Figure 3.8: Throughput versus distance at 23 dBm output power [30]

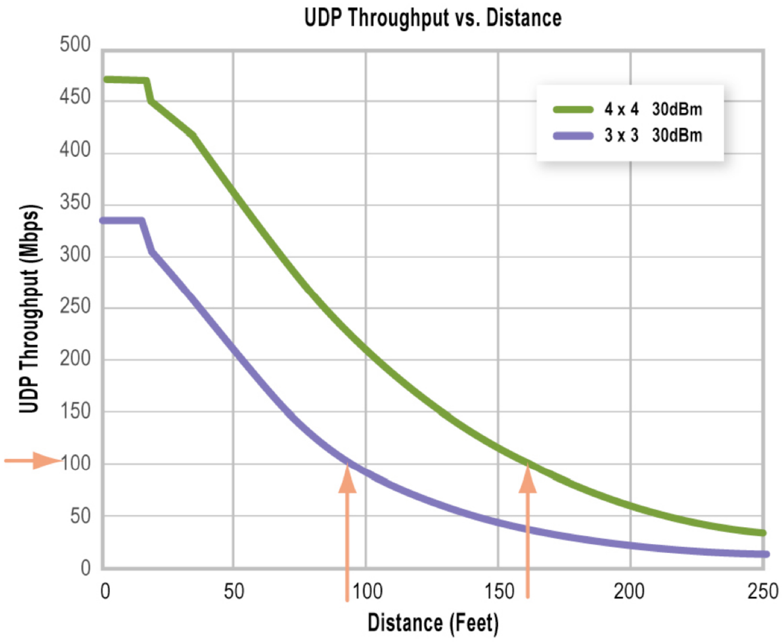


Figure 3.9: Throughput versus distance at an output of 30 dBm [30]

3.4 802.11p Performance Evaluation

Another amendment of IEEE 802.11 is the 802.11p protocol, also known as Wireless Access in Vehicular Environments (WAVE). The protocol aims to support ITS and V2V and V2I communication [31] and is included in the dedicated short range communication (DSRC) standards. The goal is to support communication between vehicles to improve the safety of passengers and thereby reduce fatalities. As mentioned in the background chapter, the protocol uses the 5.9 GHz band and reaches up to 1000 meters.

The authors of [32], used one-way communication in one of their experiments where they calculate throughput, loss rate and communication range of the 802.11p protocol. The setup was a static communication between two 802.11p devices that communicated without moving. As in previous tests, one device acted as the transmitter while the other was receiving packets. The results showed that the throughput was affected by the interval time. Figure 3.10 illustrates how throughput is affected by interval time when two 802.11p devices perform one-way communication 1 meter apart. We can see that as the interval time increases, more time is needed to transmit messages, which leads to reduced throughput. The test also showed that the throughput was not so much affected by the number of messages in the network but other factors such as the already mentioned interval time, I/O bandwidth and device processing speed.

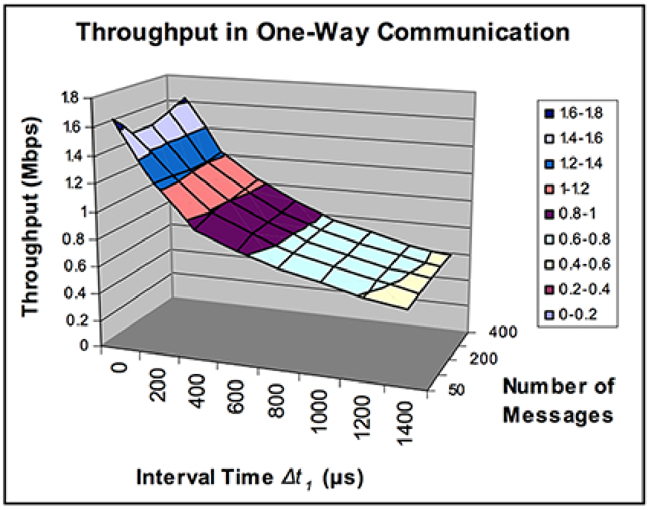


Figure 3.10: The relation between throughput and interval time [32]

The message loss rate (LR) was calculated by using the following formula:

$$LR = (\text{transmitted messages - received messages})/\text{transmitted messages} \times 100\%$$

It was noticed that when the interval time was very small, the 802.11p device was unable to receive the packets in time due to a limited buffer size and processing speed. This produced rather high message loss rates of 45% that can be found in figure 3.11.

In figure 3.12, we see the number of received messages over the distance in meters. The test was conducted in an open area where the devices were moved apart up to a point where no more messages could be received. The communication range reached approximately 850 meters where 398 messages were received out of 400 being sent in an interval time of 1400 μs. At 900 meters, the device could no longer receive any messages.

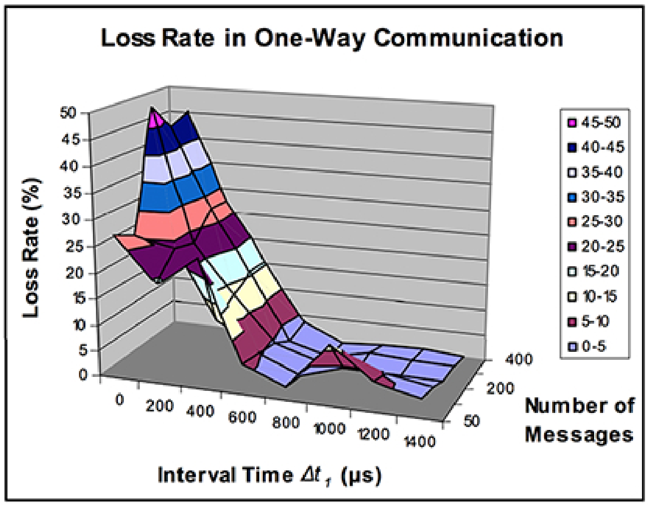


Figure 3.11: One-way communication loss rate [32]

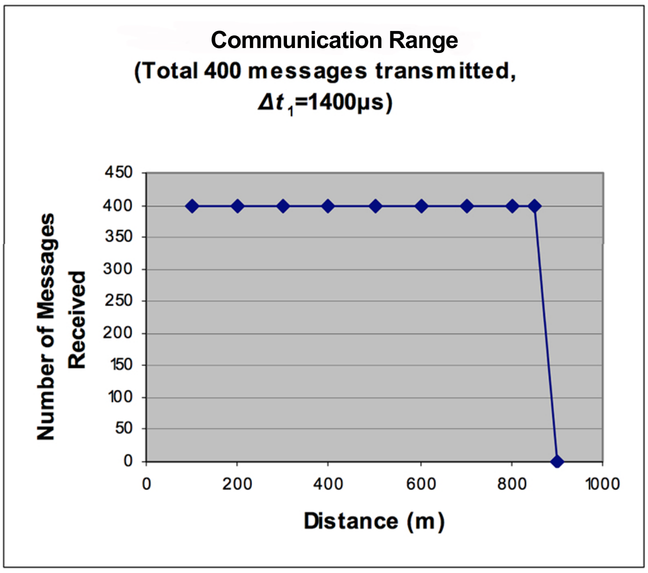


Figure 3.12: Communication range over distance [32]

3.5 802.15.4 in Sensor Networks

The IEEE 802.15.4 standard provides low data rate and low power consumption communication in the first two layers of the OSI model, the physical and the link layer. In [33], Zen et al. investigate packet loss, throughput and delay in the ns-2 simulation environment. The experiments included one or several moving nodes depending on the current setup. According to the authors, this study was the first attempt to evaluate 802.15.4 in mobile sensor networks. A brief of the study presentation follows.

Zen et al. evaluated the communication between moving nodes in single-hop networks with a data rate of 250 Kbps. The size of each packet was 90 bytes and every simulation ran for a duration of 500 seconds. One of the experiments allowed communication between one moving node and one coordinator that were placed 10 meters apart. During the simulation, the moving node had different speeds as it moved towards and away from the coordinator. An interesting finding of this study was that the packet loss seemed to be affected by the speed of the node. The faster the node was moving, the higher the packet loss. In addition, the nodes with high speeds also experienced difficulties with maintaining connectivity in beacon-enabled mode. The problem with the high speeds was that the node did not have enough time to establish an association with the coordinator and the node could therefore not maintain connectivity.

4

Measurements and Test Cases

This chapter specifies the test cases that aim to answer our research questions, which will guide us in our evaluation of the set of selected wireless technologies for the quarry site. The goal is to have a well-defined testing suite with a number of cases that each focuses on a given environment where the tests are carried out. During our work, two platforms are used that are able to handle our three frequency bands of interest: 868.0 - 868.6 MHz, 2.4 - 2.4835 GHz and 5855 - 5925 MHz.

After the tests are performed for the various cases, a comparison can be made where we pay attention to packet loss and range. We will look at the results obtained from the two platforms and see if and how they differ but also observe the impact of the environment where the tests are conducted. The wireless protocols that will be evaluated during this study are limited to 802.15.4, ZigBee radio frequency (RF), 802.11g and 802.11p. The standards 802.15.4 and ZigBee RF are tested using equipment from Libelium with a Waspmote board and gateway while the Alix boards used in the COSMO platform provide communication with 802.11g and 802.11p. More information about the equipment can be found in the chapter Design and Implementation.

4.1 Measurements

The quality of our performed evaluation is of great importance. The aim is to describe our tests with enough detail so that they can be replicated given the same parameters and equipment that we used. This section clarifies the conditions surrounding our test cases to better describe the environment they were conducted in.

The data rates used during the experimental setup was set to 6 Mbps for 802.11g and 802.11p in the COSMO platform. For the Libelium equipment, a rather low data rate of 250 Kbps was used for 802.15.4 in the 2.4 GHz range, following the specification of the standard. For ZigBee radio frequency that is communicating in the 868 MHz ISM band, 20 Kbps was used as a data rate, also according to the standard's specification.

The target when purchasing the Libelium equipment was to reach the peak of the maximum transmission gain that is allowed as specified by FCC (Federal Communications Commission). The wireless interface XBee PRO module 802.15.4 had a transmission power of 315 mW or approximately 25 dBm. Meanwhile, the wireless interface XBee module ZigBee RF achieved 50 mW or roughly 17 dBm. The output gain for 802.11g and 802.11p was 20 dBm.

As already mentioned, the parameters we are interested in are packet loss and range; this calls for a more fine-grained definition. By packet loss, we simply mean the number of packets that do not reach their intended destination. When discussing range, we intend the distance in meters between two vehicles where the receiving node is able to receive packets from the sending node.

The packet sizes have been adjusted to fit the tested standards. In ZigBee/802.15.4 where packets are sent with a low data rate, the specification has set out a maximum packet size of 128 bytes [34]. We adhered to the standard and used a quite small packet size of 19, 20 and 21 bytes where the variation in size depends on the space needed for the packet counter. A one digit packet number uses a 19 byte packet while a two digit packet number needs a 20 byte packet. This small packet size was chosen in order for two packets to be sent out during the same second. When using larger packets with the Libelium equipment, it would consequently take more time to create and send the packet, meaning that we were not able to send two packets per second at a stable transmission rate. In turn, sending two packets per second was important in order to get detailed measuring points for our visualization tool WTDQ. Figure 4.1 shows the frame that was sent from the Waspmote boards and the XBee modules for 802.15.4 and ZigBee RF.

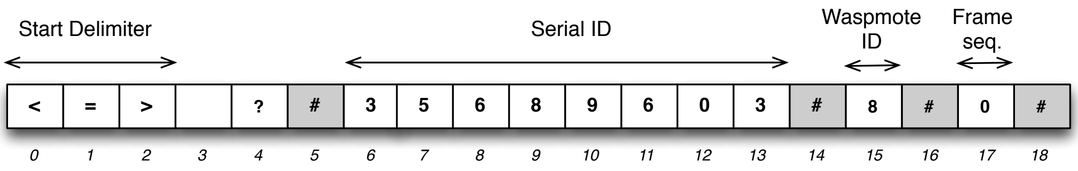


Figure 4.1: Waspmote frame used during testing 802.15.4 and ZigBee RF

Regarding the set of protocols 802.11g and 802.11p, a packet size of 214 bytes was chosen that contained information of the message ID and GPS data such as latitude, longitude, heading along with a GPS timestamp. The rest of the packet was filled up with random data as can be seen in Figure 4.2.

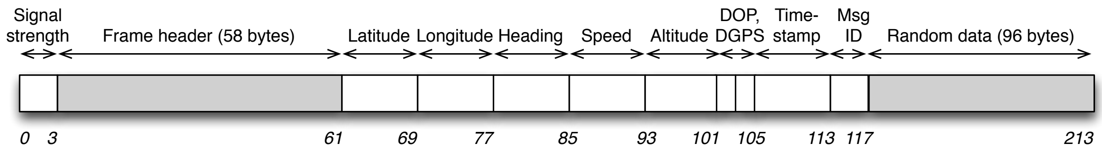


Figure 4.2: A COSMO packet of 214 bytes sent with 802.11g and 802.11p

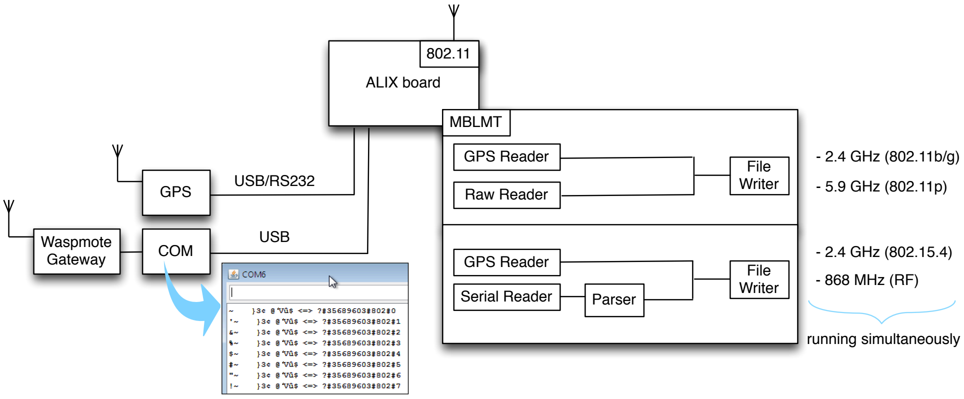
When publishing standardization documents for communication in the different ISM bands, ETSI defines the testing environment where normal and extreme test conditions are described. Normal test conditions set out the temperature and humidity ranges where the temperature should be between +15 °Cto +35 °C. The relative humidity should be in the range of 20% to 75% [35]. Extreme test conditions on the other hand are given wider temperature ranges from -30°Cto +70°Cand do not mention the relative humidity. All of our measurements were conducted in the end of May where we fulfilled the criteria for normal test conditions. Furthermore, we performed our tests while the weather was either sunny or partly cloudy and never when it was raining. The measurements should thus not have been affected by any weather conditions.

While measuring in the quarry, the vehicle speed was approximately 25-30 km/h. This speed was suitable for the quarry environment since it is a rocky environment with steep cliffs and narrow roads without fences or other protection. It also allowed us to get more detailed measuring points since the Libelium equipment only allowed a stable transmission rate at no more than 2 packets per second.

Performing LOS measurements in Volvo Cars Demo Center had to be conducted with a higher speed. Volvo Cars who are the owners of the 2.2 km long LOS high-speed track in Torslanda had strict guidelines on the speed limit. Driving 90 km per hour or more was recommended due to security reasons since very high speeds are used on this track. We eventually managed to drive with a speed of 45 km per hour during a non-busy lunch hour slot using the 1.8 km driveway to the high-speed track.

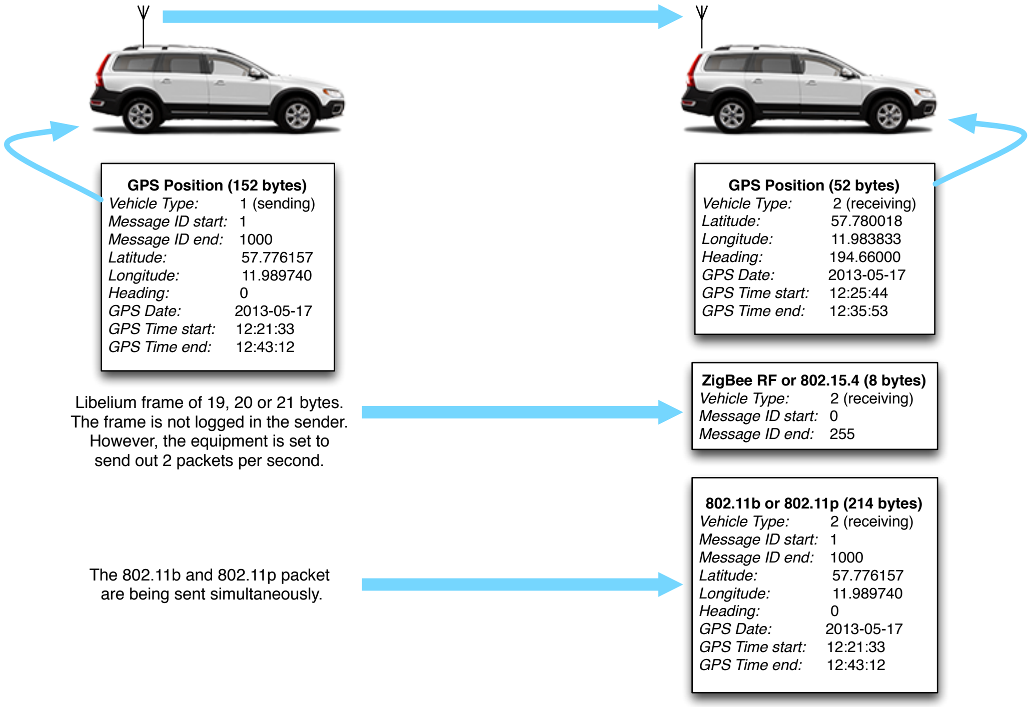
4.2 Test Cases

This section contains the test cases used during the evaluation. To first give an overview of how the measurements were conducted, the testing setup can be viewed in Figure 4.3 and Figure 4.4. The first figure shows how the transmitted data was collected at the receiving node. Figure 4.4 gives a complete overview of the entire test setup.



```
~    }3¢ @'Vû$ <=> ?#35689603#802#0
'~    }3¢ @'Vû$ <=> ?#35689603#802#1
&~    }3¢ @'Vû$ <=> ?#35689603#802#2
%~    }3¢ @'Vû$ <=> ?#35689603#802#3
$~    }3¢ @'Vû$ <=> ?#35689603#802#4
#~    }3¢ @'Vû$ <=> ?#35689603#802#5
"~    }3¢ @'Vû$ <=> ?#35689603#802#6
!~    }3¢ @'Vû$ <=> ?#35689603#802#7
```

Figure 4.3: Data collection in the receiving node using the COSMO platform



GPS Position (152 bytes)
Vehicle Type: 1 (sending)
Message ID start: 1
Message ID end: 1000
Latitude: 57.776157
Longitude: 11.989740
Heading: 0
GPS Date: 2013-05-17
GPS Time start: 12:21:33
GPS Time end: 12:43:12

GPS Position (52 bytes)
Vehicle Type: 2 (receiving)
Latitude: 57.780018
Longitude: 11.983833
Heading: 194.66000
GPS Date: 2013-05-17
GPS Time start: 12:25:44
GPS Time end: 12:35:53

Libelium frame of 19, 20 or 21 bytes. The frame is not logged in the sender. However, the equipment is set to send out 2 packets per second.

ZigBee RF or 802.15.4 (8 bytes)
Vehicle Type: 2 (receiving)
Message ID start: 0
Message ID end: 255

The 802.11b and 802.11p packet are being sent simultaneously.

802.11b or 802.11p (214 bytes)
Vehicle Type: 2 (receiving)
Message ID start: 1
Message ID end: 1000
Latitude: 57.776157
Longitude: 11.989740
Heading: 0
GPS Date: 2013-05-17
GPS Time start: 12:21:33
GPS Time end: 12:43:12

Figure 4.4: Complete test setup illustrating the sending and receiving nodes

The 802.11g and 802.11p packets were received directly in the Alix board while the 802.15.4 and ZigBee RF packets first had to be sent to the Waspmote gateways. Since the gateways for 802.15.4 and ZigBee RF were connected to COM ports read by the Alix board, the needed packet information such as protocol type and packet ID could be collected and put in a new packet as seen in figure 4.5. This 8-byte packet was later collected in a log file together with the 802.11g and 802.11p packet information.

Protocol 2, as shown in below figure, represents an 802.15.4 packet since it is communicating in the 2.4 GHz range. ZigBee RF that uses the 868 MHz ISM band is identified by protocol 8. As set by Libelium, the frame number indicating the message ID counts up from 0 to 255. The next sent frame is then mapped to the value zero when the counter starts over again. The protocol and packet ID fields are stored as a 4 byte integer where protocol is mapped from byte 0 to 3 while packet ID can be found at byte 4 to 7.

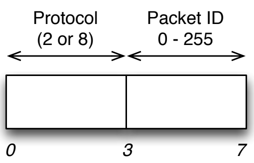


Figure 4.5: A COSMO packet of 214 bytes sent with 802.11g and 802.11p

In order to obtain the exact location of the nodes, a GPS position packet was generated in both of the vehicles to later be used in the visualization tool and Android application WTDQ. Before that, it also had to be logged in COSMO and parsed by LogAnalyzer. The structure of the position packet from the receiving node is displayed in figure 4.6. A position packet from the sending vehicle contains a bit more information and is thus larger with a size of 152 bytes. However, both position packets contain the same core structure as illustrated by below figure. The fields speed, altitude, dilution of precision (DOP) and differential GPS (DGPS) were not used in this project.

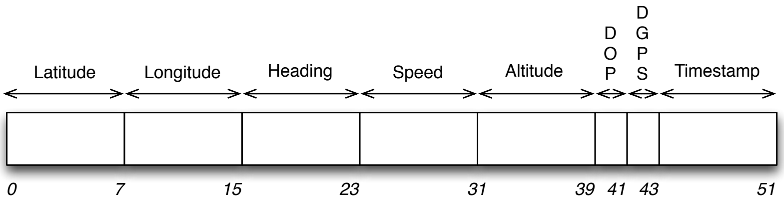
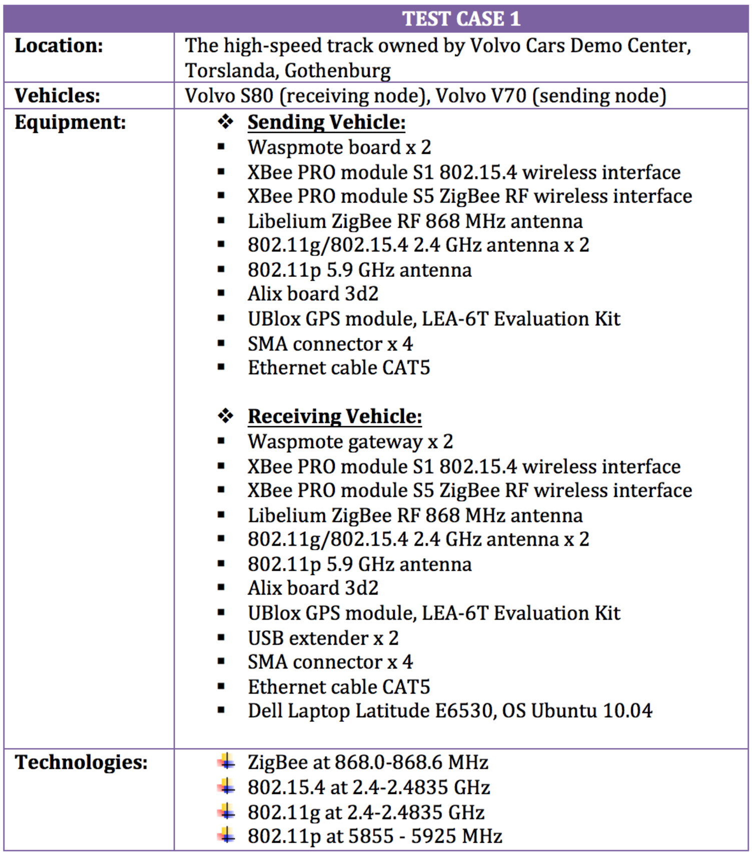


Figure 4.6: A GPS position packet consisting of 52 bytes

4.2.1 Test Case 1: Outdoor LOS Range Measurement

Test case 1 was conducted outdoors in a line-of-sight (LOS) at the high-speed track of Volvo Cars with antennas mounted on each vehicle. The vehicle responsible for sending packets was parked at the beginning of the driveway to the track while the receiving vehicle was driving away from the sending node in a LOS with a speed of 45 km per hour. The equipment was placed in both of the vehicles either in the trunk or in the back seat of the cars. Meanwhile, the antennas for all technologies were mounted on the car roof. All standards were tested simultaneously.

The purpose of this test case was to examine the range and packet loss for each standard when transmitting/receiving in a line-of-sight. Possible minimal interference was caused by the surrounding building, passing by vehicles, the speed of the receiving vehicle and a low pile of sand close to the sending vehicle. The use of the two cars is assumed to have a negligible effect on the obtained results. Figure 4.7 shows a table of the equipment and standards used during testing.



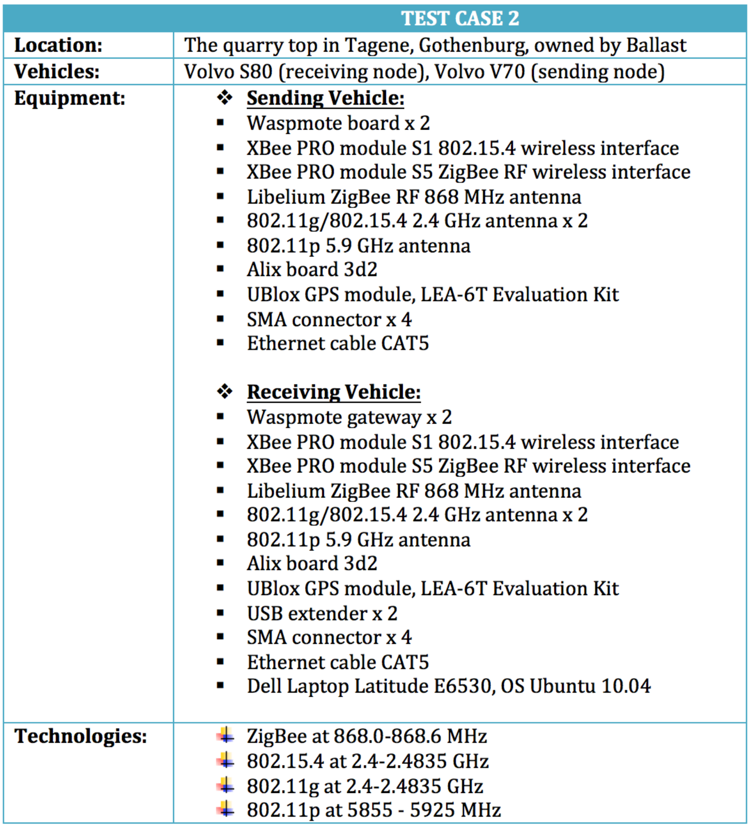
TEST CASE 1	
Location:	The high-speed track owned by Volvo Cars Demo Center, Torslanda, Gothenburg
Vehicles:	Volvo S80 (receiving node), Volvo V70 (sending node)
Equipment:	❖ **Sending Vehicle:** ▪ Waspmote board x 2 ▪ XBee PRO module S1 802.15.4 wireless interface ▪ XBee PRO module S5 ZigBee RF wireless interface ▪ Libelium ZigBee RF 868 MHz antenna ▪ 802.11g/802.15.4 2.4 GHz antenna x 2 ▪ 802.11p 5.9 GHz antenna ▪ Alix board 3d2 ▪ UBlox GPS module, LEA-6T Evaluation Kit ▪ SMA connector x 4 ▪ Ethernet cable CAT5 ❖ **Receiving Vehicle:** ▪ Waspmote gateway x 2 ▪ XBee PRO module S1 802.15.4 wireless interface ▪ XBee PRO module S5 ZigBee RF wireless interface ▪ Libelium ZigBee RF 868 MHz antenna ▪ 802.11g/802.15.4 2.4 GHz antenna x 2 ▪ 802.11p 5.9 GHz antenna ▪ Alix board 3d2 ▪ UBlox GPS module, LEA-6T Evaluation Kit ▪ USB extender x 2 ▪ SMA connector x 4 ▪ Ethernet cable CAT5 ▪ Dell Laptop Latitude E6530, OS Ubuntu 10.04
Technologies:	✚ ZigBee at 868.0-868.6 MHz ✚ 802.15.4 at 2.4-2.4835 GHz ✚ 802.11g at 2.4-2.4835 GHz ✚ 802.11p at 5855 - 5925 MHz

Figure 4.7: The details of Test Case 1

4.2.2 Test Case 2: Quarry Top Measurement

Test Case 2 was performed at the quarry in Tagene at the top road that surrounded the entire site. While the sending vehicle was standing still at a fixed position, the receiving vehicle drove around the quarry using the road enclosing the area. At certain points, the line-of-sight was blocked by obstacles such as hills, stones, rocks and trees. Other points along the road provided clear LOS to the sending vehicle. The standards were yet again evaluated together.

The purpose of the second test case was to investigate the packet loss for each standard when transmitting/receiving in both LOS and NLOS conditions. Figure 4.8 displays a table containing the details of the measurement setup.



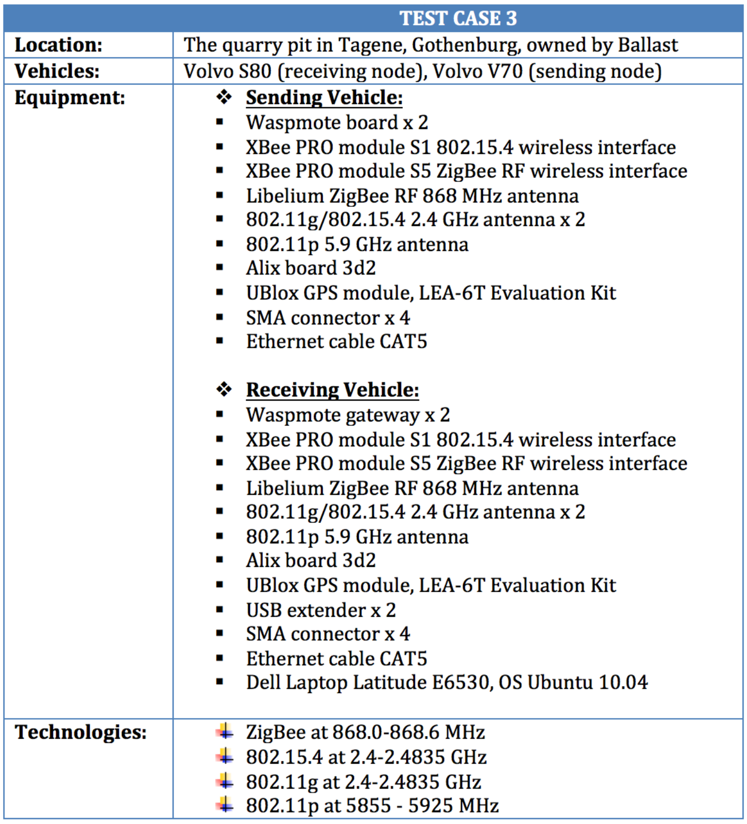
TEST CASE 2	
Location:	The quarry top in Tagene, Gothenburg, owned by Ballast
Vehicles:	Volvo S80 (receiving node), Volvo V70 (sending node)
Equipment:	❖ **Sending Vehicle:** ▪ Waspmote board x 2 ▪ XBee PRO module S1 802.15.4 wireless interface ▪ XBee PRO module S5 ZigBee RF wireless interface ▪ Libelium ZigBee RF 868 MHz antenna ▪ 802.11g/802.15.4 2.4 GHz antenna x 2 ▪ 802.11p 5.9 GHz antenna ▪ Alix board 3d2 ▪ UBlox GPS module, LEA-6T Evaluation Kit ▪ SMA connector x 4 ▪ Ethernet cable CAT5 ❖ **Receiving Vehicle:** ▪ Waspmote gateway x 2 ▪ XBee PRO module S1 802.15.4 wireless interface ▪ XBee PRO module S5 ZigBee RF wireless interface ▪ Libelium ZigBee RF 868 MHz antenna ▪ 802.11g/802.15.4 2.4 GHz antenna x 2 ▪ 802.11p 5.9 GHz antenna ▪ Alix board 3d2 ▪ UBlox GPS module, LEA-6T Evaluation Kit ▪ USB extender x 2 ▪ SMA connector x 4 ▪ Ethernet cable CAT5 ▪ Dell Laptop Latitude E6530, OS Ubuntu 10.04
Technologies:	✚ ZigBee at 868.0-868.6 MHz ✚ 802.15.4 at 2.4-2.4835 GHz ✚ 802.11g at 2.4-2.4835 GHz ✚ 802.11p at 5855 - 5925 MHz

Figure 4.8: The setup used during the execution of Test Case 2

4.2.3 Test Case 3: Quarry Pit Measurement

Similar to Test Case 2, Test Case 3 also took place in the quarry. This time, the conditions in the quarry pit were investigated. The sending vehicle parked behind a large pile of sand at the very end of the quarry pit while the receiving vehicle drove towards the other end of the pit. While driving away, the receiving vehicle passed piles of sand, stone and metallic construction equipment in order to evaluate the affects on the various technologies by the presented obstacles. All standards were tested at the same time.

The purpose of Test Case 3 was to get an idea of the experienced packet loss for the different standards when transmitting/receiving in the presence of obstacles typical for the quarry site. Minimal interference from dust, EMC, vibrations and other vehicles may have been present. Figure 4.9 presents more detailed information of the test setup.



TEST CASE 3	
Location:	The quarry pit in Tagene, Gothenburg, owned by Ballast
Vehicles:	Volvo S80 (receiving node), Volvo V70 (sending node)
Equipment:	❖ **Sending Vehicle:** ▪ Waspmote board x 2 ▪ XBee PRO module S1 802.15.4 wireless interface ▪ XBee PRO module S5 ZigBee RF wireless interface ▪ Libelium ZigBee RF 868 MHz antenna ▪ 802.11g/802.15.4 2.4 GHz antenna x 2 ▪ 802.11p 5.9 GHz antenna ▪ Alix board 3d2 ▪ UBlox GPS module, LEA-6T Evaluation Kit ▪ SMA connector x 4 ▪ Ethernet cable CAT5 ❖ **Receiving Vehicle:** ▪ Waspmote gateway x 2 ▪ XBee PRO module S1 802.15.4 wireless interface ▪ XBee PRO module S5 ZigBee RF wireless interface ▪ Libelium ZigBee RF 868 MHz antenna ▪ 802.11g/802.15.4 2.4 GHz antenna x 2 ▪ 802.11p 5.9 GHz antenna ▪ Alix board 3d2 ▪ UBlox GPS module, LEA-6T Evaluation Kit ▪ USB extender x 2 ▪ SMA connector x 4 ▪ Ethernet cable CAT5 ▪ Dell Laptop Latitude E6530, OS Ubuntu 10.04
Technologies:	✚ ZigBee at 868.0-868.6 MHz ✚ 802.15.4 at 2.4-2.4835 GHz ✚ 802.11g at 2.4-2.4835 GHz ✚ 802.11p at 5855 - 5925 MHz

Figure 4.9: The details concerning Test Case 3

As can be seen, all three test cases used the same type of equipment and setup where the four technologies were evaluated simultaneously in every case. This facilitated the analysis of the test results but also enabled a fair comparison between the standards. Furthermore, it also made it possible to visually display the results together, giving a more complete overview of the performance of the protocols.

5

Design and Implementation

This section describes the equipment and software used during our evaluation. Firstly, an overview of the experimental setup is given showing the communicating nodes and how they handle the sending and receiving of data. The hardware of each platform is subsequently outlined in detail providing information about components such as board and chipset. Finally, the implemented software is presented that was custom-made for the purpose of our test cases. This includes not only the software written for the hardware platforms but also the tools used to analyze and present the data such as our Java parser LogAnalyzer and Android application WTDQ.

5.1 Hardware

Two hardware platforms have been used to evaluate the set of wireless technologies. The COSMO platform was provided by Volvo while the Waspmote solution had to be ordered from Libelium, a company providing wireless sensor network equipment. In the following sections, both the COSMO and Libelium platforms are described in detail.

5.1.1 COSMO Platform

COSMO, a part of the co-operative systems for sustainable mobility and energy efficiency, is a pilot project funded by the European Commission [36]. The platform that was developed during this project was also named COSMO. It consists of an Alix board, a WiFi chipset and a vehicle-integration device that is a Volvo Telematics Gateway (TGW). The experimental setup used two nodes, one being the transmitter and the other the receiver. Both nodes were represented by Alix boards, one in the receiver and one in the transmitter. The two transmitting boards were of the model 3d2. Figure 5.1 shows the Alix board 3d2 inside of its protective box that has been opened.

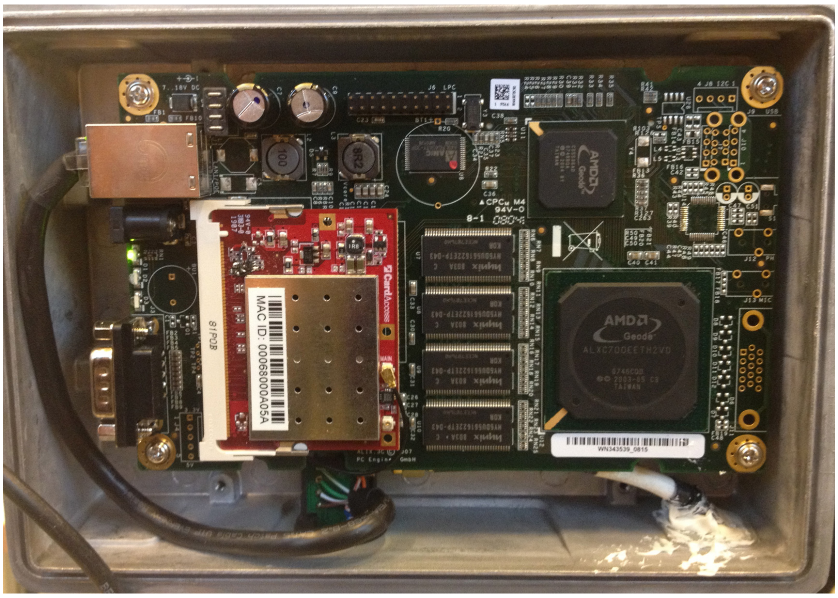


Figure 5.1: One of the used Alix 3d2 boards to test 802.11g and 802.11p

As can be seen in Figure 5.1, a WLAN card is also attached to the board. The WLAN card used during this thesis was of the model UNEX DCMA-86P2. This model was the very first WIFI mini-PCI designed to support 802.11p and DSRC for the purpose of vehicle communication [37]. It provided 802.11g and 802.11p communication during our experiments. Some characteristics of the AMD CPU platform Alix 3d2 are [38]:

- LX-800 with integrated RAM
- CPU: 500 MHz AMD Geode LX800
- DRAM: 256 MB DDR DRAM
- Firmware: tinyBIOS
- Power: DC jack or passive POE, min. 7V to max. 20V

802.11g/802.11p Output Power

The output power from the 802.11g card was set to 20 dBm. A cable loss of approximately 1.7 dB per meter also had to be taken into account. This resulted in a loss of roughly 5 dB due to the 3 meter long coaxial cable. The used ECOM5-2400 antenna had a gain of 5 dBi, which gave an output power of 20 dBm for 802.11g if measured from the antenna. 802.11p had an output power of 32 dBm from the card and also used a 3 meter coaxial cable to the 6 dBi antenna, giving a total output power of almost 33 dBm. The antenna providing 802.11p communication was of the model ECOM6-5500.

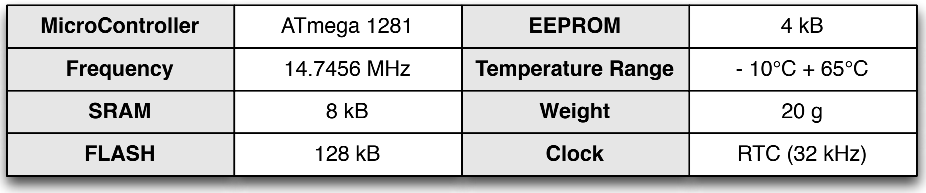
5.1.2 Libelium Platform

The Libelium platform was used to support the IEEE 802.15.4 standard in the 2.4 GHz band as well as the ZigBee standard at the 868 MHz frequency. For each technology, we used a pair consisting of one Waspmote board and one Waspmote gateway accompanied with the respective XBee modules and antennas. This enabled connectivity between two wireless nodes for each protocol; 802.15.4 and radio frequency (ZigBee) communication. A list of all the components forming the Libelium platform is given below:

- Waspmote board x 2
- Battery x 2
- Waspmote gateway x 2
- 4.5 dBi antenna x 2
- 5 dBi antenna x 2
- XBee module S5 for ZigBee RF (868MHz) x 2
- XBee module S1 for 802.15.4 (2.4GHz) x 2

Waspmote Board and XBee Modules

The Waspmote board is a sensor device that supports different protocols such as ZigBee, Bluetooth, GPRS, Wi-Fi and radio frequency (RF) communication in the 868 MHz, 900 MHz and 2.4 GHz band [39]. A Waspmote board with attached battery, XBee module and antenna can be seen in figure 5.2. According to the information given by Libelium, the equipment is able to communicate up to a maximum distance of 12 km. The board is able to work on lower power modes, so as to save energy when not transmitting any data. This allows the device to function for one or even several years. Waspmote is compatible with more than 50 sensors, but these were not needed for this specific project. The specifications of the Waspmote board are presented in the following table (see table 5.1).



MicroController	ATmega 1281	**EEPROM**	4 kB
Frequency	14.7456 MHz	**Temperature Range**	- 10°C + 65°C
SRAM	8 kB	**Weight**	20 g
FLASH	128 kB	**Clock**	RTC (32 kHz)

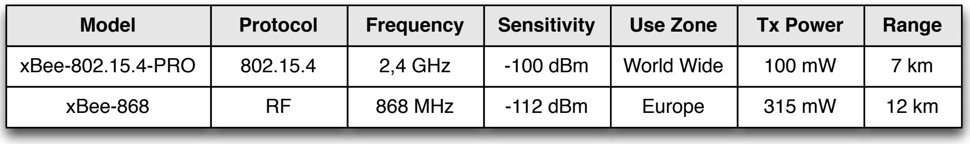
Table 5.1: Specification of the Waspmote PRO board

Figure 5.2: Waspmote board with XBee module and antenna

One great advantage with the Waspmote equipment is the ease of programming. The used programming language is C++ and Libelium also provides an open source API that allows the developer to program high level functions without dealing with hardware specific commands. Digi, a manufacturer of networking devices, offers modules for communication in various protocols that can be fitted to the Waspmote board. Table 5.2 presents the XBee modules that were used during this master thesis project.

Waspmote Gateway

Libelium provides several alternatives to access the data gathered by the Waspmotes in the sensor network. For this thesis, we have selected the Waspmote gateway, a device which allows the collection of data that flow in the network to be stored if connected to a computer or device with a USB port. It is a highly popular solution for indoor networks with few nodes or in cases where testing is needed while configuring the network.



Model	Protocol	Frequency	Sensitivity	Use Zone	Tx Power	Range
xBee-802.15.4-PRO	802.15.4	2,4 GHz	-100 dBm	World Wide	100 mW	7 km
xBee-868	RF	868 MHz	-112 dBm	Europe	315 mW	12 km

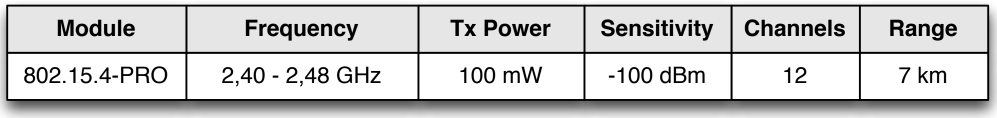
Table 5.2: The XBee modules for 802.15.4 and ZigBee RF communication

Moreover, by using the gateway, the user is able to send commands to the sensor network for configuration purposes. One disadvantage with the gateway is the inability of uploading code as this device cannot be programmed since it is only a converter. The Waspmote equipment can be used with operating systems such as Windows, Linux and Mac OS X [39]. Figure 5.3 shows a gateway with attached XBee module and antenna.

Figure 5.3: Waspmote gateway with XBee module and antenna

XBee Module 802.15.4

Digi's XBee module S1 provides communication for the 802.15.4 protocol in the 2.4 GHz band using either 12 or 16 channels of 5 MHz bandwidth each. Two functionalities offered by this wireless interface are node discovery and duplicated packet detection. A standard XBee module uses all of the 16 channels of the frequency band while the PRO module that was selected for this project uses 12 channels. Table 5.3 presents the features of the PRO module such as transmit power, sensitivity and range [39].



Module	Frequency	Tx Power	Sensitivity	Channels	Range
802.15.4-PRO	2,40 - 2,48 GHz	100 mW	-100 dBm	12	7 km

Table 5.3: 802.15.4 XBee module specification

Figure 5.4 shows the transmit power values for XBee PRO with the relation between output power given in dBm and mW. As stated in table 5.3, the transmit power for XBee PRO 802.15.4 is 100 mW, which translates to 20 dBm [39]. A loss of 1.7 dB per meter is then experienced in the 3 meter coaxial cable that connects the module to the 5 dBi antenna, resulting in approximately 20 dBm output power from the antenna.

Figure 5.3 depicted the original antenna that was provided by Libelium. As this antenna could not be fitted easily on the car roof when conducting the measurements, a magnet mount antenna with 5 dBi gain was purchased of the model ECOM5-2400 that was used during all tests. Figure 5.5 displays all the existing 16 channels in the 2.4 GHz band with a bandwidth of 5 MHz. Each channel is numbered using its hexadecimal representation. Table 5.4 shows the frequency band of every channel. It also indicates which channels that are supported by the normal XBee module and the PRO version.

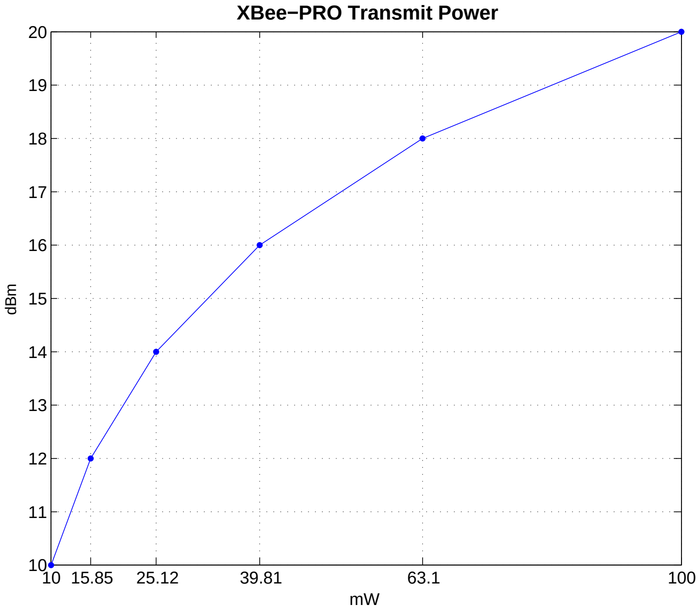


Figure 5.4: XBee-PRO Transmit Power

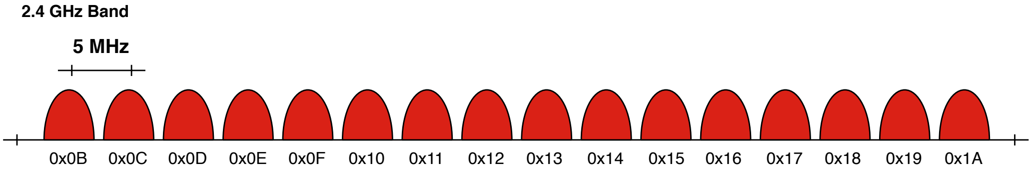


Figure 5.5: All channels of the 2.4 GHz ISM band

Channel Number	Frequency	Supported by
0x0B - Channel 11	2,400 - 2,405 GHz	Normal
0x0C - Channel 12	2,405 - 2,410 GHz	Normal/PRO
0x0D - Channel 13	2,410 - 2,415 GHz	Normal/PRO
0x0E - Channel 14	2,415 - 2,420 GHz	Normal/PRO
0x0F - Channel 15	2,420 - 2,425 GHz	Normal/PRO
0x10 - Channel 16	2,425 - 2,430 GHz	Normal/PRO
0x11 - Channel 17	2,430 - 2,435 GHz	Normal/PRO
0x12 - Channel 18	2,435 - 2,440 GHz	Normal/PRO
0x13 - Channel 19	2,440 - 2,445 GHz	Normal/PRO
0x14 - Channel 20	2,445 - 2,450 GHz	Normal/PRO
0x15 - Channel 21	2,450 - 2,455 GHz	Normal/PRO
0x16 - Channel 22	2,455 - 2,460 GHz	Normal/PRO
0x17 - Channel 23	2,460 - 2,465 GHz	Normal/PRO
0x18 - Channel 24	2,465 - 2,470 GHz	Normal
0x19 - Channel 25	2,470 - 2,475 GHz	Normal
0x1A - Channel 26	2,475 - 2,480 GHz	Normal

Table 5.4: Channels used by xBee modules in the 2.4 GHz band

XBee Module 868

The XBee module 868 utilizes one single channel where the actual used frequency is in the 869 MHz band that is specified for the European market. This means that the XBee 868 only can be used in Europe [39]. The features of the module can be seen in table 5.5. We see from the table that the transmit power is 315 mW or approximately 25 dBm.

Module	Frequency	Tx Power	Sensitivity	Channels	Range
868	869,4 - 869,65 MHz	315 mW	-112 dBm	1	12 km

Table 5.5: Features of the 868 XBee module

The possible output power levels from the XBee 868 module are shown in figure 5.6. Again, the relation between mW and dBm is illustrated in the graph. During the evaluation, a 5 meter coaxial cable was used instead of the 3 meter cable provided for the other technologies. This resulted in a cable loss of 8.5 dB (1.7 dB per meter). The antenna that allowed ZigBee RF communication had a gain of 4.5 dBi. In total, we could thus achieve an output power from the point of the antenna of 21 dBm. Figure 5.7 depicts the specified channel for the XBee 868 module in the 869 MHz ISM band.

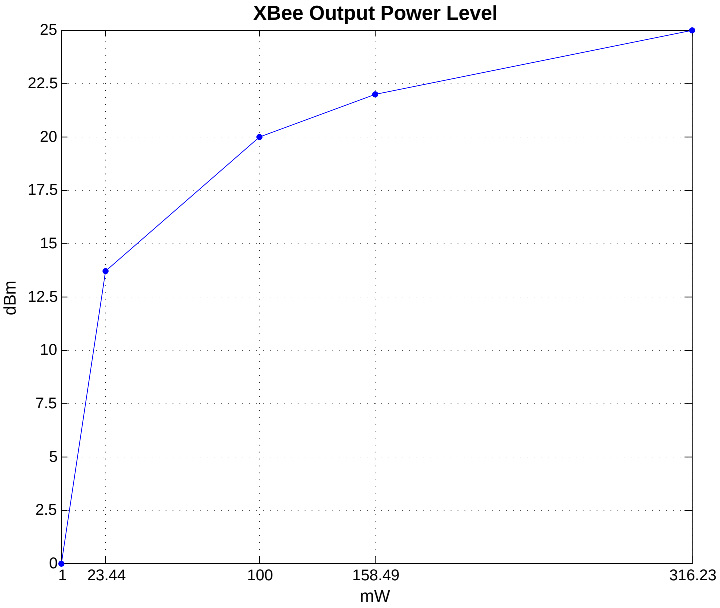


Figure 5.6: The output power levels of XBee 868

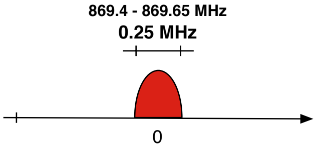


Figure 5.7: The used channel by our XBee 868 module

5.2 Software

5.2.1 COSMO platform

Although the COSMO platform is able to transmit packets at very high rates such as 100 packets per second (pps), we had to adjust COSMO to the Libelium platform that had much lower transmission rates. COSMO was therefore set to send out 2 pps using channel 13 (0x0D) to channel 15 (0x0F) for 802.11g communication.

The COSMO platform is equipped with MBLMT, a C++ software environment developed and provided by Volvo that easily could be adapted to the given test cases. MBLMT consists of separate modules that when needed can be selected and loaded to fit the needs of the current test setup. UML charts are depicted in figure 5.8, 5.9 and 5.10 to give an overview of the connected MBLMT modules that were used during our evaluation to transmit, collect and log data. Figure 5.8 shows the MBLMT modules used during the logging of our measurement data. Figure 5.9 depicts the modules used for the sending vehicle while figure 5.10 illustrates the modules of the receiving vehicle.

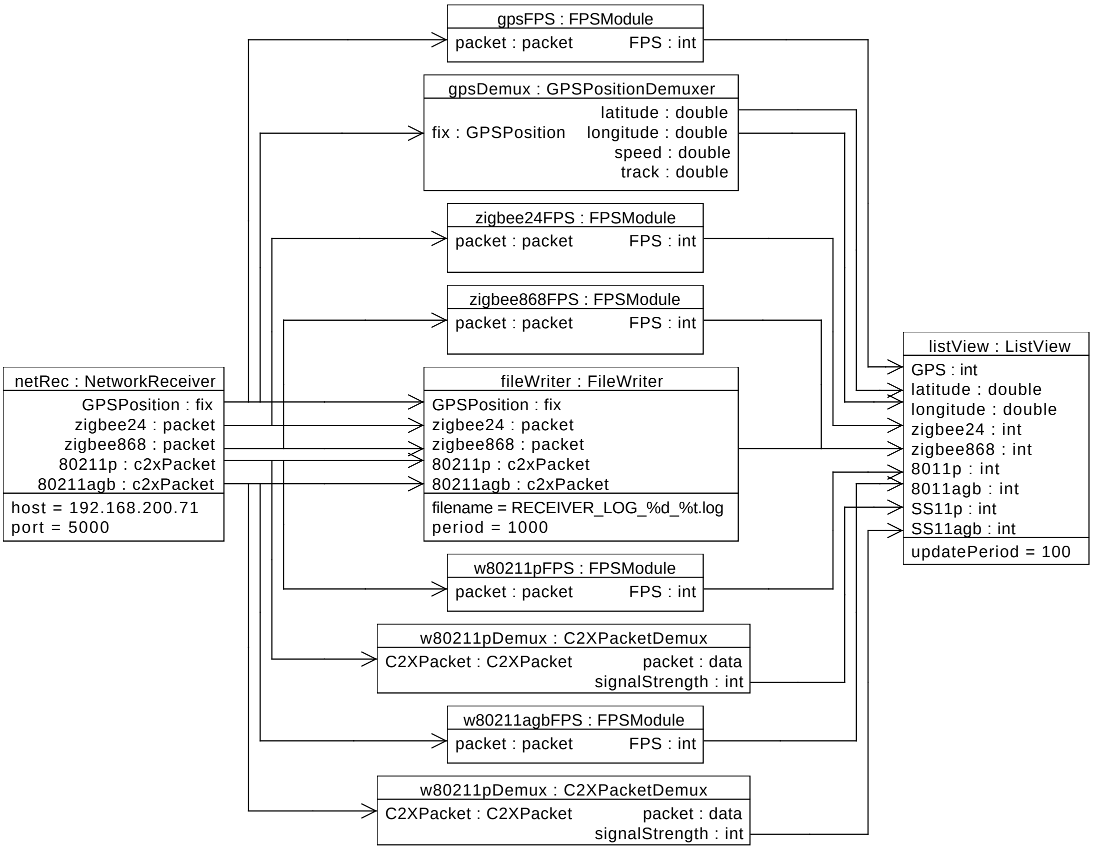


Figure 5.8: UML chart of used MBLMT modules during logging

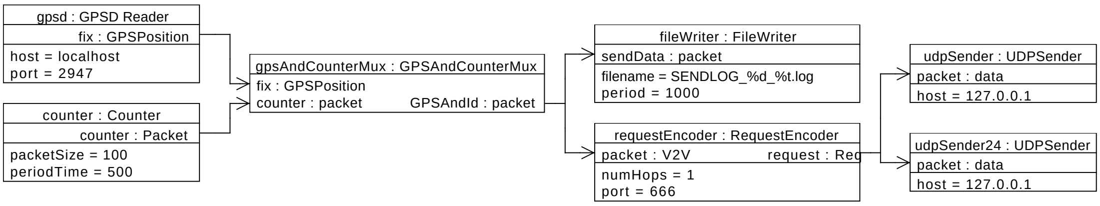


Figure 5.9: MBLMT modules for the sending side

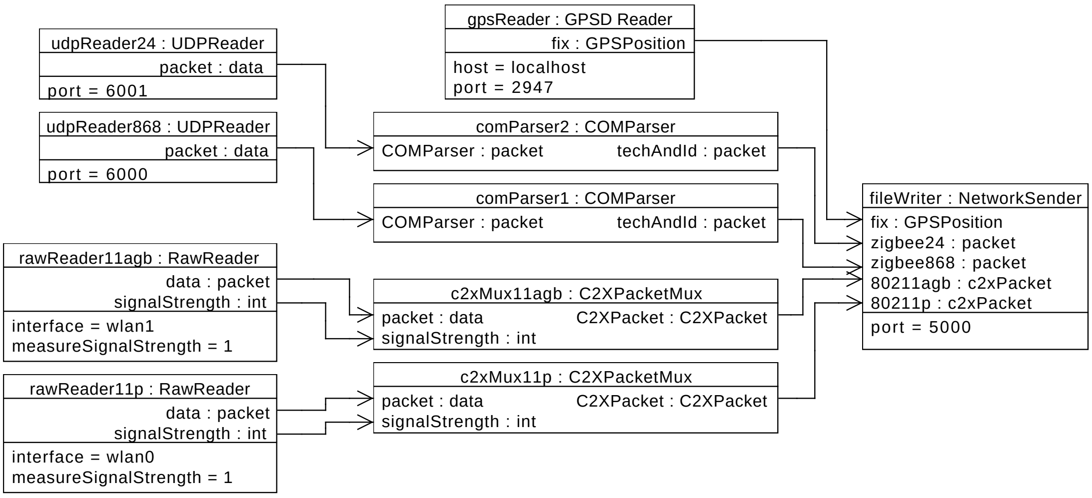
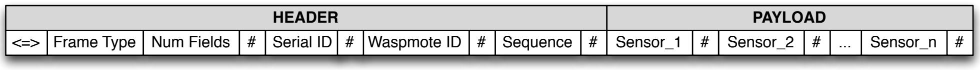


Figure 5.10: MBLMT modules in the receiving node

5.2.2 Libelium Platform

As the Waspmote gateways could not be programmed, the only equipment that had to be configured was the Waspmote boards. We set the transmission rate of the board to 2 pps. This is a rather high rate as it normally is set to transmit 1 packet per minute or less. After conducting some initial experiments, we discovered that higher transmission rates than 2 pps increased the packet loss and instability of the communication. This was later verified by a Libelium technician who stated that their equipment is not ideal for a real-time system with requirements on high transmission rates.

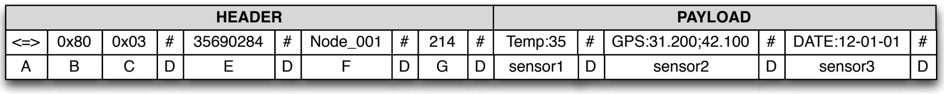
Libelium provides several coding examples for common tasks on their web page such as sending and receiving packets and transmitting unicast and broadcast messages. Examples are available for both XBee modules 802.15.4 and 868. We used a simple example that sends an ASCII frame from the board to the gateway that had to be slightly rewritten to fit our test cases. Figure 5.11 shows the format of a typical ASCII frame that can be sent from the Waspmote board [40].



HEADER										PAYLOAD						
<=>	Frame Type	Num Fields	#	Serial ID	#	Waspmote ID	#	Sequence	#	Sensor_1	#	Sensor_2	#	...	Sensor_n	#

Figure 5.11: The Waspmote frame structure

Figure 5.12 gives an example of the values that every field may hold. To make the structure more clear to the reader, each field has been given a letter that is subsequently explained in the text below. As can be seen, the frame consists of two parts: the header and the payload. While the header maintains the same structure as it cannot be changed, the payload contains fields that can all be modified. The ASCII payload includes the data gathered by the sensors. Three types of sensor fields are supported: the simple data that contain values such as temperature, the complex data that are composed of more than one value and finally the special data holding date and time [40].



HEADER										PAYLOAD					
<=>	0x80	0x03	#	35690284	#	Node_001	#	214	#	Temp:35	#	GPS:31.200;42.100	#	DATE:12-01-01	#
A	B	C	D	E	D	F	D	G	D	sensor1	D	sensor2	D	sensor3	D

Figure 5.12: An example of a typical Waspmote frame

Field A: is the starting delimiter that always holds the string "<=>" with a length of 3 bytes. Field A is useful for indicating the beginning of each frame.

Field B: helps to identify if it is an ASCII or a binary frame. The field is only represented by 1 byte and can also indicate the aim of the frame (event or alarm frame).

Field C: gives the number of sensor fields used to calculate the frame length (1 byte).

Field D: this 1 byte field contains the # character that functions as a field separator.

Field E: holds the unique serial ID identifying each Waspmote device (max. 10 bytes).

Field F: this user-defined string functions as a Waspmote ID to represent the node in the current network. The length of the field varies from 0 to 16 bytes.

Field G: contains the frame counter used to detect frame loss. The 8-bit counter starts from 0 and ends at 255 that then automatically is reset back to 0 again (1-3 bytes).

Waspmote 802.15.4

While programming the XBee modules for the 802.15.4 standard, we used the two header files WaspFrame.h and WaspXBee802.h from the Waspmote PRO API version 0.01. The latter makes use of WaspXBeeCore.h that provides most of the functionality for managing the XBee modules such as broadcasting, encryption modes and RSSI configuration.

By using above header files along with WaspXBeeCore.cpp and WaspXBee802.cpp, we have access to parameters such as the MAC address and the channel of the current frequency band. A useful option is the selection of channel in which the Waspmote will transmit the data that can be modified to avoid interference [40].

Waspmote ZigBee RF

Developing for ZigBee RF communication in the 868 MHz band meant using the same header file WaspFrame.h that was provided for the XBee 802.15.4 modules. We also made use of the WaspXBee868.h file, which is the main library for managing the XBee 868 modules. The standard functionality could be given by using WaspXBee868.cpp and WaspXBeeCore.cpp where the latter is shared between both XBee modules [40].

5.2.3 Java Parser: LogAnalyzer

LogAnalyzer is a parser written in Java (see figure 5.13). It takes a log file as input, created by MBLMT, and provides all packet information from the conducted measurements. In turn, the LogAnalyzer produces a database and text file, holding measurement information. The text file is merely created for the ease of our analysis while the database serves as input for the Android visualization tool WTDQ. A Java class sample of how to interpret the fields of the log file was provided by Volvo and this logic was later used in LogAnalyzer. All other logic, classes and methods have been developed by the authors of this thesis work with exception of the open-source package Geodesy.

Figure 5.14 displays a UML chart of the classes of LogAnalyzer without the classes from the Geodesy package. LogDataMain initially calls LogDataAnalyzer that takes two log files as input, the log files from the sending and receiving vehicles. It is then able to create a database and text file over the results. Logger picks out the fields such as latitude, longitude, heading and message ID from the various packets of the log file with support from the Packet class. MessagePacket, PositionPacket and LibeliumPacket hold static information about the exact position of the fields in the different packet types. DBConnection takes care of the creation of the sqlite database and also updates the database columns with new rows of packet information.

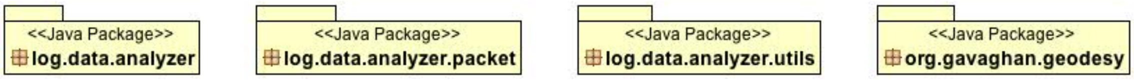


Figure 5.13: The packages of LogAnalyzer

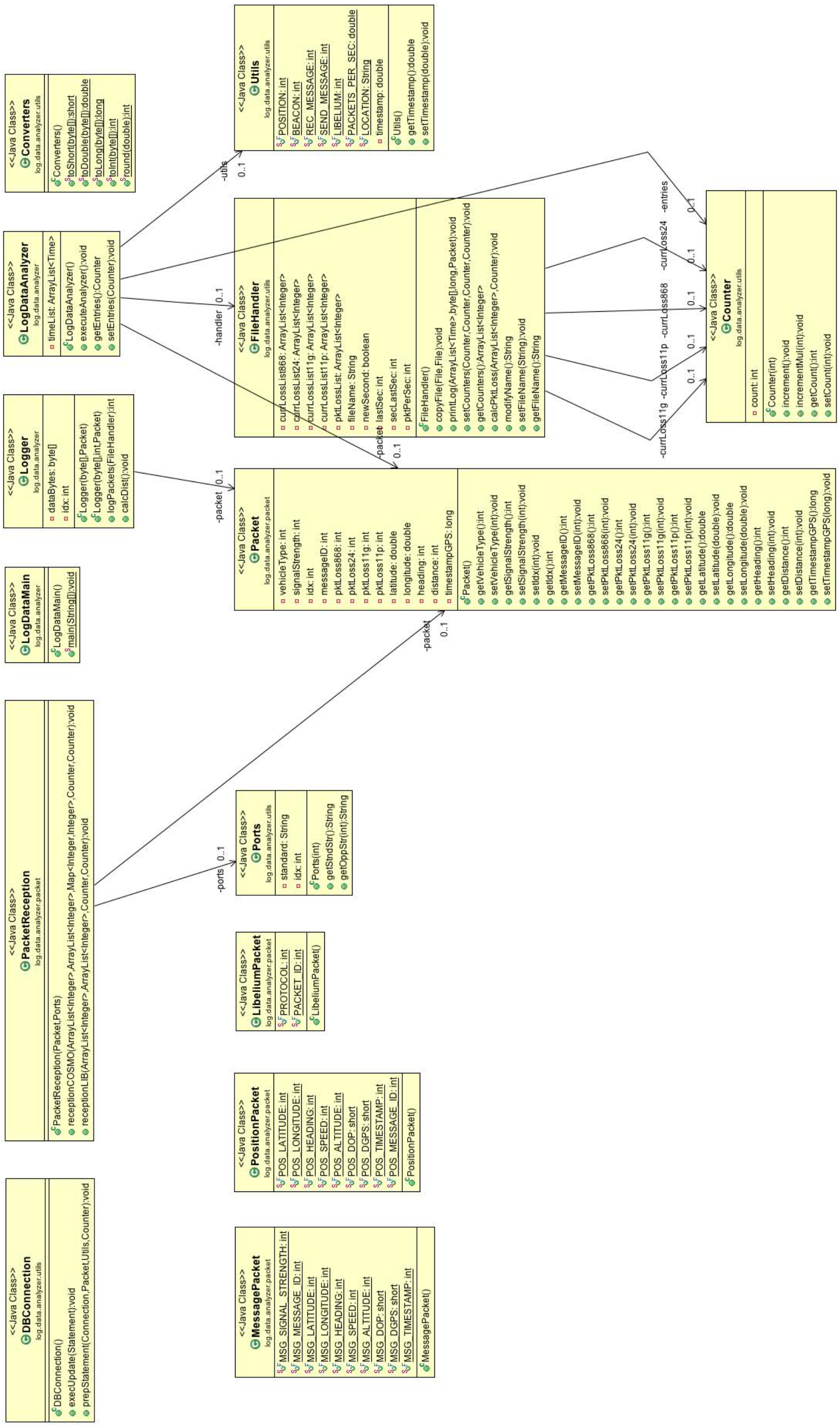


Figure 5.14: A UML chart of all classes from LogAnalyzer excluding the Geodesy classes

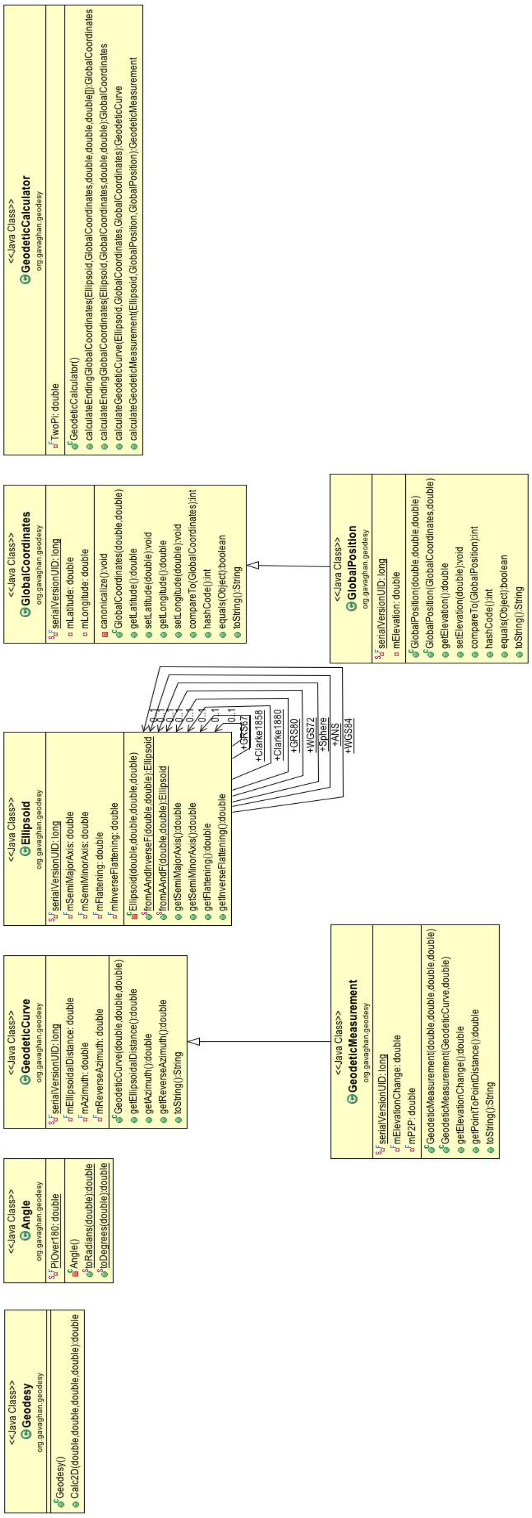


Figure 5.15: The classes of Mike Gavaghan's Geodesy Java implementation

In figure 5.15 above, we see the components of the Geodesy package. As earlier mentioned, Geodesy is an open-source project developed by Mike Gavaghan that uses Vincenty's formulae in order to calculate the distance between two points on Earth. The package takes as input a source and destination pair of latitude and longitude values and returns the distance between these points in meters [41].

5.2.4 Android Application: WTDQ

An Android application named WTDQ, Wireless Technologies Demonstrator in Quarries, was created for the purpose of illustrating the test case scenarios of two moving vehicles communicating with antennas. It shows how the communication quality decreases as the vehicles move further away from each other. The graphical view displays packet loss and range while the cars move apart on a Google map image taken from the two testing locations: Tagene quarry and Volvo Cars Demo Center (VCDC).

Volvo provided a sample Android project with moving vehicles on an offline map and this logic was used to implement the moving node on the map of Tagene and VDC. The authors of this thesis provided the rest of the functionality for the Android application WTDQ. The sqlite database files produced by LogAnalyzer functioned as input to WTDQ in order to illustrate the moving receiving node and the fixed sending node. This also allowed us to display parameters such as packet loss and node distance.

Figure 5.16 shows a UML chart of the complete Android project with all dependencies among the classes. MainActivity, LibraryActivity, AboutActivity as well as ChartActivity represents the four main activities that can each be selected with the click of a button. This is the view initially presented to the user when first launching the application. MapsActivity along with SimDataHandler stand for most of the functionality concerned with the moving vehicle on the map view.

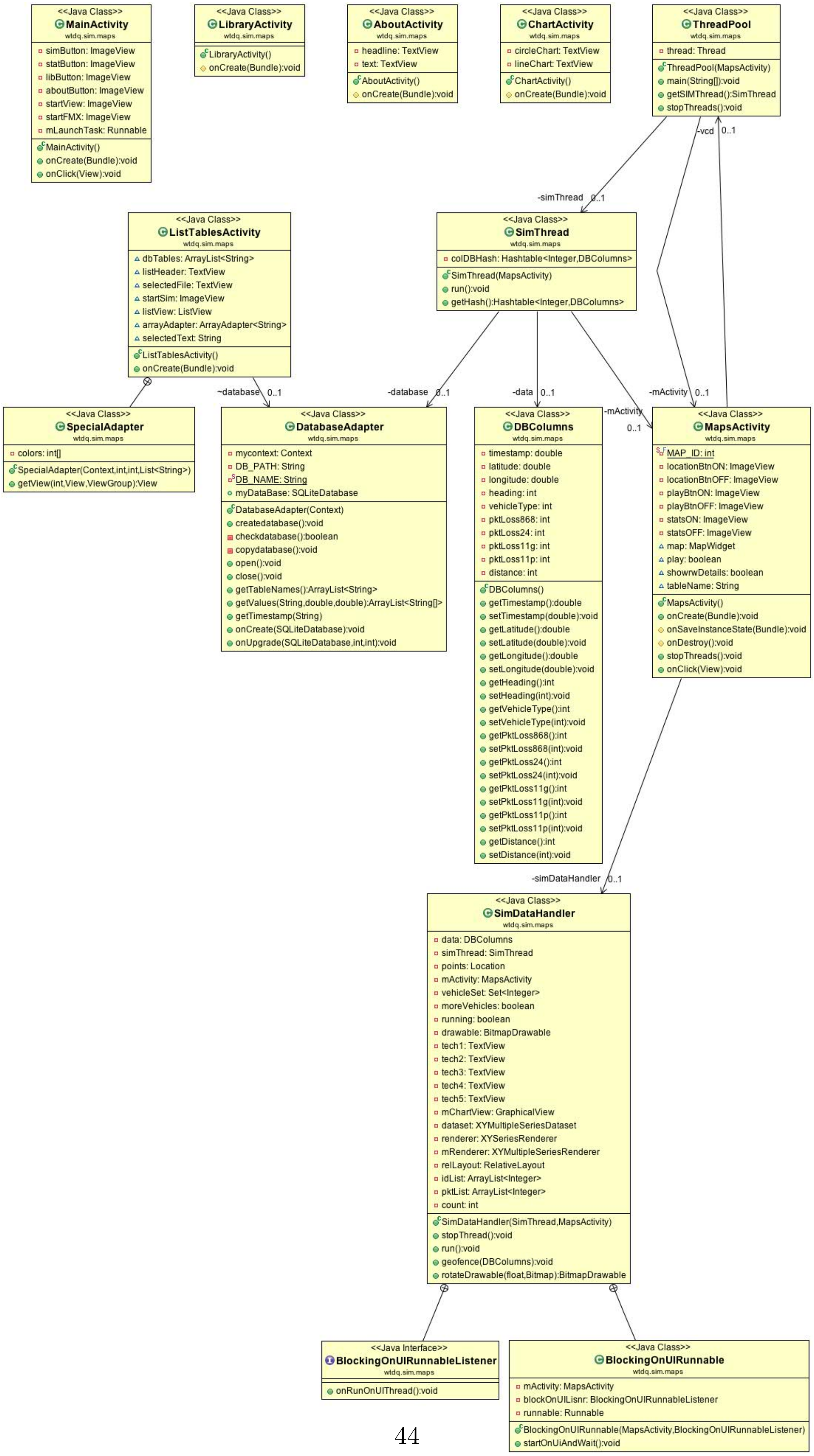


Figure 5.16: The classes of WTDQ, a visualization tool developed for the Android platform

6

Results

In order to follow the previously stated test cases, great care was taken before choosing a location for our measurements. We first selected a quarry located in Tagene where we would conduct most of our measurements. Tagene Grus is a medium sized quarry in Gothenburg that provides gravel and sand to its customers. Fortunately, site manager Björn Falkenby gave us permission to drive not only on top of the quarry, but also inside the quarry pit where trucks, articulated haulers and crushers do most of their work. This was scheduled after regular working hours when the traffic in the quarry was not as busy as during the day.

Another important decision to make was to find a suitable place for our line-of-sight range measurements. This task is normally quite tricky as it is hard to find a road that is straight for more than 1 kilometer other than airplane landing strips that are inaccessible to the public. With the help of Google maps, a straight track of approximately 2 km could be found that turned out to be located in Volvo's facilities in Torslanda.

The chosen road was called the high-speed track and belonged to Volvo Cars that mainly used the road for high-speed testing of new cars. Due to safety reasons, the minimum speed for using the track was 90 km per hour. This presented a problem for us as the Libelium equipment had difficulties with transmitting packets robustly when sending more than 2 packets per second. To be able to get detailed measuring points, we either had to decrease our speed while driving or increase the number of packets sent per second. Since the latter was not an option, we had to drive with a decreased speed. The problem was solved by performing the tests at Volvo Cars Demo Center (VCDC) during lunch time when there was less traffic which made it possible for us to drive with a speed of 45 km per hour on the 1.8 km driveway to the track.

6.1 Tagene Quarry: Top Measurements

The environment at the top of the quarry varies a lot from the one in the pit. Just imagine a hole that has been dug several tens of meters into the ground. The conditions at the bottom level of the hole are obviously quite different from the conditions at the ground level with surrounding walls of soil, stones, rocks or mountain. We wanted to find out how the selected wireless technologies behaved at the top of the quarry as oppose to the bottom pit level. Figure 6.1 gives the reader an idea of the altitude differences in a quarry and the enclosing mountain walls that are present while being in the pit.

Figure 6.1: A picture taken at the bottom pit of the quarry in Tagene with enclosing mountain walls in the background

Figure 6.2: The two vehicles used during our measurements, a Volvo S80 (receiving node) and a Volvo V70 (sending node)

The first measurement was taking place at the top level when driving on the narrow road around the quarry with one vehicle while the other vehicle was parked along the road. Figure 6.2 illustrates the two cars used during the testing, a Volvo S80 and a Volvo V70. The driving vehicle S80 initially had limited line-of-sight due to small hills, trees and rocks from the fixed vehicle V70 before appearing at the other end of the quarry where line-of-sight could be obtained. MBLMTs graphical interface allowed us to see the amount of received packets while driving in the S80 that functioned as the receiving node. When obstacles such as hills, trees and piles of stones were encountered, all technologies but ZigBee RF experienced packet loss.

Figure 6.3 and 6.4 display the quarry in Tagene as seen on Google Maps. The blue line shows the route that the receiving Volvo S80 was following while the sending Volvo V70 was parked at the position of the green arrow. The yellow lines in Figure 6.3 represent examples of line-of-sight points between the two vehicles. The red lines in Figure 6.4 indicate non line-of-sight areas due to hills, trees, rocks etc.

Figure 6.3: Google Map image over Tagene quarry indicating points of LOS

Figure 6.4: The same map image of the quarry showing points of NLOS

Figure 6.5 and 6.6 show the packet reception ratio (PRR) over the distance in meters for each wireless technology. The lines are stacked on top of each other where all standards have been given PRR values from 0 to 1 where 1 stands for full packet reception while 0 represents a state of 100% packet loss. It can here clearly be seen where the different technologies experienced simultaneous non line-of-sight issues except for ZigBee RF that seemed indifferent to NLOS spots. These points correspond to the LOS/NLOS spots that were indicated on the two maps of figure 6.3 and 6.4.

As seen in figure 6.5, 802.15.4 experienced full packet loss from a distance of approximately 70 meters up to 320 meters. 802.11g and 802.11p also performed poorly during this period but were able to recover faster. 802.11g provided almost full connectivity from 320 to 350 meters and again between 420 and 480 meters. Meanwhile, ZigBee RF only lost 1 packet while driving up to a distance of 520 meters.

In figure 6.6, the receiving vehicle was driving back towards the sending vehicle by following the route outlined on the maps of figure 6.3 and 6.4. This road consisted of NLOS spots which can be seen between a distance of 410 to about 200 meters. 802.15.4 was here able to recover faster to almost full packet reception rate at 200 meters in comparison to 802.11p that could not provide 100% PRR until 120 meters. 802.11g also recovered faster than 802.11p where it was able to receive packets at times when the p standard did not function at all. Again, ZigBee RF did not seem to be affected by any NLOS issues. Figure 6.6 contains double lines at certain points for 802.15.4, 802.11g and 802.11p. This can be explained by the fact that the distance during these points was not constantly decreasing due to the position of the road from the fixed sending vehicle.

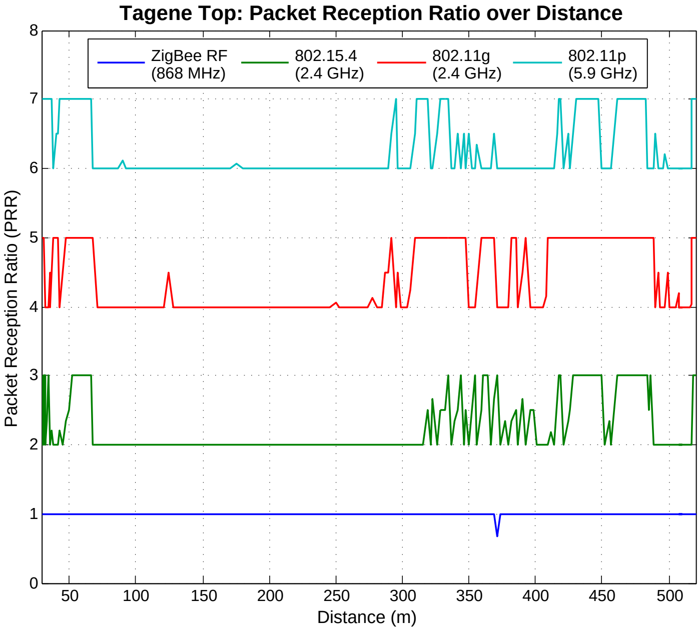


Figure 6.5: PRR over distance during the first 500 meters in Tagene quarry

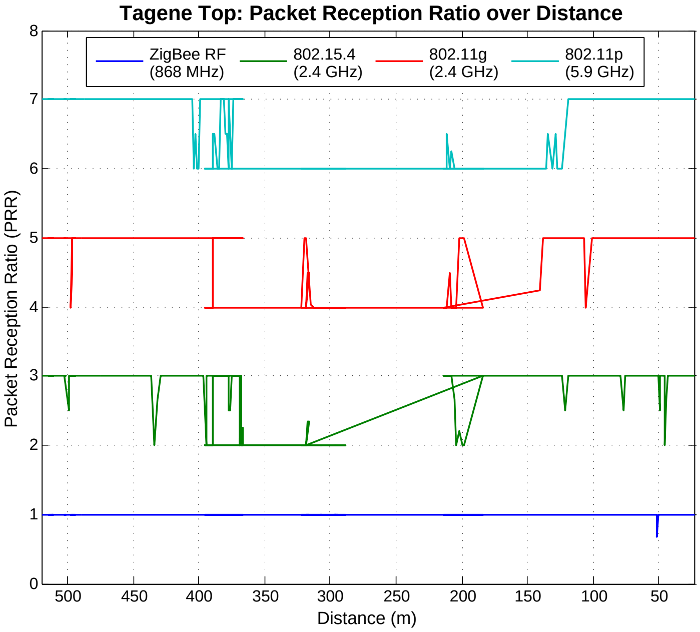


Figure 6.6: PRR over distance when driving back towards the sending vehicle

Figure 6.7 shows the total amount of lost packets for each technology after the first test round. As illustrated in the figure, we see that ZigBee RF experienced the lowest rate of packet loss with only 2 lost packets during the entire test round. The second best performing technology was 802.11g that lost a total number of 164 packets.

802.11p did not perform as well as 802.11g and ended up on a third place with a total loss of 216 packets. By looking at figure 6.5, 6.6 and 6.7, it is evident that 802.11p on the 5.9 GHz band was sensitive to obstacles such as rocks and hills that it could not recover from as fast as the other technologies. On the other end of the frequency band scale, we find ZigBee RF at 868 MHz that had the opposite behavior. This wireless standard did not seem to be affected at all by NLOS issues and was able to provide a robust connection throughout the entire test round.

The least satisfying result was given by 802.15.4 at the 2.4 GHz band that in total lost 241 packets. At one point during the measurement, 802.15.4 lost over 100 packets in a row at a time when the other technologies only had minor problems with receiving packets. At this point, it was not clear whether the receiving XBee module was unable to obtain packets or if the transmitting XBee module had problems sending packets.

Figure 6.5, 6.6 and 6.7 give a coherent image of the results from the top of Tagene quarry. 802.15.4 stood for the most unstable behavior in connectivity and lost most packets. 802.11p was also pending quite frequently between 100% and 0% PRR and experienced high packet loss. 802.11g was unstable at times but only lost 164 packets. ZigBee RF gave a very robust performance where it lost as little as 2 packets.

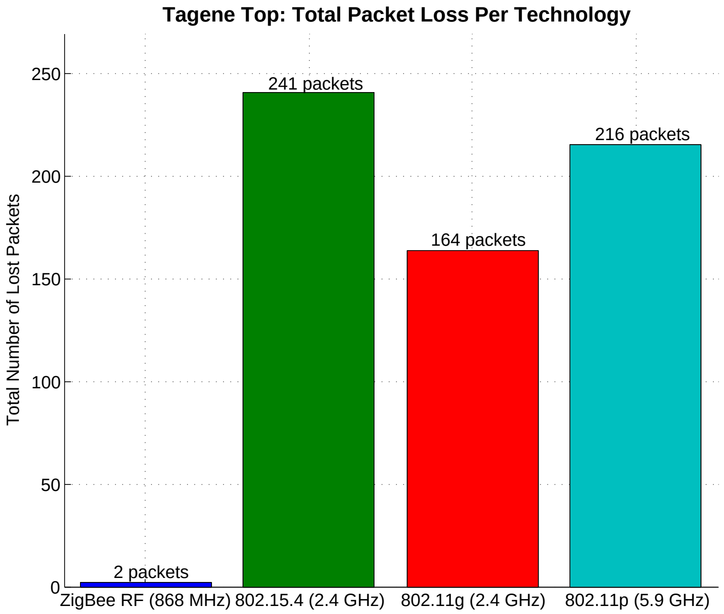


Figure 6.7: Packet loss per technology at the end of the first test round

6.2 VCDC Line-of-Sight Testing

As already stated, the line-of-sight range measurements were carried out at Volvo Cars Demo Center (VCDC). Figure 6.8 displays the Google Map image of the high-speed track and the blue-marked 1.8 km driveway that was used during the range measurements. Figure 6.9 shows an image taken at the driveway leading to the high-speed track.

Figure 6.8: A Google Map image of VCDC with a blue line marking the track

Figure 6.9: A picture taken at the start of the high-speed track in VCDC [42]

The maximum distance in meters per wireless protocol is shown in figure 6.10. As can be seen, 802.11p reached the furthest with a distance of 1767 meters. ZigBee RF also gave a good performance with a top distance of 1753 meters. 802.11g received the last packet at 1682 meters while 802.15.4 stopped receiving packets already at 385 meters.

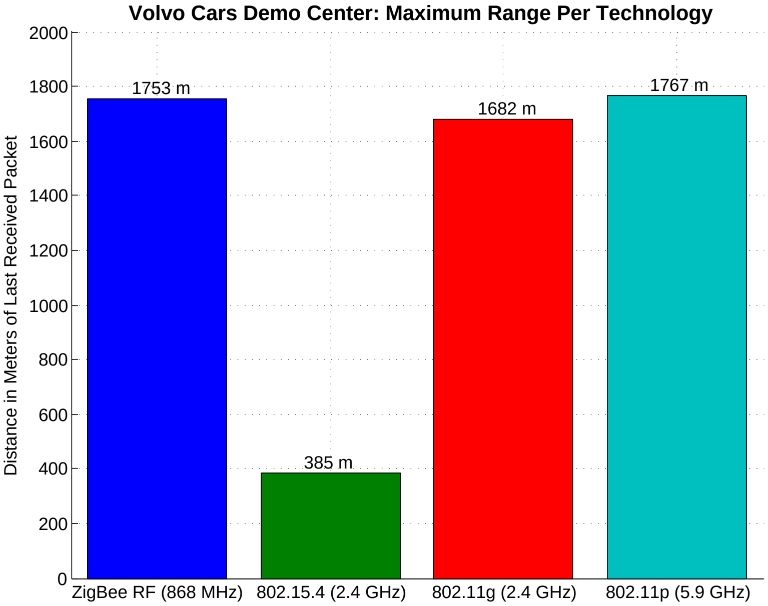


Figure 6.10: Maximum range in meters for all tested standards

For the LOS tests, the maximum reached range was more interesting than the total packet loss. To understand why, it is important to know that when one technology has reached its maximum distance, it stops receiving packets altogether. For example, when 802.15.4 receives its last packet at 385 meters, its total packet loss will be set to 30 packets. Meanwhile, the other technologies still have transmission ability, which will gradually decrease with the distance and correspondingly lead to more lost packets.

A perhaps more interesting result is the amount of lost packets at the point when 802.15.4 stopped functioning (see figure 6.11). When 802.15.4 received its last packet at 385 meters, all other technologies were experiencing little or no packet loss at all.

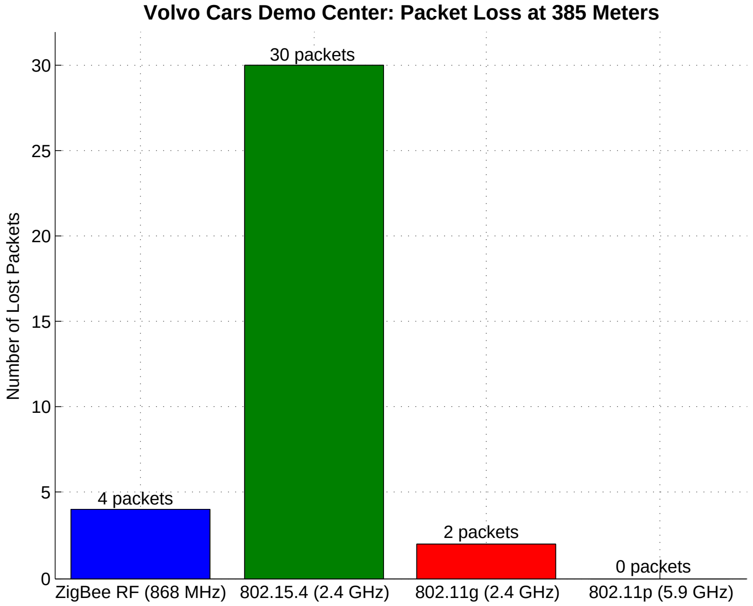


Figure 6.11: While 802.15.4 stopped sending/receiving, other standards functioned well

Figure 6.12 presents the packet loss at the time of the last received packet for respective technology. It also shows the maximum range in meters for each technology to stress the relation between packet loss and distance. Figure 6.13 displays the PRR over the distance per wireless technology.

As can be seen, 802.15.4 was unstable already from the start before it stopped functioning at 385 meters. 802.11g performed well with minor connectivity issues before its stability decreased just before 700 meters. After 1400 meters, 802.11g mostly experienced 100% packet loss except for some points where it was able to receive packets. The last 802.11g packet was received at 1682 meters. ZigBee RF gave quite a robust performance except for some points when the connectivity was lost. At a distance of 1100 meters, ZigBee RF started to lose its robustness but could still frequently receive packets until 1753 meters. 802.11p almost had 100% PRR up to a point of 1100 meters and could still receive packets frequently at an increasing distance until 1767 meters. It is worth to mention that LOS could not be obtained after this point, which is why we are confident that both ZigBee RF and 802.11p could have reached even further distances.

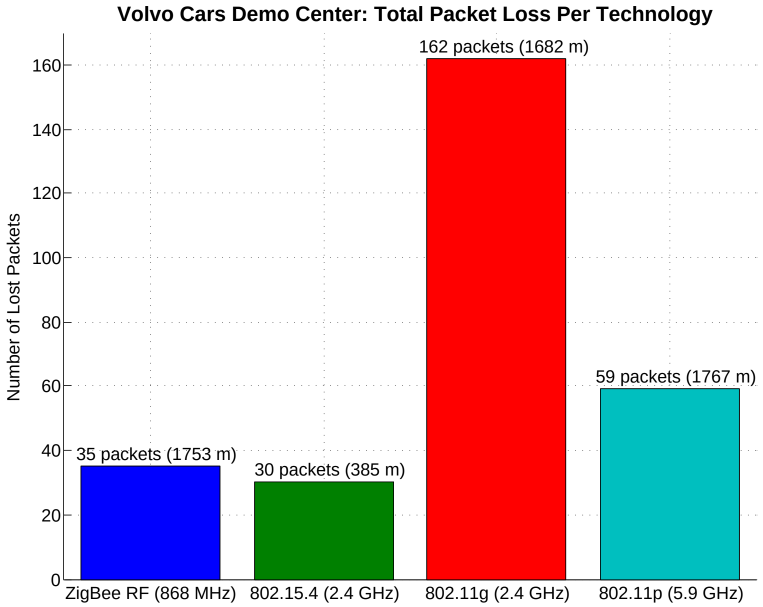


Figure 6.12: Packet loss at a point of maximum distance per technology

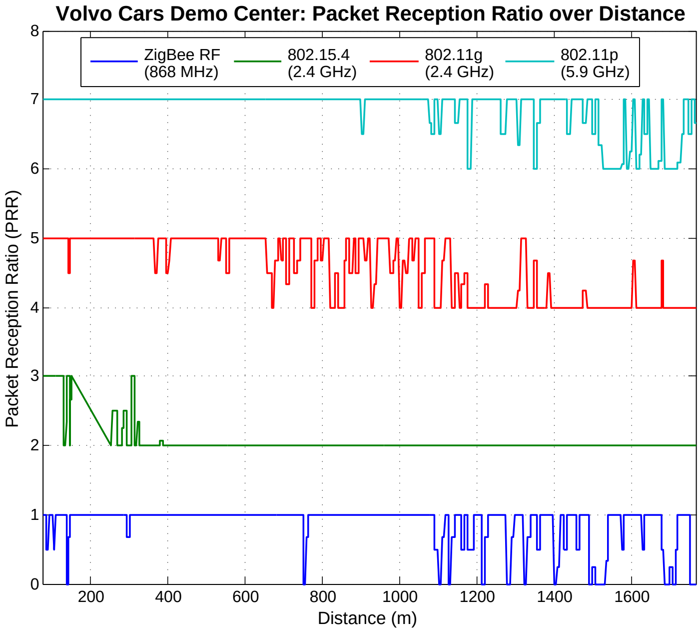


Figure 6.13: PRR over distance in meters from the measurements at VCDC

6.3 Tagene Quarry: Pit Measurements

The final measurements took place in Tagene pit. Figure 6.14 shows the total packet loss from this test round where we see that ZigBee RF yet again experienced the lowest packet loss rate. Just like for the top quarry measurements, it only lost 2 packets during the entire test route. The second best performing technology this time was 802.15.4 with a total packet loss of 159 packets. On the third place we find 802.11p with a loss rate of 283 packets. The least satisfying results were given by 802.11g that lost 650 packets.

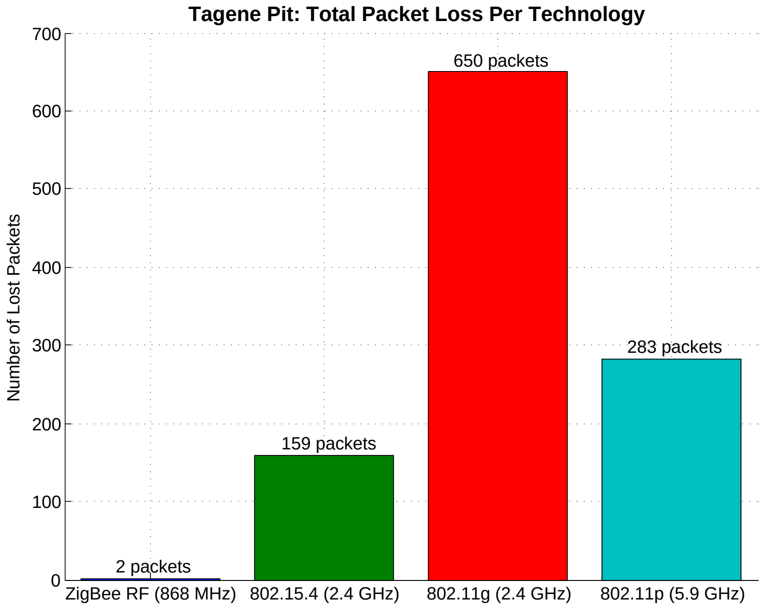


Figure 6.14: Tagene pit measurements showing packet loss for all technologies

During the quarry pit tests, we could again see from the graphical interface in the receiving vehicle when the technologies experienced packet loss due to obstacles. These mostly consisted of piles of sand or stone as seen in figure 6.15 and 6.16. This time, it was the protocol 802.11g that experienced most difficulties in handling the obstacles.

Figure 6.15: A pile of sand typical for the quarry pit presenting a LOS obstacle

Figure 6.16: Another common pile in Tagene pit, this time consisting of stones

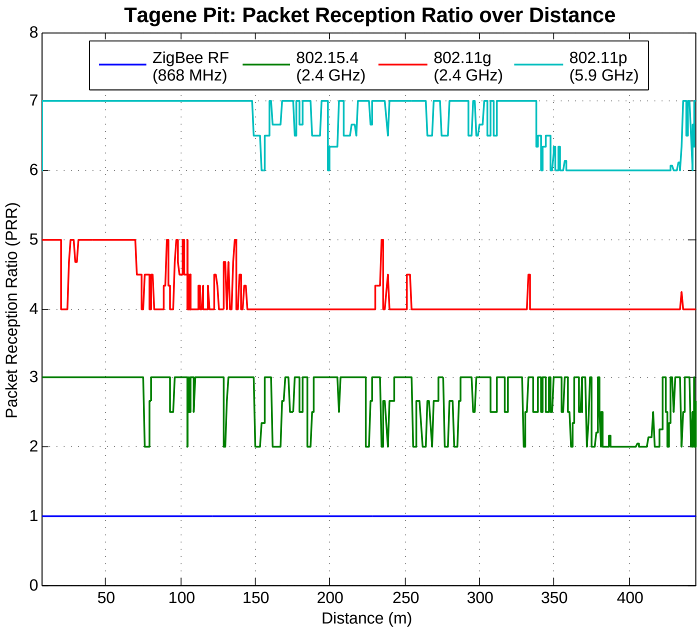


Figure 6.17: PRR over distance during the first 400 meters in Tagene pit

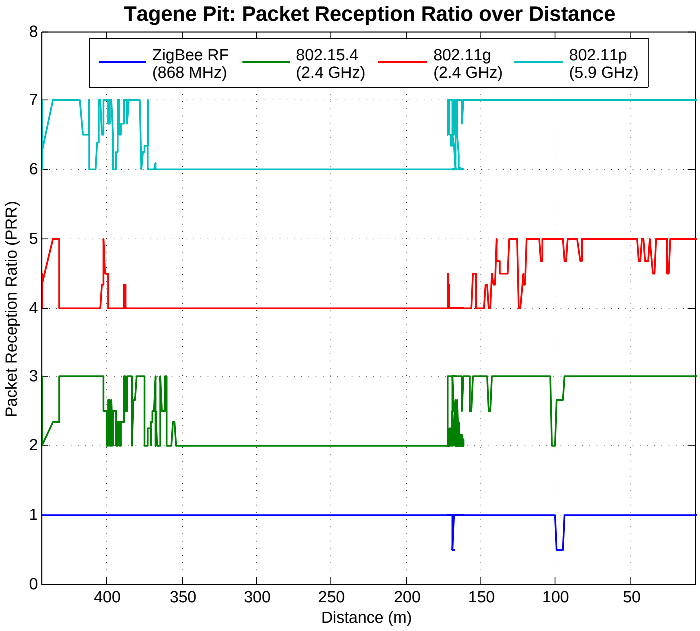


Figure 6.18: PRR over distance when driving back towards the sending vehicle

Above figures 6.17 and 6.18 depict PRR over distance in the quarry pit of Tagene. Figure 6.17 shows the scenario when we were driving away from the sending vehicle up to a distance of approximately 400 meters before reaching the other end of the quarry pit. Figure 6.18 illustrates the opposite scenario when we were driving back towards the sending vehicle that was parked close to the mountain wall surrounding the pit.

As can be seen in the diagram, ZigBee RF was yet again the technology that could provide the most stable communication. During the first 400 meters, it had a constant PRR value of 1. 802.11g, on the other hand, was unstable already from the start. Both figure 6.17 and 6.18 show how this technology often had a PRR value of 0 and could only provide connectivity during the first and last 150 meters.

802.15.4 gave a better performance than 802.11g on the same 2.4 GHz frequency. It was able to provide connectivity throughout large parts of the test route although it was not always that robust with pending PRR values between 1 and 0. 802.11p stood for one of the best communication links in the pit. It had a 100% reception rate up to 150 meters from the sending node and could generally provide a stable connection.

The obstacles present in the quarry pit are visible in the two diagrams of figure 6.17 and 6.18. We see that both 802.11g and 802.15.4 start to experience packet loss after 75 meters in figure 6.17, which was caused by driving behind a large pile of sand. After this point, we did not have a clear line-of-sight between the transmitting and receiving vehicle where also 802.11p started to lose packets. ZigBee RF operating on the low 868 MHz band was able to penetrate these obstacles and deliver a 100% reception rate.

In figure 6.18, it is possible to see when we were driving down in the lowest part of the pit with enclosing obstacles that blocked the LOS completely. This lead to a PRR value of 0 for all technologies but ZigBee RF between approximately 380 to 170 meters. 802.15.4 could recover faster than 802.11p and 802.11g from this point. 802.11p was able to provide a very robust connection after its recovery until the end of the route. 802.11g, in contrast, did not recover well after the NLOS area and gave an overall unstable impression. The only point in time when ZigBee RF lost any packets was after the NLOS spot where piles of stone were present that it was unable to penetrate. Figure 6.19 show the beginning of the quarry pit where the transmitting vehicle was parked. Figure 6.20 displays the lower end part of the pit where we had problems achieving LOS.

Figure 6.19: One end of the quarry pit where we started the measurement round

Figure 6.20: The other end of the pit; on a lower altitude and with LOS issues

6.4 A Comparison of Technologies

Most of the technologies showed different characteristics in the quarry pit as oppose to the outdoor LOS or the quarry top environment. An exception to this behavior was ZigBee RF that showed the same robust behavior at the top of the quarry as in the quarry pit. In addition, ZigBee RF performed well in the VCDC range measurements where only 802.11p gave better results. In the figures below, we look at 802.15.4, 802.11g and 802.11p to get a more clear image of the type of environment where each technology achieved the best results. We start off by looking at 802.15.4 in figure 6.21. We can here see that the standard performed better in the quarry pit than at the quarry top.

Another interesting finding from the 802.15.4 standard is the range that was achieved in the quarry pit. At the VCDC track, 802.15.4 only reached a distance of 385 meters while the standard could receive packets from 444 meters in the quarry pit (see figure 6.22). In summation, 802.15.4 gave the least satisfying performance at the quarry top, both in terms of robustness and packet reception/packet loss rate. The same could be seen at the high speed track in VCDC. In the quarry pit on the other hand, 802.15.4 performed well as it had the second best packet loss rate and could provide for good communication quality and fast recovery after NLOS spots.

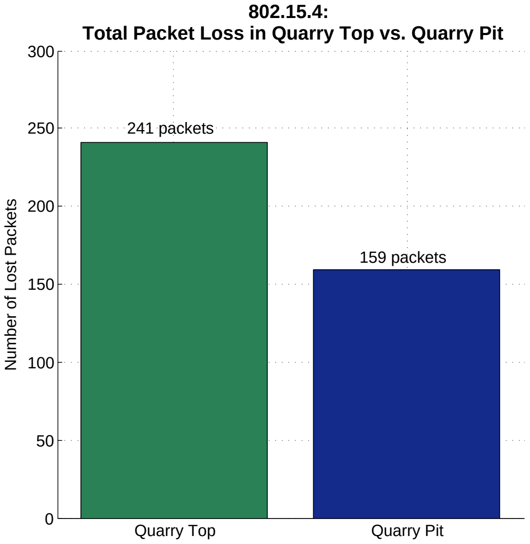


Figure 6.21: Top and pit packet loss

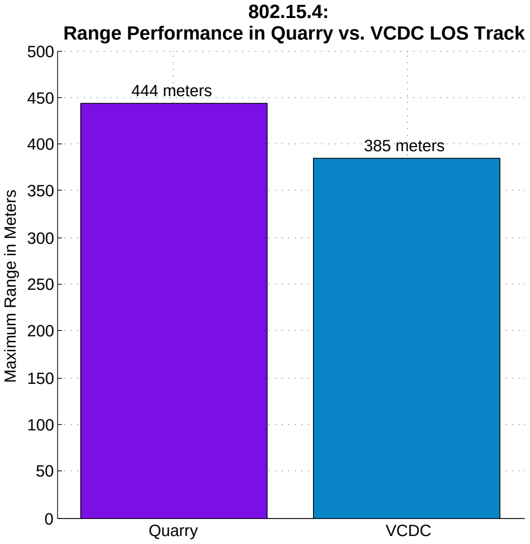


Figure 6.22: Maximum LOS range

802.11g also experienced a difference in packet loss when measuring in the two quarry environments. This technology achieved a low packet loss rate at the top of the quarry while performing very poor in the pit. Figure 6.23 depicts this scenario. In short, 802.11g gave the second best performance at the quarry top as it delivered a low packet loss rate along with a relatively stable and fast recovering communication link. It also gave good range results at VCDC. In the quarry pit however, 802.11g was the least satisfying technology with a high loss of packets and a weak and sensitive communication link.

The last technology to look at is 802.11p. Figure 6.24 displays the total packet loss comparison from the measurements at the quarry top and pit. As can be seen, the difference is not as great as for 802.11g. The quarry top results are slightly better with a packet loss of 216 packets compared to 283 packets for the quarry pit. These results must nevertheless be put in relation to how the other technologies performed in a similar environment. More importantly, we must also look at the stability and quality of the communication link. If this is taken into account, we can say that 802.11p gave the best performance in the quarry pit apart from its excellent result at VCDC.

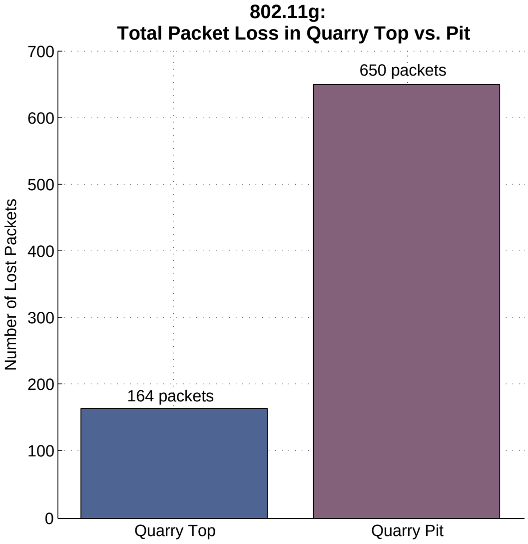


Figure 6.23: 802.11g packet loss

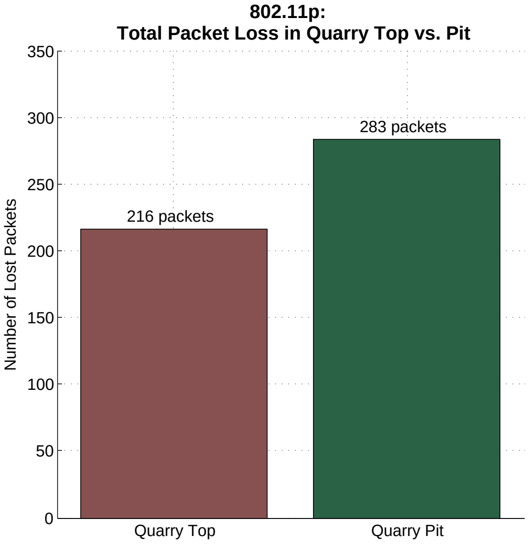


Figure 6.24: 802.11p packet loss

Above comparison presents the difference in behavior of the evaluated standards in the two quarry environments. Meanwhile, there are points that need to be considered when comparing the two test rounds. The time taken to conduct the measurements at the top of the quarry was 10 minutes and 10 seconds while the quarry pit measurement was conducted in 8 minutes and 2 seconds. A longer test round may mean that we get a higher packet loss rate due the increased likelihood of meeting more obstacles during the extended time period. When looking at the packet loss rate after the 8 minutes long quarry top test round, we can see a slight decrease in the packet loss for all technologies with approximately the same percentage for every standard. Thus, there is nothing that indicates a change in the relation of packet loss between the protocols. We can therefore assume that above figures give a correct view of each protocol's ability.

For a completely fair comparison, the top and bottom quarry would have to have the exact same set and number of obstacles of identical materials. To achieve a 100% fair comparison of the technologies at the VCDC track, all standards would have to use the exact same output power from the point of the antenna. In our case as mentioned in the previous chapter, we used an output power of 20, 33, 21 and 20 dBm for 802.11g, 802.11p, ZigBee RF and 802.1.5.4 respectively.

7

Discussion

This chapter discusses our gathered results and elaborate on their importance to wireless communication in the quarry environment. We also compare our collected measurement data to the expected values as reported in the related work, our literature study and by the manufacturers of our equipment.

As stated by Libelium, 802.15.4 was supposed to reach up to a distance of 7000 meters. As this is a range achieved in ideal LOS conditions reported by the vendor, we did not expect to reach or even be able to measure from such far distances. However, when conducting the range measurements at VCDC, we could not even reach 6% of the maximum range. In fact, the unit stopped receiving packets already at 385 meters. In addition, 802.15.4 was the least satisfying technology at the quarry top with the lowest packet reception rate and the most unstable communication link. The only time when 802.15.4 performed well was in the quarry pit where it was the technology with the second best results in terms of packet loss and communication robustness.

A number of reasons could have caused the poor performance of 802.15.4. One simple explanation is that the XBee module was not properly connected to the Waspmote board. Reasons such as a malfunctioning pin could have negatively affected the performance. At one point during the quarry top tests, more than 100 packets in a row were lost. It did not become clear to us if this was caused by an issue in the receiving gateway or in the sending board. The poor results could also have been caused by high speed when testing at VCDC. As stated in our related work, high speed may affect 802.15.4.

In a typical scenario, the boards send out one packet per minute or less. To obtain a more robust communication, we had to lower the transmitted packets per second to two. A valid question at this point is perhaps why the long gap of lost packets only was seen in 802.15.4 and not in ZigBee RF. Both protocols use the same board and gateway where the only difference lies in the uploaded code version and the XBee modules used. Since the code versions only differ in object type, this should not have caused the low PRR. A more valid question is perhaps if the issue was related to the XBee module.

The XBee module S1 enables 802.15.4 connectivity in the 2.4 GHz band while the S5 module supports 868 MHz communication. A possible reason for the large packet loss could be explained by interference with 802.11g that also operates in the 2.4 GHz frequency. Libelium states that 802.15.4 hops between 12 channels from channel 12 (0x0C) to 23 (0x17). Meanwhile, COSMO uses channel 13 (0x0D) to 15 (0x0F) for 802.11g. It is possible that when experiencing the highest packet loss for 802.15.4, we were simply using the same channel as for 802.11g. The standards could have been set to use channels that were at least 4 channels apart, which is said to prevent interference. According to our related work, however, it is still possible to experience interference when applying this rule. A better option would be to test the protocols separately, which unfortunately was not possible during this thesis due to time constraints.

A surprising but positive finding was that 802.11g performed well both in the range tests as well as at the quarry top. As stated by the WiFi alliance, 802.11g normally reaches up to 250 meters in the outdoors. During our range tests, we managed to receive 802.11g packets at a distance of 1682 meters. This is an increase in range by more than 6 times from the expected value. Meanwhile, 802.11g gave the least satisfying results of all technologies in the quarry pit in terms of packet reception and communication robustness. More measurements are needed to find out why 802.11g was unable to benefit from the surrounding environment in the same way as the other protocols.

The main environmental parameter that affected the performance of the wireless standards in the quarry seemed to be reflections. As seen during testing, the reflections from the enclosing mountain wall of the quarry pit greatly enhanced 802.11p in comparison to 802.11g. It is also possible that this was beneficial for 802.15.4. To obtain a higher degree of certainty, more measurements are needed to see how the communication can benefit from reflections and if similar results are received in other quarries.

One important point is that the specific protocol being used is less important than the actual frequency. We see that the two best performing standards ZigBee RF and 802.11p can be found at very diverse places in the frequency span. One major demand is that the protocol is able to function in NLOS in the presence of obstacles of piles of stone and metal infrastructure typical for the quarry. ZigBee RF and 802.11p proved that this was possible either by penetrating through the obstacle using low-frequency communication or by reflecting from the surface of mountain walls.

ZigBee RF gave the most satisfying results of all standards. It only lost 2 packets at the quarry top and pit and gave an excellent range result. It also seemed unaffected by NLOS and could deliver a stable communication throughout the tests. However, one question related to this standard raises a concern. Which type of quarry application can be built on top of a protocol with a maximum data rate of 250 Kbps?

802.11p also achieved promising results at VCDC and in the quarry pit and can thus be considered to be used in the quarry. Its communication link was robust and had a high PRR. Nevertheless, the 802.11p protocol is a fairly new standard. It was also the standard that used the highest output power (33 dBm in comparison to 20 and 21 dBm). The question is if 802.11p is ready to be used in the quarry where a secure and stable communication is necessary to guarantee the safety of future quarry applications.

8

Conclusion

The measurements conducted during this work has shown that two vehicles can communicate from much greater distances than initially expected. 802.11p was able to reach a range of 1767 meters in LOS conditions. We estimated far shorter distances as common literature report a maximum range of 1000 meters. In the quarry pit, 802.11p benefited from the reflecting surface of the enclosing mountain and provided a robust communication with low packet loss. The protocol was here also able to recover fast from NLOS spots. At the quarry top, in contrast, 802.11p gave one of the least satisfying results with a low PRR and a weak communication.

802.11g performed well at the quarry top but gave poor results in the quarry pit where it lost most packets out of all standards. 802.11g delivered an unstable communication in the pit and was sensitive to NLOS areas and obstacles. This technology could nevertheless obtain excellent range results of 1682 meters. As reported by the WiFi Alliance, only 250 meters were expected in the outdoors. Since 802.11g performed poorly in the pit, we did not consider it as a suitable candidate for quarry applications.

802.15.4 delivered poor results in all test cases except for the quarry pit where it had a relatively high PRR, perhaps due to reflections from the mountain. The range tests for 802.15.4 only reached 385 meters, which can be compared to the reported top distance set by the vendor of 7 km. 802.15.4 gave an overall weak communication quality, which may be explained by interference with 802.11g in the 2.4 GHz band. We did not consider this protocol as suitable for the quarry due to its generally unstable performance.

Out of all standards, ZigBee RF was the one that provided us with the best results and seemed to be unaffected by NLOS. It only lost 2 packets at the quarry top and pit where it delivered a constantly stable communication link. It also achieved the second best range result of 1753 meters. The reported top range for ZigBee RF of 12 km could not be tested. However, we did see that it could reach near the end of the 1.8 km VCDC track. We believe that this standard can reach further if tested at a longer LOS track.

Following our results, the two most suitable technologies for the quarry are 802.11p and ZigBee RF. These protocols are each others opposites in terms of the frequency band they use as one is communicating in the 868 MHz ISM band while the other can be found at 5.9 GHz. This fact, however, can be seen as the key to their success in the quarry. The technology is either penetrating the pit obstacles by using a low frequency or by reflecting from the surface of the quarry mountain to maintain connectivity. From this perspective, the significant factor is the frequency rather than a specific protocol. Output power is another relevant factor. It is therefore important to stress that 802.11p had an output power of 33 dBm while the other technologies used 20 and 21 dBm.

It is nevertheless not evident which protocol that practically can be used in the quarry. The issue with ZigBee RF is the low data rate of 250 Kbps or less which may be insufficient for future quarry applications. 802.11p is a promising technology for the quarry with data rates up to 54 Mbps. At the same time, it is a relatively new standard that perhaps is not yet ready for implementation in the quarry environment.

8.1 Future Work

This section is dedicated to the future work that we believe is necessary in order to adapt V2V and V2I communication to the quarry environment. In the previous chapter, a discussion of the results showed that more measurements are needed for all standards to determine the best suited candidate technology for wireless quarry communication.

Moreover, during this master thesis, the evaluation criteria used were packet reception/packet loss and distance. In a future experimental study, it would also be interesting to test the available throughput, message delay and signal strength. These criteria should be able to determine which standard is most suitable for quarry applications. Further research projects should carry out several repetitions of the same test case to provide a more stable result not affected by temporarily malfunctioning test units.

Another point of interest would be to perform more precise measurements where various types of obstacles preventing the communication were tested separately, both inside the pit and outside of the quarry. This could show the behavior of the different technologies when exposed to different materials such as sand, rock and stone. Furthermore, the tests could be conducted in different weather conditions to evaluate the sensitivity to rain, hail and wind to expose potential variations between the protocols.

Last but not least, the most interesting finding that showed how 802.11p may benefit from the reflections of the surrounding quarry mountains should be investigated thoroughly. By looking at the results, it is also possible that 802.15.4 experienced the same benefit. However, to be certain, additional measurements of the evaluated standards and other promising technologies should be conducted to reveal more possibilities.

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