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Understanding Data Analysis in an End-to-End IoT System

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Abstract

Internet of Things (IoT) is known as the concept of connecting everyday physical devices to the Internet. It is natural to assume that the popularity and development within this field will increase in the following years. This means that more and more things will be able to communicate over the Internet. In the process of developing IoT, an important part is to build reliable and scalable networks, and understanding where data should be processed concerning power consumptions and costs of transferring data in different parts of the network.

The task of the thesis will be to access data in a complete prototype of an IoT network, and both collect and analyse the data. The goal is to study different alternatives for a typical IoT system, and provide an overview of current state-of-the-art technologies, products and standards that can be used in such a setting. Data can be generated by using and comparing different sensors connected to end nodes in the network.

This thesis will therefore aim to test the use of microcontrollers as end nodes in an IoT network. The main focus is to establish a connection between a Raspberry Pi as a central point in a 6LoWPAN network, and connect nRF52 devices from Nordic Semiconductor to this. Using different versions of CoAP to transfer data over a Bluetooth Low energy (BLE) connection, it will be discussed the advantage and disadvantage of sending data rather than doing computation in end nodes, with a main focus on optimal throughput through the network. Optimizing packet sizes, fragmentation and maximising throughput at the same time as minimizing power usage are other key words.

To achieve these goals, a central part will be to understand the benefits of processing data in the end nodes, concerning power, costs and time. This means much less data needs to be sent through the network. If the calculations needed are too complex, the measured data needs to be transferred to a central node with higher processing power and easier access of energy.

Results from this work includes graphs and discussions in which case the two main versions of CoAP is preferred, and putting them up against each other in the form of tables and graphs from tests done on the IoT system. These show that CoAP NON is generally preferable if the data sent is larger than 500 bytes. It is also more stable than CoAP CON in tests performed on this system. However CoAP CON can transfer packets

at a higher rate for small packets (< 500 byte), even though each packet needs to receive an ACK, which will use some of the network connection capacity in situations where this is very limited.

Sammendrag

Tingenes Internet, mer kjent under det engelske navnet Internet of Things (Iot), er konseptet der hverdaglige fysiske gjenstander kobles til Internet. Det er naturlig å anta at populariteten og utviklingen rundt dette vil være økende de kommende årene. Dette betyr at flere og flere ting vil kunne kommunisere over Internet. I prosessen der Tingenes Internet utvikles, er en viktig del å bygge pålitelige og skalerbare nettverk, samt å forstå hvor i nettverket data bør prosesseres med tanke på energibruk og kostnader ved å overføre data mellom deler av nettverket.

Hovedoppgaven presentet i denne avhandlingen vil være å jobbe med data i en komplett prototype av et Tingenes Internet-nettverk, og både samle og analysere dataene. Målet er å studere de forskjellige alternativene for et typisk slik nettverk, og lage en oversikt over teknologiene og produktene som kan bli brukt i denne sammenhengen. Data som trengs til dette kan bli hentet ved å sammenligne forskjellige sensorer koblet til løvnodene i nettverket.

Med dette som utgangspunkt vil avhandlingen bli kul.

Preface

This thesis was issued by the Department of Telematics (ITEM) at the Norwegian University of Science and Technology (NTNU) the spring of 2016 as a Master Thesis in Telematics. The responsible professor has been Frank Alexander Kraemer, ITEM, who has given helpful advices on how to build up and write such a large project, as well as answering questions and giving support the whole period. David Palma has been the supervisor, giving impressively close monitoring of the project to fill in ideas, thoughts and good advices to help me finish the thesis. I would like to thank both these ITEM representatives for the work they have put down to make this project as good as possible.

Secondly I would like to thank fellow students for the many discussions, good advices and other more social activities during the period. I would like to point out the guys at A-179 for their support, Jon Anders for helping me with code specific problems during the programming period, and Anders for the many hours we spent together setting up central parts of the network described in this thesis. Special thanks to you!

Last, but not least, I would like to thank my family for their support both during the period of this thesis, but also during my entire period as a student. Special thanks to my father, Svenn Arne, for helping me review the thesis and to get a discussion point with someone without a technical background.

Contents

List of Figures	xi
List of Tables	xiii
List of Acronyms	xv
Glossary	xvii
1 Introduction	1
1.1 Motivation	1
1.2 Scope and Objectives	3
1.3 Structure	4
2 Background	7
2.1 Hardware	7
2.2 Communication technologies	12
2.3 Transport protocols	15
2.4 Software tools	19
3 System Architecture	21
3.1 Connecting Raspberry Pi and nRF52	22
3.2 Raspberry Pi to Network Computer or Server	25
3.3 Connecting nRF52 and ADXL345	26
3.4 Discussion	29
4 Network Measurements	31
4.1 Description of measurements	31
4.2 Possible limitations in the Network	32
4.3 Measurements	35
4.4 Comparison	46
4.5 Quantity test	51
4.6 Summary	51

5 Discussion	53
5.1 Set up network	53
5.2 Gather sensor data	54
5.3 Send data through network	54
5.4 Analyse data	55
5.5 Ease of use	56
6 Conclusion and Future Work	57
6.1 Future Work	57
References	59
Appendices	
A Appendix A	61
B Appendix B	65
C Appendix C	67

List of Figures

1.1 Example of IoT architecture	2
2.1 Raspberry Pi 3	8
2.2 Nordic Semiconductor nRF52	9
2.3 Nordic Semiconductor nRF52 chip in detail	10
2.4 ADXL345 Accelerometer	11
2.5 BLE protocol stack	13
2.6 BLE Data Unit Structure	14
2.7 CON CoAP set up sequence diagram	17
2.8 NON CoAP set up sequence diagram	17
2.9 CoAP NON, set up sequence, Wireshark capture	18
2.10 CoAP message format	18
2.11 MQTT subscription sequence diagram	19
2.12 Copper example	20
3.1 End-to-End architecture in the presented system	21
3.2 Connected nRF52 – ADXL345	26
4.1 Comparison: ping nRF52 and ping google.com	33
4.2 Ping nRF52, different time	34
4.3 Packet fragmentation - train comparison	35
4.4 CoAP CON, 0-200 bytes sent	38
4.5 CON vs NON 0-200 bytes	40
4.6 CoAP CON plot, 200 bytes to 1 kB	43
4.7 NON 0-1000 bytes	45
4.8 NON 200-1000 bytes	46
4.9 CON vs NON 0-1000 bytes	46
4.10 CON vs NON 200-1000 bytes	47
4.11 Time used per packet	48
4.12 Number of bytes per second	49
4.13 Number of bytes per second	51

6.1 Complete system architecture	58
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List of Tables

3.1	Connection scheme nRF52 to ADXL345	26
4.1	Wireshark CoAP CON 0 bytes	36
4.2	Wireshark CoAP CON 100 bytes	37
4.3	Wireshark CoAP NON 0 bytes	39
4.4	Wireshark CoAP NON 100 bytes	40
4.5	Wireshark CoAP CON 700 bytes	42
4.6	Wireshark CoAP NON 700 bytes	44
4.7	Comparison of CON and NON	52

List of Acronyms

6LoWPAN IPv6 over Low Power Wireless Personal Area Networks.

ACK Acknowledgement.

ACL Asynchronous Connection-Less.

BLE Bluetooth Low Energy.

CoAP Constrained Application Protocol.

CON Confirmable CoAP message.

CPU Central Processing Unit.

DNS Domain Name System.

GUI Graphical User Interface.

HCI Host Controller Interface.

HTTP Hyper Text Transport Protocol.

I2C Inter-Integrated Circuit.

ICMP Internet Control Message Protocol.

ICMPv6 Internet Control Message Protocol version 6.

IDE Integrated Development Environment.

IoT Internet of Things.

IPv4 Internet Protocol version 4.

IPv6 Internet Protocol version 6.

ISM Industrial Scientific Medical.

L2CAP Logical link control and adaption protocol.

LAN Local Area Network.

M2M Machine-to-machine.

MQTT Message Queueing Telemetry Transport.

MTU Maximum transmission unit.

NDP Neighbor Discovery Protocol.

NON Non-Confirmable CoAP message.

NTNU Norwegian University of Science and Technology.

OS Operating System.

PAN Personal Area Network.

QoS Quality of Service.

radvd Router Advertisement Daemon.

RAM Random Access Memory.

RTT Round Trip Time.

SoC System on chip.

SPI Serial Peripheral Interface.

TCP Transmission Control Protocol.

TDMA Time Division Multiple Access.

TFTP Trivial File Transfer Protocol.

UDP User Datagram Protocol.

USB Universal Serial Bus.

Glossary

ADXL345 Accelerometer	Small accelerometer mounted on a chip delivered by Adafruit. Connected to the nRF52 in the system presented.
byte	Used as a synonym for <i>octet</i> , meaning 8 bits put together as one unit.
goodput	The number of bytes in a packet that contains the intended message, sent one way through the network per time unit.
message code	Is a code for a message in CoAP, for instance PUT, SET or GET.
message type	Is a type of message in CoAP, for instance CON, NON or ACK.
microcontroller	Small computer that contains processor, memory and programmable parts in one integrated circuit.
nRF52	Nordic Semiconductor nRF52 DK , Development Kit for the nRF52 microcontroller used as end nodes in this system. From now on noted as "nRF52".
packet	A network packet is a chunk of data transported through the network as one piece. The packet size may wary from protocol to protocol.
payload	The part of the transmitted data that is the intended message.

Raspberry Pi	Mini computer in the size of a credit card. Runs on electric power from a cord in this system. From now on noted as "Raspberry Pi" or shortened to "Pi".
single-board computer	Small computer that contains processor, memory and programmable parts and I/O features like ports and antennas on a single circuit board.
throughput	The total amount of data sent one way through the network per time unit. The sum of payload and additional header files needed to transport the packet.

Chapter 1

Introduction

1.1 Motivation

Internet of Things (IoT) is a general term describing a network of small devices connected to the Internet with either a direct connection or using a forwarding device as a central point of connection. The term includes all sort of devices, from small sensors and microcontrollers to everyday smart objects, from phones and glasses to cars and buildings. A common factor for all of these is Machine-to-machine (M2M) communication, where machines can communicate with each other without Human-computer interaction. The term Internet of Things (IoT) was first used by Kevin Ashton in 1999 [10], when describing a global network of objects. He later explained how he thinks that most of the data contained on the Internet today will be overtaken by the amount of sensor collected data with M2M communication in the future. Both with this as an argument, and the high interest for smart devices and sensors in the general population, it can be said with a high certainty that this will be a central part of the coming years of the Internet.

In order for this development from a network mostly based on human made material to a network based more on data from sensors using M2M communication, several factors have to be considered. It is natural to believe that most end nodes must be battery powered for practical reasons. If a complete system contains hundreds of sensors and microcontrollers it would be impracticable to set up a power cable to all of these. For a users perspective, it would also be very annoying to have to change these batteries very often. Because of this, the available computational power in the end nodes is very limited, and should be limited further as much as possible to increase the battery life.

A very central point of discussion in any glslot system will therefore be how to transport data as efficient as possible. Raw data from sensors are seldom useful to an end user, therefore the data also needs to be analysed and often represented in another form before it can be useful to the user. A device in the network therefore

2 1. INTRODUCTION

needs to analyse the data, find out what is important or unimportant, find patterns, draw graphs or figures and forward the results a monitor, a web page or to be stored on a server to be used later. Should this process of analysing take place in the end nodes, or is it more preferable to forward raw data to a central component of the network? Or maybe in some cases this is not even enough, but the central computer needs even more computational power from a supercomputer, before data can be displayed?

In order for this to work in a proper way, a number of things are needed. Protocols, batteries, so on so on.

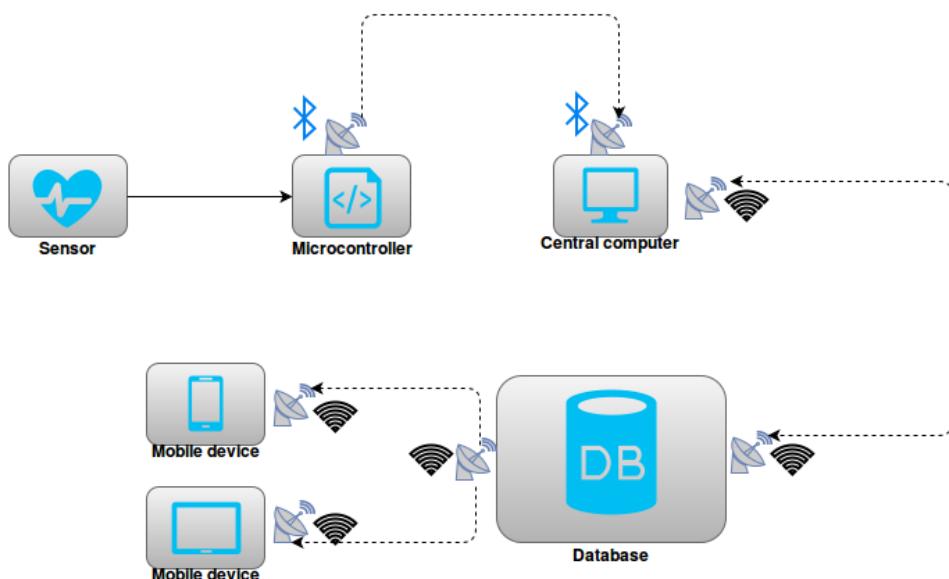


Figure 1.1: Example of IoT architecture

Figure 1.1 shows an example architecture of IoT. Here a sensor (or in real life scenarios most likely several sensors) is connected to a microcontroller by a standard interface using cables.

A central prosecutor in developing technologies to be used is Nordic Semiconductor. As described on their web page:

The future of electronics is wireless and portable due to an almost insatiable consumer demand for ever greater levels of freedom and flexibility. Nordic Semiconductor is playing a key role in the realization of that future, by providing ultra low power (ULP) wireless chips that can run for a long time from small power sources, like watch batteries [5].

This

1.2 Scope and Objectives

1.2.1 Scope

This thesis will mainly focus on the best way of optimizing transportation and analysing of data in an IoT network. The goal is to find the optimal solution on how to treat data, concerning:

- Gathering data from sensor efficiently, both concerning time and power consumption
- Transporting data efficiently, concerning power consumption and optimal throughput, both concerning time spent and amount of useful data that gets through
- Where in the network it is preferable to analyse the raw data, concerning energy consumption and time spent in total

To achieve this, some explanation of background protocols, devices used and network topology will be touched as well, in addition to low level details needed to set up the system architecture to maintain a stable and reliable network.

1.2.2 Objectives

O.1: Build a star network of microcontrollers

This is the most elementary objective, to build a network that can be tested. All the other objectives are dependent in this.

O.2: Connect sensors to the end-nodes to collect data

Objective two involves gathering real data. To do this, some kind of sensor is needed, and needs to be correctly configured to the end node to be sure that the data read can be trusted and reliable. Objective three and four can still be successful without this, since simulated data can be a replacement.

O.3: Gather information of the data sent through the network

Objective three is to find tools or write programming code to gather and analyse the data sent through the network, and present these in a way that makes it easy to spot the advantages or disadvantages of the different protocols and technologies.

O.4: Analyse and discuss the gathered information

Objective four involves discussing the given results, and use these to draw conclusions of how to optimize the network and propose solutions, improvements or further work.

1.2.3 Research Questions

R.1: Which transport protocols are suitable in such a network?

To answer this question, the network must be built and tested, to see if there are any noticeable differences in the protocols tested.

R.2: What are the main limitations when it comes to transporting data?

This question must be answered by measuring time spent in the different parts of the network during routing of packets, to determine the bottle neck of the network or system.

R.3: Are the microcontrollers powerful enough to gather data this frequently?

This is not specified in the documentation of the microcontrollers, since this depends on the network, the type of sensor and the type of data. To answer this question, the sensors must therefore gather data at a higher and higher rate to see if it is possible to reach an acceptable sampling rate.

R.4: Could data analysing be done in the end nodes in this network?

This is dependent on the result from R.3. This might be possible if results tell that the microcontrollers can easily handle the gathering of data and still have power to do calculations. The alternative is to forward raw data to a central node.

1.3 Structure

Chapter 2 describes the technical background of technologies, protocols and devices needed to understand the rest of this thesis, and explains why some solutions was chosen over others in this particular network. This chapter answers objective O.1 in detail, and discusses research questions R.1 and R.2.

Chapter 3 describes in detail how the different components of the network is connected and set up to communicate with each other. This chapter answers objective O.2, and discusses research question R.2 further.

Chapter 4 describes, explains and discusses the measurements done on the network by using tables and graphs of gathered data as a central point of discussion. This chapter answers objective O.3 and discusses the research questions R.3 and R.4. The chapter concludes that both Constrained Application Protocol (CoAP) Confirmable CoAP message (CON) and Non-Confirmable CoAP message (NON) has its advantages in different scenarios, which is summarized in chapter 4.6. CON has still been without doubt the most reliable when tested in this network.

Chapter 5 discusses the results found in chapter 4 further, by going through the central points of the objectives. It discusses what was most successful, what could have been better and what should be considered doing in further work. At the end the chapter contains an overall evaluation of the devices and technologies used, and how the experience gained in this project can be used in the future.

Chapter 6 summarizes the entire work, done in this project and presents the final conclusion.

Chapter 2

Background

This thesis describes the setup and usage of an End-to-End IoT system. In order for this to be set up by others later to perform reproducible tests, a detailed description of components, sensors and protocols used is needed. This chapter will go through the background information of the devices, technologies and protocols used, and why these were chosen over other alternatives.

2.1 Hardware

The hardware section will go through the physical devices used to build the IoT network, which is central to solve objective O.1.

2.1.1 Raspberry Pi

Developed by Newark Element 14, the Raspberry Pi has become a central tool for many people wanting to get started using small computers [4]. The device has been known as a single-board computer the size of a credit card specially designed for small network projects and to be used as an educational tool used all the way from elementary schools to here at Norwegian University of Science and Technology (NTNU). This was therefore a natural device to use as a starting point in this system as well.

The Raspberry Pi is a single-board computer on the size of a credit card. Model 3 of this was released in February 2016, just in time to become a part of the system set up in this project. This includes a Central Processing Unit (CPU) speed of 1,2 GHz and 1 GB of Random Access Memory (RAM). This makes it approximately 12 times faster than the first Raspberry Pi. Both Bluetooth and WiFi is included, and it was quite easy to set up, given that the right Unix kernel has been used in the Operating System (OS) of the Pi. Along with the Raspberry Pi, we needed a good and stable operating system with a kernel that supported the IPv6 over Low Power Wireless Personal Area Networks (6LoWPAN) architecture. For this, Ubuntu

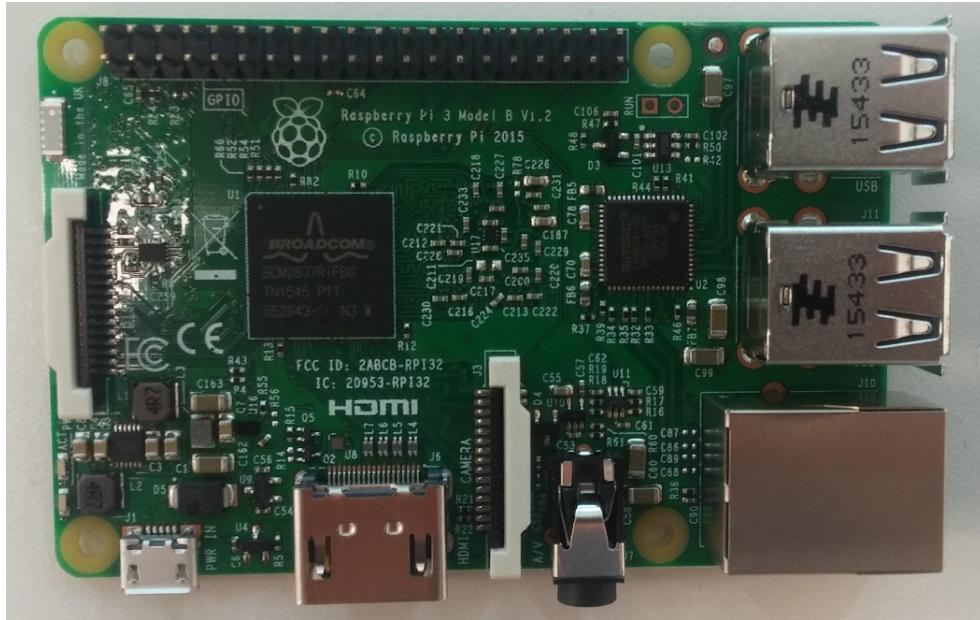


Figure 2.1: Raspberry Pi 3

Mate version 15.10 with kernel version 4.15 was chosen, and used on the Raspberry Pi. As other versions of Ubuntu this is Unix based, and has a complete Graphical User Interface (GUI) of a full OS. The set up of this will be explained in chapter 3.1.

2.1.2 nRF52

The most central device of this network is the microcontroller used as end-nodes, the nRF52 developed by Nordic Semiconductor with the IoT development kit. This is presented as a family of highly flexible, multi-protocol system on chip devices.

This device has been advertised as a powerful multiprotocol single chip solution, with both a 32-bit ARM processor, a 512kB flash and 64kB of flash memory. The building blocks of the chip in its entirety is shown in 2.3. The key features mentioned by Nordic Semiconductor [7] that will be relevant in this network are:

- Multi-protocol 2.4GHz radio
- 32-bit ARM Cortex M4F processor
- 512kB flash + 64kB RAM

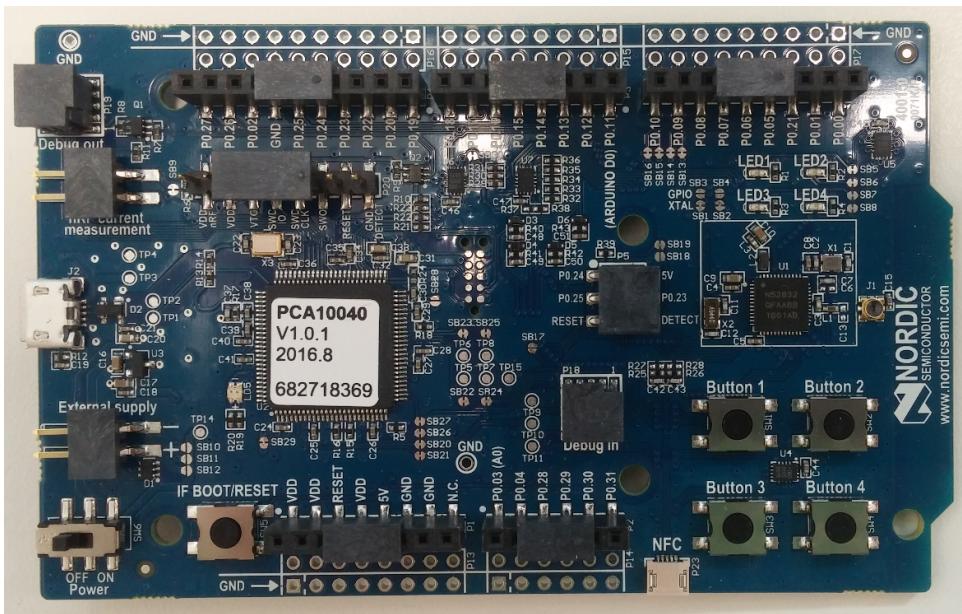


Figure 2.2: Nordic Semiconductor nRF52

- Application development independent from protocol stack
- Dynamic on air payload length up to 256 Bytes
- Flexible and configurable 32 pin GPIO
- Programmable Peripheral Interface – PPI
- Full set of digital interfaces including: SPI/2-wire/UART/PDM/
- I2S, all with EasyDMA
- Low cost external crystal 32MHz \pm 40ppm for Bluetooth, \pm 50ppm for ANT
- Wide supply voltage range (1.7 V to 3.6 V)
- On-chip DC/DC buck converter

The most interesting points here are the processing power, the flash storage and RAM, the Inter-Integrated Circuit (I2C) and Serial Peripheral Interface (SPI) buses and the bluetooth antenna.

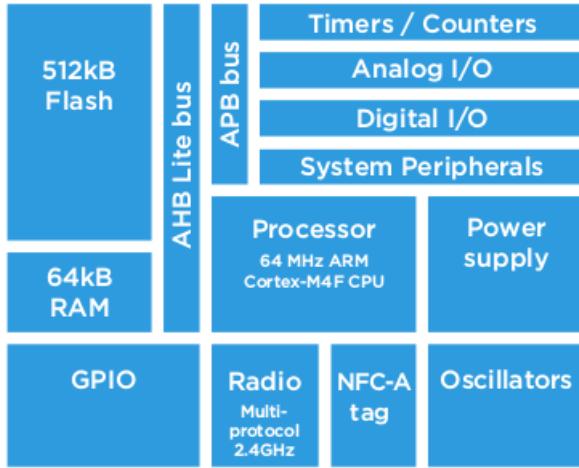


Figure 2.3: Nordic Semiconductor nRF52 chip in detail

Figure 2.3 shows how the different sections are distributed on the nRF52832 System on chip (SoC) 2.3.

A SoftDevice is a precompiled binary software that implements Bluetooth Low Energy (BLE) on the nRF52. This means that the user can start to work directly in a standard C language interface, which is independent from the Soft Device implementation [8]. This makes it possible for users to write standard programming code instead of require a deep knowledge of device specific configurations. There are several versions of SoftDevices to the nRF52 that can be downloaded from <http://www.nordicsemi.com>.

2.1.3 Adafruit ADXL345 Accelerometer

As seen in the previous section, the nRF52 has good computational power for a microcontroller, and several possibilities when it comes to radio communication. But in addition to this, an external sensor was needed to collect data. Supporting both the I2C and SPI, the nRF52 has got the most standard interfaces needed to do this build in. Objectives presented in the introduction to this thesis states that is preferable both to collect, transport and analyse data in this network. The sensor chosen to do this was the ADXL345 accelerometer from Adafruit. This was selected for the following main reasons:

- It can measure acceleration in all three axes, X, Y and Z.

- It sends digital data right away. This means there is no need to use computational power to calculate digital values as needed if the data was captured by an analog accelerometer.
- It supports both I2C and SPI, which makes it easy to connect to the nRF52.
- It supports voltage of 3.3V-5.0V, which fits within the range of output from the nRF52.



Figure 2.4: ADXL345 Accelerometer

When connecting to the nRF52, using the I2C interface was chosen because it is simple with few cables, supports an acceptable bit rate and several sensors in the same link. Ports VIN, GND, SDA and SCL will be used in this connection, which will be explained in detail in chapter 3.

2.1.4 Additional computational power

Devices presented so far are small network devices with limited or no computational power, that can be used as end nodes or more central nodes in an IoT network. The Raspberry Pi already has network connectivity, and can therefore be used as the final node before the results are presented on a screen, a web page or to be stored on a server. In many cases however, it will be an advantage to include another node with a lot more computational power before the results are being published. This both limits the computations needed to be done at the Raspberry Pi, and means that the system are able to do more deep analyses of the data gathered from the system, without the fear of a system overload. A central stationary computer, a supercomputer or computational power from a web service are possible solutions. In this network a standard stationary computer running a Linux Ubuntu based system was used as this node. Because of the limited time provided for this thesis the scope

focuses mostly on data analysing and transportation between small nodes in an end-to-end IoT system. The results were mostly obtained and calculated on the Raspberry Pi, meaning this last central node was not much used in this solution. This could however be a central topic for future projects aiming to more complex data analysis.

2.1.5 Alternative devices

There was never considered an alternative for the Raspberry Pi, since this is a well known device with a good reputation. This should mean that it would be easy to use, easy to find advices and help when needed, and easy get hold on devices when needed. There are of course other alternatives available, for instance the Ardurino Uno, Banana Pi or the BeagleBone Black, that could have been considered if there where any problems with the Raspberry Pi. The main contestant to replace the nRF52 was the Zolertia Z1 microcontroller. This was a good alternative to use since it already has got an accelerometer fitted on the board. It does not have the same computational power as the nRF52, and Nordic Semiconductor is a well known company based in Trondheim. This therefore seemed like a very interesting device to be tested in a thesis at NTNU. Should there have been any problems with the nRF52 the Zolertia Z1 would have been a natural contestant as a replacement. ADXL345 is the same accelerometer built in on the Zolertia Z1 microcontroller. This was therefore a natural choise when these two microcontroller where considered the main candidates in the network. If future works will do similar tests later, the results will be comparable between these two.

2.2 Communication technologies

After the devices to use had been selected, the next step was to find relevant communication technologies that could be used to establish a reliable, fast and low power connection between the nRF52 and the Raspberry Pi.

2.2.1 Bluetooth Low Energy

BLE, also known as *Bluetooth Smart*, is a wireless technology for short range communication developed by the Bluetooth Special Interest Group. The idea was to create a low energy single-hop network solution for Personal Area Networks (PANs). A major advantage of this solution is that Bluetooth 4.0 already is a well established technology in cell phones, laptops and several other devices. This means that few changes needs to be made to these devices to be able to work with bluetooth smart. Still to this date, a device that only implements BLE is not able to communicate with a device that only implements classic Bluetooth [13]. The 6LoWPAN Working Group has recognized the importance if BLE in IoT [14].

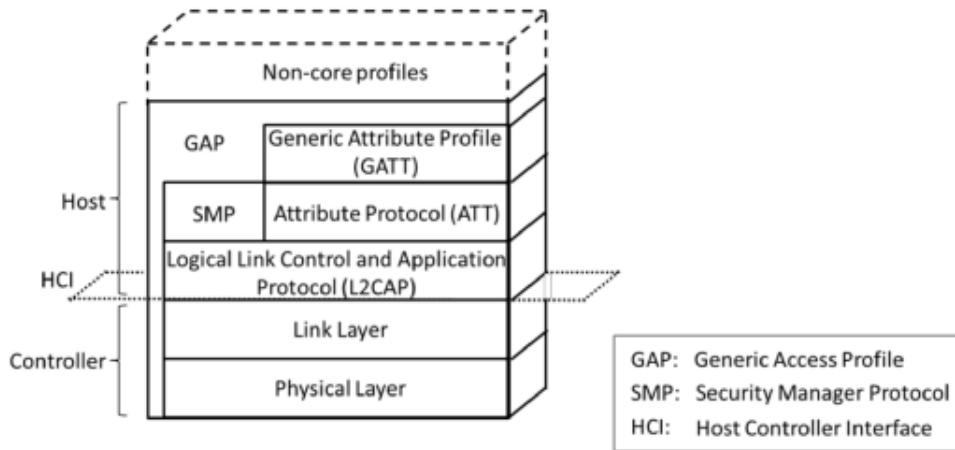
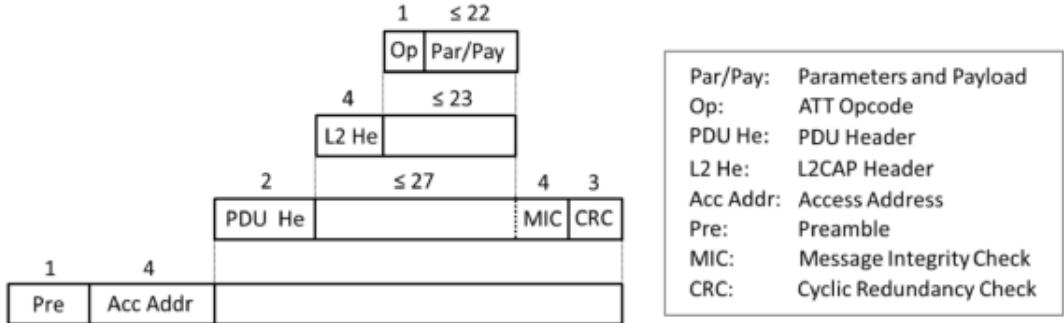


Figure 2.5: BLE protocol stack

The protocol stack of BLE has two main parts, the controller and the host, as shown in 2.5 [13]. In the system presented in this thesis this represents the Raspberry Pi as the controller (master) and Nordic nRF52 as the host (slave). The communication between these is done through the standard Host Controller Interface (HCI), a bluetooth protocol. All slaves are in sleep mode by default, and are woken up by the master when communication is needed. Links are being identified by a randomly generated 32-bit code, and the Industrial Scientific Medical (ISM) band used is 2,4 GHz [13]. Other protocols used include Logical link control and adaption protocol (L2CAP) used to multiplex data between higher protocol layers, and the segmentation and reassembly of packets. From here packets are being passed to the HCI, which is the interface used to communicate between the two BLE devices. This is being used in conjunction with Asynchronous Connection-Less (ACL), which is used to create the Time Division Multiple Access (TDMA) scheme used to transfer packets over the network link, as well as controlling uptime of the end nodes, as this link is set to disconnect automatically after a given time period if there is no activity on the link. Concrete examples of these protocols will be shown later in the thesis.

Figure 2.6 shows the data unit structure in BLE, meaning the different fields that can be used in a packet [13]. The header fields of 4 byte of access addresses and L2CAP will be central topics of discussion later in this thesis. In the case of the network presented here, when the BLE slave has been connected to a master, it stops searching for other connectible points. This means that it is not possible to connect to several masters, and it will only be possible create a *star network*, not a *mesh*

**Figure 2.6:** BLE Data Unit Structure

network. A mesh network would in many cases be preferable, since BLE is considered a PAN with a very limited range. In a mesh network end nodes can communicate with each other, meaning they can span a larger area without the need of a central and common point of connection. This could possibly be an idea for improvement later. Other than this, BLE seems like a very good alternative in this project.

2.2.2 6LoWPAN

Write even more in this section?

6LoWPAN is a defined protocol for using Internet Protocol version 6 (IPv6) in low energy networks, to identify sensors and devices, as defined in the IEEE 802.15.4. To use the Internet Protocol in low energy networks in addition to standard networks was proposed by Geoff Mulligan and the 6LoWPAN Working Group. This was chosen because it seemed like a simple and smart protocol definition. Since packets in this network can end up being forwarded all the way from a ?? to a central computer through several nodes without being changed, it makes sense to use the same base protocol for all links. In [19], the advantage of 6LoWPAN is explained as not too big to be used in small networks with a small header field, and more flexible to network sized compared to Zigbee and Zensys.

Utilizing IP in these networks and pushing it to the very edge of the network devices flattens the naming and addressing hierarchy and thereby simplifies the connectivity model. This obviates the need for complex gateways that, in the past, were necessary to translate between proprietary protocols and standard Internet Protocols and instead can be replaced with much simpler bridges and routers, both of which are well understood, well developed and widely available technologies [19].

6LoWPAN was developed to be used in small sensor networks, and implementations can fit into 32Kb flash memory parts. The Maximum transmission unit (MTU) is given to be 1280 byte, and it also uses a complex header comparison mechanism that allows the transmission of IPv6 packets in 4 bytes, much less than the standard IPv6 40 bytes. This is done by using stacked headers, same as in the IPv6 model, rather than defining a specific header as for Internet Protocol version 4 (IPv4). The device can send only the required part of the stack header, and does not need to include header fields for networking and fragmentation [14]. The maximum packet size of the physical layer is set to be 127 bytes, far below the limit of 1280 byte [17]. It is expected that other layers will produce packets of the desired size to fit the system. In the system presented in this thesis by the example code on the nRF52 is the side set to 270 bytes for every packet, as will be shown in practical examples and tests later in the thesis.

2.2.3 Other alternatives

ANT was the main other alternative to BLE when network protocols where chosen. It also uses the 2,4 GHz ISM band, and is made to be used in sensor based networks [2]. It is supported by the nRF52, and could be used with a Raspberry Pi if an ANT Universal Serial Bus (USB) dongle is fitted. This would have solved the BLE problem with not being able to connect several devices together in a mesh network, since ANT supports this. Other than this the difference is not very large. BLE is supported by other mobile devices on the other hand, meaning it is possible to use a mobile application developed by Nordic Semiconductor to test the connection. This was assumed to be a very useful feature, and was one of the main reasons why BLE was chosen.

Two other contestants than 6LoWPAN was *Zigbee* and *Zensys*, being compared directly in [19]. The major factors here are that 6LoWPAN has a much higher network size than the others, supports Internet connectivity using routers as well as the use of User Datagram Protocol (UDP) and Transmission Control Protocol (TCP), supports low amounts of RAM and small headers [19].

2.3 Transport protocols

In order to transfer data from the end nodes to the central points of the network, either for analysing or already analysed data, a fast, efficient and stable transport protocol has to be used. This is a central aspect in this network, because the limitations of sending rate is thought to be one of the main limitations, either in the form of limits of data at once or number of transmissions per second. The protocol needs to be stable and energy efficient and work with both BLE and 6LoWPAN.

Luckily, Nordic Semiconductor provides example code and examples on how to get started with this.

2.3.1 CoAP

CoAP is a transport protocol designed to be used in constrained networks for M2M communication. It is UDP based, and works good in low-power and lossy networks. It can be used with microcontrollers, and with IPv6 and 6LoWPAN. Both GET and PUSH functionality can be used, as well as *observable* GET. This means that a server can "subscribe" to end nodes in the network, and get updates either after a given timespan or when changes have been made. This therefore looked like a promising protocol to use, and was chosen as the main transport protocol to test in the network [21]. The main technical features described in CoAP includes fulfilling M2M requirements, support of asynchronous messages, glsudp based communication and stateless mapping to Hyper Text Transport Protocol (HTTP).

CoAP has several similarities with HTTP, using the same client and server roles. The client sends a request, and the server sends a response back. Many of the response codes are also very similar, with *404: Not found* as the best known. When M2M communication is used, both participants sometimes needs to be both client and server, and the CoAP protocol handles this with a two-layer approach. . There are four different main messages defined in glscoap [21].

- A Confirmable message, CON, require one Acknowledgement (ACK) for every packet received. If a message is not received correctly, the receiver will ask for exactly return message of the type Acknowledgement.
- A Non-confirmable message, NON, does not require an ACK. This means a higher possibility of a packet getting lost, especially in lossy networks, but it requires less capacity from the network and should in general be faster.
- An Acknowledgement acknowledges that a specific CON packet has reached its destination.
- A Reset message tells the sender that a specific message was received, but some content is missing to be able to understand it, for instance if the receiver has had a reboot during the transmission. An empty Reset message represents a ping test of Round Trip Time (RTT), which will be used when testing a connection.

Other commands used in CoAP are *GET, PUT, POST and DELETE*, to get or change data.

make figure of
CoAP Layer-
ing

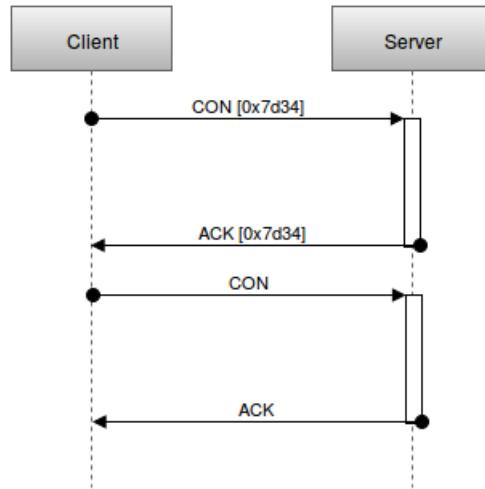


Figure 2.7: CON CoAP set up sequence diagram

Figure 2.8 shows the basic message sequence between the client and the server in a CoAP CON network. Every request CON message needs to be given an ack back.

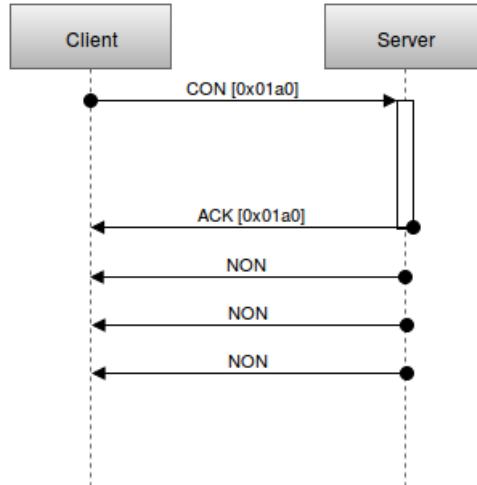


Figure 2.8: NON CoAP set up sequence diagram

Figure 2.10 shows the same for NON, where no ACKs are needed. The same initial set up with con and ack messages are still needed, to establish a connection between the client and server before a stream of NON messages can be sent. This means a much more unreliable connection than using CON, since messages can be dropped without either the client or the server getting notified. Systems where a few

packets can be lost without difficulties, for instance in a sensor based network like the network presented in this thesis, can use this as an advantage. A message ID is still provided to every message to remove duplicated messages, but dropped messages are lost data. If the packages sent contained data that could not be dropped, for instance containing crucial patient information from censors on a patients body, this is not a good solution. The more reliable solution CON is a much better alternative in this case. These differences are the same as being experienced in the IoT system described in this thesis, which can be seen in figure 2.9. A CON message is sent several times, to set up the initial connection. When an ACK is received as a response, the continuous transportation of NON packets without ACKs can begin.

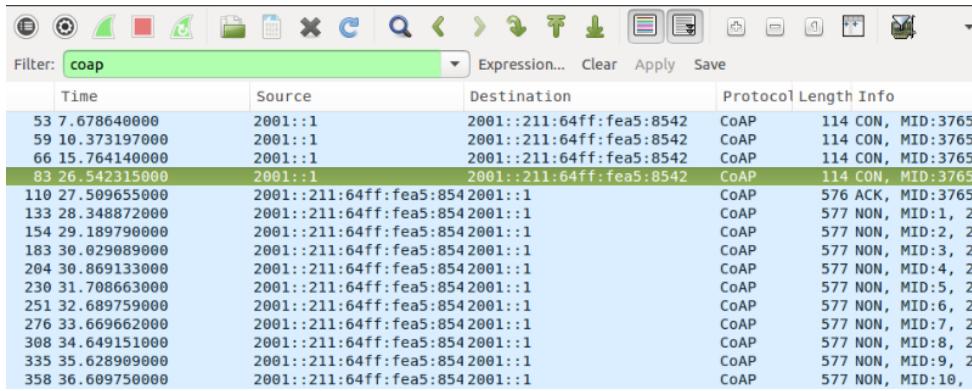


Figure 2.9: CoAP NON, set up sequence, Wireshark capture

The message format used in CoAP is very simple, and can be seen in figure 2.10. The 4 first byte are header files, followed by optional tokens and options. When these are not being used, like in this network, the minimal header size of either 4 or 5 bytes. This is a huge advantage in IoT networks.

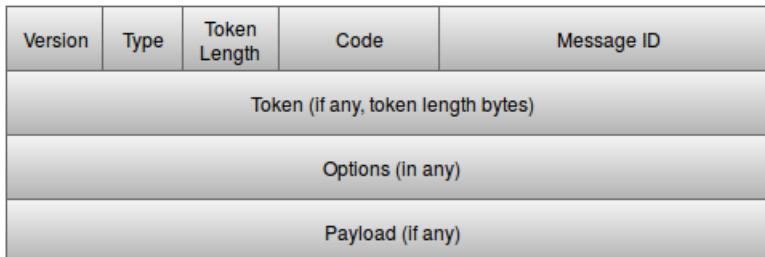


Figure 2.10: CoAP message format

2.3.2 MQTT

An alterntive transport protocol in a system such as this is Message Queueing Telemetry Transport (MQTT). This is known as a publish-subscribe messaging system based on TCP for M2M communication. A client will in this case *subscribe* to a *publisher* in the network [15]. When a publisher updates a field of interest for the subscriber, the subscriber will get notified. Subscriptions are being coordinated by a *broker*, as seen in figure 2.11. Messages sent in such a network are either *sub(topic)* to subscribe to a topic, or *pub(topic, data)* to publish data [3].

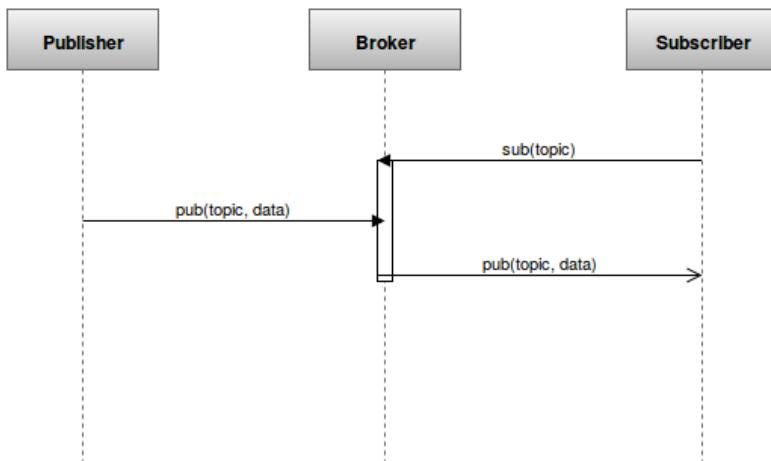


Figure 2.11: MQTT subscription sequence diagram

MQTT supports end-to-end Quality of Service (QoS), and has a simple and good message architecture. This protocol would also be possible to use in such a system. Because of the limited time frame of this thesis however, it was decided to study CoAP in depth first, and leave the testing of MQTT to future work.

2.4 Software tools

As Integrated Development Environment (IDE), the *KEIL Vision* was used, as recommended by Nordic Semiconductor in [1], for writing C programming. For other programming languages (for instance Python 3.4) Text 2 for Windows and Linux was used, as well as *Pluma* for Ubuntu Mate on the Raspberry Pi.

Wireshark is a software tool used to analyse networks and capture packets sent with different technologies [18]. Later the data can be filtered and analysed, for instance by filtering out all packets except CoAP and BLE, which was used in this case. Wireshark has been one of the most important tools to be able to analyse data to such an extent as done in this thesis. An example of use is shown in 2.9.

Copper is a generic browser which can be used in *Firefox*. It is Made to be used in IoT networks based on CoAP, just like this network. Using Copper it was easy to use GET and PUT messages, as well as observing a server by using a simple GUI. By removing the need of using terminal commands and programming scripts this makes the system easier to use with less computer knowledge. An example of the program can be seen in figure 2.12. [16]

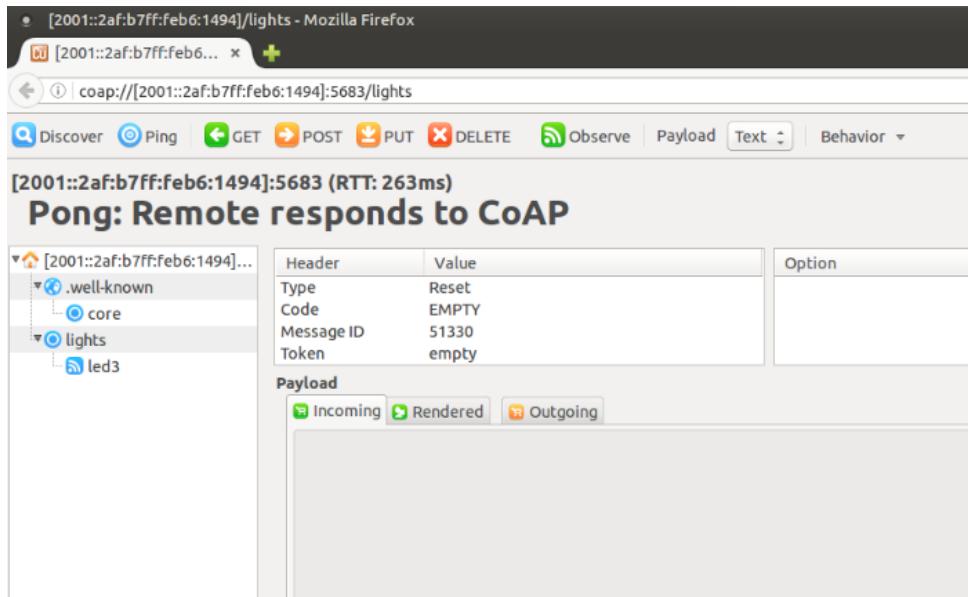


Figure 2.12: Copper example

Router Advertisement Daemon (radvd) is a software tool that can be used to advertise IPv6 addresses in a local network, using Neighbor Discovery Protocol (NDP) [11]. This is being used to multicast and forward packets in this network. When a packet is sent from an end node to another, the communication needs to go through the central point in the star network, the Raspberry Pi in this case. Here, radvd ensures that the packages are being routed to the right end point, or the right nRF52 in this system. To make the most basic figures in this thesis the web based tool *draw.io* was used, unless other is specified. *polt.ly* was used to draw the graphs used. All the images of devices in the network has been taken by the author.

Chapter 3

System Architecture

The purpose of this thesis is to build an end-to-end system, that will be able to transfer data all the way from sensors connected to a microcontroller to a server. This chapter will describe in detail how the different components of the system has been connected together, and how the different protocols has been configured to read, process and transfer data efficiently.

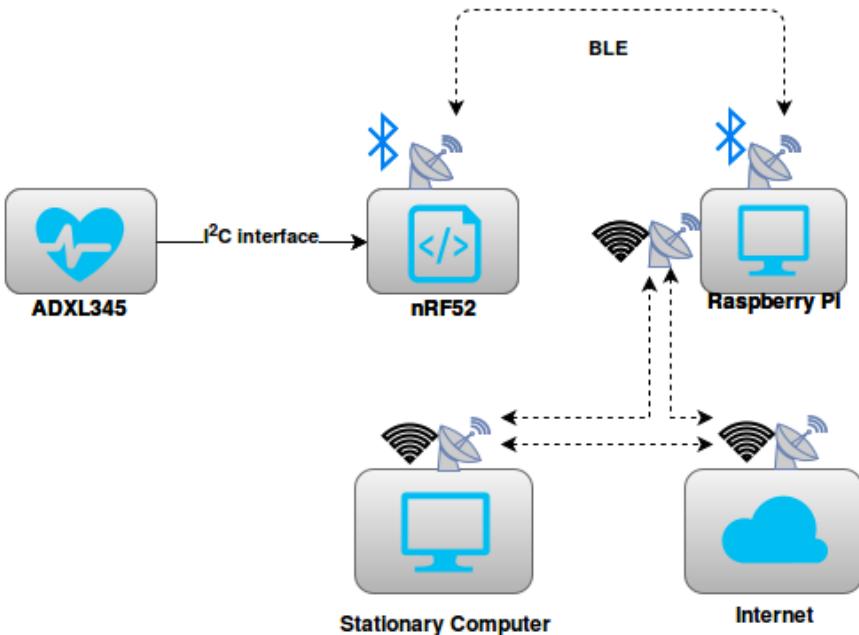


Figure 3.1: End-to-End architecture in the presented system

Figure 3.1 shows how the complete end-to-end system of this thesis is set up. In short terms, the ADXL345 Accelerometer accelerometer is connected to the nRF52, using the I²C interface. The nRF52 is connected to a Raspberry Pi using 6LoWPAN

and BLE. The Raspberry Pi is connected to the Local Area Network (LAN), and can therefore forward data to a central stationary computer if additional computational power is needed. Otherwise the results can be sent to the web, to a screen or anywhere else. Several microcontrollers can possibly be connected to a Pi at the time, forming a star network. Up to eight connections has been tested successfully in this network.

There are in general three main limitations in a network such as this:

- Computational power in the different nodes
- Battery capacity of the end nodes
- Network limitations between the nodes

A central part of the testing in this thesis will be to test the different limitations, and to understand the pros and cons of doing computations in end nodes, compared to transferring information to a server with much more computational power. Power usage is very often closely related to computational power, and will also be a central factor. The next section will contain a walk-through of the system, and discuss these three main limitations in each node and the links between them.

3.1 Connecting Raspberry Pi and nRF52

Since its not possible to connect a screen to the nRF52, it makes sense to connect this to the Pi first, before measuring values. To set up the communication between a Raspberry Pi and the nRF52, the two code examples TWI and Observable server from Nordic Semiconductor was used as a starting point for coding on the nRF52. It was however quite tricky to connect these two together the first time. Following is a listing of unix terminal commands that was run on the Raspberry Pi to get the system up and running [6].

Install an OS on the Raspberry Pi that has a Linux kernel version later than 3.18. On *Raspbian* version 3.18 is the only stable (Note: Jan. 2016), but *Ubuntu Mate* is stable in version 4.15. Ubuntu Mate was therefore chosen as the best and most stable OS, and was being installed on the memory card from another computer [9]. When this is done, a resizing of the file system is needed to use all the capacity of the memory card. This is not crucial to get the OS up and running, but recommended to be able to use more than 4GB of the memory card. Recommended size of the memory card is 16GB. To resize, after the initial boot of the OS on the Raspberry Pi, run the following commands

```
sudo fdisk /dev/mmcblk0
```

Delete partition (d,2), and run the following after a reboot

```
sudo resize2fs /dev/mmcblk0p2
```

All the following commands require admin rights on the system. Its therefore easier to type in the following command to temporarily become a *super user*. Alternatively type in *sudo* before every command in the rest of the recipe.

```
sudo su
```

It should now be possible to exploit the whole memory card, and start downloading and activating services needed in the system. To use BLE, install Bluez and radvd using *apt-get*:

```
apt-get install radvd
apt-get install bluez
apt-get upgrade
apt-get update
```

IPv6 forwarding is needed to let the end nodes discover each other through the central node in the star network. To activate this, uncomment the following line (remove "#") in the file */etc/sysctl.conf*

```
net.ipv6.conf.all.forwarding=1
```

To find the IPv6 prefix in the network, run the command *ifconfig*. Find a field named *inet6 addr*, and write down the first and last number on this line (For instance 2001 and /64). The communication will in this case go through a custom designed interface. This will be named bt0. Start by creating the *radvd.conf*-file, and open it for editing.

```
touch /etc/radvd.conf
pico /etc/radvd.conf
```

Write in the following bt0 interface. Replace the number 2001 and /64 with the numbers found in the previous step.

```

interface bt0
{
    AdvSendAdvert on;
    prefix 2001::/64
    {
        AdvOnLink off;
        AdvAutonomous on;
        AdvRouterAddr on;
    };
};

```

To mount the modules *bluetooth_6lowpan*, *6lowpan* and *radvd*, add the following to */etc/modules*. If the file does not exist, create it by entering *touch /etc/modules* first.

```

bluetooth_6lowpan
6lowpan
radvd

```

When the system is booted after this, these modules will be automatically loaded. The *hcitool* command should now be available. This is a tool designed to connect and keep track of connected devices, both through standard bluetooth and BLE.

```
hcitool lescan
```

lescan will scan for BLE devices nearby, and find the bluetooth address, for instance *00:AA:11:BB:22:CC*. The normal procedure in this case would be to run the following command:

```

echo 1 > /sys/kernel/debug/bluetooth/6lowpan_enable
\color{red}{hcitool lecc 00:AA:11:BB:22:CC}
service radvd restart

```

These commands never established a stable connection in this system. It was not possible to test the connection, and each connected device became automatically disconnected after about 15 seconds. The reason for this was never found. Instead it was possible to not use *hcitool* for this part. Instead, the following commands worked fine:

```
cd /sys/kernel/debug/bluetooth
echo 1 > 6lowpan_enable
echo "connect 00:AA:11:BB:22:CC 1" > 6lowpan_control
service radvd restart
```

The command *hcitool con* shows the connected BLE devices. If the device is connected, the connection can be tested by typing:

```
ping6 2001::02AA:11FF:FEBB:22CC
```

Note that *2001::02AA:11FF:FEBB:22CC* is the full IPv6 address of the device when the bluetooth address is *00:AA:11:BB:22:CC* in this system. The IPv6 address can be used to route packets using 6LoWPAN. Using the basic examples provided by Nordic Semiconductor described in chapter 3.3, it was now possible to send messages both using CoAP CON and NON.

Computational power is closely related to power usage. The nRF52 microcontroller is battery powered using a small *3V Lithium CR 2032* battery. Given this limitation the computational power will be limited as well. The optimal solutions therefore seems to handle as little data as possible here.

3.2 Raspberry Pi to Network Computer or Server

When running the Unix based OS Ubuntu Mate, the raspberry Pi can be used more or less like a regular computer. This has a pre-installed version of the most basic programs needed, for instance *Mozilla Firefox Browser*, *Pluma text editor* and *Unix terminal*. In this system it has been connected to the *lan* using either a wireless or a wired connection. This makes the link from the Pi to another computer very stable and quick, capable of much higher transfer rates than the other links discussed in the system. Neither the Pi or the central computer is battery powered in this system, this is therefore not a consideration. Using a forwarding script it is simple to forward data either to the computer or directly to a location on the web, as shown in 3.1. All these factors implicates that these links will not be a bottle neck in the system. Since this is higher level computer programming and not as limited concerning computational power or battery usage, it will be more interesting to look at the other links in more detail in this thesis. To test these links with higher capacity in more detail will therefore be left to future works, discussed in 6.

3.3 Connecting nRF52 and ADXL345

The ADXL345 Accelerometer used was connected using I2C, which is quite straight forward using the nRF52. Connection scheme is as follows (nRF52 -> ADXL345):

Table 3.1: Connection scheme nRF52 to ADXL345

Pin connection	Explanation
5V - VIN	Power source, green cable in Figure 3.2
GND - GND 0	Ground, red cable in Figure 3.2
P0.27 - SDA	I2C Serial Data Line, orange cable in Figure 3.2
P0.26 - SCL	I2C Serial Clock Line, brown cable in Figure 3.2

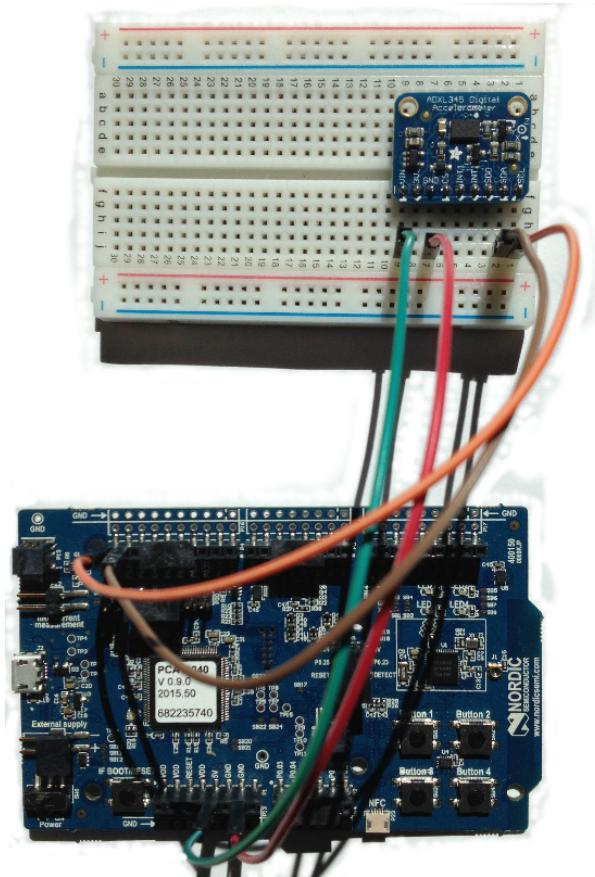


Figure 3.2: Connected nRF52 – ADXL345

nRF52 supports both I2C and SPI serial computer buses. I2C was chosen in this case, because it is fast enough, flexible and simple to set up with use of few cables. As seen in table 3.1 and in figure 3.2, this interface only requires four cables, for power, ground, data and clock. This gives a bandwidth of 1 bit and a maximum bitrate of 5 Mbit/s [20]. The is approximately the same as the assumed max rate capable from the nRF52.

After the physical connection was complete, it was possible to start the process of initializing the ADXL345 Accelerometer. Acceleration values can only be read from this sensor if this has been correctly initialized at compile time. In order to do this, code to write to and read from the registers had to be added. To esablish this communication, another example from Nordic Semiconductor was used as a starting point, named *TWI master with TWI slave*. By using specific methods from this example and writing to the right accelerometer registers in the right order [12], it was possible to configure the accelerometer as wanted. The detailed description of the programming code used to do this can be seen in appendix C.

It turned out to be quite difficult and very time consuming to configure the ADXL345 Accelerometer to work as expected with the nRF52. In short, registers for *data format control*, *initial power saving*, *interrupt enable control* and *the offset of each axis* has to be written to in that order before the acceleration value from the different axes can be read. It was then possible to read from the registers containing current acceleration values using the following code:

```
static uint16_t read_reg(uint8_t register_address, uint8_t data_returnValue)
{
    uint16_t rd;
    ret_code_t ret;
    uint8_t buff[2];
    uint8_t addr8 = (uint8_t)register_address;

    ret = nrf_drv_twi_tx(&m_twi_master, ADXL345_SLAVE_ADDRESS, &addr8, 1,
                         true);
    if(NRF_SUCCESS != ret)
    {
        break;
    }
    ret = nrf_drv_twi_rx(&m_twi_master, ADXL345_SLAVE_ADDRESS, buff, 2,
                         false);
    rd = (uint16_t)(buff[0] | (buff[1] << 8));

    return rd;
}
```

In the solution proposed in this thesis the acceleration values are being read as often as possible, limited by the processing power of the nRF52 and the I2C connection. After this the read value is being stored in a simple dynamical char array in the nRF52 before being sent and reset when the BLE channel is ready. The highest obtained measurement frequency in this system was 11 times per main loop, and 150 within this, resulting in 1650 measurements every second. Considered a quite decent measuring frequency this looked promising at this point. The ADXL345 Accelerometer updates its acceleration value when instructed by the master, and the default setting is to follow the oscillator *tick* of the nRF52. This gives an update approximately every second. The result was that even though the register was being read as often as possible, the same value was read up to 1650 times before it was updated.

To solve this problem the default setting of updating the register when told by the oscillator needed to be changes. This turned out to be very time consuming and hard to solve in a good way, both because of problems with initializing the accelerometer correctly and making the nRF52 read and store the values fast enough to get proper data. The ideal solution would be to read at least 1000 values every second, to get a good starting point before analysing values. At this point it was not possible to get enough real data to be used in data analysis at another point in the system. To not loose too much time on hardware problems, it was decided to focus more on analysing the data sent over the network communication with random generated data.

It would have been possible to use these values to test the network, even though the same value was being read several times in a row. However, the accelerometer did never give out a fixed number of measured values, and all the measured values could be from 0 to 5 digits long. Since the main focus of this thesis is to understand how data travels through the network, it was decided to not focus further on getting real data due to hardware problems. It would be preferable for the network measurements to use predictable data of fixed length, to get directly comparable results. To test the system with real data will therefore be discussed in the future work section, in chapter 6. Since the network connection between the nRF52 and Raspberry Pi was already stable, it was easy to generate random values of fixed length to send on the nRF52, and do measurements to calculate the optimal throughput between these two.

The next chapter will describe the data analysis of the data sent through this network in detail, and how to optimize the percentage of usable data being transported.

3.4 Discussion

Now the full system shown in figure 3.1 has been connected. Due to problems explained in the previous section, the rest of the thesis will focus mainly on the link between the nRF52 and the Raspberry Pi, with the option of using extra computational power from the stationary computer or a web service if this is necessary. The central point of discussion at this point is how to process and analyse data in the system. The main options to consider in all the different devices concerning how much computation to do in this link are the following:

- No computation: All data arrives as useful data, and can be posted directly to a web page or a server for storage
- No computation: Forward all data directly to a computer with more computational power
- Some computation: Analyse the data to find data that is not relevant to filter out
- Full computation: Do a full analyse of the data. The results can then be posted directly to a server or displayed on a web page.

Which of these four options that is most relevant depends on the data, and how computational power is needed. It is possible to run the Raspberry Pi from a power bank, but this has not been tested in this project. When set up without a battery as power source, the Pi is the first node that could possibly do computations without having to take power limitations as a great concern. The main limitation is therefore computational power, while the main limitation may be battery power on the nRF52. It therefore makes sense to do some easy computation on this device. For instance, if this network is being used to measure vibrations, it is reasonable to assume about 1000 acceleration values every second, which represents a measuring rate of 1 kHz. It would then be perfectly reasonable to assume that the Pi could go through these values, and calculate whether or not the current acceleration value has breached a given threshold. This result can then be displayed directly on a web page or a connected monitor from the Pi. If however the system is to calculate *patterns* in the acceleration values several values needs to be compared together. The need of complex algorithms to find these patterns is expected, before the results can be displayed. In this case it is reasonable to assume that the Pi would need additional computational power. The Pi can then be set up as a forwarding device, that forward data directly to a computer with more computational power.

3.4.1 Connection Challenges

Following instructions from a representative from Nordic Semiconductor, the bt0 interface was set up using the recommended IPv6 prefix: `2001:bt8::1/64` in the file `/etc/sysctrl.conf`, and after that trying to connect and test the connected devices using addresses on the form:

```
ping6 2001:bt8::0211:22FF:FE33:4455
```

This turned out not to work on the IPv6 network used on NTNU, where the standard prefix is `2001::1/64`, without the `db8`. Both solutions should however work in other IPv6 networks.

3.4.2 Ease of use

Describe
bt8-problem
and dev-
zone.nordicsemi.com
and infocen-
ter.nordicsemi.com

Comment
ease of use
here?

Include the
following,
Nordix Ex-
ample code
somewhere?

Chapter 4

Network Measurements

This chapter will display the experiments carried out concerning data sending rate from the nRF52 to the Raspberry Pi in the form of graphs, tables and figures. The goal will be to determine the most efficient combination when it comes to amount of data to send at a time, sending frequency and protocols to use in the different situations.

4.1 Description of measurements

The following sections will discuss if *fragmentation* is a major issue when sending data through low energy networks, and which of the protocols described in chapter 2 is the most efficient to use when the goal is to get as high goodput as possible. Data will be sent through the network, containing a payload of constant length. Wireshark will be a central , and then increasing the packet size to see the changes. These problems are central in the discussion of objective O.3 and O.4.

Before these experiments started, the expected results was that sending a small amount of data at a time would not be preferable, because of the needed bytes to set up the connection, header files and so on. It was not known how big the packages needed to be before it would be considered *profitable* to send.

When sending BLE packets over the network, observations from the system shows that the maximum packet size over BLE is 31 bytes. Each of these packages needs a header field of 4 bytes, meaning 27 bytes left for useful data. However, to start the connection at all, 76 byte is needed, meaning three BLE packets. The ratio between *useful* and *needed* (known as *goodput* and *throughput*) data transferred therefore start out very poorly if the payload sent is very small.The best possible percentage of useful data we can hope to achieve will also be limited by this, 27 bytes goodput and

4 bytes header field, shown in the following calculation.

$$\frac{27 \text{ byte}}{31 \text{ byte}} * 100 \% = 87,094776 \% \approx 87,1 \% \quad (4.1)$$

In the physical system the number will be a lot lower than this because 6LoWPAN packets also require some additional fields for each packet.

4.2 Possible limitations in the Network

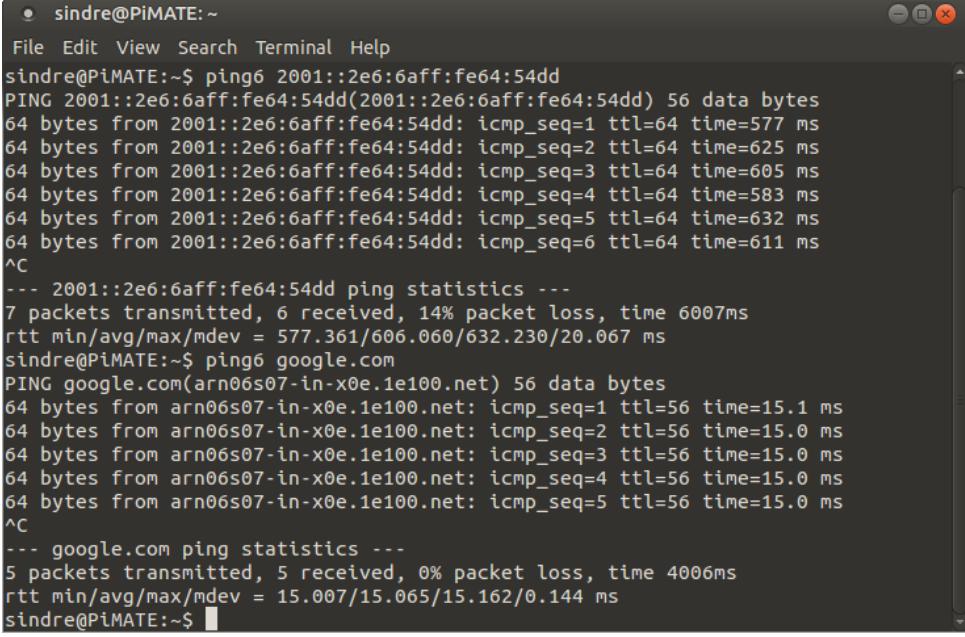
4.2.1 Stable transfer rate

As soon as the end nodes of the network could communicate with the Raspberry Pi using CoAP, the next step was to test the transfer rate of the connection. To measure the network transfer rate, *ping6* was used. This is a software tool used to test networks using IPv6 in a network. The results is measured in ms used for every Round Trip Time.

```
ping6 2001::2e6:6aff:fe64:54dd
ping6 google.com
```

When tested, the connection turns out to be very slow and in some cases very unstable, especially at maximum transfer rate. In the test of ping shown in figure 4.1 the connection between the Raspberry Pi and the nRF52 had 14 % packet loss, 1 out of 7 packets. This was the first test carried out, and the connection became a lot faster in tests later than this, but the CoAP CON has in general got a higher stability at maximum sending rate than CoAP NON. After a test period it was therefore decided that the best solution for NON would be to gather data from sensors at a higher rate, and store them in the nRF52 temporarily. Every second all the measured values are being transferred to the Raspberry Pi, the temporarily values are deleted and the measurement continues. This has proven to be a very stable solution, with successful tests over several days. CON can handle more frequent transportations than this in this system, on average 4 times per second. See the test shown in chapter 4.6. Figure 2.9 shows the initial set up of a NON connection, where the stable transfer rate of one second can be seen at the timestamps at the bottom of the figure.

Results from this first test period showed an approximate average of 250 ms RTT. In total 10 different measurements at different time where performed, an example can be seen in figure 4.2. These measurements was performed over using different versions of nRF52s, and a different amount of these devices connected to the central Raspberry Pi at once. This is considered quite slow in such a system, and way



```

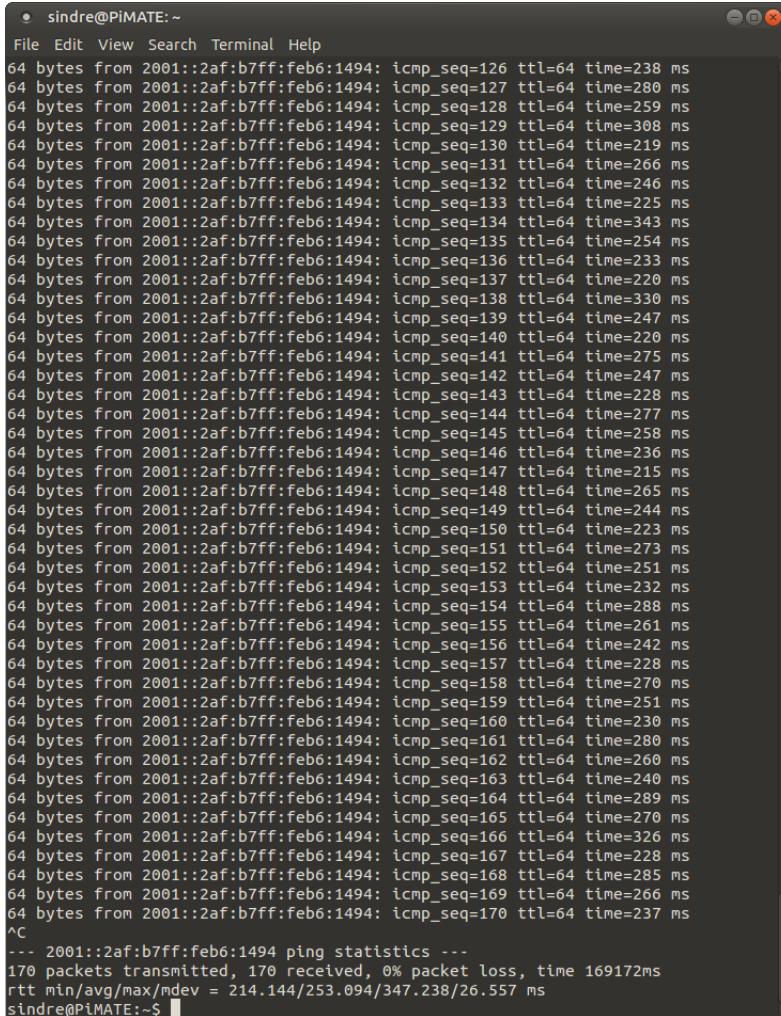
sindre@PiMATE:~ 
File Edit View Search Terminal Help
sindre@PiMATE:~$ ping6 2001::2e6:6aff:fe64:54dd
PING 2001::2e6:6aff:fe64:54dd(2001::2e6:6aff:fe64:54dd) 56 data bytes
64 bytes from 2001::2e6:6aff:fe64:54dd: icmp_seq=1 ttl=64 time=577 ms
64 bytes from 2001::2e6:6aff:fe64:54dd: icmp_seq=2 ttl=64 time=625 ms
64 bytes from 2001::2e6:6aff:fe64:54dd: icmp_seq=3 ttl=64 time=605 ms
64 bytes from 2001::2e6:6aff:fe64:54dd: icmp_seq=4 ttl=64 time=583 ms
64 bytes from 2001::2e6:6aff:fe64:54dd: icmp_seq=5 ttl=64 time=632 ms
64 bytes from 2001::2e6:6aff:fe64:54dd: icmp_seq=6 ttl=64 time=611 ms
^C
--- 2001::2e6:6aff:fe64:54dd ping statistics ---
7 packets transmitted, 6 received, 14% packet loss, time 6007ms
rtt min/avg/max/mdev = 577.361/606.060/632.230/20.067 ms
sindre@PiMATE:~$ ping6 google.com
PING google.com(arn06s07-in-x0e.1e100.net) 56 data bytes
64 bytes from arn06s07-in-x0e.1e100.net: icmp_seq=1 ttl=56 time=15.1 ms
64 bytes from arn06s07-in-x0e.1e100.net: icmp_seq=2 ttl=56 time=15.0 ms
64 bytes from arn06s07-in-x0e.1e100.net: icmp_seq=3 ttl=56 time=15.0 ms
64 bytes from arn06s07-in-x0e.1e100.net: icmp_seq=4 ttl=56 time=15.0 ms
64 bytes from arn06s07-in-x0e.1e100.net: icmp_seq=5 ttl=56 time=15.0 ms
^C
--- google.com ping statistics ---
5 packets transmitted, 5 received, 0% packet loss, time 4006ms
rtt min/avg/max/mdev = 15.007/15.065/15.162/0.144 ms
sindre@PiMATE:~$ 

```

Figure 4.1: Comparison: ping nRF52 and ping google.com

beneath the transfer limitations of both BLE, 6LoWPAN and CoAP, as explained in chapter 2. Another factor could be limited power supply and computational power, but it is not clear what is the main cause at this point. This will regardless be a major limitation in the network.

The general conclusion from these initial tests is therefore that CoAP CON is stable at lower transfer interval than CoAP NON in this system. CON can in best case send a message every 250th ms, which is very good compared to the high RTT in this network. NON has shown unstable results in the initial tests. Because of this, it was decided to only send messages once every second. This makes quite a huge difference when testing the different protocols. From this starting point it is expected that CON can send a lot more *goodput* per second, but NON requires less power to send each message. In addition it is expected that NON will get a higher percentage of goodput compared through the total throughput, since no ACKs are required in this solution.



```

● sindre@PiMATE: ~
File Edit View Search Terminal Help
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=126 ttl=64 time=238 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=127 ttl=64 time=280 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=128 ttl=64 time=259 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=129 ttl=64 time=308 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=130 ttl=64 time=219 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=131 ttl=64 time=266 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=132 ttl=64 time=246 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=133 ttl=64 time=225 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=134 ttl=64 time=343 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=135 ttl=64 time=254 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=136 ttl=64 time=233 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=137 ttl=64 time=220 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=138 ttl=64 time=330 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=139 ttl=64 time=247 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=140 ttl=64 time=220 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=141 ttl=64 time=275 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=142 ttl=64 time=247 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=143 ttl=64 time=228 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=144 ttl=64 time=277 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=145 ttl=64 time=258 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=146 ttl=64 time=236 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=147 ttl=64 time=215 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=148 ttl=64 time=265 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=149 ttl=64 time=244 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=150 ttl=64 time=223 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=151 ttl=64 time=273 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=152 ttl=64 time=251 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=153 ttl=64 time=232 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=154 ttl=64 time=288 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=155 ttl=64 time=261 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=156 ttl=64 time=242 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=157 ttl=64 time=228 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=158 ttl=64 time=270 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=159 ttl=64 time=251 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=160 ttl=64 time=230 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=161 ttl=64 time=280 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=162 ttl=64 time=260 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=163 ttl=64 time=240 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=164 ttl=64 time=289 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=165 ttl=64 time=270 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=166 ttl=64 time=326 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=167 ttl=64 time=228 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=168 ttl=64 time=285 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=169 ttl=64 time=266 ms
64 bytes from 2001::2af:b7ff:feb6:1494: icmp_seq=170 ttl=64 time=237 ms
^C
--- 2001::2af:b7ff:feb6:1494 ping statistics ---
170 packets transmitted, 170 received, 0% packet loss, time 169172ms
rtt min/avg/max/mdev = 214.144/253.094/347.238/26.557 ms
sindre@PiMATE:~$ 

```

Figure 4.2: Ping nRF52, different time

4.2.2 Packet fragmentation

In Internet Routing, fragmentation is known as the action of splitting data into smaller packets, to satisfy the maximal limits of the different technologies or protocols used (e.g. BLE and 6LoWPAN in the network described in this thesis). Each of these packets needs header fields of a certain size, or other requirements. In a network of microcontrollers described in this thesis, fragmentation can be a factor that needs to be taken into account to optimize the goodput of the system. This will be a central part of the testing, and will therefore be explained in detail in the following section.

To better understand fragmentation, imagine a train with carriages as shown in Figure 4.3. To be able to operate at all, the train needs a locomotive with an engine driver, a conductor and a cafe carriage. As soon as these things are already there, the company owning the train gets better and better off for every passenger buying a ticket. Lets assume that every carriage can carry 4 employees and 27 passengers, to make it directly comparable to the BLE packets in the network. Eventually all the carriages will be full, and a decision has to be made if it will be profitable to fit another carriage. It will in general be most profitable to use as many carriages as the locomotive can handle, and to fill up every carriage as much as possible. It will however not be a good idea to connect another carriage if there will only be one additional passenger sitting there, since the extra weight of the carriage adds unnecessary additional weight to the train set compared to the income.

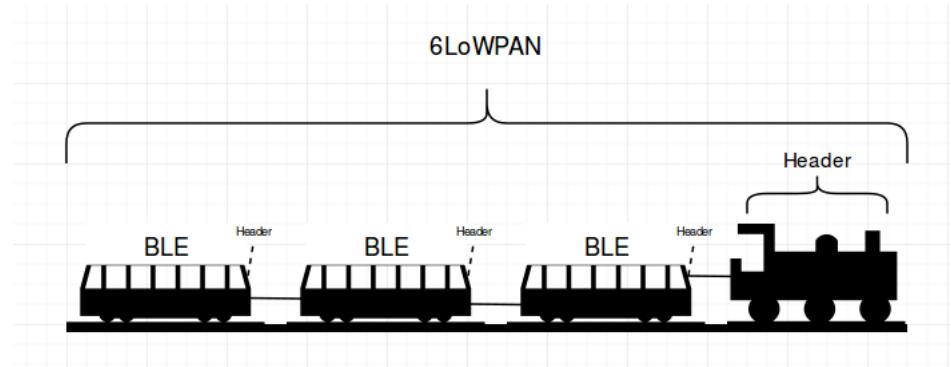


Figure 4.3: Packet fragmentation - train comparison

In this example, the locomotive and employees are the 6LoWPAN packet, that are needed no matter what to get the train working. Each additional carriage is a BLE packet. The goal is therefore to find the maximal number of passengers compared to the cost of adding additional carriages, in other words the maximal number of bytes compared to the number of packets sent. This is known as fragmentation, fragmenting data into smaller pieces to satisfy the maximal limitations of packet sizes in the different protocols. This can be exploited by a system developer to maximize goodput compared to throughput in the network.

4.3 Measurements

As explained in Chapter 4.1.1, CoAP can be split into two different main sections. CON messages can be sent quite frequently, but every message needs to get an ACK before the next message can be sent. This means that it is quite fast, but a lot of

packets needs to be transported through to get usable data at the other end. The other alternative is NON, where each message does *not* need an ACK.

Table 4.1: Wireshark CoAP CON 0 bytes

Number	Time	Protocol	Length	Info
36	3.7471	CoAP	72	ACK, MID:57083, 2.05 Content
37	3.7759	CoAP	113	CON, MID:57084, GET
38	3.9571	HCI_ACL	31	Rcvd [Reassembled in #40]
39	3.9584	HCI_ACL	31	Rcvd [Continuation to #38]
40	4.0274	L2CAP	5	Rcvd Connection oriented channel
41	4.0367	L2CAP	58	Sent Connection oriented channel
42	4.0368	L2CAP	50	Sent Connection oriented channel
43	4.0975	L2CAP	16	Rcvd LE Flow Control
44	4.0977	HCI_EVT	7	Rcvd Number of Completed Packets
45	4.1678	HCI_EVT	7	Rcvd Number of Completed Packets
46	4.0275	CoAP	72	ACK, MID:57084, 2.05 Content
47	4.0366	CoAP	113	CON, MID:57085, GET

Table 4.1 shows the most basic example of a capture of packets in Wireshark¹. The full capture can be seen in the Appendix A. In this case an empty char array was sent, meaning an goodput equal to 0 byte. All of these bytes are therefore sent to route packages through the network. The maximum of 31 bytes per BLE packet have been exceeded twice, meaning that three packets needed to be sent. The first packet is labeled *[Reassembled in #40]*, the second *[Continuation to #38]* and the last *Connection oriented channel*. After this, the ACK packages follows, two packages of 58 and 50 bytes, respectively. The last bytes received tells how many packages was completed, as a built in feature in BLE HCI and ACL. All of these packages can fit into one 6LoWPAN packet, since the total number of bytes are less than 270 bytes.

Note that packet number 46 and 47 in table 4.1 has got a timestamp that indicates that they originally was sent from the end node in the network as packet number 41 and 42, but used longer time than the other packets sent through the network at the same time. The main reason for this is of course that they are bigger than the rest of the packets, but since the network limit should be much higher than this it can maybe be seen as a weakness that this gives a clear impact even at these small values.

¹When measuring packet sizes, all measurements had the same result when the size of data was constant. The tables therefore takes only one of the measurements at a time in account. All the measured data can be found on <https://www.github.com/sische/MasterThesis>

Table 4.2: Wireshark CoAP CON 100 bytes

Number	Time	Protocol	Length	Info
29	2.4514	HCI_ACL	31	Rcvd [Reassembled in #36]
30	2.4516	HCI_ACL	31	Rcvd [Continuation to #29]
31	2.2425	CoAP	173	ACK, MID:16354, 2.05 Content
32	2.2538	CoAP	113	CON, MID:16355, GET
33	2.5217	HCI_ACL	31	Rcvd [Continuation to #29]
34	2.5218	HCI_ACL	31	Rcvd [Continuation to #29]
35	2.5907	HCI_ACL	31	Rcvd [Continuation to #29]
36	2.5921	L2CAP	25	Rcvd Connection oriented channel
37	2.6099	L2CAP	58	Sent Connection oriented channel
38	2.6100	L2CAP	50	Sent Connection oriented channel
39	2.6610	L2CAP	16	Rcvd LE Flow Control
40	2.6621	HCI_EVT	7	Rcvd Number of Completed Packets
41	2.5922	CoAP	173	ACK, MID:16355, 2.05 Content
42	2.3097	CoAP	113	CON, MID:16356, GET
43	2.7311	HCI_EVT	7	Rcvd Number of Completed Packets

In table 4.2, 100 bytes of goodput is being sent through using CON. The same basic packages needed are still there, but in addition the 100 bytes of data is added. This means adding more BLE packets, but also that the percentage of useful data sent through is a lot higher, approximatley 55 % in this case. By doing several experiments like this, it was possible to create the graph in Figure 4.4. This shows the correlation between goodput and throughput compared to the number of packets sent, measured every 10th byte from 0 byte to 200 bytes large packets.

In this particular case shown in 4.4 it makes no sense to send less than 50 bytes of useful data at once, since more than 50 % of the bytes sent will be header files. This is comparable to having a locomotive and full crew at disposal, but only a few or none paying passengers. The best possible result is to have every carriage full, with 27 passengers and 4 employees. Since at least 4 bytes out of every 31 sent needs to be used to header information, the best possible result will be 87,1 %, as shown in equation 4.1. In mathematics, this is described as a *horizontal asymptote* since the distance between the graph and $y = 87,1$ will approach zero after an infinite number of bytes has been transferred. The graph will therefore converge to 87,1 %, just as the values climbing in figure 4.4, even before packet size of 200 bytes.

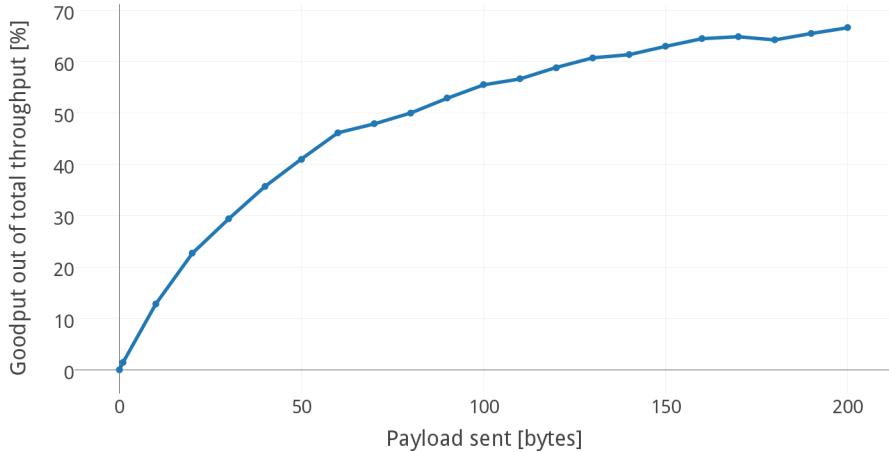


Figure 4.4: CoAP CON, 0-200 bytes sent

4.3.1 Discussion

Even though this first test was done with a very limited amount of data transferred, it is easy to see that the curve clearly flattens out and forms the shape of a *parabola* with a vertical *directrix* at $x = 0$. The next step would be to transfer a larger amount of data, to verify that the assumptions that the graph will converge to the asymptotic value $y = 87,1$ when $\lim_{x \rightarrow \infty}$. The limitations of transfer rate is not nearly yet met by either BLE or 6LoWPAN. This test will therefore be explained in the next section.

Since there is already a clear trend in the form of the graph in figure 4.4 even before the transfer rate reaches 200 bytes, it makes sense to also test the other version included in CoAP, CON. If it is possible to find a way of transportation that could give a higher mathematical maximum, and also get to this limit faster, it could be very profitable to the system. It also makes sense to test CoAP NON because it doesn't need to send an ACK for every packet, as CON does. Maybe this means that the header files can be split up in another way, and that the useful amount of data sent through therefore will be higher.

To see what happened when the limit of a 6LoWPAN packet was breached in the system, tests was being set up to send larger amounts of data than 200 bytes. This would also be a good way to test if the percentage of goodput will converge to 87,1 %, only considering BLE packets. The following test and examples will therefore send a fixed number of bytes at once from 0 to 1000 bytes (1 kB), with a 50 byte interval. As before, the messages are being sent as soon as possible, meaning approximately four messages per second on average using CoAP CON. In addition will NON be

tested in detail.

4.3.2 CoAP NON comparison

A CoAP NON request does not require a response in form of an ACK. This means that the 108 bytes sent to and handled by the end node can be skipped, which means less computational power in the end node and network capacity to the node is needed. This solution makes sense to use in networks where the demand for all data is low, since packets can be lost without the use of ACKs. As explained in chapter 4.1.1, the transfer frequency is limited using NON in this system, due to unstable results in tests at the beginning of the set up. The transfer rate is therefore set to one per second for this protocol.

4 LEDs image?

Table 4.3: Wireshark CoAP NON 0 bytes

Number	Time	Protocol	Length	Info
90	23.0405	HCI_ACL	31	Rcvd [Reassembled in #92]
91	23.0411	HCI_ACL	31	Rcvd [Continuation to #90]
92	23.1107	L2CAP	9	Rcvd Connection oriented channel
93	23.1109	CoAP	76	NON, MID:14, 2.05 Content

A basic example of the CoAP NON connection is shown in table 4.3. The entire Wireshark capture can be seen in Appendix A. This is directly comparable to table 4.1, that shows a Wireshark capture of CoAP CON packages. It is easy to see that a lot fewer packages needs to be sent using BLE, without the use of ACKs. The total amount of bytes sent is $31+31+9=71$ bytes, meaning three BLE packages and one 6LoWPAN packet. This is less than half of what was needed using CoAP CON, where the 108 ACK packages was needed in addition. The packets are still recognizable the same way as before, the first packet is labeled [*Reassembled in #40*], the second [*Continuation to #38*] and the last *Connection oriented channel*.

Fewer packages sent means less energy used, less network capacity needed and less computational power in the end node. Hopefully this will lead to a higher percentage of goodput compared to throughput as well. it would therefore be interesting to compare the rest of the measured values.

Table 4.4 shows the case where 100 bytes of data are sent using CoAP NON. This is directly comparable to the test shown in table 4.2, where the same amount of data is sent over CON. The overall structure is the same as before. Since it is only one packet noted *Reassembled in #n*, which marks the beginning of a new 6LoWPAN packet. The total amount sent must therefore be under 270 bytes, which makes

Table 4.4: Wireshark CoAP NON 100 bytes

Number	Time	Protocol	Length	Info
39	11.0363	CoAP	177	NON, MID:2, 2.05 Content
40	11.9452	HCI_ACL	31	Rcvd [Reassembled in #45]
41	11.9465	HCI_ACL	31	Rcvd [Continuation to #40]
42	12.0154	HCI_ACL	31	Rcvd [Continuation to #40]
43	12.0168	HCI_ACL	31	Rcvd [Continuation to #40]
44	12.0857	HCI_ACL	31	Rcvd [Continuation to #40]
45	12.0858	L2CAP	29	Rcvd Connection oriented channel
46	12.0860	CoAP	177	NON, MID:3, 2.05 Content

sense. The NON packet size is here 177 bytes, compared to 173 bytes in CON, which represents one more header field of 4 bytes needed in NON. Overall a small difference in the packets containing data, but as expected a lot more packets needs to be sent in total in CON.

Using these measurements the following plot could be drawn.

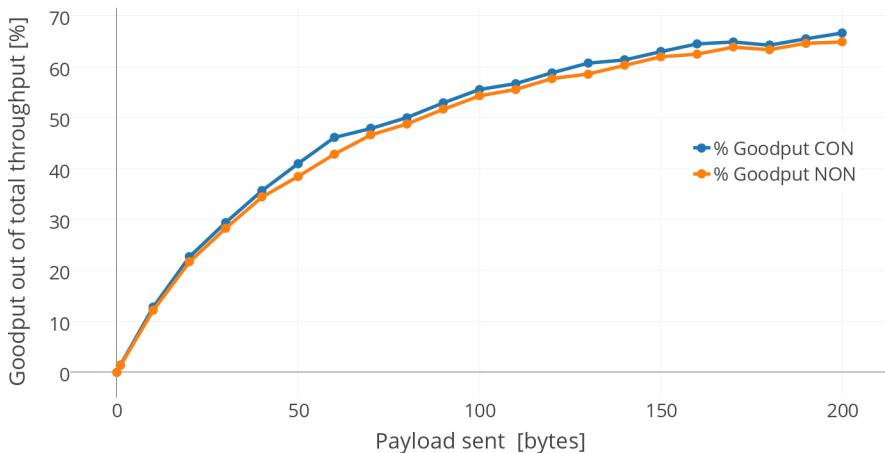
**Figure 4.5:** CON vs NON 0-200 bytes

Figure 4.5 shows the comparison between sending between 0 and 200 bytes of useful data through the network at once. Keep in mind that this does not show sending rate per time (which will be discussed in chapter), but percentage of the data sent that is useful data. CON can be sent much more often than NON in practice. It could therefore maybe be expected that this could give NON an advantage. . NON does not need to send ACKs for every package, which should be an advantage

concerning to maximize throughput. Still it is the more complex and more frequently sent CON that gets the best results in this test, with a small margin.

4.3.3 CoAP, testing with more data

Table 4.5 shows a bigger and more complex case, where a payload of 700 byte is being sent at once. In total 889 bytes are being sent in this process, with a CON packet size of 774 bytes. This gives a percentage of goodput at 78.74 %. The maximum packet length of a 6LoWPAN packet in this system of 270 bytes is therefore exceeded. This can be seen in the table, after 8 BLE packages of 31 bytes each has been sent, there is only room for 22 bytes in the last packet before the 6LoWPAN packet has reached its maximal capacity. This is repeated several times, once for each 6LoWPAN packet, until the last BLE packets at the size of 17 bytes. After this the standard packages for ACK and *Number of completed packages* follows. This is in general a good example on how fragmentation of packets works in this system.

Table 4.5: Wireshark CoAP CON 700 bytes

Number	Time	Protocol	Length	Info
53	3.2570	CoAP	774	ACK, MID:35081, 2.05 Content
54	3.2727	CoAP	113	CON, MID:35082, GET
55	3.4671	HCI_ACL	31	Rcvd [Reassembled in #63]
56	3.4747	HCI_ACL	31	Rcvd [Continuation to #55]
57	3.5374	HCI_ACL	31	Rcvd [Continuation to #55]
58	3.5375	HCI_ACL	31	Rcvd [Continuation to #55]
59	3.6077	HCI_ACL	31	Rcvd [Continuation to #55]
60	3.6078	HCI_ACL	31	Rcvd [Continuation to #55]
61	3.6767	HCI_ACL	31	Rcvd [Continuation to #55]
62	3.6782	HCI_ACL	31	Rcvd [Continuation to #55]
63	3.7533	L2CAP	22	Rcvd Connection oriented channel
64	3.7534	L2CAP	16	Sent LE Flow Control
65	3.8172	HCI_EVT	7	Rcvd Number of Completed Packets
66	3.8172	HCI_ACL	31	Rcvd [Reassembled in #74]
67	3.8185	HCI_ACL	31	Rcvd [Continuation to #66]
68	3.9575	HCI_ACL	31	Rcvd [Continuation to #66]
69	3.9577	HCI_ACL	31	Rcvd [Continuation to #66]
70	4.0266	HCI_ACL	31	Rcvd [Continuation to #66]
71	4.0342	HCI_ACL	31	Rcvd [Continuation to #66]
72	4.0979	HCI_ACL	31	Rcvd [Continuation to #66]
73	4.0982	HCI_ACL	31	Rcvd [Continuation to #66]
74	4.1671	L2CAP	22	Rcvd Connection oriented channel
75	4.2372	HCI_ACL	31	Rcvd [Reassembled in #83]
76	4.2373	HCI_ACL	31	Rcvd [Continuation to #75]
77	4.3075	HCI_ACL	31	Rcvd [Continuation to #75]
78	4.3076	HCI_ACL	31	Rcvd [Continuation to #75]
79	4.3777	HCI_ACL	31	Rcvd [Continuation to #75]
80	4.4466	HCI_ACL	31	Rcvd [Continuation to #75]
81	4.4480	HCI_ACL	31	Rcvd [Continuation to #75]
82	4.4481	HCI_ACL	31	Rcvd [Continuation to #75]
83	4.5170	L2CAP	22	Rcvd Connection oriented channel
84	4.5871	HCI_ACK	31	Rcvd [Reassembled in #86]
85	4.5875	HCI_ACL	31	Rcvd [Continuation to #84]
86	4.6574	L2CAP	17	Rcvd Connection oriented channel
87	4.6731	L2CAP	58	Rcvd Connection oriented channel
88	4.6732	L2CAP	50	Rcvd Connection oriented channel
89	4.6577	CoAP	774	ACK, MID:35082, 2.05 Content
90	4.6729	CoAP	113	NON, MID:35083, GET

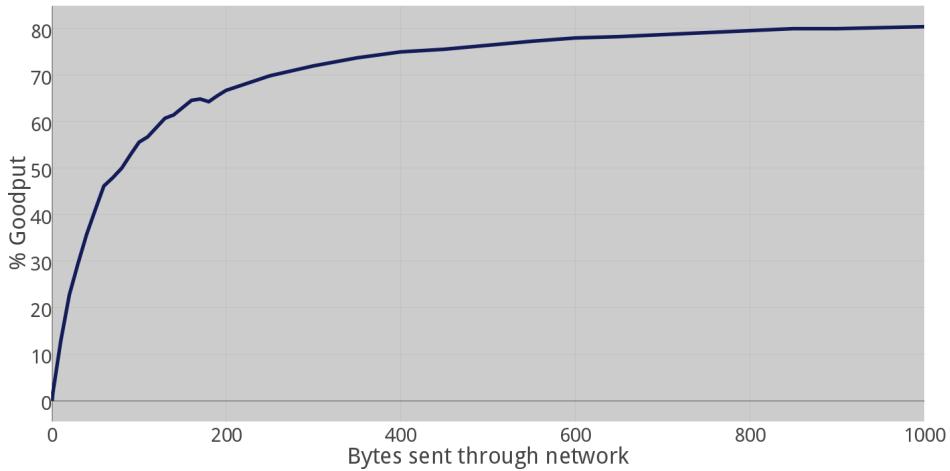


Figure 4.6: CoAP CON plot, 200 bytes to 1 kB

Using these results it was possible to plot the graph in figure 4.6 . Here it is easy to see the same trends as in 4.4, but in more detail over a wider span of bytes sent. These results are as expected after the previous tests, and in compliance with the calculations done in equation 4.1.

Make graph more clear

In this example points in the graph was denoted every 50th byte sent. This gives us

set in graph for 0-1000 before this, to see the flatness?

Table 4.6: Wireshark CoAP NON 700 bytes

Number	Time	Protocol	Length	Info
264	57.1476	CoAP	777	NON, MID:3, 2.05 Content
265	57.2177	HCI_ACL	31	Rcvd [Reassembled in #273]
266	57.2178	HCI_ACL	31	Rcvd [Continuation to #265]
267	57.2879	HCI_ACL	31	Rcvd [Continuation to #265]
268	57.2943	HCI_ACL	31	Rcvd [Continuation to #265]
269	57.3570	HCI_ACL	31	Rcvd [Continuation to #265]
270	57.3583	HCI_ACL	31	Rcvd [Continuation to #265]
271	57.4272	HCI_ACL	31	Rcvd [Continuation to #265]
272	57.4286	HCI_ACL	31	Rcvd [Continuation to #265]
273	57.4975	L2CAP	22	Rcvd Connection oriented channel
274	57.4979	L2CAP	16	Sent LE Flow Control
275	57.5676	HCI_ACL	31	Rcvd [Reassembled in #284]
276	57.5685	HCI_EVT	7	Rcvd Number of Completed Packets
277	57.5753	HCI_ACL	31	Rcvd [Continuation to #275]
278	57.6378	HCI_ACL	31	Rcvd [Continuation to #275]
279	57.6379	HCI_ACL	31	Rcvd [Continuation to #275]
279	57.7080	HCI_ACL	31	Rcvd [Continuation to #275]
280	57.7082	HCI_ACL	31	Rcvd [Continuation to #275]
281	57.7771	HCI_ACL	31	Rcvd [Continuation to #275]
282	57.7785	HCI_ACL	31	Rcvd [Continuation to #275]
283	57.7785	HCI_ACL	31	Rcvd [Continuation to #275]
284	57.8474	L2CAP	22	Rcvd Connection oriented channel
285	57.9176	HCI_ACL	31	Rcvd [Reassembled in #293]
286	57.9176	HCI_ACL	31	Rcvd [Continuation to #285]
287	57.9878	HCI_ACL	31	Rcvd [Continuation to #285]
288	57.9879	HCI_ACL	31	Rcvd [Continuation to #285]
289	58.0580	HCI_ACL	31	Rcvd [Continuation to #285]
290	58.0581	HCI_ACL	31	Rcvd [Continuation to #285]
291	58.1270	HCI_ACL	31	Rcvd [Continuation to #285]
292	58.1284	HCI_ACL	31	Rcvd [Continuation to #285]
293	58.1972	L2CAP	22	Rcvd Connection oriented channel
294	58.2673	HCI_ACK	31	Rcvd [Reassembled in #296]
295	58.2688	HCI_ACL	31	Rcvd [Continuation to #294]
296	58.3378	L2CAP	20	Rcvd Connection oriented channel
297	58.3379	CoAP	777	NON, MID:4, 2.05 Content

Table 4.6 shows the case where 700 bytes were sent at once through the network, using CoAP NON. The NON packet size is at 777 bytes, which is as expected from the previous tests. This means 4 bytes larger than the same test using CON, meaning an additional header field.

$$\frac{78,47}{78,74} \approx 0,9966 \rightarrow 100\% - 99,66\% = 0,34\% \quad (4.2)$$

Calculations in equation 4.2 show that the goodput here is 78,47 %, compared to 78,74 % in CON. The difference between these two is 0,34 %, which in this case is considered *very* small. This can also be seen clearly in 4.9. Because of this, it was concluded that the results for using NON and CON can be considered as negligible for transmissions larger than 1 kB. Tests with larger amounts of data than this at once was therefore not conducted in this project.

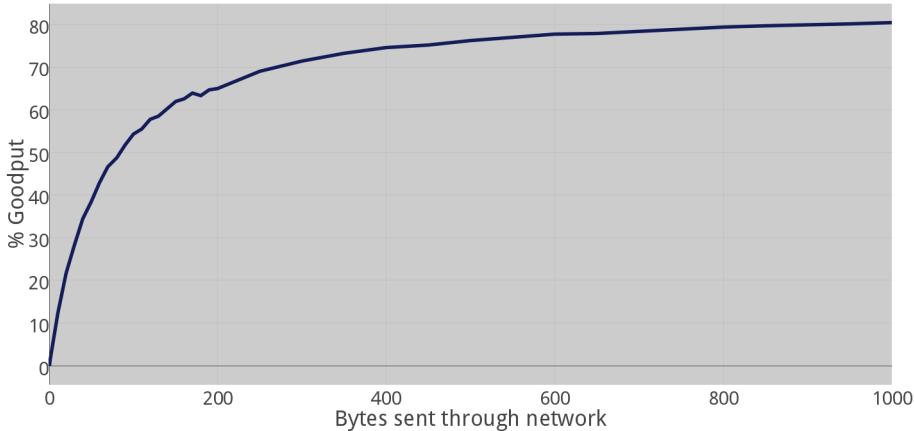
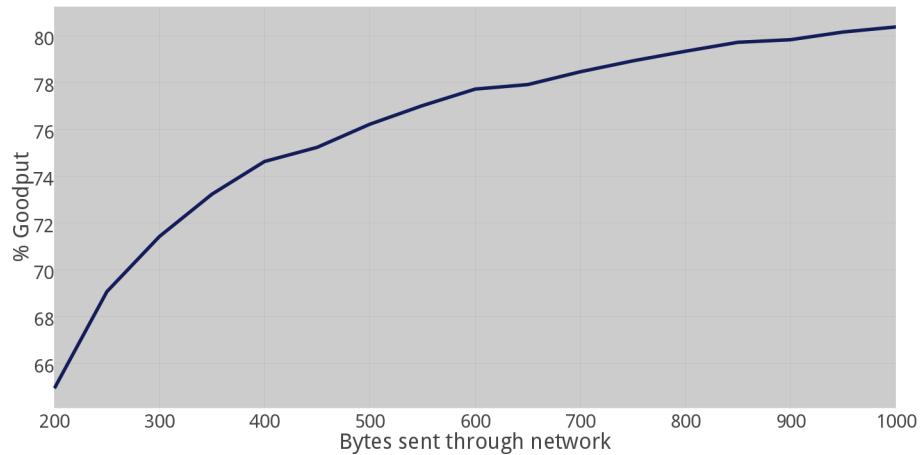


Figure 4.7: NON 0-1000 bytes

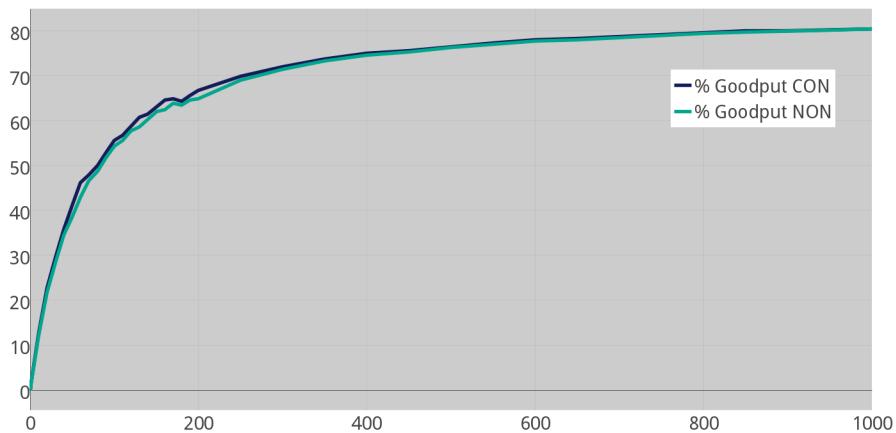
The entire scope of the tests done on CoAP NON in this system is shown in figure 4.7. Given these results, it can be concluded that to send less data than 200 bytes at the time is not preferable, since the percentage of goodput compared to the total amount sent can be very low. On the other hand, the graph stabilizes around 75-80 %. Given these measurements it looks like 400 bytes and bigger packets are preferable in this system. The system shows no signs of weakness as the packet size grows, and it will therefore be possible to send as large packets as needed until the limitations of BLE with the same amount of goodput at about 80 %.

Remove figure
4.8 200-1000?

**Figure 4.8:** NON 200-1000 bytes

4.3.4 Discussion

4.4 Comparison

**Figure 4.9:** CON vs NON 0-1000 bytes

Insert graph
of ALL bytes
sent?

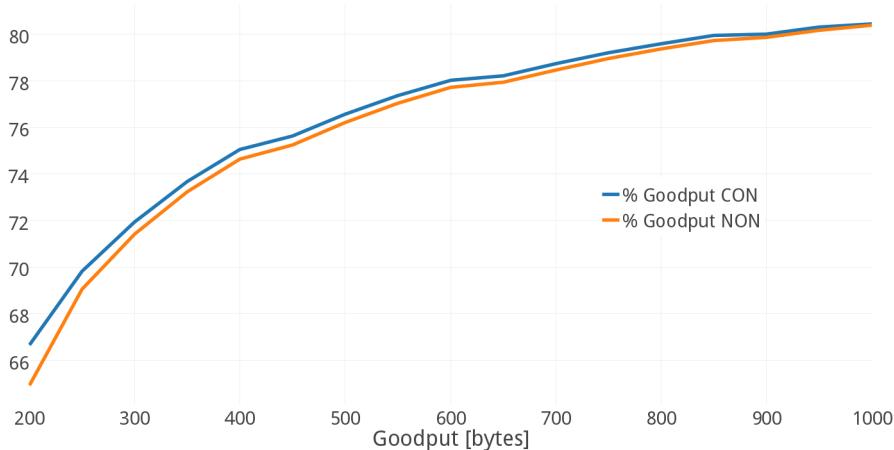


Figure 4.10: CON vs NON 200-1000 bytes

4.4.1 Goodput per time interval

Previous sections in this chapter has shown the percentage of bytes sent through that has been goodput, useful data, compared to the total amount of bytes. This is a good overview of how the protocols are able to exploit the network, and tells a lot about the different protocols. In a real world scenario however, the actual *throughput per time* would be more relevant, since this tells how much data can be transported for every second.

CoAP CON and NON has been compared in this thesis, but in the system build NON was quite unstable at high transfer rates, as explained in chapter 3.1. Because of this, CON seems like a better solution only considering the number of bytes transferred per second. As it turns out, this depends.

As seen in Table , this might be a too early conclusion.

insert table

The table shows timestamps of packets received on the Raspberry Pi, sent with both CON and NON. Packets was captured with Wireshark, and the timestamp is created by Wireshark on the form *number of seconds since start of capture*. The first value for each packet size in the table therefore approximately notes the number of seconds from the connection starts until the first packet containing useful data has arrived ². The first thing that is noticeable here is the big difference before useful data can be received. Equation ?? shows the calculations of average start time on

²values far off from the expected results due to e.g. connection issues have been excluded in calculations

CON, which is a lot higher than for NON shown in equation ?? . The main reason for this is that the NON needs to have a connection establishment using CON packets with ACKs without data before NON packets can be transferred. In addition severe connection issues was experienced in a much higher grade using NON than CON, especially for packets larger than 500 bytes, as shown in table .

Refer to table

Re-write

There are in general two ways to measure throughput compared to time. Either by calculating the number of seconds it takes to transfer a known number of bytes, or the number of bytes that are transported on average every second. To calculate this, measurements shown in table was used. This represent measurements done several times, and graphs used here are drawn by average values³.

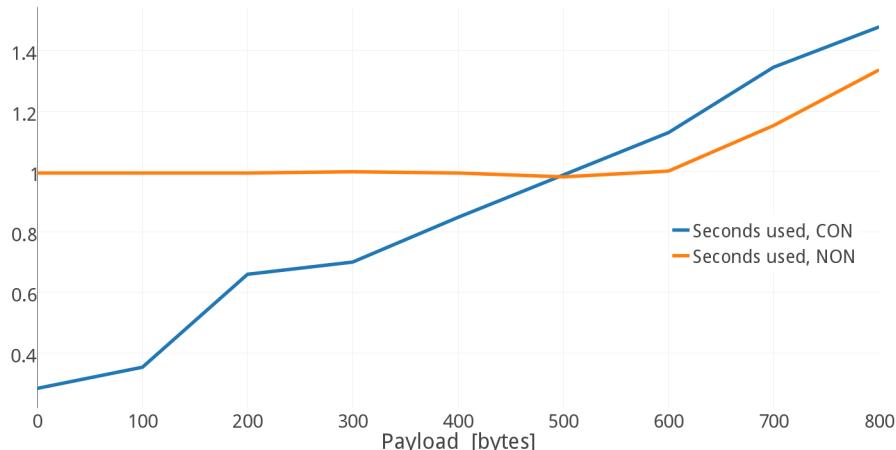


Figure 4.11: Time used per packet

To get a better understanding of this comparison, take a look at the graph in figure 4.11. As explained in chapter 3, tests has shown that CoAP NON is only stable in this system if the transfer frequency is set fixed to once every second. CoAP CON on the other hand can transfer more often if the payload is small. The figure shows how long it takes for the different protocols to transfer a fixed number of bytes of useful data. For instance, it only takes 0.35 seconds to transfer 100 bytes goodput in CON, while this takes 1 second using NON. However, as the graph shows, if the goodput is 500 byte, both versions of the protocol uses 1 second to transfer the data. When the payload reaches 600 byte, CON needs to use 1.12 seconds to transfer the data, while NON still is able to only use 1 second. After this CON is about 150 ms

³All measurements can be seen on GitHub: <https://github.com/sische/MasterThesis>

slower than *non* to transfer the same payload, as both plots rise with linear growth. In this case it is quite easy to see a trend - CON is definitely faster at small rates of data, below 500 byte. If the payload is bigger than this, glsnon will be preferable, only taking the time to transfer a given number of data one way into account.

From the other approach, it is possible to look at how many bytes it is possible to send every second using the two different versions of the protocol. Figure 4.12 shows the direct correlation between the number of bytes sent every second. For instance: using CoAP CON, it takes on average 7.93 seconds to transport 15 packets of 200 bytes goodput.

$$\frac{200\text{byte} * 15\text{packets}}{7.93\text{seconds}} \approx 378\text{byte/second} \quad (4.3)$$

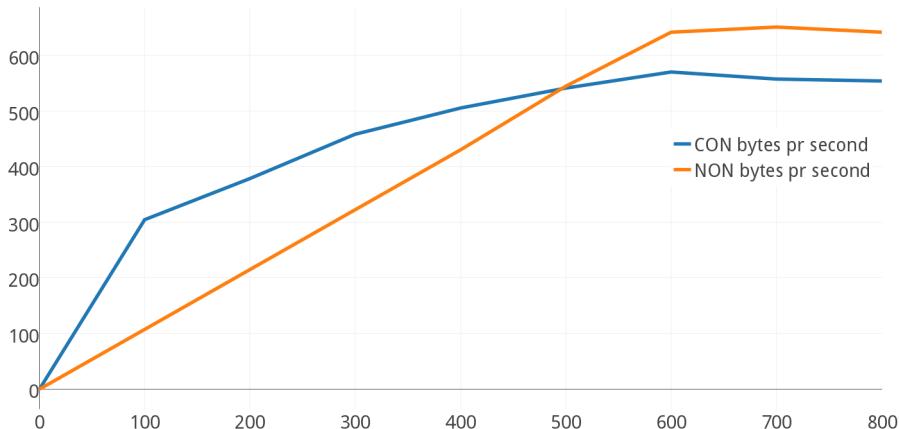


Figure 4.12: Number of bytes per second

In this case both plots starts at *0 byte/second*, since the payload is 0. After this, the graphs have quite different forms. NON has a very linear rise, all the way up to 600 byte payload. This makes sence, since figure 4.11 shows that all up to this size has taken 1 second. CON can transfer more often, and this difference can clearly be seen here. When transferring a payload of 100 byte, is almost three times faster at *305 byte/second* compared to *108 byte/second* using NON. The conclusion here will then be the same as in the last graph, CoAP CON is much more efficient for a small amount of data, but for payload bigger than 500 byte NON is preferable.

4.4.2 Bytes sent through network, best and worst case

These previous two tests shows the throughput per time, while the tests earlier in the thesis has focused on goodput compared to throughput, how much of the data sent is useful data. Since these microcontrollers are used as end nodes in the network, it is natural to assume that they will run on battery power only. In this case it is preferable that they do as little work as possible, meaning also handle as few packets as possible. It will therefore be compared how many packets that needs to go through the end nodes in the different cases, CON and NON ⁴.

The main argument for trying the NON version of CoAP in this network, was that fewer bytes needed to be sent through the network, meaning less overall usage of the network. This is very relevant in a case where the network should be taken to its maximum capacity with several sensors and microcontrollers.

But, as seen in figure 4.13, this turns out not to always be the case. The figure shows best and worst case of how many bytes that needs to be sent to transfer a given number of payload. For example, using NON it takes 576 byte to transfer 500 byte payload in best case, but 856 byte in worst case. This is because of the architecture of the two different versions of CoAP. Even though NON does not require ACKs, underlying parts of the bluetooth architecture like ACL adds on some support for this. Also, to prevent a situation where the end node sends data forever without anyone receiving the data, ACK messages are still being sent regularly, approximately every 15th second in this network. This means, as shown in figure 4.13, that NON *normally* requires a lower amount of bytes to transport a given payload, but in *worst case scenario* it needs even more bytes than CON.

The main question to comparison comes down to how often the worst case occurs in comparison to best case. Sending payload of 500 byte in both cases, NON results in most best case scenarios, while CON results in *only* worst case scenarios. In specific numbers, this gives an average of *598 bytes* sent for NON, and *791 bytes*. This gives us on average:

$$\frac{500 \text{ byte payload}}{\frac{791 \text{ bytes} * 15 \text{ packets}}{15}} * 100\% \approx 63,21\% \text{ payload} \quad (4.4)$$

$$\frac{500 \text{ byte payload}}{\frac{(576 \text{ bytes} * 13 \text{ packets}) + (856 \text{ bytes} * 2 \text{ packets})}{15}} * 100\% \approx 83,56\% \text{ payload} \quad (4.5)$$

⁴Before the test, it was clear that fewer packets are needed using NON, since no ACKs are required. The test is therefore done to see *how much* fewer packets are needed here

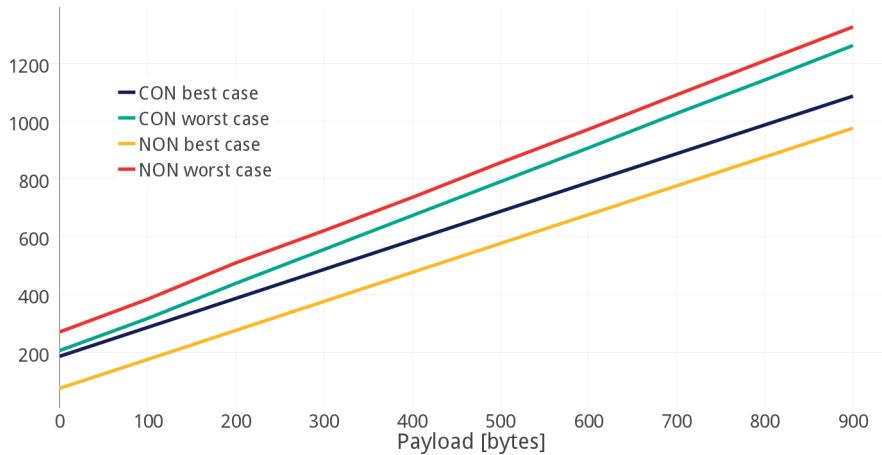


Figure 4.13: Number of bytes per second

From these results it can be concluded that even though NON is considerably worse in worst case than CON,

4.5 Quantity test

[Remove?](#)

This section will show a test of several nRF52 devices connected to the same Pi at the same time, to ensure stability and performance in the network. Even though this puts more pressure on both the network and the Pi, it is not expected to be considerably noticed in the transportation of packets.

4.6 Summary

As a summary of this chapter, the positive and negative aspects of the two versions of CoAP that has been tested will be directly compared to get a more clear understanding of the discoveries that has been made. The results are shown in 4.7.

Table 4.7 shows all the main results found in conjunction with the comparison of CoAP CON and NON in the network presented in this thesis. Results from the table shows that in 7 of the 10 cases presented, NON shows the best results. This should still not be a final result without discussion. As discussed in chapter , NON has been considerably more unstable than CON during the test period. It was not possible to get a stable connection when sending more frequently than once every second,

[Add chapter ref](#)

Table 4.7: Comparison of CON and NON

Case	CON	NON	Comments
Need of ACKs	Yes	No	Accational connection test at 16+7+7 bytes in both cases
Minimum number of bytes needed for empty CoAP message	74+104	76	
Fastest for payload <500 byte	X		Almost 3x faster payload <10 byte
Fastest for payload >500 byte		X	On average 0,2 s faster for payload >600 byte
Average time [seconds] to send 200 bytes payload	0,66	1,00	
Average time [seconds] to send 700 bytes payload	1,35	1,15	
Highest measured goodput [bytes] per second	554	642	
Overall best stability in the network	X		
Calculated lowest power consumption		X	
% payload of all packets sent through network (in case of 500 byte sent)	63,21	83,56	On average 20% more efficient in the number of packet sent in total

and the connection became unstable if the payload was greater than 800 bytes. As a conclusion from this table it is clear to say that NON works best if the conditions are right, sending data every second with a payload between 500 and 800 bytes. In other cases than this, CON works better in the practical experiments presented.

Chapter 5

Discussion

5.1 Set up network

O.1: Build a star network of microcontrollers

This objective was fulfilled by using the Raspberry Pi as a central node and nRF52s as end nodes. Central points in the solution was the use of a version of Linux with pre-configured kernel of version 4.15 or later on Raspberry Pi 3. In addition it was important to understand how prefix in glsipv6 works, and how this can be used on a bluetooth device. In this solution the end nodes woth nRF52s works as servers, while the central Raspberry Pi works as a client requesting services from these servers.

R.1: Which technologies and transport protocols are suitable in such a network?

BLE is the obvious network technology to use to the end nodes, simply because this is the only antenna fitted to the nRF52. This version of bluetooth is designed to use a minimal amount of energy and still be reliable and fast, which is central criterias in such a network. As a result of this 6LoWPAN also seemed like a suitable communication protocol, both because it is made to work together with BLE and because it is an up an coming technology that is assumed to be more and more used in the coming years. In the application layer the two main choices was between CoAP and MQTT. Because of time restrictions CoAP was chosen to be studied in depth in this thesis, which worked as expected.

IDEA: "Collect" the strings put out in the first chapter, which told us the challenges in a system of microcontrollers. This chapter could tell what we learned from the system, and what is still a challenge. Or should all of this be in the Result chapter?

5.2 Gather sensor data

O.2: Connect sensors to the end-nodes to collect data

This objective was partially fulfilled. An accelerometer was connected to two of the end points in the network, with the goal of gathering vibration data to be sent through the network. Problems with getting the accelerometer to communicate properly with the end node, meaning that it was possible to gather acceleration data, but not as frequently as expected. Getting reliable vibration data was therefore not possible. Due to these problems, in addition to that the scope of this thesis has a limited time frame, it was decided to measure the different aspects of the network with simulated data. This would eliminate the possibility of margin of error due to sensor error, and can easily be added later by future work with a larger time frame.

Even though this objective was not fully completed, a lot of coding was done on the nRF52 to be able to initialize and use the accelerometer connected. This code can be useful for later projects in future works, and important methods from the code will therefore be included in appendix C.

5.3 Send data through network

O.3: Gather information of the data sent through the network

This object was fulfilled by using both Python scripts and Wireshark on the Raspberry Pi to measure the packets sent through the network. Different Python scripts was used to get data from the servers, save data locally after receiving, drawing graphs directly to represent the data, or forward the data to another device or online storage facility. All these code samples can be seen in appendix A. Wireshark was used to monitor the live capture of packets, and to manually do a detailed analysis of how packets where fragmented differently in the different scenarios.

R.2: What are the main limitations when it comes to transporting data?

Already in the first tests of *ping* shown in chapter 4.1.1, it became clear that the major limitation in this network would be the initial transfer speed. This was not expected, and was not included as one of the main objectives in this thesis, which concentrates more on the analysing the data sent through the network, and transport protocols used. This problem is assumed to be caused by a problem in a lower level of the protocol stack, and will be left for future work to solve. Other than this, limitations found has been to get the network stable. Several of the solutions tested was not able to transfer data at all, or only for a very short period (< 20 seconds). But when a stable solution is found the link can be open as long as needed, successful tests have been stable for several days. During these tests it was discovered that the

message ID implemented in CoAP uses an 16 bit counter. After 65536 messages have been sent the counter will be reset, and changed to 18 bits. This did not affect the performance in this system, and will most likely not be a problem in other systems either.

R.3: Are the microcontrollers powerful enough to gather data this frequently?

To gather detailed acceleration data to be analysed in another node of the network, it is assumed that a measuring frequency of 1MHz is needed, which is 1000 times every second. . The maximum achieved in this system was to call a method from the main loop 11 times every second, and then read a measured values from the accelerometer 150 times for each of these 11 method calls. This adds up to 1650 measuring points every second in a best case scenario. Yes, this is fast enough to gather data, even though problems explained in chapter 3 means this practical experiment will be left for future work in this thesis. The programming code referred to here can be seen in appendix C.

Source?

5.4 Analyse data

O.4: Analyse and discuss the gathered information

This object was fulfilled by analysing the data by printing out table and plotting graphs. Using basic tools like this it was possible to document both the differences and similarities in the different protocols tested in this thesis. The results where presented and discussed in detail in chapter 4.

R.4: Could data analysing be done in the end nodes in this network?

Referring to the result from research question R.3, where the maximum capacity of the microcontroller is needed to capture acceleration data from the accelerometer to get the desired quality of the data, and forward this to a central node. The end nodes are running on battery power, and is already consuming a lot of energy. To do even more calculations in these nodes will not be preferable in this network. The answer is therefore no, more detailed analysing and representation of the data should be done in a central node with more computational power and better access to power sources.

5.4.1 Power consumption

5.5 Ease of use

5.5.1 Raspberry Pi

5.5.2 nRF52

In the case of the system built in this thesis, the small CR 2032 batteries were drained so fast that an additional power source was needed to keep a stable and reliable system, since tests have shown that the probability of an nRF52 disconnecting from the connected BLE service is higher at low battery. This meant connecting either a power bank with higher capacity or drain power from an outlet using a micro USB.

Chapter 6

Conclusion and Future Work

In this thesis I have used microcontrollers, sensors and single-board computers to build and an IoT network and test the choices when transporting data through the network, and discussed analysis of data with respect to power usage.

The results described in chapter 5 shows that both versions of CoAP tested works in a network like this, but they have different qualities and should therefore be used in different settings. CON is most efficient to send small chunks of data where the extra power usage to send ACKs isn't a problem. NON is the most efficient for payloads bigger than 500 bytes, where the average sending frequency was 200 ms faster than the same size using CON.

6.1 Future Work

6.1.1 Microcontrollers

6.1.2 Sensors

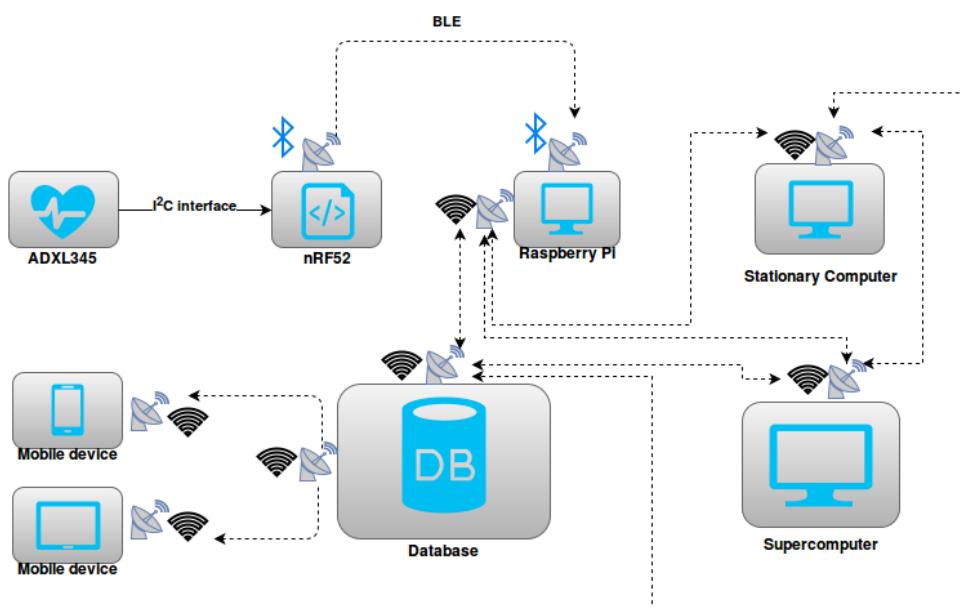


Figure 6.1: Complete system architecture

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Chapter A

Appendix A

Appendix A contains samples of programming code used to gather and transfer data in the IoT system described in this thesis.

This first example is the most simple, using *GET* commands to get the measured values from CoAP CON. All the python scripts uses example code from Nordic Semiconductor in

```
import asyncio
from aiocoap import *

SERVER_ADDR = '2001::2AF:B7FF:FEB6:1494'
SERVER_PORT = '5683'
SERVER_URI = 'coap://[' + SERVER_ADDR + ']:' + SERVER_PORT

@asyncio.coroutine
def main():
    protocol = yield from Context.create_client_context()
    sequence_number = 1
    number_of_measurements = 200
    while sequence_number < number_of_measurements:
        request_acceleration = Message(code=GET)
        request_acceleration.set_request_uri(SERVER_URI + '/lights/led3')
        response = yield from protocol.request(request_acceleration).response
        print('Acceleration'+str(sequence_number)+': '+str(response.code))
        sequence_number += 1

if __name__ == "__main__":
    asyncio.get_event_loop().run_until_complete(main())
```

This script was written to get observable values stored in a local file.

```

import asyncio
from aiocoap import *

#SERVER_ADDR = '2001::211:64ff:fea5:8542'
#SERVER_ADDR = '2001::2e6:6aff:fe64:54dd'
#SERVER_ADDR = '2001::2af:b7ff:feb6:1494'
#SERVER_PORT = '5683'
#SERVER_URI = 'coap://[' + SERVER_ADDR + ']:' + SERVER_PORT

responseList = []
def observe_handle(response):
    f = open('/home/sindre/Desktop/desktopAccelValues', 'a')
    if response.code.is_successful():
        responseList = bytes.decode(response.payload)
        for i in range(0, (len(responseList))):
            f.write((str(responseList[i]) + ','))
        f.write(responseList)
        f.write('\n')
        print("Written to file!")
    else:
        print('Error code %s' % response.code)
    f.close()
@asyncio.coroutine
def main():
    protocol = yield from Context.create_client_context()
    request = Message(code=GET)
    request.set_request_uri(SERVER_URI + '/lights/led3')
    request.opt.observe = 0
    observation_is_over = asyncio.Future()
    try:
        requester = protocol.request(request)
        requester.observation.register_callback(observe_handle)
        response = yield from requester.response
        exit_reason = yield from observation_is_over
        print('Observation is over: %r' % exit_reason)
    finally:
        if not requester.response.done():
            requester.response.cancel()
        if not requester.observation.cancelled:
            requester.observation.cancel()

if __name__ == "__main__":
    asyncio.get_event_loop().run_until_complete(main())

```

This example is to get observable measurements directly displayed in a graph:

```

import asyncio
from aiocoap import *
import matplotlib.pyplot as plt

#SERVER_ADDR = '2001::211:64ff:fea5:8542'
SERVER_ADDR = '2001::2e6:6aff:fe64:54dd'
#SERVER_ADDR = '2001::2af:b7ff:feb6:1494'

SERVER_PORT = '5683'
SERVER_URI = 'coap://[' + SERVER_ADDR + ']:' + SERVER_PORT

responseList = []
drawValuesList = []

def observe_handle(response):
    if response.code.is_successful():
        responseList = bytes.decode(response.payload)
        print(responseList)

    for i in range (0,len(responseList)):
        drawValuesList.append(int(responseList[i]))
    plt.plot(drawValuesList)
    plt.xlabel('Measurement number')
    plt.ylabel('Acceleration values')
    plt.show()

else:
    print('Error code %s' % response.code)
@asyncio.coroutine

def main():
    protocol = yield from Context.create_client_context()
    request = Message(code=GET)
    request.set_request_uri(SERVER_URI + '/lights/led3')
    request.opt.observe = 0
    observation_is_over = asyncio.Future()
    try:
        requester = protocol.request(request)
        requester.observation.register_callback(observe_handle)
        response = yield from requester.response
        exit_reason = yield from observation_is_over
        print('Observation is over: %r' % exit_reason)
    finally:

```

```
if not requester.response.done():
    requester.response.cancel()
if not requester.observation.cancelled:
    requester.observation.cancel()

if __name__ == "__main__":
    asyncio.get_event_loop().run_until_complete(main())


---


```

Chapter **B**

Appendix B

Appendix B contains screenshots and detailed figures from the measurements done in the network built in this thesis. This is meant to be a supplement to the figures presented earlier in the thesis to give the reader a deeper understanding of the system. In addition to the measurements presented here, all data gathered from the system and code used will be public GitHub, <http://github.com/sische/MasterThesis>.

Goodput	Throughput	NON packet size	(Goodput/Throughput)*100
0	71	76	0
1	73	78	1,37
10	82	87	12,20
20	92	97	21,74
30	75	107	30,0
40	85	117	47,06
50	99	127	50,51
60	109	137	55,05
70	119	147	58,82
80	133	157	60,15
90	143	167	62,94
100	153	177	65,36
110	167	187	65,87
120	177	197	67,80
130	191	207	68,06
140	207	217	69,65
150	211	227	71,09
160	225	237	71,11
170	235	247	72,34
180	253	257	71,15
190	263	267	72,24
200	277	277	72,20

Chapter C

Appendix C

Appendix C contains samples of programming code written to read acceleration data from the Adafruit ADXL345 accelerometer connected to the nRF52 using the I2C interface. This code was not being used in the testing of this thesis, as explained in chapter 3. The code has been included and explained so it can be used by others in later projects.

The following code sample in C programming is parts of the main function in the file *main.c*. From here methods *accelerometer_init* and *start_measuring* are being called to initialize the different registers of the accelerometer, and start the measuring from the main loop.

```
int main(void){
    uint32_t err_code;

    app_trace_init();
    leds_init();
    timers_init();
    accelerometer_init();

    ...

    for (;;)
    {
        power_manage();
        start_measuring();
    }
}
```

`accelerometer_init` will initialize the different registers to be able to read from the accelerometer. These registers should first be defined in a header file along with information about the slave address and which nRF52 pins that represented SCL and SDA, to clarify the code.

// Part of header file:

```
#define ADXL345_SLAVE_ADDRESS      0x53

#define TWI_SCL_M                  27 //!< Master SCL pin
#define TWI_SDA_M                  26 //!< Master SDA pin

#define X_AXIS_OFFSET               0x1E
#define Y_AXIS_OFFSET               0x1F
#define Z_AXIS_OFFSET               0x20
#define DATA_RATE_AND_POWER_INIT   0x2C
#define POWER_SAVING_INIT          0x2D
#define INTERRUPT_ENABLE_CONTROL   0x2E
#define DATA_FORMAT_CONTROL         0x31
#define READ_X_AXIS                 0x32
#define READ_Y_AXIS                 0x34
#define READ_Z_AXIS                 0x36
```

```
// Initialize accelerometer in main.c file:
```

```
static void accelerometer_init()
{
    write_reg(DATA_FORMAT_CONTROL, 0x00, 2);
    write_reg(POWER_SAVING_INIT, 0xFF, 2);
    write_reg(INTERRUPT_ENABLE_CONTROL, 0xFF, 2);
    write_reg(X_AXIS_OFFSET, 0xFF, 2);
    write_reg(Y_AXIS_OFFSET, 0xFF, 2);
    write_reg(Z_AXIS_OFFSET, 0xFF, 2);
}
```

The initialization of the accelerometer calls the function `write_reg`, which is used to write to a register.

```
static uint32_t write_reg(uint8_t register_address, uint8_t data_to_write,
    uint8_t size)
{
    ret_code_t ret;
```

```

    uint8_t addr8 = (uint8_t)register_address;
    ret = nrf_drv_twi_tx(&m_twi_master, ADXL345_SLAVE_ADDRESS, &addr8, 1,
        true);
    if(NRF_SUCCESS != ret)
    {
        break;
    }
    ret = nrf_drv_twi_tx(&m_twi_master, ADXL345_SLAVE_ADDRESS,
        &data_to_write, size, false);
    return ret;
}

```

After this initialisation process is successful, the *start_measuring* can begin.

```

static void start_measuring()
{
    char stringa[150];
    char anotherString[150];

    for (int j = 0; j < 150; j++)
    {
        int r = read_reg(READ_Z_AXIS, 0x00);
        int t = numberOfMeasurements++;
    }

    sprintf(stringa, "%d,", numberOfMeasurements);

    for (in i=0; i < 200; i++)
    {
        if (stringa[0] == '\0')
        {
            measuringCounter = i;
            break;
        }
        else
        {
            if (!stringToSendOccupied)
            {
                appendChar(stringToSend, 150, stringa[i]);
            }
        }
    }
}

numberOfMeasurements = 0;

```

}

This method calls the function *read_reg*, to read the registers that have been set to update earlier.

```
static uint16_t read_reg(uint8_t register_address, uint8_t data_returnValue)
{
    uint16_t rd;
    ret_code_t ret;
    uint8_t buff[2];
    uint8_t addr8 = (uint8_t)register_address;

    ret = nrf_drv_twi_tx(&m_twi_master, ADXL345_SLAVE_ADDRESS, &addr8, 1,
        true);
    if(NRF_SUCCESS != ret)
    {
        break;
    }
    ret = nrf_drv_twi_rx(&m_twi_master, ADXL345_SLAVE_ADDRESS, buff, 2,
        false);
    rd = (uint16_t)(buff[0] | (buff[1] << 8));

    return rd;
}
```

After this it is possible to get the acceleration value from another point in the code, to be stores in a char array *str until it is being sent.

```
static void acceleration_value_get(coap_content_type_t content_type, char **
str)
{
    stringToSendOccupied = true;

    strcpy(newString, stringToSend);
    *str = newString;
    stringToSend[0] = '\0';

    stringToSendOccupied = false;
}
```
