



**NTNU – Trondheim**  
Norwegian University of  
Science and Technology

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

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## Abstract

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After this fourth paragraph, we start a new paragraph sequence. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of

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## Sammendrag

Sikkerheten til nesten all offentlig nøkkel-kryptografi er basert på et vanskelig beregnbarhetsproblem. Mest velkjent er problemene med å faktorisere heltall i sine primtallsfaktorer, og å beregne diskrete logaritmer i endelige sykliske grupper. I de to siste tiårene, har det imidlertid dukket opp en rekke andre offentlig nøkkel-systemer, som baserer sin sikkerhet på helt andre type problemer. Et lovende forslag, er å basere sikkerheten på vanskeligheten av å løse store likningssett av flervariabe polynomlikninger. En stor utfordring ved å designe slike offentlig nøkkel-systemer, er å integrere en effektiv “falluke” (trapdoor) inn i likningssettet. En ny tilnærming til dette problemet ble nylig foreslått av Gligoroski m.f., hvor de benytter konseptet om kvasigruppe-strengtransformasjoner (quasigroup string transformations). I denne masteroppgaven beskriver vi en metodikk for å identifisere sterke og svake nøkler i det nylig foreslalte multivariable offentlig nøkkel-signatursystemet MQQ-SIG, som er basert på denne idéen.

Vi har gjennomført et stort antall eksperimenter, basert på Gröbner basis angrep, for å klassifisere de ulike parametrene som bestemmer nøklen i MQQ-SIG. Våre funn viser at det er store forskjeller i viktigheten av disse parametrene. Metodikken består i en klassifisering av de forskjellige parametrene i systemet, i tillegg til en innføring av konkrete kriterier for hvilke nøkler som bør velges. Videre, har vi identifisert et unødvendig krav i den originale spesifikasjonen, som krevde at kvasigruppene måtte oppfylle et bestemt kriterie. Ved å fjerne denne betingelsen, kan nøkkelerings-algoritmen potensielt øke ytelsen med en stor faktor. Basert på alt dette, foreslår vi en ny og forbedret nøkkel-genereringsalgoritme for MQQ-SIG, som vil generere sterkere nøkler og være mer effektiv enn den originale nøkkel-genereringsalgoritmen.



## Preface

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# List of Algorithms



# List of Acronyms

**6LoWPAN** IPv6 over Low Power Wireless Personal Area Networks.

**ACK** Acknowledgement.

**BLE** Bluetooth Low Energy.

**CoAP** Constrained Application Protocol.

**DNS** Domain Name System.

**GUI** Graphical User Interface.

**HCI** Host Controller Interface.

**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.

**LAN** Local Area Network.

**M2M** Machine-to-machine.

**MQTT** Message Queueing Telemetry Transport.

**NDP** Neighbor Discovery Protocol.

**NTNU** Norwegian University of Science and Technology.

**OS** Operating System.

**PAN** Personal Area Network.

**radvd** Router Advertisement Daemon.

**RTT** Round Trip Time.

**SPI** Serial Peripheral Interface.

**TCP** Transmission Control Protocol.

**TFTP** Trivial File Transfer Protocol.

**UDP** User Datagram Protocol.

# Chapter 1

# Introduction

## 1.1 Motivation

This is a test in the introduction chapter.

## 1.2 Methodology

## 1.3 Structure



# Chapter 2

## Background

This thesis describes the setup and usage of an End-to-End Internet of Things (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 Bluetooth Low Energy (Bluetooth Smart)

Bluetooth Low Energy (BLE) is a wireless technology for short range communication developed by the Bluetooth Special Interest Group [4]. The idea was to create a low energy single-hop network solution for Personal Area Networks (PANs). A major advantage of this is that Bluetooth 4.0 is already a well established technology in cell phones, laptops and several other devices, and BLE can use several similarities with this. The 6LoWPAN Working Group has recognized the importance of BLE in IoT [5].

The protocol stack of BLE has two main parts, the controller and the host. In the system used 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 HCI. 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.

In the case of the network used in this thesis, when the BLE slave has been connected to a master, it stops searching for other masters, and it is not possible to connect to several masters. This means that we are only able to create a *star network*, not a *mesh network*. This could possibly be an idea for improvement later. Other than this, BLE seems like a very good alternative in this project.

Check out: Mikhail Galeev - BLE

## 4 2. BACKGROUND

### 2.1.1 HCI

### 2.1.2 ACL

## 2.2 6LoWPAN

IPv6 over Low Power Wireless Personal Area Networks (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 was proposed by Geoff Mulligan and the 6LoWPAN Working Group in [7]. In this paper the advantage of 6LoWPAN is explained as the easiest way to use standard protocols such as User Datagram Protocol (UDP), Transmission Control Protocol (TCP), Internet Control Message Protocol (ICMP), glsdns and Trivial File Transfer Protocol (TFTP), since they can be used directly without the requirement of a translation mechanism. They are already adapted to run over IPv6.

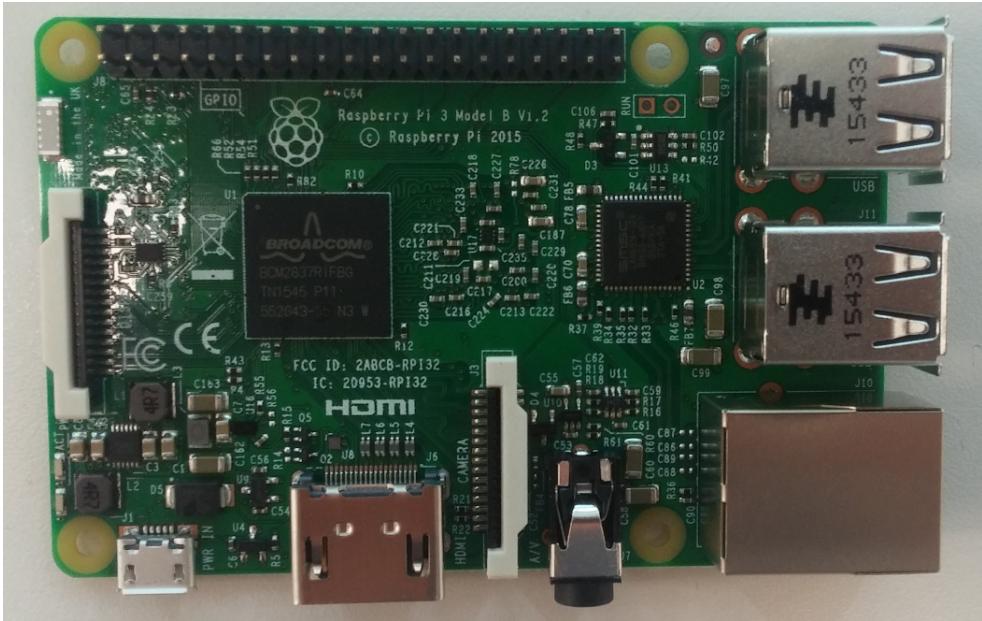
In addition to this, the paper argues that 6LoWPAN was developed to be used in small sensor networks. Implementations can fit into 32Kb flash memory parts, which is smaller than Zigbee and Zensys (which is the two main comparisons made in the paper). It also uses an impressive header compression mechanism that allows the transmission of IPv6 packets in 4 bytes, much less than the standard 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). This means that a device can send only the required part of the stack header, and does not need to include header fields for networking and fragmentation [5].

6LoWPAN was therefore a natural tool to use in this project, in the IPv6 and BLE based network.

## 2.3 Raspberry Pi

Developed by Element 14, the Raspberry Pi has become a central tool for many people wanting to get started using microcomputers. This was therefore a natural starting point for us as well.

The Raspberry Pi 2 model B+ is the second generation of its kind, and its *ARMv7 processor* has approximately six times the performance of the predecessor [3]. With a USB Bluetooth dongle connected, it is quite simple to enable both 6LoWPAN and BLE, given that the right Unix kernel has been used in the Operating System (OS) of the Pi.



**Figure 2.1:** Raspberry Pi 3

Later in this thesis, the processing power of the Pi compared to performing calculations in the end-points will be a central topic for discussion.

### 2.3.1 Ubuntu Mate

Along with the Raspberry Pi, we needed a good and stable operating system with a kernel that supported the 6LoWPAN architecture. For this, Ubuntu 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.

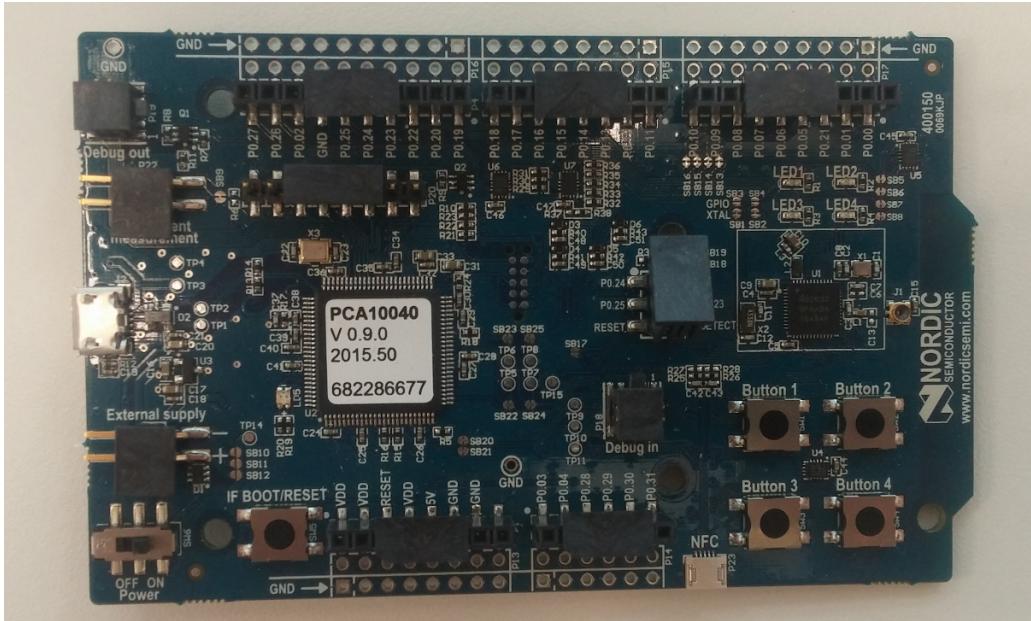
## 2.4 nRF52

The nRF52 is developed by Nordic Semiconductor, and is being described as a family of highly flexible, multi-protocol system on chip.

[2]

Running at 64MHz it racks up impressive stats: EEMBC Coremark® score of 215 and 58 Coremark®/mA. Built in a cutting edge 55nm process technology the

## 6 2. BACKGROUND



**Figure 2.2:** Nordic Semiconductor NRF52

nRF52 Series is architected for today's need for speed, speed to carry out increasingly complex tasks in the shortest possible time and return to sleep, conserving precious battery power. Introducing a Cortex-M4F processor at its heart, it is the most capable Bluetooth Smart SoC on the market today. With a brand new multiprotocol radio architecture limits are pushed even further for Bluetooth Smart: A total link budget of 100dBm, -96dBm sensitivity, +4dBm output power and -42dBm selectivity, it is built to exist reliably and effectively in a busy 2.4GHz band. Couple this RF resilience with outstanding power consumption: 5.3mA at 0dBm TX output power and 5.4mA RX it is miserly with power when getting things done on-air.

Designed with wealth of digital and analog interfaces and peripherals, there's something to cover every design requirement. The demands of today's Bluetooth smart single chip designs are increasingly varied and complex, they can range from digital audio processing, to FFT/FIR and security algorithms, to driving device displays and UIs. Whatever the task, nRF52 series has it covered.

We've truly made low power easy. We haven't just great datasheet numbers, but an automatic and adaptive power management system which combined with extensive EasyDMA and PPI makes the nRF52 Series positively frugal with power.

nRF52 Series brings NFC for the first time to a Bluetooth Smart SoC. The on-chip NFC-A tag allows developers to take advantage of NFC ‘touch-to-pair’ functionality in their designs.

Maintaining the total flexibility philosophy of the nRF51 Series, it is a flash device. With 512kB flash + 64kB RAM on chip, developers keep all the software stack flexibility and Over-The-Air Device Firmware Upgrade (OTA-DFU) features they enjoyed with the nRF51 Series.

We understand that in the world of wearables, size really is everything, so we built a device that is the smallest Bluetooth Smart SoC to date measuring as small as 3.0 x 3.2mm (CSP). With an on-chip balun and a minimum of external components it has the smallest design footprint out there.

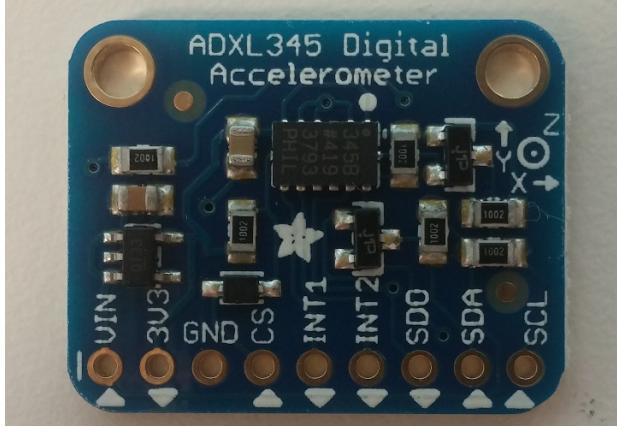
Tomorrow’s Bluetooth Smart Solutions are going to ask a lot. The nRF52 Series delivers.

#### 2.4.1 Softdevice

### 2.5 Adafruit ADXL345 Accelerometer

In order to do collect data, a sensor needed to be connected to the Nordic Semiconductor nRF52. The main thought behind the thesis was to measure vibrations, and a good accelerometer was needed. The Adafruit ADXL345 accelerometer was chosen for several reasons.

- It is the same accelerometer built in on the Zolertia Z1 microcontroller
- 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 Inter-Integrated Circuit (I2C) and Serial Peripheral Interface (SPI), which makes it easy to connect to the nRF52.



**Figure 2.3:** ADXL345 Accelerometer

## 2.6 Transport protocols

### 2.6.1 Network layers

### 2.6.2 CoAP

CoAP is a transport protocol designed to be used in constrained networks for Machine-to-machine (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 first transport protocol to test the network [8].

### 2.6.3 MQTT

Another transport protocol that could be used in such a network of microcontrollers is MQTT. This is known as a publish-subscribe based on TCP, using a MQTT broker. Norwegian University of Science and Technology (NTNU) does have a broker that is possible to use, or a broker can be rented from several other places. Here a

#### 2.6.4 radvd

### 2.7 Software tools

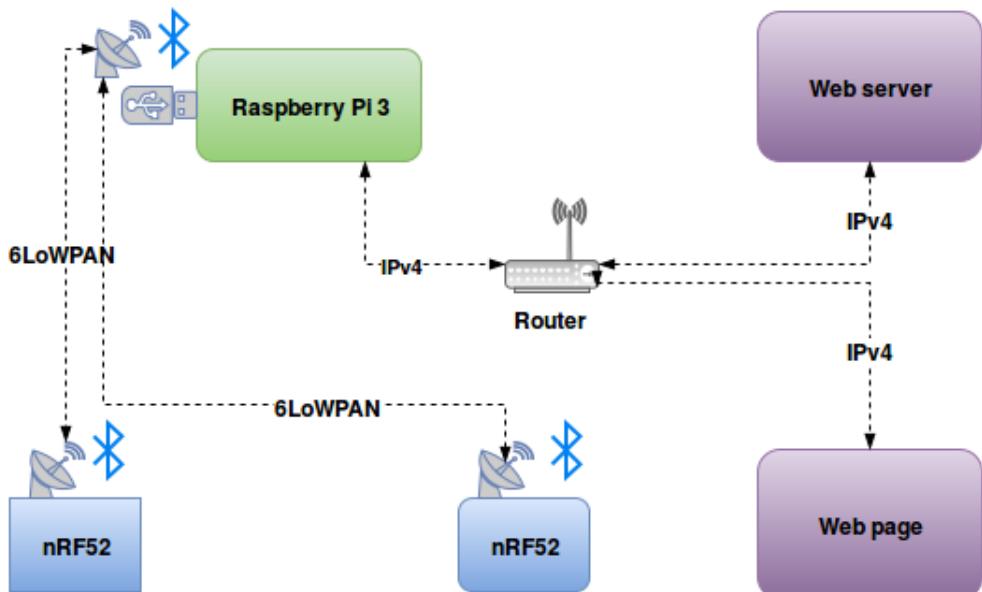
As Integrated Development Environment (IDE), the *KEIL Vision* was used, as recommended by Nordic Semiconductor (where?), for writing C programming. For other programming languages (for instance Python 3.4, HTML, CSS, JavaScript, Flask and AJAX) *Sublime Text 2* for Windows and Linux was used, as well as *Pluma* for Ubuntu Mate on the Raspberry Pi.



# Chapter 3

## System Architecture

The purpose of this thesis is to build an end-to-end system, to be able to transfer data all the way from a sensor 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 and transfer data efficiently.



**Figure 3.1:** System architecture

Figure 3.1 shows how the complete end-to-end system of this thesis is set up. In short terms, the *Nordic Semiconductor nRF52* is connected to a *Raspberry Pi 3* using 6LoWPAN and BLE. This means that they are able to communicate using

IPv6 addresses, even though the nRF52 only has a bluetooth antenna built in. The limitations of BLE means that the nRF52 can only connect to *one* device at the time. Several of these put together are therefore forming a *star network* using the *Raspberry Pi* as a central point of connection. Computations can now either be done in the end nodes at the *nRF52s*, at the *Raspberry Pi*, or forwarded to a web server or another computer with more computational power. Data can also be displayed directly to a web page from the *Raspberry Pi*.

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, from the smallest to the biggest component, to explain their computational and power capabilities, and how they can communicate efficiently.

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.

### 3.1 Connecting Raspberry Pi and nRF52

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 set connect these two together the first time. The following recipe is what worked best.

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. When this is done a resizing of the file system is needed to use all the capacity of the memory card.

To use BLE, install Bluez and radvd using *apt-get* in a *Unix terminal*:

---

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

---

To activate IPv6 forwarding, uncomment the following line (remove "#") in the file *etc/sysctl.conf*

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

Add the *bt0 interface* in *radvd.conf*:

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

Write in the *bt0 interface*

```
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*.

```
bluetooth_6lowpan
6lowpan
radvd
```

It is now possible to use the *hcitool* command.

```
hcitool lescan
```

This command will scan for BLE devices nearby, and find the bluetooth address, for instance `0211:22FF:FE33:4455`. To connect, run the following:

```
echo 1 > /sys/kernel/debug/bluetooth/6lowpan_enable
echo "connect 0211:22FF:FE33:4455 1" > /sys/kernel/debug/bluetooth/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::0211:22FF:FE33:4455
```

Using the basic example of the observable server it was easy to send CoAP messages without the need of an Acknowledgement (ACK) for every message.

## 3.2 Nordic Semiconductor example code

Nordic Semiconductor has provided several examples along with the nRF52-DK documentation, that can be used as a starting point when programming applications to the device. These files are written in the programming language *C*.

### 3.2.1 CoAP

As a first step, the nRF52 needed to communicate with the Raspberry Pi. As explained in section 2.6, a good starting point for this is to use the CoAP trasnport protocol, and the example of the use of this on the device. The *CoAP Server* and *CoAP Observer* was loaded into two different nRF52 devices, and both of them connected to the Raspberry Pi. Now radvd had to be activated on the Pi, to be able to use this as a *forwarding server*.

Figure 3.5 shows the initial CoAP example, by using two nRF52 devices, BLE over 6LoWPAN and a BLE enabled router (Raspberry Pi) on both ends in this case. As the figure 3.5 shows, the code example for the CoAP client includes two different cases:

- \* In the fist case the CoAP client acts as a client requesting services from the CoAP server. Button 1 and 2 will control light 1 and 2 on the nRF52 server,

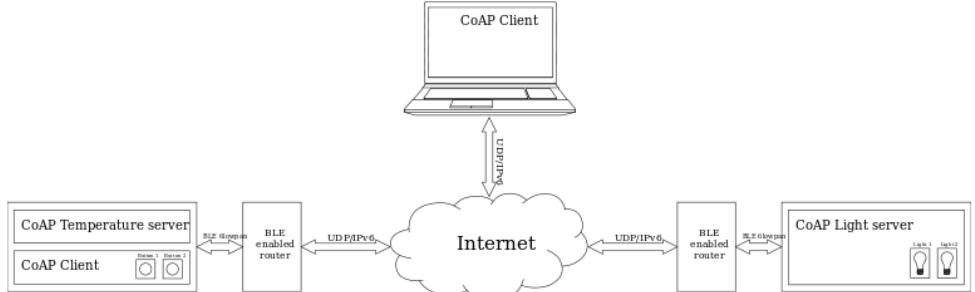


Figure 1: Setup of CoAP examples.

Figure 3.2: CoAP Client-Server communication example

which will send a conformation back if the light was changed or if something went wrong.

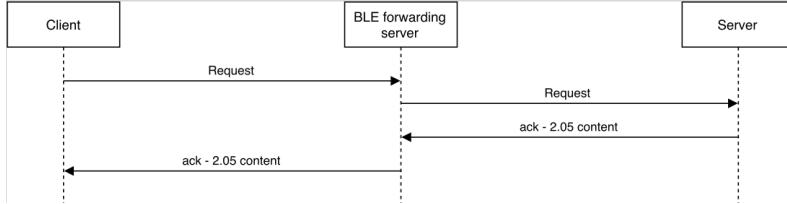
- \* In the second case the CoAP server is excluded, but the CoAP client works as a server that can handle requests from the router. In this case it is possible to use *Copper* in a *Firefox browser* on the Raspberry Pi to act as a client to request values from a simulated temperature sensor on the server. The server will then send the current simulated temperature back, or tell if something went wrong.

When packets are captured using *Wireshark*, we get the following capture:

No.	Time	Source	Destination	Protocol	Length	Info
1	0.0000000000	fe80::21a:7dff:feb1:7105	ff02::1	ICMPv6	104	Router Advertisement
2	11.6497668000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698979, GET, TKN:00 00 03 26, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
3	11.6500000000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698979, 2.05 Content, TKN:00 00 03 26
4	11.9192980000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698979, GET, TKN:00 00 03 27, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
5	12.1897680000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698979, 2.05 Content, TKN:00 00 03 27
6	12.2021430000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698971, GET, TKN:00 00 03 28, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
7	12.2021430000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698971, 2.05 Content, TKN:00 00 03 28
8	12.4630228000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698972, GET, TKN:00 00 03 29, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
9	12.7571658000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698972, 2.05 Content, TKN:00 00 03 29
10	12.7680178000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698973, GET, TKN:00 00 03 29, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
11	13.0544408000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698973, 2.05 Content, TKN:00 00 03 29
12	13.0544408000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698974, GET, TKN:00 00 03 27, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
13	13.3096605000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698974, 2.05 Content, TKN:00 00 03 27
14	13.3119945000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698975, GET, TKN:00 00 03 28, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
15	13.3119945000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698975, 2.05 Content, TKN:00 00 03 28
16	13.5985778000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698976, GET, TKN:00 00 03 29, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
17	13.8772178000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698976, 2.05 Content, TKN:00 00 03 29
18	13.9017706000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698977, GET, TKN:00 00 03 29, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
19	14.1675458000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698977, 2.05 Content, TKN:00 00 03 29
20	14.1675458000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698978, GET, TKN:00 00 03 29, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
21	14.4298040000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698978, 2.05 Content, TKN:00 00 03 29
22	14.4693306000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698979, GET, TKN:00 00 03 30, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
23	14.4693306000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698979, 2.05 Content, TKN:00 00 03 30
24	14.7182980000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698980, GET, TKN:00 00 03 31, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
25	14.9959180000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698980, 2.05 Content, TKN:00 00 03 31
26	15.0965710000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698981, GET, TKN:00 00 03 32, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
27	15.0965710000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698981, 2.05 Content, TKN:00 00 03 32
28	15.2825918000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	113	CON, MID:698982, GET, TKN:00 00 03 33, coop://[2001::2af:b7ff:feb6:1494]:5683/lights/led3
29	15.5497820000	2001::1	2001::2af:b7ff:feb6:1494	CoAP	72	ACK, MID:698982, 2.05 Content, TKN:00 00 03 33

Figure 3.3: CoAP Client-Server example Wireshark capture

This gives us the sequence diagram shown in Figure 3.4.



**Figure 3.4:** Sequence diagram CoAP Client-Server example

This works fine, and by writing a Python script running on the *Raspberry Pi* it is possible to request data by *GET messages* as soon as the *nRF52* is ready. However, as shown in figure 3.6 and figure 3.7, the network transfer rate can vary a lot. The limitations in BLE and 6LoWPAN makes this much slower than a normal IPv6 connection, and the *ping* Round Trip Time (RTT) varies from 100 ms all the way up to over 600 ms. As a comparison, to *ping google.com* from the same Raspberry Pi using IPv6 takes on average 15 ms. A comparison of this is shown in figure 3.6. This is therefore a clear limitation of sending rate in the system. Because of this, the maximum transfer rate achieved in the system using the standard CoAP server example is one message every 200 ms.

Using the standard CoAP, described as *CoAP CON* in this thesis, messages are sent with a "TCP mindset". This means that every message sent by the client must receive an ACK. This is very stable, and ensures that every message gets to its destination, but it requires a lot of unnecessary computational power in the leaf node in systems where the importance of each message is not that high. The system is meant to be used with tools for analysing, and it is not essential that data needs to get to its destination right away. In these cases there is another alternative, known in this thesis as *CoAP NON*. This is more like a "*glsudp mindset*", where each packet does *not* need an ACK. This halves the number of packages sent, saves a lot of the network as well as actions needed to be done by the nRF52 where power consumption is a huge issue. Therefore the *CoAP Observable* function looked very interesting, and will therefore be directly compared to *standard glscoap* later in this thesis.

### 3.2.2 Observable CoAP

In the given Nordic example of a CoAP observable server, the problem of unnecessary packets being sent can be resolved. Using this it is easy to set up a server that can be observed by either a nRF52 client or a BLE forwarding server. The observable end point sends a *CON-ACK request* in a given time interval to assure that the observing client is still there. As long as this message is being responded the server will continue to send data without any requirements of an ACK.



Figure 2: Setup of the CoAP client with Light server application.

Figure 3.5: CoAP Observable Server example

### 3.2.3 Stable transfer rate

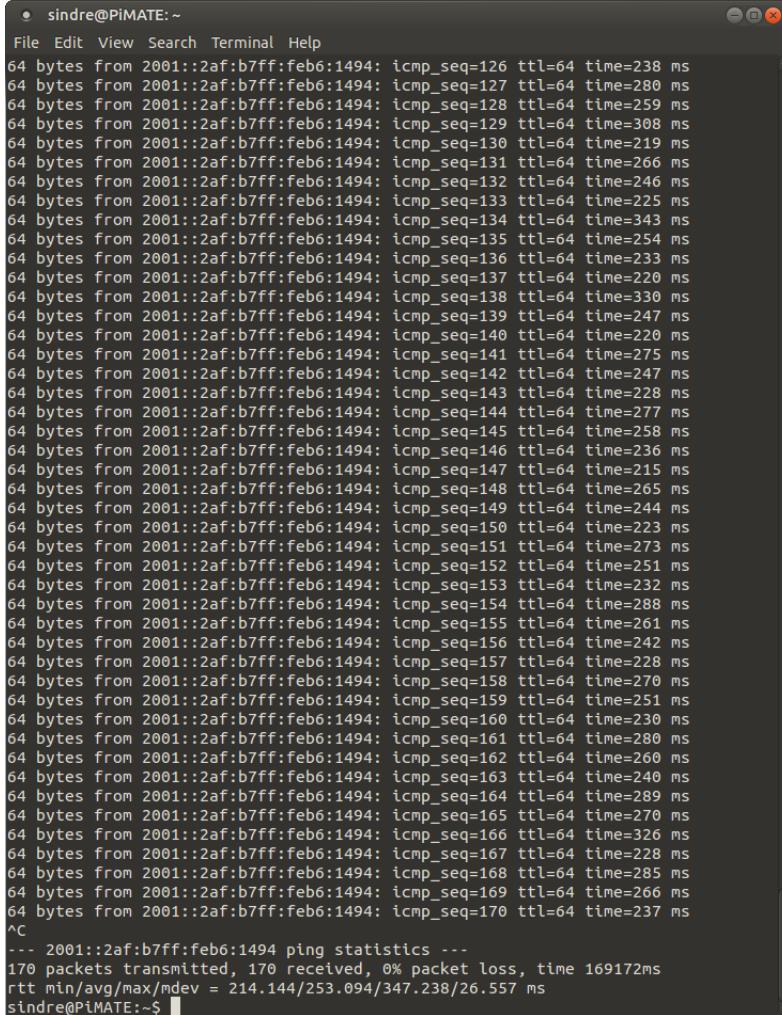
When the observable CoAP is working fine, the next step is to determine the optimal transfer rate of the connection. Since the number of messages sent has been halved, it should be possible use this as an advantage. However, the link in itself is quite slow.

```
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 3.6: Comparison: ping nRF52 and ping google.com

When tested, the connection turns out to be quite unstable at maximal transfer rate. Even in the test of ping shown in figure 3.6 the connection between the Raspberry Pi and the nRF52 had 14 % packet loss, 1 out of 7 packets. Other tests

showed similar results, and that any sending rate much faster than once per second was more or less unstable when sending data. A more stable and quicker test was later done, as shown in 3.7. After a test period it was therefore decided that the best solution 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.



```

● 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 3.7: Ping nRF52, different time

For *CoAP CON* with ACKs however, the story is not the same. Here it is possible to *GET* values as soon as the network allows, in best case every 200 ms during tests in this network. This makes quite a huge difference when testing the different protocols, as *CoAP CON* can send a lot more *goodput* per second, but *CoAP NON* requires less power to send each message, and a much higher percentage of the packets sent through the network contains useful data.

### 3.3 Raspberry Pi to Network Computer or Server

When running the Unix based OS Ubuntu Mate, the raspberry Pi can be used more or less as 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*. This means that the user has several options on how to process data on this device:

- \* 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 three that is most relevant depends on the data, and how computational power is needed.



# Chapter 4

## Network Measurements

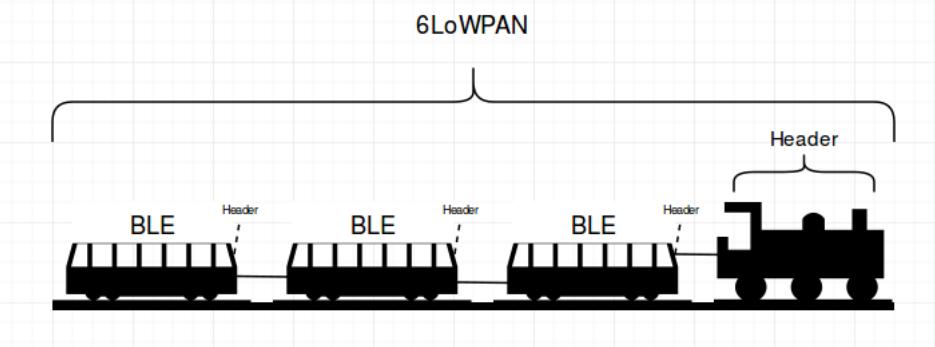
This chapter will display the experiments conducted on data sending rate from the nRF52 to the Raspberry Pi in the form of graphs, tables and figures to try to determine the most efficient combination of amount of data to send, sending frequency as well as protocols to use.

### 4.1 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.

To better understand fragmentation, imagine a train with carriages as shown in Figure 4.1. 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.

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



**Figure 4.1:** Packet fragmentation - train comparison

bytes compared to the number of packets sent. This is known as *fragmentation*, to maximize *goodput* vs *throughput*.

#### 4.1.1 Description of measurements

The following sections will show experiments performed to test if *fragmentation* is a huge 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. This will be done by sending data of constant length, capture packets using *Wireshark*, and then increasing the packet size to see the changes.

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.

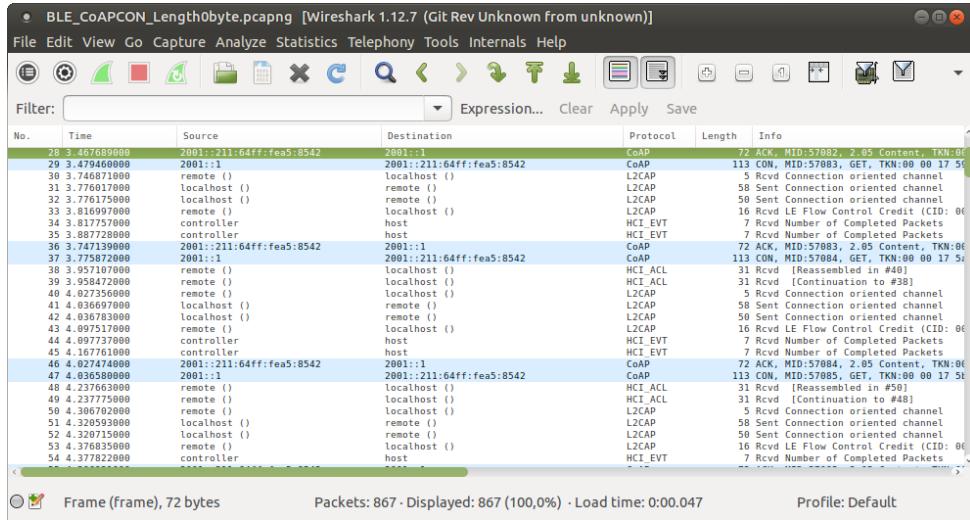
The best possible percentage of useful data we can hope to achieve will also be limited by this, 27 bytes goodput and 4 bytes header field, shown in the following calculation.

$$27/31 * 100\% \approx 87,1\% \quad (4.1)$$

In the actual system the number will quite certain be a lot lower than this. Both because header files in 6LoWPAN packages needs some bytes, and because of other limitations.

## 4.2 CoAP CON

As explained in Chapter 3, CoAP 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.

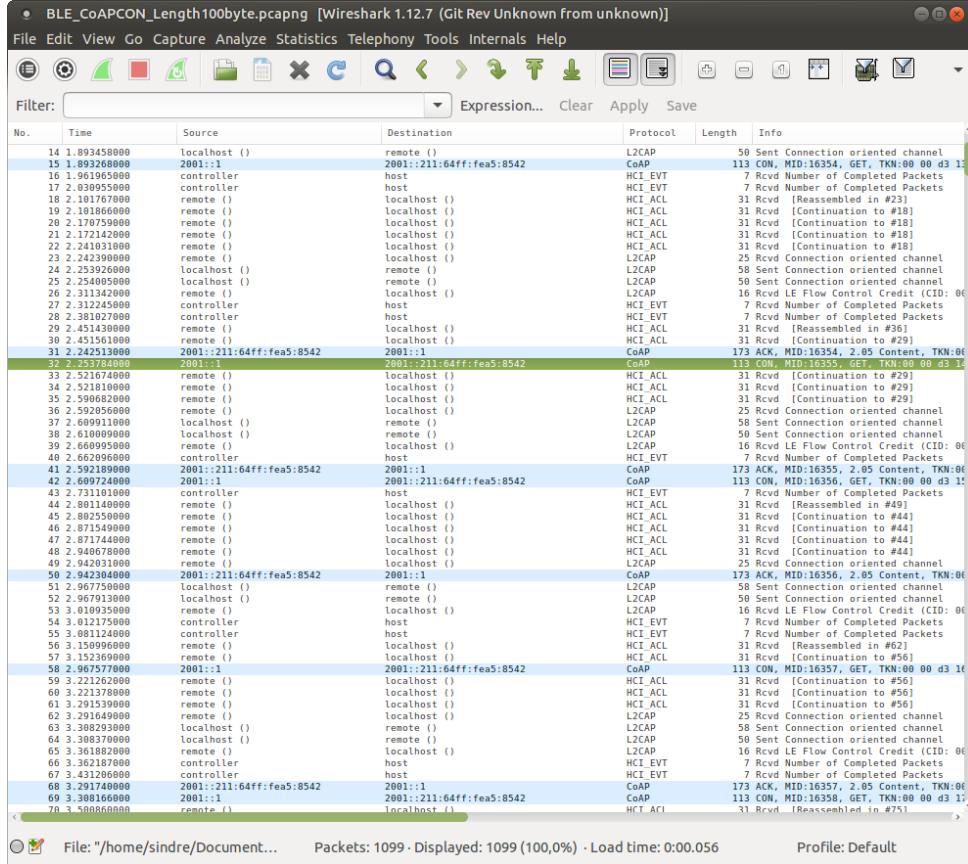


**Figure 4.2:** Wireshark capture, CoAP CON, 0 bytes goodput

Figure 4.2 shows an excerpt of a capture of packets in Wireshark. The full capture can be seen in the Appendix (?). 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,

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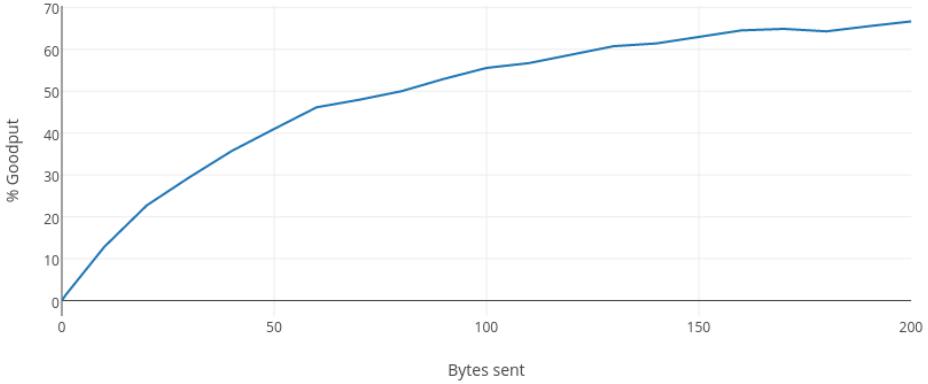
as a built in feature in BLE HCI and Asynchronous Connection-Less (ACL). All of these packages can fit into one 6LoWPAN packet, since the total number of bytes are less than 270 bytes.



**Figure 4.3:** Wireshark capture, CoAP CON, 100 bytes goodput

In figure 4.3, 100 bytes of goodput is being sent through. 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 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



**Figure 4.4:** CoAP CON, 0-200 bytes sent

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. Mathematically, 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 shown in figure 4.4, even before packet size of 200 bytes.

### 4.2.1 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 to the asymptote of the graph at 87,1 %. The next step would normally be to transfer a larger amount of data, just to verify that these assumptions are true. 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.

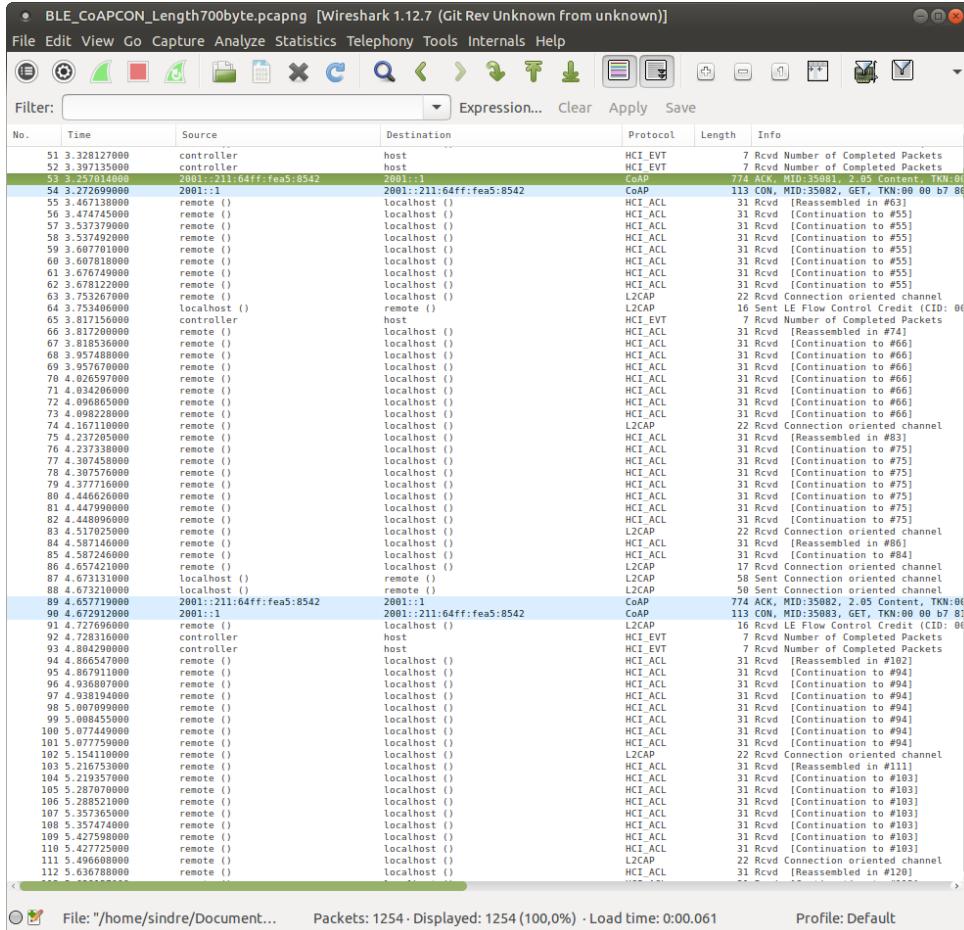
However, given that there is already a clear limit in figure 4.6 even before the transfer rate reached 200 bytes, way before expected, it also makes sense to test various other transfer protocols. If it is possible to find a way of transportation that could give a higher mathematical maximum, and also get to this limit faster, it would be very profitable to the transfer of goodput in the system. Because the

stable transfer interval at the moment is once every second, it also makes sense to test CoAP with ACK for every packet, *CON* instead of *NON*. Maybe this means that the header files can be smaller for each packet, and that the useful amount of data sent true therefore will be higher.

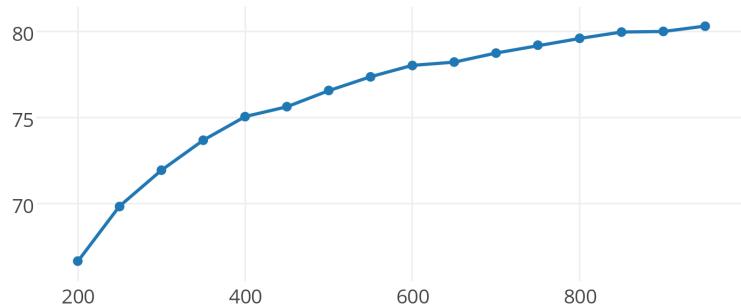
### 4.3 CoAP CON with more data

To see what happened when the limit of a 6LoWPAN packet was breached, tests was being set up to send bigger amounts of data than 200 bytes. This would also be a good way to prove that 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 using CoAP Confirmable CoAP message (CON).

Figure 4.5 shows one of these cases, where 700 bytes of data are being sent at once. In total 889 bytes are being sent, 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, as we can see in the figure. 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 is full. 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.



**Figure 4.5:** Wireshark capture, CoAP CON, 700 bytes goodput

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

## 4.4 CoAP NON

### 4.4.1 Discussion

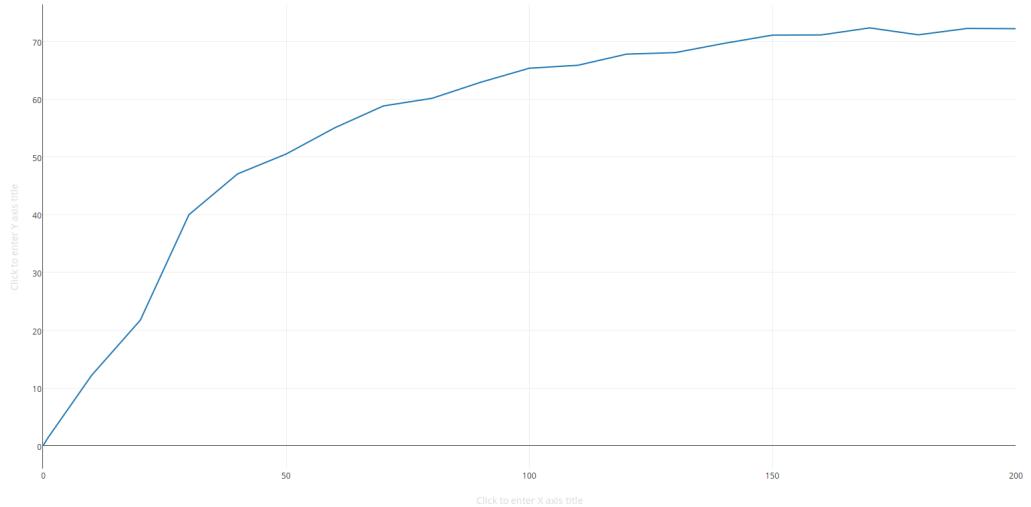
## 4.5 CoAP CON

### 4.5.1 Discussion

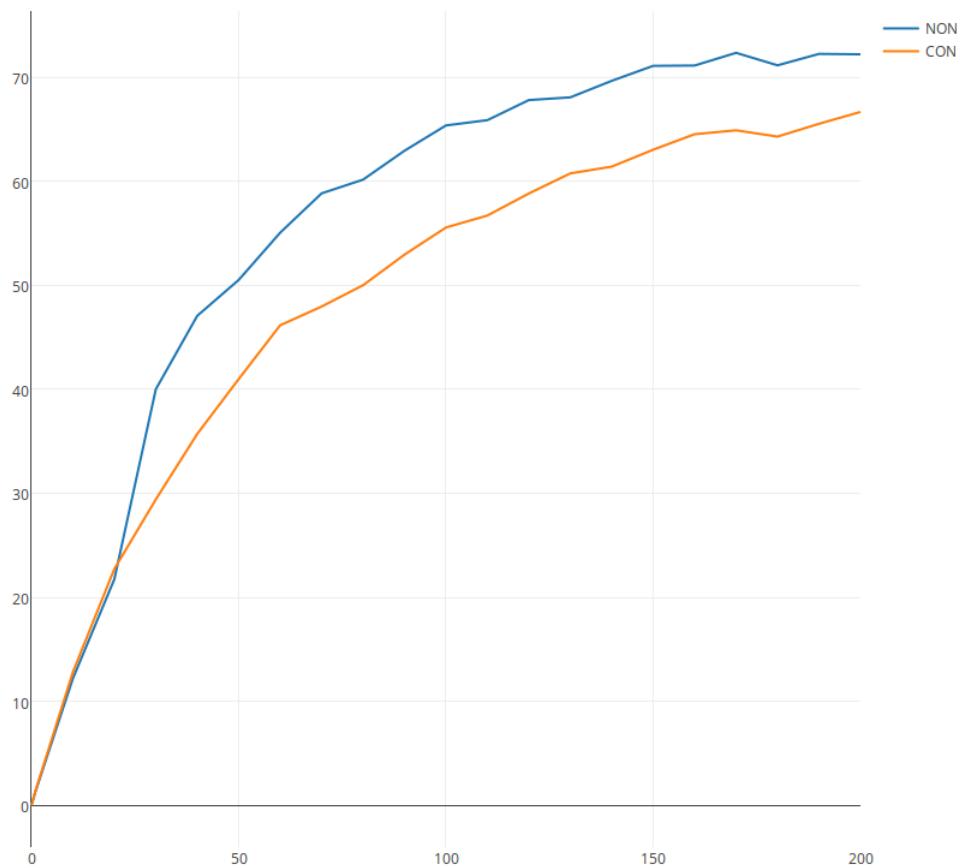
### 4.5.2 CoAP CON, with more data

### 4.5.3 Discussion

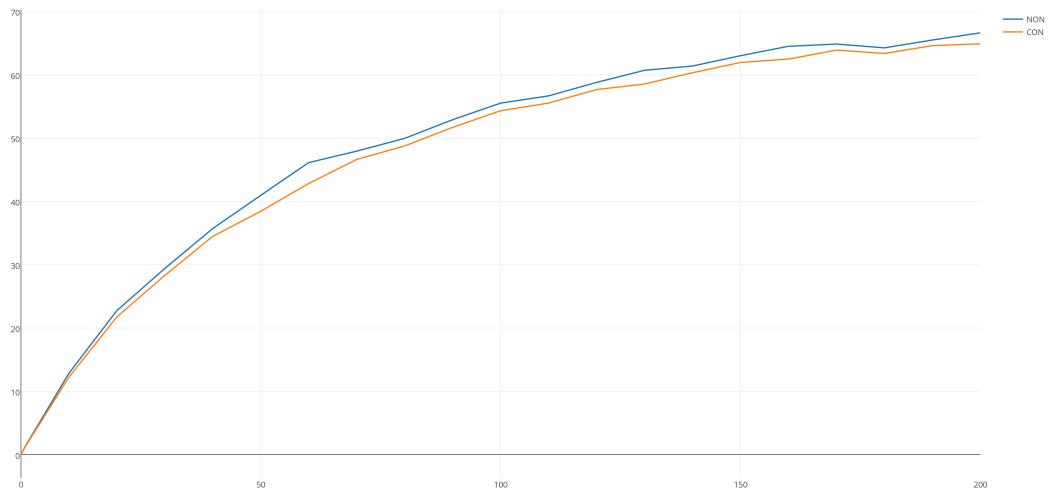
Goodput	Throughput	NON packet size	(Goodput/Throughput)*100
0	71	76	0
1	73	78	1,37
10	82	87	12,20
20	92	97	21,74
30	75	107	30,0
40	85	117	47,06
50	99	127	50,51
60	109	137	55,05
70	119	147	58,82
80	133	157	60,15
90	143	167	62,94
100	153	177	65,36



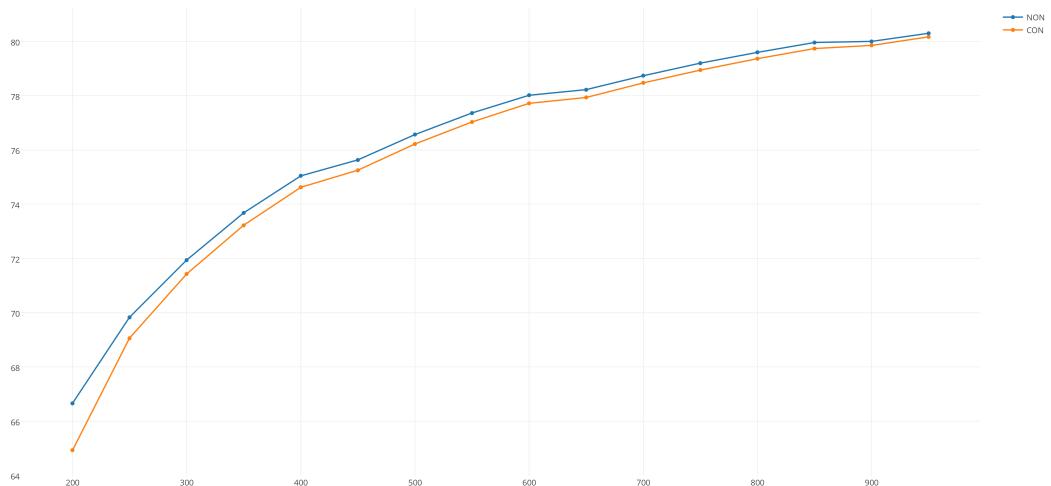
**Figure 4.7:** Goodput compared to throughput in %



**Figure 4.8:** CON vs NON



**Figure 4.9:** CON vs NON 0-200 bytes



**Figure 4.10:** CON vs NON 200-950 bytes



# Chapter 5

## Data Anaysis discussion

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?

### 5.1 Data analysis in microcontrollers

### 5.2 Computational Power

#### 5.2.1 Power consumption

### 5.3 Devices used

#### 5.3.1 Raspberry Pi

#### 5.3.2 nRF52

The nRF52 is perhaps the biggest disappointment in the system, from the authors perspective.

As a comparison, take the successful hybrid car Toyota Prius. Even though the factory tells that the car is able to drive X kilometres per liter of fuel used, this is only possible for a trained driver in a fixed environment. The average driver can still use the car, but is not skilful enough to drive as careful when it comes to power usage. The average driver therefore ends up using up the batteries much faster than the test driver, and uses the petrol powered engine after this. It may still be more economical than a normal car, but it is worth discussing if this is optimal, given that a car with two engines is more heavy and expensive to make in a direct comparison with a fully petrol powered car.

Its the same story with the nRF52. A professional skilled programmer working on this specific device from Nordic Semiconductor will be able to use the low power

abilities and still use do efficient computations. When starting from the example code for the device that is not optimized for power consumption and trying to make it do more and more work, the battery consumption simply is too much for this device. An average programmer will not have specific experience enough to program this device to be power efficient.

In the case of the system built in this thesis, the small CR 2033 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 Universal Serial Bus (USB). In this case, it would have been able to use the Raspberry Pi right away, since this needs the same source of power. This means in the end, that the system only had low performance end points that still needed a power source.

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