Hybrid Wireless Data Transfer In A Medical Sensor Node

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Hybrid Wireless Data Transfer In A Medical Sensor Node

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Abstract

More than 17.9 million new patients worldwide suffer from heart diseases. In order to conduct a proper diagnosis and treatment, it is necessary to develop a functionality for patients and doctors, which has the possibility to transfer the continuously measured data to the doctor for several days. In addition, such a tool should have the function to wirelessly transmit an alarm to the doctors, provided in the event of a critical situation. Consider this, we take two technologies into account: long-range and short-range technologies.

This work presents the significant trade-offs for long-range communication: coverage, reliability and energy consumption. This consumption is also an essential parameter for short-range communication, as well as datarate and payloadsize. Besides the transfer of the data, generated by the heart monitoring patch, the patient needs to be located efficiently. That is why different types of GNSS technologies are compared.

The measurements show that the chosen communication technologies (NB-IoT and BLE) fulfill the requirement and that it is possible to, with some finetuning, only NB-IoT can achieve the requirements of both normal and critical situation. Furthermore, the localisation technologies needs improvement for more accurate localisation.

Popular Science Summary

Hybrid Wireless Data Transfer In Heart Monitoring Patch

Nowadays, heart patients wear patches to monitor their heart, but these patches have several limitations. They will store the heart data on a memory, which requires patients to revisit the doctor/hospital after all data is well processed and analysed. Such a process can take up to two weeks, which brings difficulties for a follow-up, and for emergency signals when the patient is in a critical situation.

Considering the limitations mentioned above, it is necessary to design an application that will directly transfer the cardiac performance and intervene when a critical situation occurs. The application needs to be reliable for approximately 12 days. Therefore, the connection functionality can be divided into two parts: critical, i.e., in the case of an emergency, and normal use. In a critical situation, an alarm signal is transferred directly to the cloud using long-range communication technology. The normal use will provide periodical updates directly to the cloud using long-range technology or to an external device using short-range technology. Depending on the measurements discussed later in the article, the long- or short-range technology will be required.

First, different technologies will be analysed theoretically based on the essential parameters. One of these parameters is energy consumption, which requires to be as little as possible, so the patch has a lifetime of approximately 12 days without recharging or replacing. Energy is also saved by putting the system in (deep) sleep mode when possible. A second parameter is coverage; patients need to be reachable everywhere, even in hard-to-reach locations like a basement or garage. A third essential parameter is low latency; a short set-up and transfer time are preferable, so the alarm and data can be sent immediately.

Narrowband-IoT is chosen as long-range communication technology based on guaranteed coverage and sleep modes. To be sure the alarm arrives on time in a critical situation, latency is measured. It proves the alarm will be transferred to the cloud within 30 seconds after a critical situation occurs. The requirement is achieved.

Bluetooth Low Energy will conduct the normal situation, because of its low energy consumption and high datarate. After the theoretical research, NB-IoT also turns out fulfil the requirements for a normal use. So the report also consists of a comparison, based on energy consumption, cost and surface area, between these two implementations.

A comparison is made by converting the energy consumption to the lifetime of a specific battery with a capacity of 16 kJ. The measurements show that the BLE is more energy-efficient than NB-IoT: a lifetime of 1500 days is reached when using BLE; it reduces tremendously to 12 days when transferring over NB-IoT. Considering the patch will be worn for 12 days, NB-IoT achieves this requirement. Furthermore, the costs and surface area of the patch will be reduced when only relying on NB-IoT, because only one chip is needed.

Aside from that, a localisation feature is also investigated. The location is tracked after a critical alert signal is transferred. The implemented GPS technology communicates through the cloud, instead of "classic" GPS, which communicates directly with the satellites. As in "classic" GPS, a direct line with the satellite is required. However, communicating through the clouds will obtain a faster fix and reduce energy consumption.

Acronyms

A-GPS Assisted-GPS
BLE Bluetooth Low Energy
BER Bit Error Rate
CSS Chirps Spread Spectrum
FHSS Frequency Hopping Spread Spectrum
GNSS Global Navigation Satellite System
GPS Global Positioning System
HCI Host Controller Interface
IoT Internet of Things
kB kilobytes
LAN Local Area Network
LL Link Layer
LPWAN Low-Power Wide-Area Network
MB megabytes
NB-IoT Narrowband-IoT
PAN Personal Area Network
PHY Physical Layer
PSM Power Saving Mode
PTW Paging Time Window
RRC Radio Resource Control
SoC System-on-Chip
ToA Time on Air
TTFF Time-To-First-Fix
UDP User Diagram Protocol
VS Code Visual Studio Code
WPAN Wireless Personal Area Network

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Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

Modern technologies in Internet-of-Things (IoT) technology allow us to connect electronic devices in various application areas, for example, in the health care sector. IoT is the collection of physical objects with sensors, software, actuators, etc., that connect through a network. This report performs measurements of diverse technologies to find the most suitable wireless technology for the heart monitoring patch. For this patch, a sensor measures different heart parameters that will be transferred over the network directly to the cloud or a phone. With the utilisation of an IoT device, patients proactively connect with nurses and doctors; plus, critical situations are detected more quickly with alert signals, and doctors can identify better treatment because of the continuous data coming directly from the patient.

1.1 Background and motivation

Yearly more than 17.9 million people worldwide [2] are diagnosed with heart diseases. Therefore, a reliable and continuous measuring of the heart is vital. However, the current devices to detect and monitor the heart have several limitations. First and foremost, it is challenging for existing devices to continually monitor heart irregularities for a long time due to invasive devices like a catheter. Secondly, these devices are only applicable in a hospital since it requires an ultrasound probe, which is generally inaccessible at home. Lastly, too much time passes between two doctor-consultations of the patient. The irregularities could have fallen back without any alert between these consults. Medtronic already solved some of these limitations by giving the doctor a daily update overnight; a little device is implanted just underneath the skin, and a monitor is placed close to the bed, so these two devices can connect overnight and share data. The updates are more frequent than between two consults, but it is still an invasive way to collect data, and another limitation shows up: what if the patient sleeps somewhere else and the devices cannot make a connection? Therefore, it is necessary to design a non-invasive device (for example, a patch) that will monitor and directly measure cardiac performances on a long-term basis, i.e., for more than ten days.

Existing patches operate with external memory to store the heart's data, requiring patients to revisit the doctor after all data are well processed and analysed. Such a process can take up to 2 weeks, which brings difficulty for a follow-up and alert signals. The study in [3] describes using these heart patches. A representative of these patches is Zio, the detailed information of which can be found in [4]. On other current patches, short-range communication is running to send data to the cloud [5], like heart rate monitors that monitor the athletes, for example, from Garmin [6] and Polar [7].

The ideal patch will allow real-time follow-up, especially in a critical situation. In this case, an alarm signal is sent to the doctor. For such an alarm, the foremost requirement is the reliability of wireless communication. Furthermore, the transmission has to be private and energy-efficient.

Different technologies can be implemented to satisfy the requirements, such as LoRa, NB-IoT and Sigfox for long-range communication and BLE, WiFi, NFC and Zigbee for short-range communication.

1.2 Project aims

This master's thesis aims to investigate the feasibility and potential benefits of combining both short (10 m) and long-range communication technologies for applications in the medical sector. Long-range communication with the hospital is needed when an emergency occurs, and short-range communication will handle wirelessly forwarding the data obtained from the patch to the cloud. Furthermore, the heart's transmitted data must be safe and private. Moreover, the data transmission should consume as little power as possible. The report will handle GPS possibilities to track the patient's location when a critical situation occurs.

The goals of this master's thesis are:

- Consider the best choice for these technologies taking into account reliability, performance, power, data rate, bandwidth and latency
- Considering the power trade-off between buffering or continuously sending data
- Implement a system that will buffer the data when there is no short distance connection available
- Investigate for tracking the location technologies

The thesis starts with a literature study (Chapter 3) about the diverse long-distance communication (LoRa, 5G, etc.) and short-distance communication technologies (Bluetooth, WiFi, etc.); reliability, coverage, performance, power, data rate and latency will be analysed to see if the technology achieve the requirements (Chapter 2). The different technologies will be considered theoretically, and a final technology for short- and long-range communication will be decided. In addition, a buffering system that meets the conditions (for example, memory storage) will be chosen, and a software system to implement the requirements will be written (Chapter 4). Various measurements such as power usage, latency, and time to connect will be analysed (Chapter 5) managed by the development board, virtual server and a current-measurement tool. These will give us more specific details about energy efficiency and latency to finish the report with a conclusion (Chapter 6). Furthermore, some improvements are recommended (Chapter 7).

Chapter 2

Requirements and use cases

The heart monitoring patch has various use cases with different requirements specified in Table 2.1. The patch will collect two different kinds of data, we call them Data A and Data B. They will each be collected with a different speed, respectively 100 bytes/s and 200 kbytes/s. Data B will not be collected every second, we assume it will be collected once a minute.

Use Case	Latency	Datasize
1. Emergency call	<30s	1 packet
2. Important Data	<5 min	megabytes
3. Normal Use	<30 min	100 bytes/s

Table 2.1: Requirements and use cases

When the patient is in a critical situation and needs help, the requirements of use cases 1 and 2 are applicable. These use cases involve a transfer to the doctor/hospital with an alarm and the most recent data. The alarm needs to be sent as fast (30 seconds) as possible and the **amount of data** is the minimum size (1 packet). Regarding the second use case, the most recent data, which is in a range of megabytes, must have a maximum **latency** of five minutes. Another critical parameter is network-**coverage** because the alarm and data must arrive. The server will send an acknowledgment to verify the arrival of the data. This requires a **two-way communication**. Knowing the patient's location during a critical situation is vital so the ambulance can go and give the proper treatment.

The purpose of the normal use is to give the doctor a real-time overview of the patient's heart. This periodical update will depend on the amount of memory storage and power usage when sending a specific amount of data, and it is allowed to have a **latency** of about 30 minutes. Adequate **memory size** is essential so no data will be lost. Besides a memory size that fits the number of data storage, a **back-up plan** for when a connection is not accomplished is necessary: what to do when there is no connection to send the real-time data? The options are: a buffer in the memory storage, overwrite the oldest data, or connect to the long-range communication, considering we are sure there will be a connection via the long-range technology everywhere, every time. We make a trade-off between the memory cost and the periodical update. The bigger the memory, the more it will cost, but the more data can be stored and sent to the doctor.

Furthermore, **power usage** is a parameter that must be as little as possible, or there must be a sleep mode when no connection is needed because we want wearability of 12 days. Finally, considering the product is bought by patients, the **cost** is an essential factor to look at as well.

Chapter 3

Communication technologies

To evaluate the requirements of the communication-feature of the patch, different technologies are compared to each other. For the emergency case (use case 1 and 2), where an alarm, recent data and GNSS-coordinates are transferred, we need a long-range and low-power communication. Therefore, more profound research in Low-Power Wide-Area Network (LPWAN) (LoRa, Sigfox and Narrowband-IoT (NB-IoT)) is taken. Use case 3 can be conducted by short-range communication. Trade-off between Bluetooth Low Energy, WiFi and Zigbee will be made. The third part of the chapter will discuss different GNSS operation modes, which can affect the energy consumption and latency of the patch.

3.1 Long-range communication

Thorough research of the following three technologies has been done in the studies [8, 9, 10]. These papers discuss the advantages and disadvantages and discuss the various applications of every technology. NB-IoT is implemented in applications that need low latency, high data rate, frequent communication, coverage and high Quality of Service. LoRa and Sigfox are mostly implemented in low cost-, long-range- and long battery life-devices. LoRa can also give low latency, which is not the case for Sigfox.

This section will make a theoretical trade-off of the parameters of power usage, latency, coverage, and cost for every technology.

3.1.1 LoRa

LoRa [11] stands for Long Range and is enacted to communicate wirelessly without subscription costs. This technology aims to have a low Bit Error Rate (BER), i.e., obtained using Chirps Spread Spectrum (CSS): spreading the information over a wider channel bandwidth. As a result, it is hard to interfere with the signals, and intruders without authorized access are not allowed to crack them, so the **privacy** of using LoRa is regulated with these spread spectrum chirps. Another advantage of LoRa is that it supports **bidirectional communication** so an acknowledgment can confirm that the alarm and heart data are received.

Energy consumption

LoRa is a very efficient technology that shuts down entirely when not needed. Additionally, LoRa works asynchronously, meaning it can sleep forever without connecting to the network. The energy consumption is determined by the Time-on-Air (ToA) and transmit power, which depends on, among other things, the payload size.

[12, 13] conclude that sleep current is 2µA, and the transmit energy can go up to 0.45 mJ for ten transfers in one hour.

Latency

When using LoRa, there is a trade-off between the data rate and range. A longer range results in a lower data rate. Depending on the trade-off, LoRa can manage 0.3 kbit/s to 50 kbit/s.

Coverage

LoRaWAN gateways can be placed voluntarily by individuals and companies to build their private networks. Though for this product, it is not recommended to use the existing gateways because they are placed randomly and sometimes in unpreferable places, nor to buy and put all the gateways themself because of the necessity to have coverage everywhere.

Costs

A LoRa gateway costs around 200 euros and still needs to be installed and placed. However, there are no subscription costs related to LoRa. On the other hand, the spectrum is not regulated. Therefore, interference from other systems is possible, making it challenging to ensure the measured data speed and reliability.

3.1.2 Sigfox

Sigfox is a network operator [14] that builds wireless networks; one of these networks is also called Sigfox. This technology aims to reduce energy consumption and costs. Sigfox is a 0G network [15, 16], meaning that it transfers small amounts of data with low cost and low power.

The disadvantage of Sigfox, in this case, is the low datarate (100 and 600 bit/s), the limited amount of data per message, and the limited amount of messages per day.;t is only possible to send 12 bytes per message 140 times a day.

Energy consumption

A good overview of the Sigfox energy consumption is written in the following article [17]. After sending data to the base station, the device will go into sleep mode; the current in this state is approximately 0.160 µA. This makes the 0G network (and so Sigfox) low power and secure; the time hackers can break into the network and take control of it is very short. Furthermore, they use time and frequency diversity to optimise reliability.

Latency

Sigfox is not known for its low latency contrary: Sigfox finds its applications in products insensitive to latency. The latency of Sigfox is comparable with the latency of some LoRa-types, which is a few seconds.

Coverage

The coverage of the Sigfox network is shown on their website [18]. At the time of writing, Sigfox provides live coverage for most parts of West Europe. Some parts (like Sweden) are still under roll-out.

Costs

Sigfox is a low-cost solution because they do not need SIM cards to communicate. On the other hand, there are subscription costs with different features and offers: with or without GPS/localisation technology, the number of messages per day, and subscription duration. It costs between 6 and 14 euros per device per year [19].

3.1.3 NB-IoT

NB-IoT (Narrowband-IoT) [20] can also be regarded as LPWAN. The data rate depends on a number of factors: the number of users, the data size, etc. For NB-IoT, we can rely on a data rate of tens to hundreds of kilobytes per second.

Energy consumption

The energy consumption,, and so the battery life of an NB-IoT device can be reduced by using Power Saving Mode (PSM) and eDRX-structures as described in next articles [21, 22]. eDRX [23] reduces power consumption by going into sleep mode, but the system is still reachable during specified Paging Time Window (PTW). Going out of sleep mode (eDRX) will ask less communication with the server, and so will go faster than going out of deep-sleep mode (PSM). In the PSM mode, the modem is put into a deep sleep mode while staying registered to the cellular network. Something typical of PSM is that the device is not reachable when in deep sleep mode; the modem needs to wake up automatically or manually. When it wakes up and reconnects with the network, it needs to communicate for about 100 - 200 ms before it can send and receive any messages. In PSM mode, the device will consume about 1.294 J in one day, or 0.052 J in an hour [24].

NB-IoT is a synchronous connection which means scheduling and communication between the devices are necessary. As a consequence, the NB-IoT device needs to reconnect after maximum 413 days, starting from the moment the device is put into deep sleep mode [25]. This period is much more extended than the patch will be worn.

Latency

NB-IoT is known as a technology with low latency. It finds its applications in IoT devices where latency is critical to consider. The latency is set between 1 and 10 seconds [26].

Coverage

NB-IoT ensures indoor and outdoor coverage, even in challenging locations, for example, underground garages or basements. This is realised by increasing the CE (Coverage Extension) level when a connection is established in a hard to reach-environment. Increasing the CE level will increase energy consumption due to a higher amount of repetitions and increased ToA. This means that the power consumption will depend on where it will operate.

Costs

There are higher costs involved because of the higher complexity of the technology. In contrast with Sigfox and LoRa, NB-IoT needs a SIM card to communicate over the network. Not all sim cards support NB-IoT and/or eDRX; this needs to be checked before implementing the NB-IoT/eDRX-technology. Besides, there are some subscription costs associated with the utilisation of NB-IoT. As a result of using licensed bands, the ToA per transmission and the data size per message are managed by the network, just like the activities of other users. Plus, the use of licensed free bands adds reliability to one of the advantages of NB-IoT.

We can summarise these theoretical characteristics in Table 3.1.

	LoRa	Sigfox	NB-IoT
Datarate	1-50 kbit/s	100-600 bit/s	10-250 kbit/s
Setup-time	100 ms	300 ms	100-200 ms
Latency	10 s	10 s	1-10 s
Coverage	Not guaranteed	Guarantee dependent	Guaranteed
Sleep current	2 µA	0.160 µA	1 µA
Energy efficiency	Very good	Good	Very good
Subscription costs/device	0 €	6-14 €/year	20 €

Table 3.1: Summarising characteristics of LPWAN

3.2 Short-range communication

Short-range communication (10 m) is used to implement the normal case. We need to make sure that doctors get an overview of the heart with a maximum latency of 30 minutes. When using a short-range communication, the device will connect with an external device, and this device will transfer the data to the cloud so the data analyst can look at it from the hospital.

Bluetooth Low Energy (BLE), WiFi and Zigbee will be evaluated on the following parameters: range, power consumption, datarate and cost. A comparative study of these technologies is done in the next article [27], which concludes that the energy consumption of Zigbee is at its best when transferring 500 bytes; WiFi, on the other hand, is better for data loads of 800 kB or more and BLE has the lowest overall-energy consumption when transferring data loads between 500 bytes and 800 kilobytes.

For this normal use, a memory buffer is also needed. This buffer will be filled when there is no connection.

3.2.1 BLE

Starting the research with a deeper look into BLE [28, 29]: one of the Wireless Personal Area Network (WPAN) technologies. Bluetooth Special Interest Group designs it and BLE finds its application in many diverse areas: IoT, security, healthcare, fitness, advertisement, etc.

Range

The range of BLE indoors is between 100 and 200 metres (compared to "classic" Bluetooth, which ranges from 10 to 15 metres). Depending on the applied PHY (Physical Layer), the range of BLE can go up to one kilometre.

Energy consumption

As the name suggests, this type of Bluetooth has a lower power consumption than "classic" Bluetooth. Power consumption is dependent on the activity. Relying on article [27] deep sleep mode consumes 0.4 µAand transferring 100 bytes of data asks 2.5 mJ.

Datarate

It is only possible to send small amounts of data to achieve low-power consumption. Therefore, instead of 1-3 Mbit/s in Bluetooth, BLE allows 125 kbit - 2 Mbit/s. Nevertheless, a faster connection and a lower standby time ask lower energy consumption.

Besides lower energy consumption, BLE does not require a master-slave model to operate. So it is much easier to implement this technology by using communication protocols such as GAP (Generic Access Profile), GATT (Generic ATTribute Profile), and ATT (Attribute Protocol).

Costs

BLE technology and implementation do not cost a lot. A chip and a BLE antenna will cost around 5 euros.

3.2.2 WiFi

WiFi is part of the Local Area Network (LAN), which has a range that is longer than the Personal Area Network (PAN). Its purpose is to provide high-speed wireless connectivity and datatransfer [30].

Range

WiFi is a Local Network Area: its range goes further than Personal Area Network (like Bluetooth and Zigbee). The range will be around 100 metres indoor or 300 metres outdoor for WiFi.

Energy consumption

The disadvantage of WiFi is the large power consumption: it will take around 190 mA while transferring data, which corresponds to 30 mJ when transferring 100 bytes [27]. There is no idle mode in WiFi, only a deep sleep mode that corresponds to a shutdown and then 0.5 µA is measured.

Datarate

The datarate of WiFi is in the range of hundreds of megabytes, due to its wide bandwidth. That is very fast in comparison with BLE and Zigbee.

3.2.3 Zigbee

Zigbee was developed because there was a need for a low-cost, low-power technology in short-range communication. Furthermore, it is known for its easy implementation, reliable data transfer and security features.

Range

Zigbee is attractive for short distance (70-100 metres) applications requiring low power consumption and tolerating low data rates.

Energy consumption

In a deep sleep mode, Zigbee only consumes 0.03 µA

Datarate

Zigbee is a WPAN. The data rate of Zigbee is between 20 kbit/s and 250 kbit/s (dependent on the used frequency), so the data rate is low and not enough for this application.

Costs

Furthermore, Zigbee is known for its low cost of the device, installation and low maintenance.

3.2.4 NFC

NFC [31] stands for Near Field Communication. Near field can be interpreted as a few centimetres. When transferring data, NFC only consumes around 5 mA. Despite this very energy-saving technology, it is not usable for this application because of its very short range.

The characteristics of BLE, WiFi and Zigbee are summarised in Table 3.2. NFC is not taken in to account because its range is too low.

	BLE	WiFi	Zigbee
Range	100-200 m	100-300 m	70-100 m
Transfer data, 100 bytes ([27])	2.5 mJ	30 mJ	1 mJ
Data rate	125 kbit - 2 Mbit/s	600 Mbit/s	20-250 kbit/s
Sleep current	0.4 µA	0.05 µA*	0.03 µA
Cost antenna	5 €	20 €	10 €
Cost transceiver	7 €	10 €	20 €

Table 3.2: Summarising characteristics for short-range technologies
**shut down

3.3 GNSS

Global Navigation Satellite System (GNSS) is the collective name for every satellite positioning system. One of these systems is Global Positioning System (GPS). Satellites send unique signals that a GPS receiver receives. The receiver's location is calculated with the signal's information, including satellite position and time of transferring. Tracking the location must involve at least four satellites to get a 3D position.

Interesting parameters of GPS in this use are Time-To-First-Fix (TTFF), energy per fix and reliability.

TTFF is a measure of the performance of a GNSS receiver. It is the time that passes between switch-on until the determination of the location, and it depends on the kind of start. There are different ways to start when there is a switch-on. A "cold start" means nothing known about the location, date, time, internal clock oscillator frequency or satellite data. We talk about a "hot start" when a fix recently occurred. A "warm start" is something in between: approximate position, date, time, internal clock oscillator, frequency and almanac is known.

GPS can also be divided into different technologies [32]. Every technology has advantages and disadvantages.

A-GPS [33, 34] was developed when new applications popped up where blocked places such as trees and roofs needed to be covered. Besides improving coverage, A-GPS achieves a faster fix than GPS. This results from communicating over the LTE network instead of directly to the satellite. When using "classic" GPS, it takes about one minute to get the first fix; contrary, A-GPS is much faster due to the high datarate of NB-IoT.

A-GPS can also assist in providing an almanac, then we call it "A-GPS with minimal assistance". It includes information of different satellites and has been reliable for several months. When the program starts, the data of the satellites is downloaded; when a new fix is necessary, the device knows which satellites it should search for and what the expected Doppler frequencies are.

P-GPS works very similarly to A-GPS. The difference is that it allows downloading up to two weeks of predicted satellite location data. With this information, The device can make a quick satellite location determination without needing an active network connection. So this results in a fast TTFF but slower than A-GPS.

An essential requirement of using GPS is a direct line of sight to the satellite. Unfortunately, the unique signals sent from the satellite are blocked by, for example, buildings and metal surfaces. Therefore, tracking the GPS location when the patient is inside will be very hard. In smartphones and other tracking devices, this is bypassed by using WiFi modems or indoor GPS receivers.

In this case, a problem is the person's height: what to do when the patient is situated in a building with several floors. The GPS signal will not be enough to know on which floor and in which room the patient is located.

3.4 Summary

Because of its low power options, high coverage and reliability, NB-IoT is proposed to be the best option for long-range data communication. For the GPS functionality of this use case, A-GPS with a minimal amount of necessary data is chosen by virtue of its fast TTFF. BLE seems to be the best idea for short-range communication because of its low power and data rate. Figure 3.1 shows that within 10 metres, the device will be connected to a phone that will put data in the cloud. Doctors at the hospital can read this data. Long-range communication will make sure data will go directly to the hospital.

The deep sleep current of NB-IoT is very low, and its latency is short, so it looks like we can also rely on NB-IoT to execute the normal use case. The advantage is buying only one chip and antenna instead of two, which reduces the cost and the surface area. A drawback is the energy consumption; this will be investigated in the following chapters. In this case, a trade-off needs to be investigated between latency and energy consumption: how much energy it takes to transmit a certain amount of data and how much it costs to store this data.

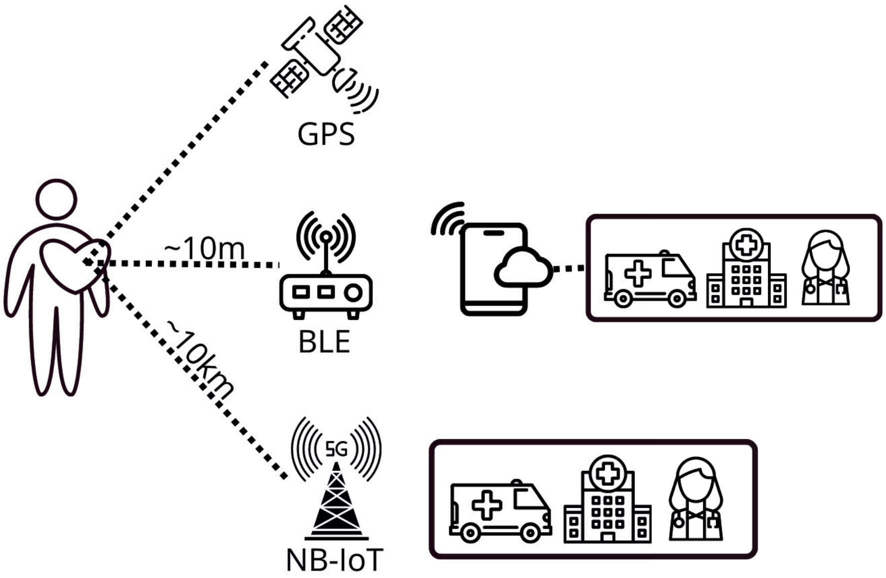


Figure 3.1: Illustration of different connections

Chapter 4

Evaluation

In this chapter, we will take a deeper look into the implementation of the device, which should fulfil all the required functions. The latter can be divided into normal and critical situations. Furthermore, we explain the methods as well as the corresponding tools, before introducing the measurement details.

To determine the battery life, the energy of connecting to and transmitting over the network is measured; this allows us to compare BLE and NB-IoT for the normal case. In order to do so, the energy per bit is calculated in terms of the size of transferred data. Furthermore, the latency is measured to evaluate the duration between a critical situation and the arrival of the alarm at the doctor.

For GNSS, the TTFF, accuracy and energy consumption is measured. TTFF shows the time it takes to get a fix; the accuracy indicates how reliable the GNSS system works and the energy consumption will give us an overview of the needed amount of energy per fix.

4.1 Method

The Flowchart in Figure 4.1 shows the normal and critical case. The normal situation starts when the patch is on the body. Then the patch starts continuously collecting data.

In this product, there are two kinds of datatypes with different sample rates; in this report we call them Data A and Data B. Data A consists of 100 bytes/second and Data B 200 kilobytes/second, but Data B is not collected every second. Let us say we will measure datatype B once a minute for 1 second.

After several minutes a connection is tried to establish, and if succeeded, data is sent. The ideal periodicity will be determined from the measurements later in the chapter. During the normal situation, suddenly, an interruption can occur due to a critical situation. As a result, an alarm and recent data are transferred directly to the doctor, as well as tracking and transferring the location of the patient so the emergency services know where to go. Due to the recent heart data, nurses and doctors are able to give the proper treatment when arrived at the emergency place.

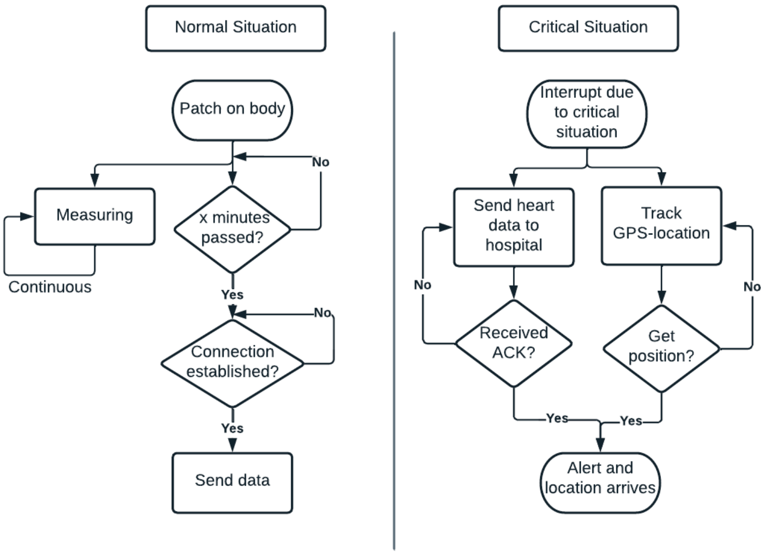


Figure 4.1: Flowchart

After a deeper look into several technologies, NB-IoT also seems to be, besides BLE, a way to fulfil the requirements of the normal case. This is why two programs are developed so BLE and NB-IoT can be compared in the normal situation; one handles the combination of BLE for a normal case and NB-IoT for the critical case; the other program only works with NB-IoT for both normal and critical case.

4.2 Implementation

4.2.1 Nordic Semiconductor and Visual Studio Code (VS Code)

The implementation of the code is realised by using VS Code and the nRF9160 Development Kit of Nordic Semiconductor [35]. This kit includes (indicated on Figure 4.2), among others, an nRF9160-chip and antenna for NB-IoT connection, nRF52840-chip and antenna for BLE-connection and a GPS antenna [36]. The buttons were used to imitate a critical situation so the functionality could be evaluated. To measure the current of the nRF9160-chip, the "current measurement"-pins are used.

Nordic Semiconductor provides a very useful platform (nRF Command Line Tools) for VS Code. Furthermore, extra extensions in VS Code and cross-platform tools [37] assist in developing nRF-devices by virtue of its accessibility in checking and evaluating the functionality of the written C++-applications, for example the LTE link monitor that shows if an NB-IoT connection is made.

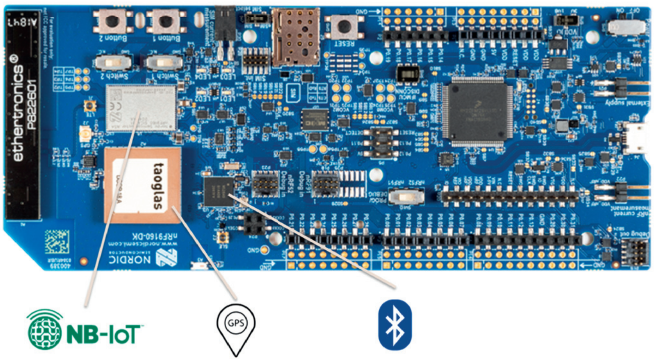


Figure 4.2: nRF9160 Development Kit

The code is structured as follows: datatransfer and connection set up can be realised using threads. Therefore, we schedule one of these threads periodically, the period is defined by a variable parameter. This makes it easy to change the periodicity, which depends on the trade-off between memory, datarate and energy consumption that will be made further in the report. In between 2 transfers, the patch will be put into the deep-sleep mode to consume as little power as possible.

It is essential that the periodic thread interrupts when the patient is in a critical situation, resulting in a transfer of an alarm. The alarm triggers an unlock function of the periodic thread. As a result, this thread interrupts and another thread is called. The latter sends an alarm and data of the last moments.

4.2.2 NB-IoT and UDP

Packages over NB-IoT are sent using the User Datagram Protocol (UDP). To set up an NB-IoT connection and to be able to send UDP packets, AT-commands assist in preparing the modem and the server to a ready state. These commands are also applied to enable PSM mode, which will be entered every time an NB-IoT connection is not necessary. Implementing PSM mode happens with two variables: the tracking area update period (TAU) and the active time while remaining registered to the network. TAU defines how often the device needs to notify its availability to the network. The maximum value of this variable is 413 days [22]. The other variable, the active timer, defines how long the device has to perform paging before entering the PSM. In this paging mode, the device is periodically available in specific Paging Time Windows (PTW). This makes it possible to receive acknowledgements while reducing energy consumption.

Sending messages is done in a connected RRC-mode. RRC [38, 39] stands for Radio Resource Control and it is a Network Layer protocol between the device and base station. A connection is established when the communication parameters are known to the terminal and the radio access network. When no connection is needed, the RRC-mode becomes idle before entering PSM mode.

The process of connecting to the network is printed out and shown in Listing 4.1. The LTE Cell ID is first identified. Then the RRC mode changes to connected, and the network registration status becomes connected. The last step is detecting the PSM parameters TAU and Active timer. The cell ID can change during the execution and the NB-IoT device will notice this.

Listing 4.1: Log: Setting up the application

```
UDP sample has started
LTE cell changed: Cell ID: 25824039, Tracking area: 1039
RRC mode: Connected
Network registration status: Connected - roaming
SPSM parameter update: TAU: 4680, Active time: 10
```

The log when transferring data is shown in Listing 4.2. Data can only be transferred in a connected RRC mode. After sending the packages, RRC becomes idle again. To determine the latency of the messages, a virtual server is set up. A Python code detects traffic on this server and shows the incoming messages. The latency is calculated as the difference of time when the log printed the transmitting message with the arrival time on the Python code.

Listing 4.2: Log: Transferring data

```
Transmitting UDP payload of 100 bytes
RRC mode: Connected
RRC mode: Idle
```

Additional, the current is measured with a Joulescope [40] to calculate and define the required capacity of the battery when handling a critical situation. Also the energy consumption of a normal use case is measured to compare NB-IoT with BLE in the normal use case.

4.2.3 BLE

BLE will provide periodical updates from the patch to an external device, for example smartphone or smartwatch. This external device will put data into the cloud.

As shown in Figure 4.3, BLE architecture is divided into three parts: the application layer executes the application; the host includes API's (like GAP, GATT, SMP, ATT), and the controller consists of the Link Layer (LL) and the Physical Layer (PHY). The controller is mostly the hardware chip connected with the IO ports; the host runs on the main CPU and provides an abstract interface for the application developer.

When the chip comes in a complete form (controller, host and application in single packet), it is called System-on-Chip (SoC). The nRF52840 is a SoC, but for this implementation with BLE, two chips are used: the nRF52840-chip is connected to the BLE antenna; that is why this chip will be responsible for the controller function. The host and application are running on the nRF9160-chip. Transport of commands and events between these chips are provided by the Host Controller Interface (HCI) protocol [41].

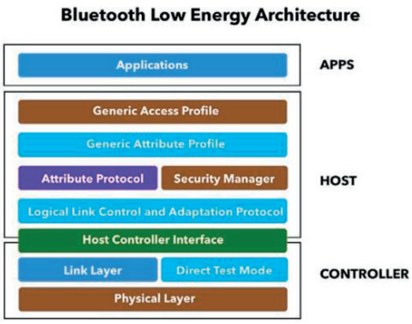


Figure 4.3: BLE architecture

Another way to implement the BLE-functionality is programming nRF52840 independent of nRF9160, but since both chips require access to the same data, a shared memory is recommended.

For this thesis, the development kit was used to include both technologies and to measure the energy consumption. Unfortunately, the block diagram [36] shows that nRF52840 is powered through the on-board debugger. This results in an always ON mode from the debugger, which has a power consumption of 0.5 mA that cannot be ignored. Resulting this, the calculations of BLE in chapter 5 will be based on the results from article [42] by M. Siekkinen, et al. who analysed how low energy BLE is.

4.2.4 Data storage

Data will be stored in a circular buffer. The structure of the buffer is shown in Figure 4.4, which explains that the memory behaves contiguous, and so an overflow will never occur, since storing will restart from the beginning when the end of the buffer is reached. A pointer will point to the next place where data can be stored. When every buffer location (there are 16 buffer locations in Figure 4.4) is filled, the pointer will start from the beginning and overwrite the oldest data, as a result, data will be lost. To avoid losing information, all the collected data needs to be sent before the buffer is full.

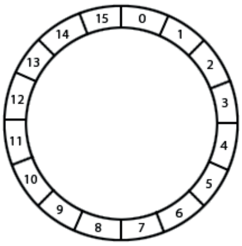


Figure 4.4: Circular Buffer [1]

There are different ways to implement this data into the memory. The first option is to afford two different buffers, one for each datatype. The advantage of this manner is the availability of both buffers: they can be approached in parallel. On the other hand, circular buffers have fixed sizes, so when using two buffers, there need to be free storage for both datatypes; which will give a larger amount of needed memory. In best-case scenario, when there is always a connection, these storage will never be affected. This limitation can be solved using one circular buffer where Data A and Data B are combined, which will result in a separation of both datatypes at the other side of the communication link.

In a critical situation the heart data of the 30 last minutes will be sent, so after 30 minutes, data can be deleted. This means we have a total of 6160 kB: thirty minutes of Data A will be 180 kB; this consists of 100 bytes per second for 30 minutes. The amount of Data B is calculated as 30 times 200 kB (because data B is not measured every second, but ones a minute), which gives 6 MBytes. To comply this case, we will look at a memory of 8 MBytes, which is large enough to store all the data.

To calculate the required buffersize, we look at the size of the total data amount of external flash memory with 8 MB of memory [43], which costs approximately 11 euros. For Data A this means

$$\frac{8\text{ MB}}{100\text{ B/s}} = 80000\text{ seconds} = 22.2\text{ hours}$$

of data that can be stored in the memory. For Data B, it means

$$\frac{8\text{ MB}}{200\text{ kB/s}} = 40\text{ seconds}$$

4.2.5 GNSS

Implementing the GNSS function is realised with a program where variables can be put on and off to activate or de-activate A-GPS. The measurement for TTFF is included in the program and printed on the LTE link monitor terminal. The accuracy is measured using an online decoder to translate the NMEA-messages into a real location. Energy analysis is again realised by current measurements with a Joulescope.

4.3 Measurements

For the energy consumption of NB-IoT, BLE and GPS, a Joulescope is used as shown in the upper middle picture of Figure 4.5. The **NMEA-values** of the GPS can be decoded very easily in an online decoder, like [44], so the accuracy can be evaluated. The **latency** is counted with the Python program that detects and visualises the received messages on a virtual server. The measurements were done in the locations shown in Figure 4.5.

4.3.1 NB-IoT

Latency

The latency of transfers over NB-IoT are shown in Table 4.1 and visualised in Figure 4.7 in terms of payloadsize and location. The latency consists of, on average, 1.04 seconds and a transfer time.

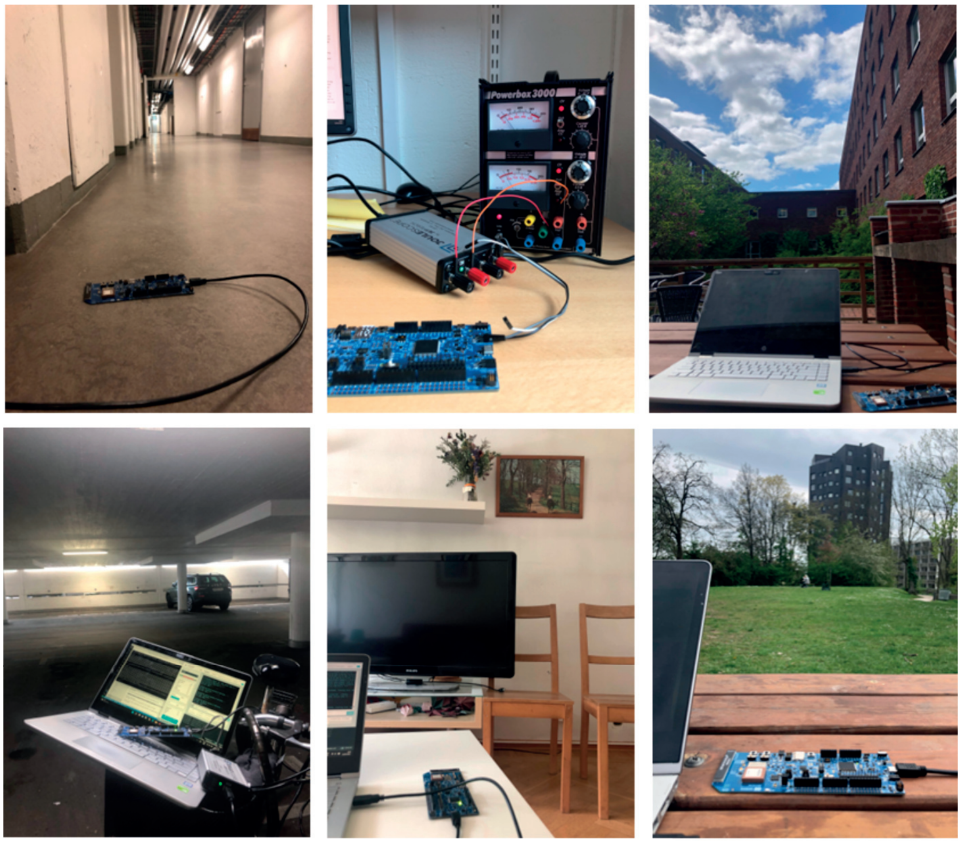
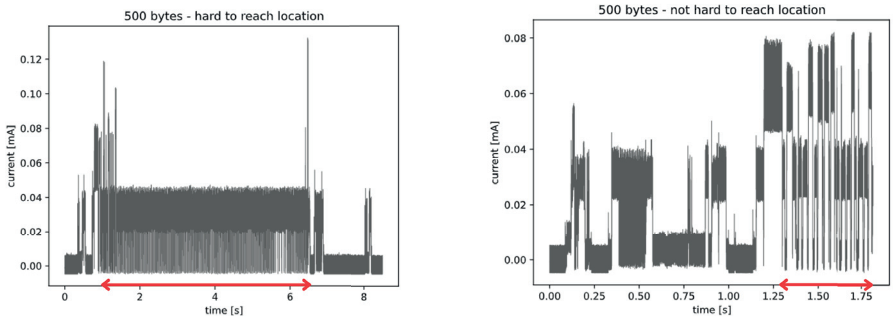


Figure 4.5: Measurement locations
upper left to the right: basement, office, outside surrounded by buildings;
lower from left to right: garage, home, outside open-air

We can draw two conclusions, the first one is the effect of different payloadsizes: the difference in latency between the 100 and 1400 bytes (the least and most measured datasizes) is minuscule. Secondly, measurements at harder to reach-locations often show a longer transfer time in comparison with the other locations; this is also shown in Figure 4.6. When looking at the x-axis, it is clear that it takes longer to transmit 500 bytes in a harder to reach-location. The worst value was measured when sending 100 bytes in a basement; it took 26 seconds to reach the server. Considering the alarm must arrive in 30 seconds, this still achieves the requirement. However, the most crucial requirement is that all the packages arrive. This can be checked with acknowledgements from the server. A lost package happened three times in 280 transfers, which roughly corresponds to 1 per cent of the sent packages.

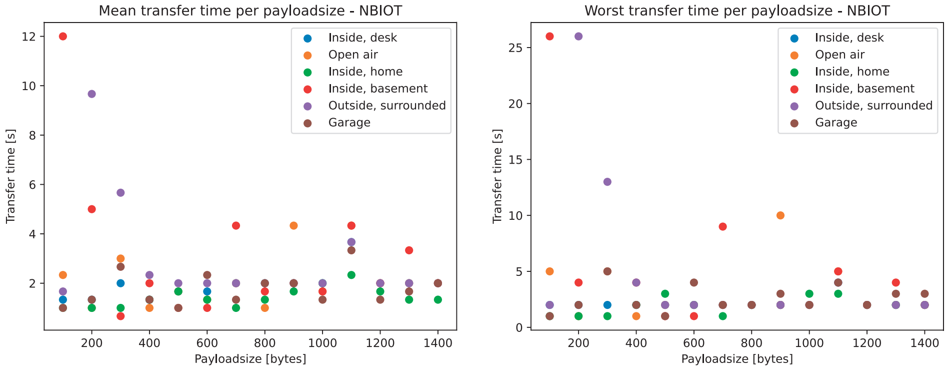


(a) hard to reach location **(b)** not hard to reach location

Figure 4.6: 500 bytes in different locations - red arrow corresponds to the length of transferring data

Bytes	Home		Basement		Garage		Desk		Open air		Surrounded	
	mean	worst	mean	worst	mean	worst	mean	worst	mean	worst	mean	worst
100	1.0	1.0	12.0	26.0	1.0	1.0	1.3	2.0	2.3	5.0	1.6	2.0
200	1.0	1.0	5.0	4.0	1.2	2.0	1.3	2.0	1.0	1.0	9.6	26.0
300	1.0	1.0	2.5	/*	2.6	5.0	2.0	2.0	3.0	5.0	5.6	13.0
400	1.3	2.0	2.0	4.0	1.3	2.0	1.3	2.0	1.0	1.0	2.3	4.0
500	1.7	3.0	1.0	1.0	1.0	1.0	1.7	2.0	1.7	2.0	2.0	2.0
600	1.3	2.0	1.0	1.0	2.3	4.0	1.7	2.0	1.3	2.0	2.0	2.0
700	1.0	1.0	4.3	9.0	1.3	2.0	2.0	2.0	2.0	2.0	2.0	2.0
800	1.3	2.0	1.7	2.0	2.0	2.0	2.0	2.0	1.0	/*	2.0	2.0
900	1.7	2.0	2.0	2.0	2.0	3.0	2.0	2.0	4.3	10.0	2.0	2.0
1000	2.0	3.0	1.7	/*	1.3	2.0	2.0	2.0	1.7	2.0	2.0	2.0
1100	2.3	3.0	4.3	5.0	3.3	4.0	3.7	4.0	4.3	5.0	3.6	4.0
1200	1.7	2.0	2.0	2.0	1.3	3.0	2.0	2.0	2.0	2.0	2.0	2.0
1300	1.3	2.0	3.3	4.0	1.6	2.0	2.0	2.0	2.0	2.0	2.0	2.0
1400	1.3	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

Table 4.1: Mean & worst latency in different locations [s]
* 1 package was lost



(a) Average latency per payloadsize and location

(b) Worst latency per payloadsize and location

Figure 4.7: Mean and worst latency per payloadsize and location

Energy

Measurements of NB-IoT energy consumption are done with the Joulescope. A typical current measurement is shown in Figure 4.8 with (1) the device wakes up and makes a connection with NB-IoT, (2) shows the transfer of the message over NB-IoT to a virtual server, during time frame (3) the device is still available in the PTW's to receive acknowledgements and in time frame (4) the device is going into deep sleep mode, called PSM. The length of time frame (2) depends on the amount of data that is transferred and the accessibility to the NB-IoT connection. These parameters will affect the latency and so the energy consumption.

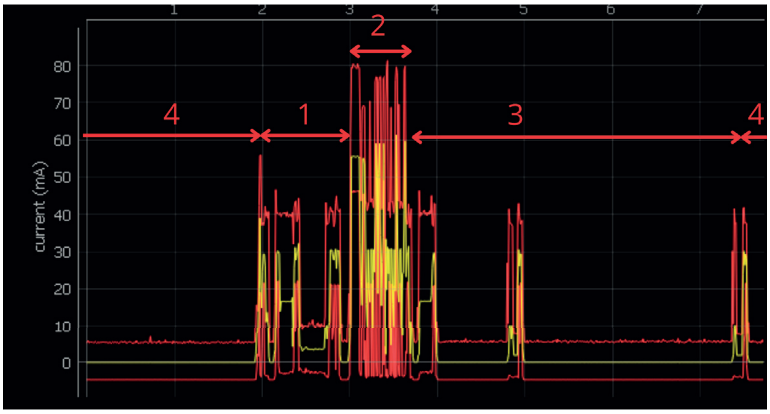


Figure 4.8: General Power Measurement: (1) connecting with network (2) transferring data (3) available to the network in PTW's (4) deep sleep mode

Figure 4.9 shows the energy per byte in function of the datasize. It clearly shows that transferring a larger amount of data will consume less energy per byte. So the trade-off is: small datasize with higher energy per byte, but faster updates, or larger datasize, so slower updates, but less energy per byte. The threshold line that represents the mean energy per byte of sending 1000 bytes, does not differ a lot from the ones in 1100, 1300 and 1400 bytes. We can conclude that the ideal datasize corresponds with 1000 bytes, and so a periodicity of 10 seconds, which corresponds to 0.15 mJ/byte.

The peak at 1200 bytes is a result of the maximum payloadsize per frame: 576 bytes. This means that when sending 1200 bytes, the first and second frame are filled with 576 bytes and the third frame has only 48 bytes. It means that the energy consumption of the third frame can only be divided over 48 bytes. We would have a peak at 577+ bytes as well, due to the same reason as mentioned before.

The descending character of the graph is a result of the wake-up data transfer that is only once per transfer and also the number of header bytes can be divided over more application bytes.

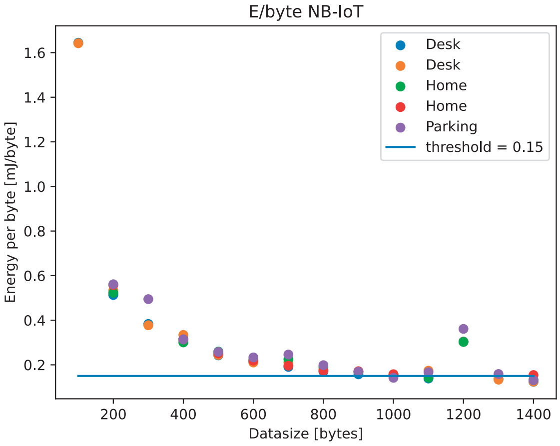


Figure 4.9: Energy per byte per datasize

The sleep current in deep-sleep mode (PSM) is measured as 0.0015 mA on average. Also a little current peak is noticed when the LTE cell changed, shown in Figure 4.10. The cell ID and tracking area are updated. This little peak is negligible.

4.3.2 GNSS

A side-note in advance: the GPS signal can only be tracked in specific circumstances. When inside or in areas surrounded by high buildings, the signal is often blocked by different materials. Only the places where a fix was detected are included in the report, so outside (open-air, between high buildings, cloudy and sunny) and inside (middle of the house and close to an open window).

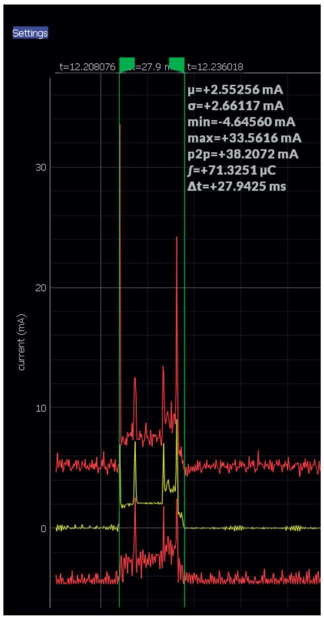


Figure 4.10: LTE cell changes

First, the average energy is measured and furthermore, the TTFF and accuracy in different locations and circumstances are discussed.

Energy

The average current of searching for a fix is 37.9 mA. The energy consumption can be measured per fix, considering the GPS search for a fix every second. With the power voltage U equal to 5V, the consumed energy per fix is $37.9 \cdot 1 \cdot 5 = 190$ mJ.

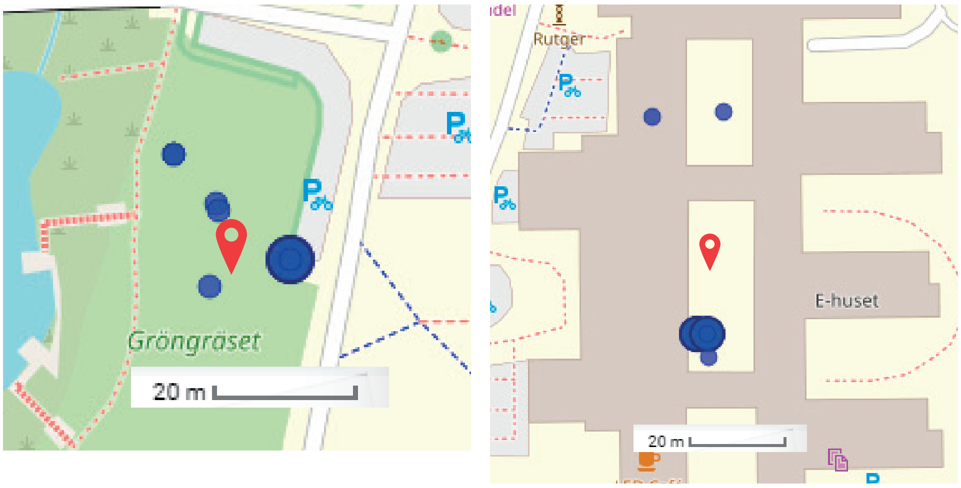
Accuracy and TTFF

On a very **sunny** day in **open air**, the TTFF, when using A-GPS, varies between one and six seconds. The accuracy of these measurements can be seen in Figure 4.11a. It shows that the accuracy is around 30 metres. The exact location is indicated with the red sign; the blue dots are the measurements. The dots become larger, when they overlap each other.

When measuring **outside** in a **sunny surrounded area**, the TTFF varies between 1 and 22 seconds. The accuracy is shown in Figure 4.11b. Remarkably, the measurements that took the longest are the most accurate ones. Nevertheless, again, the accuracy is around 30 metres.

Because A-GPS system is told to be useful when the receiver is in a location where it is difficult for the satellite signals to penetrate, some measurements were **inside**. This often resulted in no fix. When getting a fix it took 1 till 21 seconds and the accuracy is comparable with the accuracy in a surrounded area.

To compare with the normal GPS-function, two measurements were done with a TTFF of 128 and 150 seconds. This is because the GPS information is transferred directly from the satellites to the GPS-receiver with a datarate of 50 bps. Then the GPS-receiver has to process this data and make an analysis. The information-processing of the satellite is already done in the A-GPS server and then the data is transferred with a datarate of 250 kbps (datarate of NB-IoT), which is much faster.



(a) Accuracy A-GPS open-air **(b)** Accuracy A-GPS surrounded area

Figure 4.11: Accuracy A-GPS

To check the possibility when **inside**, some measurements were done in a building without levels. Close to an open window or a few metres away from windows, the GPS sometimes succeeded in getting a fix with an accuracy within 30 metres. Inside, measurements were with little successes, so they are not further discussed in the report.

Chapter 5

Analysis

In this chapter, first, the GNSS-parameters are described (TTFF, accuracy and energy consumption). Furthermore, the latency is evaluated, as well as the required energy consumption in a critical situation with and without localiation. Lastly, we analyse NB-IoT and BLE to define the battery's lifetime, which helps evaluate and compare BLE and NB-IoT in the normal situation.

The battery's lifetime is defined with the energy consumption, which is calculated with the measured current, voltage and time. The energy equals the multiplication of power, P, and time, t; $E = P \cdot t$. The power is defined by the current, I, and the voltage, U; $P = I \cdot U$.

We list the assumptions used in the experiments as follows:

- Every second, 100 bytes of Data A from the heart are collected
- Every minute, 200 kilobytes of Data B from the heart are collected
- GNSS finds its fix in a maximum of 25 seconds
- The alarm signal will be 100 bytes with, for example, the last second of heart data information
- When a critical situation occurs, heart data of the last 30 minutes will be sent to the doctor

First, the different measurements of GNSS are analysed. Furthermore, a closer look at the critical situation's energy consumption is done. The chapter then discusses the energy consumption of BLE and NB-IoT before comparing them.

5.1 GNSS

The **TTFF** strongly depends on the weather and the location. The fastest tracks were within one to six seconds under the condition that the air was open and sunny. When outside, but surrounded by buildings, a fix between 1 and 26 seconds was achieved. Almost no fix was received when inside.

The **energy consumption**, equal to 190mW/fix, is calculated in the previous chapter. The energy consumption depends on how long it takes to get a fix.

Based on the measurements, the **accuracy** is maximum 20 metres when outside in open-air and between 20 and 30 metres when outside in a surrounded area or, when a fix, inside.

There are several trade-offs; for example, what if a fix is not achieved within a certain period? Is it sufficient to send the last tracked position, or does the patch keep searching for a fix, which results in higher energy consumption? And if we track the last tracked position, how long is the patient's position reliable?

5.2 Critical situation

5.2.1 Latency

A critical situation goes as follows: first a connection with NB-IoT is made, then an alarm (package of 100 bytes) is sent. Next, the GPS will track the location for 25 seconds, and then the data of the 30 last minutes are sent. Thirty minutes of Data A will be 180 kB; this consists of 100 bytes per second for 30 minutes. The amount of Data B is calculated as 30 times 200 kB, which gives 6 MBytes.

The alarm must arrive in maximum 30 seconds. Assuming the alarm will be 100 bytes, the latency requirement is achieved as shown in Table 4.1 on page 24, where 100 bytes are sent within 26 seconds in worst case scenario.

The latency requirement for transferring the last heart data is maximum 5 minutes. Considering the transfer time difference between 100 and 1400 bytes increases with 1 second (shown in Table 4.1 and Figure 4.7 on pages 24 and 25), and the theoretical worst value of the NB-IoT datarate is 10 kbit/s, the expectations of transferring 180 kB will not last longer than 5 minutes. The 6 MB-transfer will, in the best theoretical case with datarate of 250 kbit/s, last 3 minutes. In worst-case scenario, the datarate is 10 kbit/s, which results in a transfer time of more than an hour. For 6 MB, the requirement is only achieved if the datarate is at least 160 kbit/s.

5.2.2 Energy consumption

The nRF9160-chip is directly connected with the micro-usb, powered by the USB of the computer, so U = 5V. This is shown in Table 5.1 together with the average sleep current of the chip when in PSM mode.

Sleep current [mA]	Voltage [V]
0.0015 mA	5 V

Table 5.1: General variables

The different parameters that influence the energy consumption are shown in Table 5.2 and explained in the following enumeration:

	Power [mW]	Time [s]	Energy [mJ]
1. Connection set-up	59.2	1.04	6.18
2. Alarm			164
3. GPS power	190	25	4743
4. Transfer Data A			$23.9 \cdot 10^3$
5. Transfer Data B			$798 \cdot 10^3$

Table 5.2: Variables and values

1. The values of the connection set-up are the average values of different measurements.
2. The average energy per byte for a 100 bytes-transfer is 1.64 mJ per byte (calculated in the previous chapter), so 164 mJ in total for the alarm.
3. For the GPS energy, a period of 25 tries is taken before a fix is received. So 25 times the energy of one fix is added.
4. & 5. Considering the amount of energy per byte declines, the energy per byte will not differ a lot from the energy per byte calculated for 1400 bytes. The average energy per byte for transferring 1400 bytes corresponds with 0.133 mJ.

This means that when a critical situation occurs, a total of around 827 J will be consumed. The connection set-up is negligible compared to the data transfers.

The GPS energy consumption is less than 1 per cent of the total energy; however, because the GPS is not reliable in all environments, it is possible that it will not be implemented in the patch. When not using GPS functionality, the total energy consumption of a critical situation is about 822 J.

When the battery is at the end of its life, but a critical situation (which asks for more power than normal case) needs to be handled, it still needs to handle 827 J. When less than 827 J, the patch should be replaced or charged because it will not be reliable anymore when an emergency occurs. When using a battery with a 1.2 Ah capacity and a voltage of 3.7 V, 19 critical situations with GPS tracking, and without normal use, can be handled ($= 1.2 \cdot 3.7 \cdot 3600/827$). This calculation shows that a critical situation asks a lot more energy than the periodical updates.

5.3 Normal use with BLE

The feature values of the nRF52840-chip is available in the product specification [45]. The sleep current for a system that is powered by 3 V is 0.4 µA. The peak current is 4.8 mA in transceiver mode.

As found in article [42] by M. Siekkinen, et. al, the energy consumption can be calculated with formula 5.1.

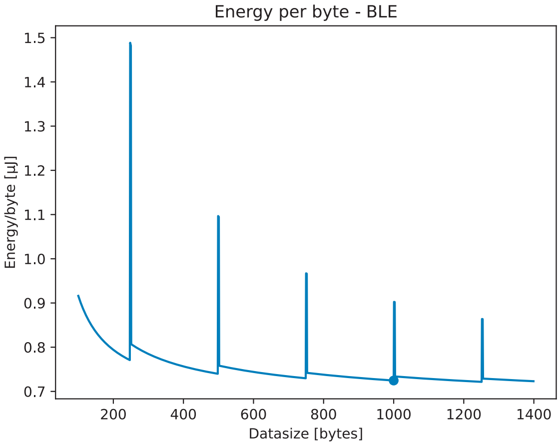


Figure 5.1: Energy per byte - BLE

$$E = E_{wu} + P_{tx} \cdot D_{tx} \cdot ((n-1) \cdot (l_{hdr} + l_{pl}) + l_{hdr} + l_{last}) \tag{5.1}$$

$E_{wu}[mJ]$	P_{tx}[mW]	D_{tx}[µs/B]	l_{hdr}[B]	l_{pl}[B]	l_{last}[B]
0.15	84	8	14	251	datasize mod l_{pl}

Table 5.3: Parameters BLE

E_{wu} is the energy that is consumed when the chip wakes up. It is calculated by the power, P_{tx}, and the duration, D_{tx}. The next part of the formula represents the transfer energy consumption by the power, P_{tx}, and the duration per byte, D_{tx}. The l_{hdr}, l_{pl} and l_{last} denote the length of the BLE link layer frame overhead, the maximum payload size per frame and the amount of data in the last frame. n is the number of frames to send. It is calculated by the number of data by the application, added with the header and then divided by the maximum payload size per frame, l_{pl}.

We make a trade-off between the datasize and the energy/byte, or in other words, between the periodicity and the energy consumption. Because the difference between energy/byte at 1000 bytes and higher is not much, we take 1000 bytes, or 10 seconds, as the ideal periodicity with an energy/byte of 0.73 µJ/byte.

The notable peaks in Figure 5.1 are the consequence of the maximum payloadsize per frame n, which is 251 byte. When sending 252 bytes, two frames are sent where the last one has only 1 byte. The same situation occurs when sending 503, 754, etc. The peak's height declines because the energy cost of the almost empty frame can be spread over more bytes.

The energy consumption of one hour in normal use is calculated to compare periodically sending after 1 second with periodically sending after 10 seconds in BLE.

The energy consumption for the transfer is added by the sleep energy:

$$\text{Per 1 second: } (100\text{Bytes} \cdot 0.92\text{µJ/Byte} + 1\text{s} \cdot 0.4\text{µA} \cdot 3\text{V}) \cdot 3600\text{s} = 0.336\text{J}$$

$$\text{Per 10 seconds: } (1000\text{Bytes} \cdot 0.73\text{µJ/Byte} + 10\text{s} \cdot 0.4\text{µA} \cdot 3\text{V}) \cdot 360\text{s} = 0.267\text{J}$$

In this case, an nRF9160-chip is still necessary to handle the critical situations. So the sleep energy consumption of NB-IoT will be added to the previous calculations. This means $336 \text{ mJ} + 0.0015 \text{ mA} \cdot 5 \text{ V} \cdot 3600 \text{ s} = 363 \text{ mJ} = 0.363 \text{ J}$ for one second-periods and $267 \text{ mJ} + 0.0015 \text{ mA} \cdot 5 \text{ V} \cdot 3600 \text{ s} = 294 \text{ mJ} = 0.294 \text{ J}$ for transferring 10-seconds periodically.

5.4 Normal use with NB-IoT

To make a trade-off between periodicity and energy consumption with NB-IoT we look at Figure 4.9 on page 26. The threshold line shows us that the ideal periodicity is, again, ten seconds, which corresponds to 1000 bytes. The energy consumption that corresponds with this transfer is $1000 \text{ Bytes} \cdot 0.15 \text{ mJ/byte} = 150 \text{ mJ}$. The duration of the deep-sleep mode (0.0015 mA) of 1000 bytes corresponds with 10 seconds, so we can calculate the energy of the deep-sleep mode: $0.0015 \text{ mA} \cdot 5 \text{ V} \cdot 10 \text{ s} = 0.075 \text{ mJ}$.

This means one cycle, which consists of 1000 bytes-transfer and 10 seconds of deep-sleep mode, consume $0.075 + 150 = 150.075$ mJ.

To compare with BLE, we calculate the energy for one hour. In one hour (3600 seconds) 360 cycles of 10 seconds are included, so: $150.075 \text{ mJ} \cdot 360 = 54027 \text{ mJ} = 54.0\text{J}$.

5.5 Comparison of BLE and NB-IoT

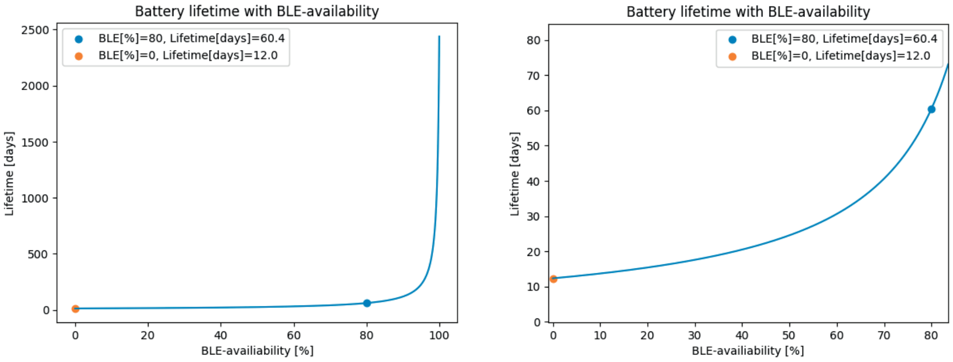
To compare both ways (BLE and NB-IoT), the lifetime of a battery (based on [46]) with 1.2 Ah capacity and 3.7 V voltage is computed: $1.2 \cdot 3.7 \cdot 3600 = 16$ kJ, which we call $E_{battery}$ in the next formulas. Due to internal chemical reactions, batteries are self-discharging, which results in a lower battery capacity than theoretically mentioned. The battery capacity and the discharging speed is dependent on the used battery material.

The simulation in Figure 5.2a shows the results of formula 5.3: the battery's lifetime in function of Bluetooth Low Energy availability (p). E_{24} is computed with formula 5.2, where $E_{\text{BLE},1000}$ and $E_{\text{NB-IoT},1000}$ are the cycle energy when transferring 1000 bytes every 10 seconds, p is the BLE availability and 8640 is the amount of cycles in one day.

A BLE-connection depends on an in-range external device that has to be charged. When a BLE-connection is not possible, data is transferred over NB-IoT. Figure 5.2a shows that the battery lifetime increases tremendously to 2500 when everything is sent over BLE. In Figure 5.2a, we take a closer look at 80 per cent of the time BLE-availability: sending 80 per cent of the heart data over BLE corresponds to a lifetime of 60.4 days. When only using NB-IoT, the battery lives 12 days. Considering the patch is worn for approximately 12 days, using NB-IoT achieves the requirement when no critical situation occurs. We should point out that only the communication technology is been taken into account, energy consumption of other sensors of the patch should be added to get a total energy consumption of the patch.

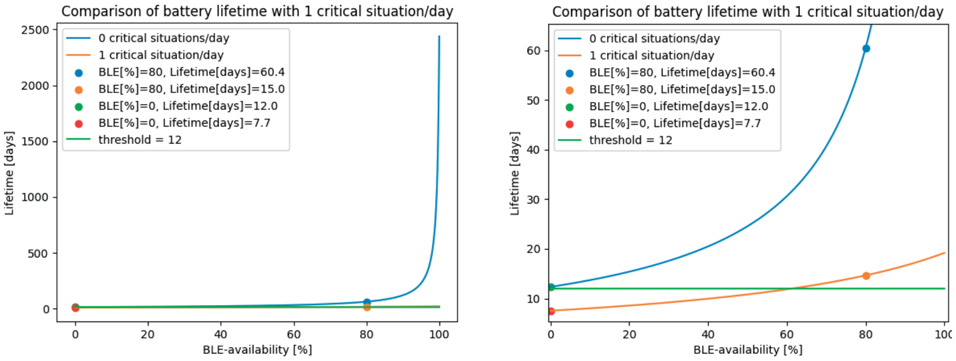
$$E_{24} = p \cdot E_{\text{BLE},1000} \cdot 8640 + (1-p) \cdot E_{\text{NB-IoT},1000} \cdot 8640 \tag{5.2}$$

$$\text{Lifetime [days]} = E_{battery}/E_{24} \tag{5.3}$$



(a) Comparison BLE and NB-IoT **(b)** Comparison BLE and NB-IoT, zoomed in

Figure 5.2: Comparison BLE and NB-IoT



(a) Comparison BLE and NB-IoT with one critical situation per day **(b)** Comparison BLE and NB-IoT with one critical situation per day, zoomed in

Figure 5.3: Comparison BLE and NB-IoT with one critical situation per day

What happens if one critical situation a day occurs? A close-up of this analysis is shown in Figure 5.3b. The lifetime reduces from 60.4 days to 15.0 days when

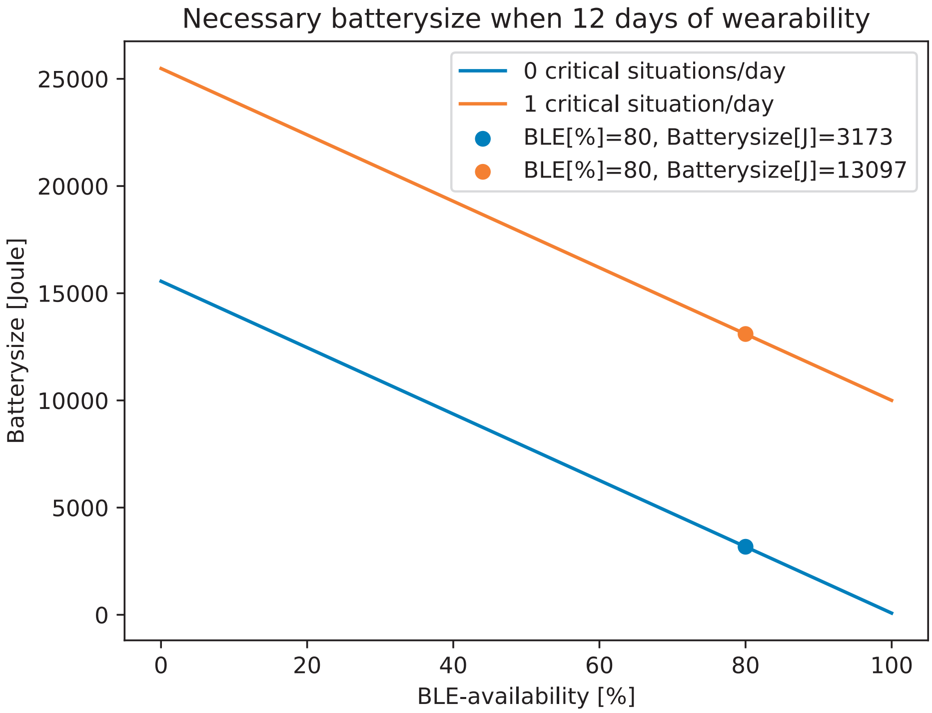


Figure 5.4: Battery size with variable BLE-availability and critical situations

80 per cent of data has been sent over BLE. The requirement of 12 days is only achieved if at least 60 per cent of the data is sent over BLE.

Implementing BLE increases the lifetime a lot, which means that the battery size can be reduced. An analysis of the needed batterysize for a wearability of 12 days is made in Figure 5.4. It shows that 10 kJ is required if 100 per cent of the data is sent over BLE and 1 critical situation a day occurs. Comparing 80 per cent BLE-availability indicates that a capacity of approximately 13 kJ is necessary when daily 1 critical situation occurs, and 3 kJ when zero critical situations a day occur.

5.6 Cost & area

Assuming both chips are used, so nRF9160 for critical situation and nRF52840 for normal use, the cost will be $28 + 9 = 37$ euros and the area of both chips together is 17x23.1mm with peripheral components. Removing the BLE-chip saves 9 euros per patch and an area of 7x7mm with peripheral components will be saved [47].

Chapter 6

Conclusion

This thesis investigated the implementation of short- and long-range technologies in a heart monitoring patch. After a literature study, NB-IoT is supposed to be best suitable for long-range communication because of its coverage and energy efficiency. For the periodic updates in a normal situation, both NB-IoT and BLE theoretically fulfil the requirements, which the measurements confirmed.

The energy analysis showed for both BLE and NB-IoT a declining energy per byte when transferring more data. Therefore, we made a trade-off between the energy consumption and update-periodicity, or in other words: a trade-off between the energy per byte and the datasize. This resulted in an ideal periodicity of 10 seconds, corresponding with a 1000 B transfer.

Simulating the battery lifetime of a battery with 16 kJ energy consumption taught us that implementing BLE increases the lifetime tremendously. But considering the patch will be worn for approximately 12 days; also NB-IoT fulfils the requirement when no critical situation occurs, which includes alert signal, localisation and transferring the recent ∼6 MB heartdata. When daily one critical situation happens, the wearability is only 7.7 days, so then a larger batterysize is necessary or some finetuning is required. Furthermore, only relying on NB-IoT will reduce the cost (∼37 €) and surface area of the patch since only one chip is necessary. We have to mention that only the communication technology is taken into account, so the energy consumption of extra sensors in the patch will change the needed battery size.

In addition to the battery lifetime, the recommended battery size when requiring wearability of 12 days in different cases shows that, if 80 per cent of the data is transferred over BLE (and 20 per cent over NB-IoT because the external device of BLE was, for example, not charged or not in range) and no critical situation occurs, approximately 3 kJ is required. When one critical situation a day happens and the same BLE availability is assumed, 13 kJ is recommended. Due to internal chemical reactions, batteries self-discharging, resulting in a lower battery capacity. It depends on the battery type.

Besides energy consumption, all transfer time measurements achieved the 30 seconds-requirement. However, sometimes it takes longer to transfer messages because of the hard-to-reach location, but more essential is that no packets are lost during transmission. Transferring the recent heart data after an alert signal happens within 5 minutes (as required) if the datarate is at least 160 kbit/s.

The GPS measurements concluded that it tracks the patient's location in a critical situation within 26 seconds. However, it is far from reliable when inside or surrounded by buildings. Therefore, other localisation functionalities must be implemented or added to the assisted GPS. Since GPS only runs in a critical situation, the energy consumption is only relevant when a critical situation occurs. Nevertheless, the energy consumption is less than one per cent compared to the energy consumption of sent heart data if the location is tracked for 25 seconds.

Chapter 7

Further work

This chapter will discuss the possible improvements and thoughts about the prototype.

- The GPS-functionality works very well when the patient is outside, but inside it is hard to obtain an accurate location. Furthermore, a GPS-signal does not specify the floor of a building. A solution can be to use WiFi-modems or call-based location technology.
- BLE-functionality can be expanded by connecting phone and patch by *bonding* instead of *pairing*. Now two devices only create a temporary encryption by exchanging security features. Bonding will go one step further and share long term keys to store in flash memory. When data needs to be sent, and so a new connection needs to be made, the patch can search for and connect with device whose keys are stored in the memory.
- To ensure that no data will be overwritten, NB-IoT can be used as back-up plan when the memory buffer is full and a BLE-connection cannot be made. So for example when a patch does not connect within 10 seconds of advertising, NB-IoT will be set-up and a data transfer is guaranteed.
- Also, we do not want data to be lost during transfer. This can be realised by the server who sends back an acknowledgement when receiving the data.

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