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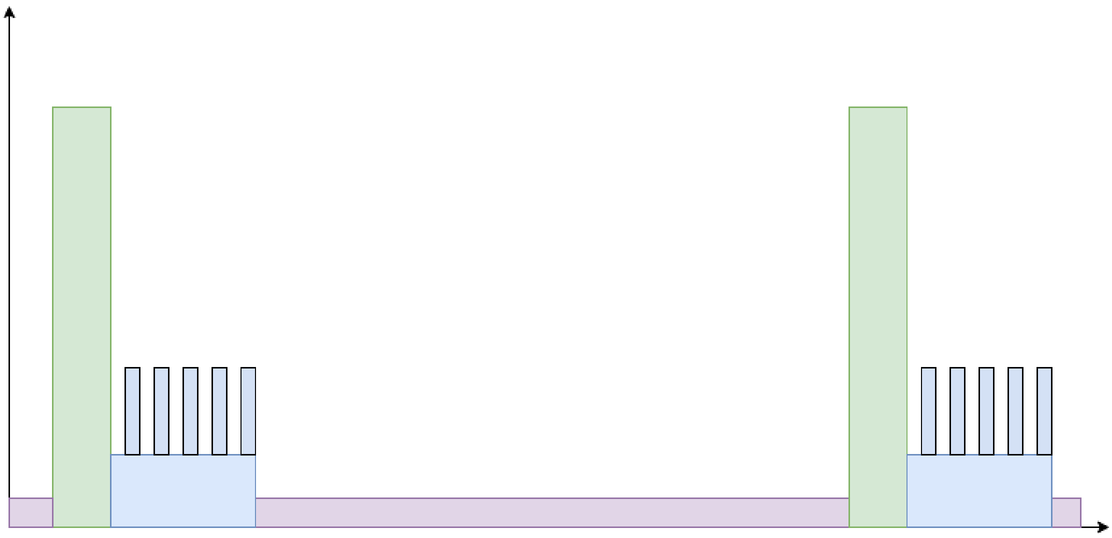

An empirical study of Cellular-IoT

Master's thesis in Communication Engineering

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Department of Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

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Cover: Illustration of a modems power profile with power save mode.

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Abstract

Narrowband-IoT and LTE-M are two cellular networks for Internet of Things and machine type communication that can be deployed within the LTE infrastructure. This report empirically evaluates the performance of these networks in terms of power profile and handover functionality. To evaluate the networks Nordic Semiconductors development kit nRF9160-DK is used and Telia is the network provider. Power profiling was performed by using a power analyzer measuring the current consumption for a device in different scenarios. The features power save mode, release assistance indicator and extended discontinuous reception were evaluated in terms of energy consumption. Handover functionality was tested using TCP and UDP, measuring round trip times and signal quality.

Narrowband-IoT showed potential in energy constraint use cases during specific conditions. Calculated battery lifetime from empirical data for a sensor use case transmitting every 30 minutes with an ideal 2000 mAh battery gives a battery life of less than 1.5 years for narrowband-IoT and 26 days for LTE-M. However the same scenario with a transmission every 24 hours gives a battery life of approximately 25 years and 3 years respectively. Release 13 compatible LTE-M user equipment and networks are not recommended for energy constrained use. The handover tests shows that TCP based communication performs poorly with up to minutes to resolve a handover. UDP based communication has better performance in terms of handovers and LTE-M using UDP has potential for a wearable application.

Keywords: Narrowband-IoT, LTE-M, Internet of Things, IoT, Cellular IoT, Power Profile,

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Tim Ekman, Samuel Jönsson, Gothenburg, August 2019

Contents

Acronyms

CE coverage enhancement
CoAP constrained application protocol
DL downlink
DRX discontinuous reception
eDRX extended discontinuous reception
eNB evolved node b
EPC evolved packet core
EPS evolved packet system
GPRS general packet radio services
HD-FDD half-duplex frequency division duplexing
HFN hyper frame number
HSS home subscriber system
IoT internet of things
ISM industrial, scientific and medical
LPWAN low-power wide-area networks
LTE-M LTE for machine-type communication
MIMO multiple-input multiple-output
MME mobility management entity
mMTC massive machine-type communication
MTC machine-type communication
NB narrowband
NB-IoT narrowband internet of things
OFDM orthogonal frequency division multiplexing
PA power amplifier
PAPR peak-to-average power ratio
PDN packet data network
PDN-GW packet data network gateway
ppm parts per million
PRB physical resource block
PSM power save mode
QoS quality of service
RAI release assistance indicator
RAN radio access network
RF radio frequency
RRC radio resource control
RSRP reference signal received power
RTT round trip time
SFN system frame number
SiP system in package
S-GW serving gateway
TA tracking area
TAU tracking area update
SNR signal-to-noise ratio
UL uplink

3GPP 3rd generation partnership project

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Introduction

The internet of things (IoT) has increased in importance during the last few years. The term is used in virtually every technology industry, often as a mean to advertise a product or service but what does it mean? The IoT can be defined in a multitude of ways but ultimately it is an umbrella term that refers to the concept of massive connectivity between objects, real and virtual [2].

In the future, it is expected that an increasing amount of non-Internet-capable everyday objects will be made "smart" through connectivity. In addition to everyday objects such as home lighting and toasters, the number of sensors connected to the Internet is expected to increase considerably. With the expectation of new connected devices, the amount of communication conducted without human involvement will increase. This type of communication, machine-type communication (MTC) demands a different kind of performance compared to the traditional use case of mobile broadband where high data rates are prioritized. An implication of the rising number of connections is the need for networks to support a massive number of devices. In addition to this, low energy consumption and extended coverage are often requirements for MTC [3].

To illustrate these requirements an agriculture example will be presented. Agriculture is one of the industries targeted by narrowband internet of things (NB-IoT) providers[4], and a sensor system for an irrigation system is a specific MTC example. To optimize and automate an irrigation system, data needs to be collected from a potentially huge area using many sensors. This area might lack easy access to a power distribution system, making cheap battery-powered modems the preferred solution. In conclusion, the irrigation system in this example requires a network facilitating devices with a long battery life using cheap hardware and improved coverage compared to LTE. Thus, allowing the system to operate in remote areas where traditional LTE coverage is inadequate.

A typical characteristic of MTC which also holds true in this example is the relatively small amount of data needed to be transmitted [3]. MTC often has a relaxed demand for latency due to infrequent transmissions. These facts are used to reduce energy consumption while facilitating device simplicity and extended coverage in IoT network technologies (relative to traditional LTE communication).

1.1 Motivation

The enabling technology for energy constraint MTC and IoT use cases is low-power wide-area networks (LPWAN)s. A collection of different LPWANs with their own advantages and disadvantages exists. LPWANs can be deployed in two fundamentally different ways, the cellular, and the non-cellular way. At the time of writing this thesis, cellular LPWANs had very recently been deployed in Sweden. This thesis will evaluate the two cellular LPWANs, NB-IoT and LTE for machine-type communication (LTE-M) deployed in Sweden by Telia. In the following section, some existing options for LPWANs will be presented followed by a more thorough presentation of NB-IoT and LTE-M.

1.2 Non-Cellular IoT

Sigfox, a French network provider was among the first companies to capitalize on the demand for LPWANs from an IoT perspective. Sigfox was founded in 2009 and has built an LPWAN with considerable coverage both in Europe and America, employing the industrial, scientific and medical (ISM) frequency bands. Other common technologies using the ISM bands are WiFi and Bluetooth. The ISM bands is unlicensed and can be used freely as long as local governing regulations are followed. Naturally, this means that all communication on the ISM bands needs to be able to handle interference from other users.

Sigfox uses an ultra-narrowband signal and a one-hop star network topology [5], as illustrated in fig. 1.1. The narrowband signal enhances the coverage by increasing the power spectral density, focusing the transmitted energy. The use of cheap hardware and highly selective receivers is made possible through the ultra-narrow bandwidth. With this selectivity comes a higher receiver signal-to-noise ratio (SNR) at the same signal strength compared to a less selective receiver [6]. The modulation format used by Sigfox is the binary phase-shift keying, i.e, data is encoded in the phase of the signal.

The main competitor to Sigfox is LoRa and LoRaWan. LoRa makes up the physical layer while LoRaWan forms the higher communication stack layers built on top of LoRa. LoRa is deployed in the ISM frequency bands but does the opposite of Sigfox in terms of bandwidth usage and employs a spread spectrum modulation format, intentionally increasing the bandwidth of the signal more than strictly needed [5]. Advantages of wideband communication includes robustness against interference, added security and mitigation of issues with multipath fading[7]. LoRa primarily uses coding gain to enhance coverage.

These are the most prominent standalone LPWANs in regard to the existing cellular networks. Separate infrastructure in terms of gateways, base stations, and network servers needs to be set up to utilize these technologies.

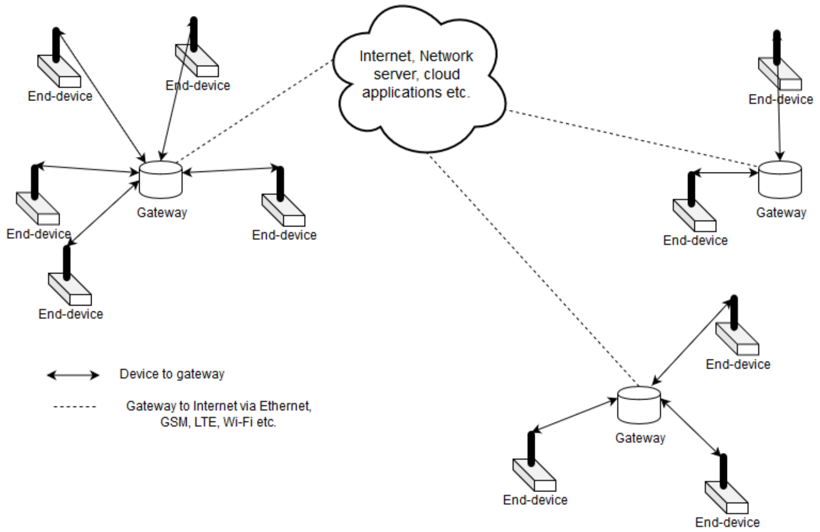


Figure 1.1: One-hop star network topology.

1.3 Cellular IoT

Currently, the LPWANs that can be deployed within the LTE infrastructure consist of 2 options, LTE-M and NB-IoT. Historically many cellular IoT applications have used GSM. The reason for this will be presented in the following section. In addition to this NB-IoT and LTE-M will be introduced.

1.3.1 GSM

GSM is the second generation of digital cellular communication standards and was first deployed 1991 in Finland [8] way before IoT became a concept. Therefore, GSM was not designed for MTC, limiting it in some IoT use cases. The GSM technology was developed specifically for voice communication, support for data transmission was added over time (originally by the support for SMS). Since then it has been upgraded with the enhanced Data rates for GSM Evolution (EDGE), which tripled the data rates [8]. GSM currently sees a lot of use in IoT applications, primarily as a cellular low-cost alternative to 3G and 4G. Low cost, both in terms of device hardware as well as subscription costs.

A major drawback with GSM for many IoT applications is the device energy consumption. GSM lacks modern solutions found in NB-IoT and LTE-M, such as, power save mode which has the potential to greatly decrease energy consumption. This combined with the fact that the GSM network has been, or will be discontinued in many parts of the world [9], motivates the need for technologies to replace the existing use cases of GSM, and enable new ones.

1.3.2 LTE-M and NB-IoT

LTE-M and NB-IoT are currently being deployed in many regions of the world. Contrary to Sigfox and LoRa, LTE-M and NB-IoT do not require additional infrastructure outside of the existing LTE networks.

LTE-M and NB-IoT can be deployed within the standard LTE frequency bands [10, p. 139], making deployment potentially cheaper and more practical than non-cellular alternatives. LTE-M and NB-IoT are more narrowband than traditional LTE and supports features such as extended retransmission protocols to enhance coverage, sleep cycles in the form of power save mode (PSM), and extended discontinuous reception (eDRX) to extend battery life. This thesis will present these features in detail.

1.3.3 3rd Generation Partnership Project

The 3rd generation partnership project (3GPP) is the organization responsible for the specifications that defines the cellular telecommunication technologies[11]. The organization was created to develop specifications for 3G, but its responsibilities has since grown to include the maintenance of older technologies as well as developing new 5G, and 5G related specifications and standards.

3GPP structures its work in numbered releases where a single release consists of hundreds of documents describing different specifications, ranging from the core network to specifications regarding modem API. In the first half of 2016, 3GPP finalized its NB-IoT and LTE-M specifications which were included in release 13. This marked the beginning of cellular technology specifically designed for MTC and IoT. Further enhancements to these technologies, primarily energy saving features were specified in release 14 that came out the following year.

1.4 Aim and Contribution

The options for LPWANs are diverse but this thesis focuses on NB-IoT and LTE-M, aiming to present an understanding of the networks and their suitable use cases. This includes an evaluation of the energy consumption for devices using the networks, and their handover functionality. Handovers will be evaluated in terms of round-trip times and correlated with signal quality during handover tests. This is the first empirical study of NB-IoT in Sweden that we are aware of, and due to the infancy of the technology, market-ready devices running NB-IoT or LTE-M are scarce. Additionally, Telia was the only network provider offering subscriptions to either NB-IoT or LTE-M at the time of writing this thesis, hence Telia's networks were evaluated.

1.5 Previous Work

In [12] early deployment of NB-IoT in Norway is studied, the networks of Telia and Telenor are compared. It is argued that a small packet size is preferable to a large packet size due to a steady increase in power usage for larger packets. Excellent coverage and latency < 10 s is achievable for NB-IoT. By spring 2018 it is concluded that there are many unknown states and bugs in both the evaluated networks and devices. NB-IoT is empirically evaluated in terms of energy consumption, reliability, and delays in [13]. When compared to LoRa, NB-IoT has equivalent or less energy consumption with the benefit of guaranteed delivery. It is concluded that due to the large variability in regard to delays and energy expenditure, applications that have service-level agreements are questionable use case for NB-IoT.

1.6 Disposition

In chapter 2 a brief overview of the overall LTE architecture and features relevant to the project is provided followed by descriptions of targets, features, and the techniques employed to reach the targets set for LTE-M and NB-IoT. Chapter 3 contain descriptions of the hardware and software used, configuration instructions and setups for the tests performed. In chapter 4 results are presented for power profiling and handover-functionality-tests followed by a discussion in chapter 5 and conclusion in chapter 6. In chapter 7 suggestion on topics for further research is provided.

2

Theory

2.1 LTE Overview

LTE-M and NB-IoT are both able to be deployed within an LTE network, consequently, an overview of the overall LTE system architecture will follow with descriptions of parts relating to IoT and functionality involved in the project.

The evolved packet system (EPS) is the name of the full LTE network. It is made up of two components. The LTE radio access network (RAN) and the core network named evolved packet core (EPC). The LTE RAN illustrated in fig. 2.1, handles all radio functionality and resides between devices and the EPC. The EPC, illustrated in fig. 2.2 handles all non-radio related functionality and is completely in the packet-switched domain. The separation between the core network and RAN enables the EPC to serve multiple radio access technologies, such as UTRAN and GSM.[14, Sec. 4.1].

The EPS is made up of logical nodes and for the purposes of this report the most

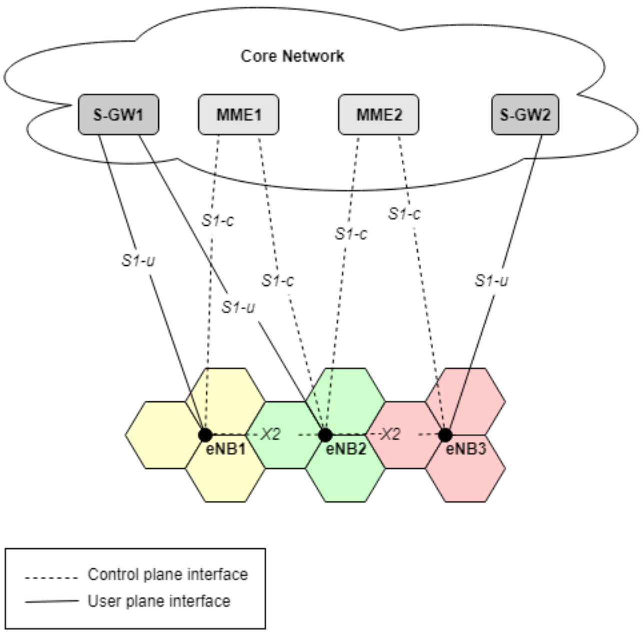


Figure 2.1: Illustration of LTE radio access network example, multiple S-GWs, MMEs, tri-sector eNBs and corresponding interfaces.

important are evolved node b (eNB), mobility management entity (MME), serving gateway (S-GW), packet data network gateway (PDN-GW) and home subscriber system (HSS). The eNB has all functionality needed to handle the wireless connections between devices and the network [15, pp. 22-23]. An eNB is connected to one S-GW and at least one MME. When a device is attached over the LTE RAN the MME handles the control plane signaling and provides security and mobility support [15, p. 23]. For devices in idle mode, the MME handles tracking area (TA) and paging, further explained in section 2.1.2. HSS is mainly responsible for authentication and authorization of devices attaching over the LTE RAN and communicates this information to the MME. User plane data to and from the LTE RAN is managed by the S-GW. For devices in idle mode the S-GW buffers downlink (DL) IP packets destined for the device [15, p. 23]. Linking of the EPC to external IP networks such as the Internet is provided by the PDN-GW. The PDN-GW is responsible for providing IP-addresses for devices [15, p. 369].

2.1.1 Radio Resource Control

In LTE, the radio resource control (RRC) is a control plane protocol located in the eNB that manages RAN procedures. The RRC enables a device to communicate with a cell by broadcasting system information, setting up bearers, managing mobility functionality, handling device capabilities, transmitting paging messages from the MME, and establishing RRC context [14, Sec. 4.3]. The RRC context is established so that parameters needed for communication between the device and RAN is known to both the network and the device. An LTE device can be in one of two RRC modes, RRC idle mode and RRC connected mode (henceforth referred to as idle mode and connected mode). When a device is in idle mode the device is not connected to any particular cell. Most of the time in idle mode the device sleeps to limit energy consumption, checking for paging messages (notification of incoming connection requests from the MME) according to its discontinuous reception (DRX) cycle. Moving to connected mode requires RRC context to be established in both the device and network. In connected mode, the device is connected to a specific cell and actively communicating i.e, transmitting or receiving messages to and from the device.

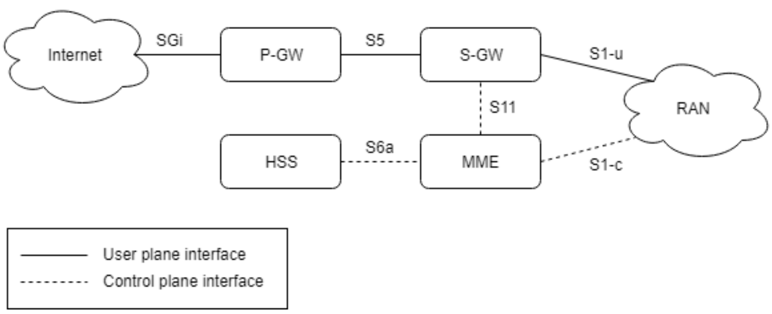


Figure 2.2: Illustration of LTE evolved packet core, logical nodes and interfaces.

2.1.2 Tracking Area and Tracking Area Update

The network knows an LTE device's position at the cell level when it is in connected mode. That means that when the device is communicating the network knows cell and eNB location for the device. When in idle mode, i.e, not actively communicating the network only knows in what TA the device is located [16]. One TA is a set of neighboring eNBs and is needed when data traffic is on its way to the device. If the device to which the data is heading is in idle mode, the network does not know where the device is located at the cell level and thus triggers a broadcast message (paging) over the radio links in the TA where the device is located. Therefore the device must wake up from idle mode periodically to check for paging messages to be able to receive data. The method by which the MME keeps track of in which TA an LTE device is residing is called tracking area update (TAU). When a device moves between TAs the MME is notified by a TAU request message to update its TA. Periodic TAU can be used for devices that utilize sleep cycles, such as PSM, as a method for battery life enhancement. The device sends TAU request messages periodically even if it is still residing in its original TA to notify the network that it is in idle mode and to trigger paging. If TAU is not performed after waking up from a sleep-cycle the network will have no information that the device can receive data and therefore paging will not occur even if data is destined for the device.

2.2 LTE-M and NB-IoT Features

NB-IoT and LTE-M share several features used to reach their performance targets. This section will present eDRX and PSM, the key supporting features for extending battery life. Additionally, the narrowband (NB) feature which allows frequency allocations in existing LTE carriers for both LTE-M and NB-IoT will be presented.

2.2.1 Narrowband

The narrowband concept was specified in 3GPP release 13 to accommodate MTC devices need for reduced complexity and energy consumption [14, Sec. 20.3.1]. Originally all LTE devices were required to support the full LTE carrier bandwidth of 20 MHz to simplify specifications and implementations. Supporting the full LTE carrier bandwidth adds little complexity to a normal mobile broadband devices due to radio frequency (RF) complexity being a small part of the overall device complexity. This is not the case for low-end IoT devices, also known as massive machine-type communication (mMTC) devices. Where a smaller bandwidth greatly lowers total device complexity, modem cost, and energy consumption. To relax bandwidth requirements for LTE-M devices, transmission and reception only utilize the minimum instantaneous LTE bandwidth of 1.4 MHz. The NB concept makes it possible for MTC devices to use one NB of a wideband carrier since the whole spectrum is split up into NBs. These NBs of 1.4 MHz consists of six physical resource block (PRB)s, each containing 12 orthogonal frequency division multiplexing (OFDM) sub-carriers of 15 kHz each, thus one PRB occupies 180 kHz as illustrated in fig. 2.3. Since some signaling channels occupy more than one NB certain specific NBs are used to

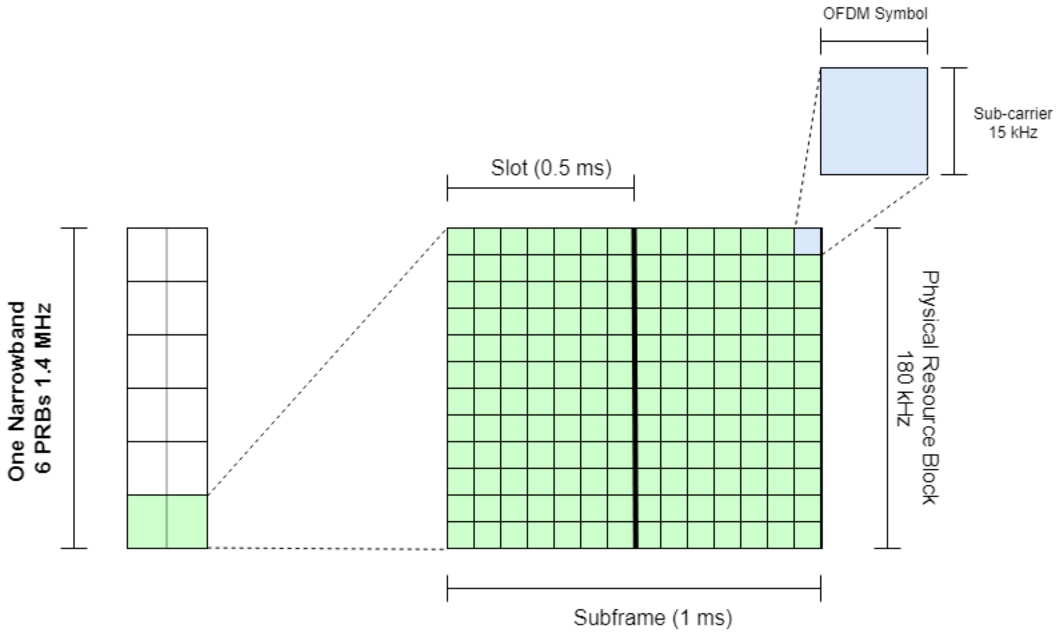


Figure 2.3: Narrowband and Physical Resource Block.

transmit equivalent signaling.

2.2.2 Power Save Mode

PSM is used to limit energy consumption while not transmitting or receiving. To reach an extremely low consumption, all RF and non-critical modem functionality are shut down [14, Sec. 20.2.4]. Using PSM is similar to powering off the device, but even though it is unable to communicate with the network it remains registered to it, and consequently does not need to re-attach or re-establish packet data network (PDN) connections. I.e, the IP prefix association between the device and the internet or another IP network is maintained. Since the network cannot reach a device in PSM the device itself must re-establish connectivity before transmission in both downlink and uplink. Due to the information about the device stored in the network the re-attach procedure demand fewer resources than a fresh connection would. If data packets from the network are expected to the device, it must reconnect from time to time and stay awake for a short period to allow for paging in the case of incoming data. This active time is controlled by the active timer t3324 further explained in 3.2.3. A user can request a value of this timer from the network. Care must be taken to make these instances infrequent and short to maintain the power-saving benefits from using PSM. Current consumption during a PSM cycle is qualitatively illustrated in fig. 2.4.

2.2.3 Extended Discontinuous Reception

DRX and eDRX makes use of the basic LTE frame structure to preserve energy by allowing a device to monitor downlink control signaling in one subframe per DRX or eDRX cycle and sleep for the rest of the time [14, Sec. 20.3.8]. A cycle in this

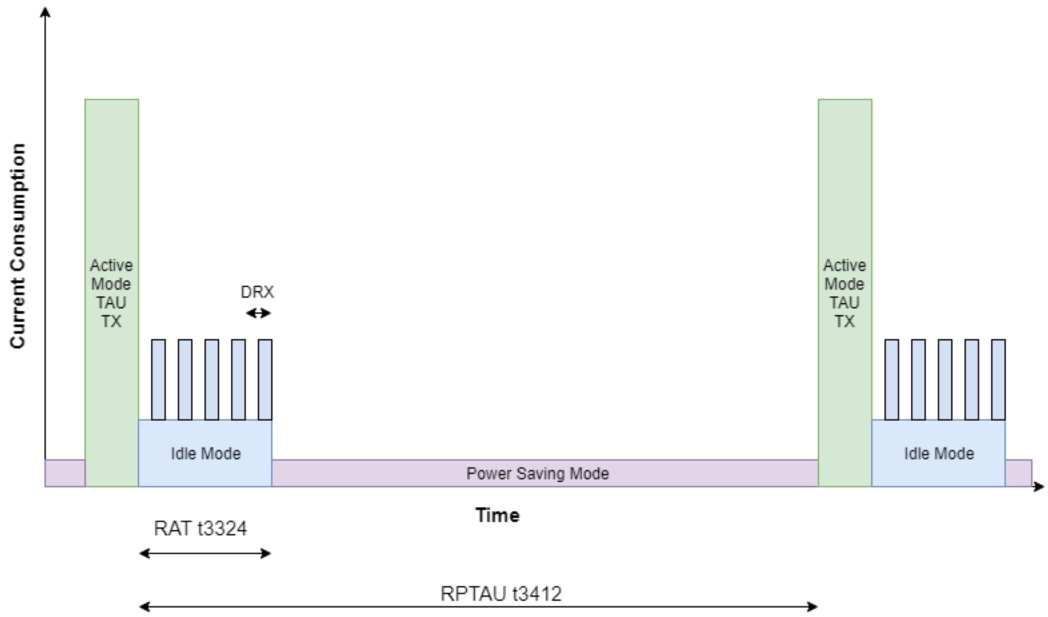


Figure 2.4: Power consumption during Power Save Mode with modes, timers and DRX.

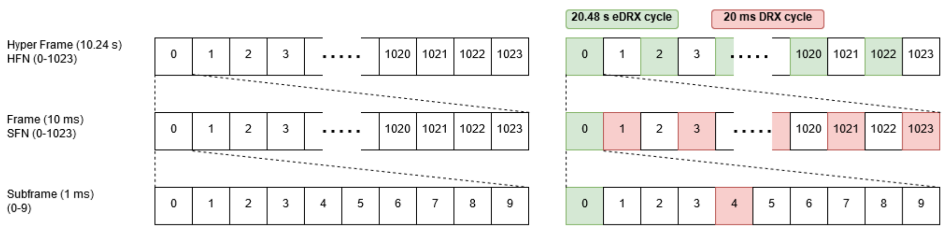


Figure 2.5: Illustration of the LTE frame structure with eDRX and DRX cycle example.

context refers to the time between two instances of a device monitoring the downlink for control messages such as paging. The maximal length of a cycle is limited by the system frame number (SFN) period or hyper frame number (HFN) period depending on which one is used.

An LTE subframe (1 ms) is illustrated in fig. 2.3 and are numbered via a subframe number between 0-9. 10 such subframes make up one frame (10 ms). All frames are numbered via a SFN between 0-1023 with a period of $(1024 * 10\text{ ms} = 10.24\text{ s})$ before repeating the SFN. A hyper frame is numbered via a HFN between 0-1023, and consist of 1024 frames giving a hyper frame duration of 10.24 s and a period of $(1024 * 10.24\text{ s} = 10485.76\text{ s})$ before repeating the HFN. The relationship between hyper frames, frames, and subframes are illustrated in fig. 2.5.

DRX can be used in both connected and idle mode. In the idle mode, DRX implies sleeping and waking up to check for paging messages. A DRX cycle is limited to 256 frames or 2.56 s for LTE which is sufficient for mobile broadband devices. Longer DRX cycles would result in unacceptably high latency when accessing the network.

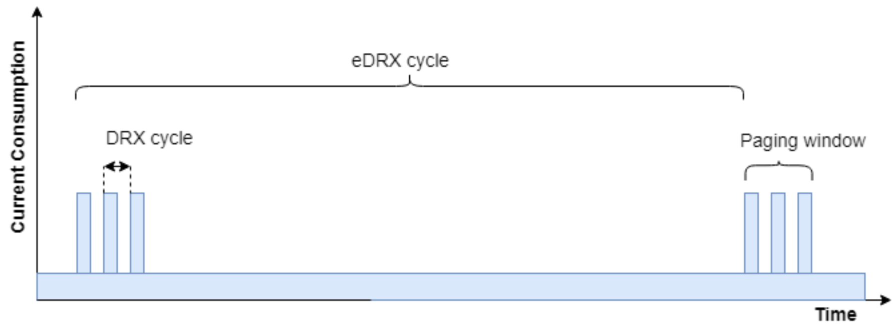


Figure 2.6: Illustration of power consumption during eDRX with eDRX cycle, DRX cycle and paging window.

For certain mMTC devices the latency requirements are a lot more relaxed and the battery life requirements are sometimes very stringent, therefore longer DRX cycles are desirable. For this purpose, eDRX was introduced and utilizes hyper frames. For example, NB-IoT can use eDRX cycles of up to 1024 frames or 10.24 s in the connected mode and up to 262144 frames or 2621.44 s ($\approx$ 44 minutes) in the idle mode.

An example of a 20.48 s eDRX cycle in green and a 20 ms DRX cycle in red is illustrated in fig. 2.5 to show how DRX and eDRX cycles are implemented. Since 20.48 s eDRX cycle is longer than a single hyper frame duration (10.24 s), the device must utilize HFN and checks for paging in one subframe within one frame of every other hyper frame. In the DRX cycle example the device does not need to track the HFN since the cycle is much shorter. A 20 ms cycle means that the device will check for paging in one subframe for every other frame.

The practical use for eDRX is when a device needs to be reachable not only after uplink communication but when unsolicited communication to it is required. Current consumption during an eDRX cycle is qualitatively illustrated in fig. 2.6 where a device is available for paging messages every DRX cycle during the paging window. In the same way, as for PSM the cycle length of eDRX can be requested from the network by the user. It is important to note that DRX and eDRX cycle length in the connected mode are set by the network and cannot be influenced by the user.

2.3 NB-IoT

NB-IoT have several design principles catering to the ultra-low-cost mMTC segment. The main purpose of NB-IoT is to achieve low device complexity and cost, significant coverage enhancement to both GSM and traditional LTE networks, as well as a long battery life and flexible deployment modes [10, pp. 220-221].

2.3.1 Device Complexity and Cost Reductions

To facilitate lower device complexity and cost, baseband processing, memory consumption, and RF requirements have been reduced [10, pp. 220-221]. To reduce the baseband processing complexity, initial cell selection and connected mode have been simplified. During initial cell selection, basic time and frequency synchronization to the network is achieved by searching for only one synchronization sequence and a low sampling frequency f_s can be used. Compared to the sampling frequency used in standard LTE which depends on sub-carrier spacing f_{sub} and FFT-size N_{FFT}

$$f_s = f_{sub} * N_{FFT} \tag{2.1}$$

which must be greater than the system bandwidth [14, Sec. 5.1]. LTE does not require implementations using FFT or any specific sampling rate. The range of standard sampling frequencies can, however, be calculated if one assumes a 15 kHz sub-carrier spacing and uses the minimum and maximum system bandwidths of 1.4 MHz and 20 MHz.

$$15kHz * N_{FFT} \geq 1.4MHz \rightarrow N_{FFT} = 128$$

Thus, a standard sampling frequency at the lower end for a system bandwidth of 1.4 MHz via (2.1) is

$$15kHz * 128 = 1.92MHz$$

And for full carrier bandwidth of 20 MHz the FFT-size is calculated as follows

$$15kHz * N_{FFT} \geq 20MHz \rightarrow N_{FFT} = 2048$$

Thus, a standard sampling frequency at the higher end can be determined with (2.1)

$$15kHz * 2048 = 30.72MHz$$

NB-IoT devices can utilize a substantially lower sampling frequency of 240 kHz. The synchronization properties and the low sampling frequency helps reduce both memory consumption and processing complexity. During connected mode, several complexity reductions are implemented in the downlink. Transport block size is restricted to $\leq$ 680 bits and processing time requirements are relaxed compared to standard LTE. Turbo codes which require iterative receiver processing are not used. NB-IoT instead uses LTE tail-biting convolutional code, which is a simpler coding scheme. Furthermore, NB-IoT uses lower order modulation compared to standard LTE, as well as no support for multi-layer multiple-input multiple-output (MIMO) schemes.

To reduce RF complexity only half-duplex is required so that the NB-IoT device only needs to be able to receive in the downlink or transmit in the uplink at any given time. I.e, with only one transmit-and-receive antenna, all RF performance targets can be achieved. Therefore there is no need for downlink receive diversity, uplink transmit diversity, or a RF front end duplexer [10, pp. 220-221]. NB-IoT is designed to tolerate up to 20 parts per million (ppm) oscillator offset during a data session, and the transmission scheme is designed for easy tracking of frequency drift. On-chip power amplifier (PA)s can be implemented to reduce cost and complexity due to the maximum transmit power of an NB-IoT device being limited to either 20 or 23 dBm. To make optimal use of available transmit power close to constant envelope waveform is used in the uplink i.e. peak-to-average power ratio (PAPR) close to 0 dB. This means that the PAs can operate close to saturation level instead of as for waveforms with higher PAPR where a 3 to 6 dB backoff from saturation level is required. This greatly reduces the PA complexity since the linearity requirements of the PAs are substantially relaxed.

2.3.2 Coverage Enhancement

Coverage enhancement is primarily achieved by sacrificing data rate for coverage [10, p. 221]. Repetition is used to ensure reliable communication in challenging coverage locations with a lower data rate as the inevitable consequence. The usage of close to constant envelope waveforms in the uplink, allows for coverage enhancement by making use of close to the maximum transmit power in coverage limited situations possible because of the lessened need for backoff from saturation level.

2.3.3 Battery Life Extension

An additional benefit from minimizing power backoff is the resulting increased power efficiency in connected mode and thus longer battery life. Still, most of the increased battery life is gained through battery consumption reduction during idle mode [10, p. 221]. This stems from the fact that many IoT devices spend most of their lifetime in idle mode due to infrequent and short transmissions. Traditionally a device in idle mode monitors paging information and perform mobility measurements. An NB-IoT device on the other hand, can implement long periods without paging or in some cases no paging at all. These reductions in idle mode battery consumption comes from eDRX and PSM, as described in sections 2.2.2 and 2.2.3.

2.3.4 Capacity

The capacity for massive amounts of connected devices per NB-IoT carrier, is achieved by high spectral efficiency in the uplink (UL) during extremely limited coverage situations i.e, for low SNR scenarios [10, pp. 221-222]. In low SNR scenarios the data rates dependency on signal bandwidth is diminished and becomes primarily determined by received signal power. Thereby, it is efficient in regard to frequency spectrum to allocate small signal bandwidths for devices in such conditions. From a system perspective the multiple uplink bandwidth options are utilized for this purpose. As little as a single sub-carrier can be allocated for a device in limited coverage conditions. NB-IoT have two options for sub-carrier spacing, 15 kHz or 3.75 kHz. This way a device in good coverage can utilize multiple sub-carriers up to a whole PRB of 180 kHz and as low as 3.75 kHz. This using a single sub-carrier in coverage limited conditions.

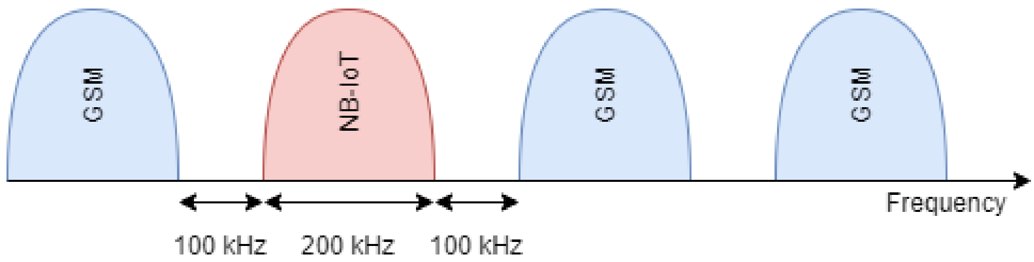


Figure 2.7: Stand-alone deployment in refarmed GSM spectrum.

2.3.5 Deployment Flexibility

Since the use of the frequency spectrum is highly regulated and the spectrum suitable for radio communication is finite, refarming frequency bands are commonly done when introducing new technologies. Refarming is the act of repurposing bandwidth to be used in a new way.

To ensure flexible deployment and options for utilizing refarmed spectrum for NB-IoT three deployment modes are specified [10, pp. 222-224]. These are stand-alone deployment, utilizing refarmed spectrum of at least 180 kHz. Guard-band deployment, deployment in an LTE carrier's guard-band and in-band deployment, deployment within the spectrum of an LTE carrier.

2.3.5.1 Stand-alone Deployment

Stand-alone deployment of refarmed GSM spectrum is illustrated in fig. 2.7 showing a network operator refarming a part of its existing GSM-spectrum for one NB-IoT carrier and the required guard-bands between the NB-IoT carrier and the remaining GSM carriers. It is recommended to use a 200 kHz guard-band between operators and 100 kHz between carriers due to the coexistence criterion [10, p. 222]. This shows that whenever a GSM operator wants to refarm its spectrum for NB-IoT deployment at least two GSM carriers must be refarmed per NB-IoT carrier. It should also be noted that the GSM spectral mask has 200 kHz channelization thus even though NB-IoT uses only 180 kHz it occupies 200 kHz for stand-alone deployment in practice.

Since NB-IoT also supports deployment within LTE networks, this ensures that refarming parts of GSM spectrum destined to later be completely refarmed to LTE is not a problem. It is also likely that this property still holds when LTE spectrum later is being refarmed to 5G [10, p. 224].

2.3.5.2 Guard-band and In-band Deployment

Guard-band deployment utilizes the fact that an LTE carriers signal only occupies $\approx 90\%$ of its channel bandwidth [10, p. 223]. Thus there is roughly 5 % of up to 20 MHz bandwidth available in a guard-band.

In-band deployment can be used for LTE carriers supporting LTE-M features that

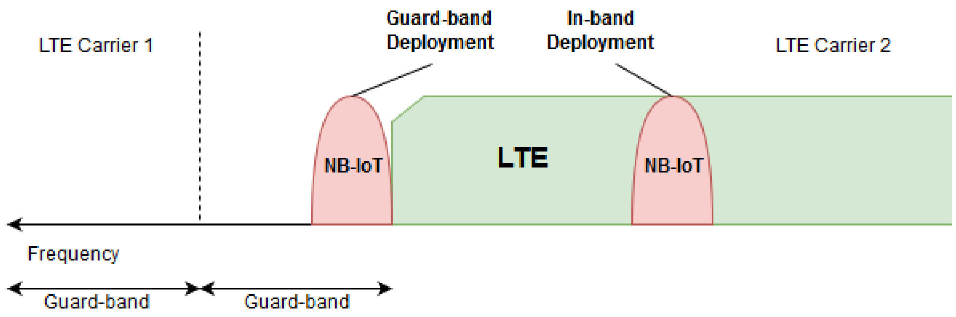


Figure 2.8: Guard-band and In-band deployment of NB-IoT.

utilize the NB concept for IoT transmissions [10, p. 223]. Some of these NBs are not used to transmit LTE-M system information block type 1 (SIB1) and one of the PRBs within such a narrowband can, therefore, be used to deploy an NB-IoT carrier. In fig. 2.8 The two deployment modes within LTE is illustrated where one NB-IoT carrier is deployed within the guard-band of an LTE carrier and one NB-IoT carrier is deployed within an LTE carrier.

2.3.6 Physical Layer Design

NB-IoT is a recently developed technology and has been designed from scratch thus with great flexibility [10, p. 224-225]. However, the ability of deployment in both refarmed GSM spectrum and existing LTE carriers introduces some restrictions. The source for these restrictions includes the need for substantial guard-bands in stand-alone deployment and the ability to deploy without guard-bands for in-band deployment. Thus, demanding orthogonality with neighboring LTE PRBs. The same frequency-time grid as LTE is required for smooth implementation and care has been taken such that no collisions with crucial LTE transmissions are allowed since legacy LTE devices predates NB-IoT.

2.3.7 Handover

Since NB-IoT caters to the low-end mMTC segment where the device is assumed to be stationary during usage there is no support for handovers in the connected mode. NB-IoT instead relies on cell reselection in idle mode and thereby do not maintain quality of service (QoS) when switching serving cell.

2.4 LTE-M

LTE-M adds support for MTC and IoT applications for LTE by features such as coverage enhancement (CE) modes, PSM, eDRX to suit the Cat-M device category. The targets for the development of LTE-M is low device cost, deep coverage, long battery lifetime, support for a large number of devices per cell and support for low- to mid-range IoT applications [10, p. 139]. Due to the fact that LTE-M is a continuation of LTE and fully compatible with legacy LTE, LTE-M shares out of necessity more of its design with legacy LTE. The following section will however focus on the differences between LTE-M and legacy LTE that improves its suitability for MTC and IoT applications.

2.4.1 Device Complexity and Cost Reductions

The target of competing with low-end MTC applications, served by GSM/GPRS, encouraged the device cost reduction development. The cost reductions are all related to performance reductions. The performance reduction for Cat-0, which is the lowest performance device category defined in standard LTE, started before the introduction of LTE-M and LTE-M borrows all the reductions made for Cat-0. These inherited performance reductions are the peak user data rate limit of 1 Mbps, support for a single receive antenna instead of two which was the minimum before Cat-0, and half-duplex operation introduced as an optional feature. Further reductions for LTE-M were the change from the mandatory full carrier bandwidth of 20 Mhz to 1.4 Mhz, support for half-duplex frequency division duplexing (HD-FDD) and maximal transmit power lowered from 23 dBm to 20 dBm. These reductions are together estimated to bring modem costs down to the same level as that of GPRS modems [10, pp. 137-138].

2.4.2 Coverage Enhancement

MTC devices are often placed where coverage is limited such as basements or in rural environments, the target for LTE-M is to provide an additional 20 dB compared to standard LTE to support these situations [10, p. 138]. The fact that most MTC devices transmits small amounts of data with long periods of inactivity makes long transmission times acceptable. Therefore the CE modes are designed to utilize extensive repetitions and retransmissions in limited coverage situations. For LTE-M two CE modes have been developed. Mode A uses up to 32 subframe repetitions and Mode B up to 2048 to reach the overall coverage enhancement of 20 dB.

2.4.3 Battery Life Extension

Extension of battery life is partly due to the power consumption reduction in the connected mode from the lowered transmit power and receive bandwidth from the complexity and cost reduction techniques described in section 2.4.1. However, the largest contributor to enhanced battery life comes from the usage of PSM and eDRX [10, p. 138] described in sections 2.2.2 and 2.2.3.

2.4.4 Deployment Flexibility

The full network operator LTE spectrum is automatically available for LTE-M traffic due to LTE-M supporting the same bandwidth as the LTE network [10, p. 139]. Thereby the spectrum can be dynamically shared between standard LTE and LTE-M traffic. To lower the performance impact on the legacy LTE network when deploying LTE-M traffic of delay-tolerant applications can be scheduled during periods of low overall traffic activity.

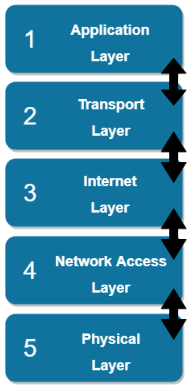


Figure 2.9: Internet protocol suite layers.

2.4.5 Physical Layer Design

LTE-M is based on legacy LTE more so than NB-IoT. All transmission schemes and modulation formats is shared and the foundation of the physical layer design is the same.

One of the facts that ensures interoperability is that in the same way as legacy LTE devices LTE-M devices always listens to the 6 center PRBs containing control information[17]. E.g the Primary Synchronization Channel. This control information is used to allocate resources by the network to LTE-M devices. Up to a maximum of 6 PRBs within a carrier can be allocated to a device when traffic is scheduled. Such a resource allocation is as mentioned called a narrowband.

Due to the use of a narrower bandwidth there is a need to make up for naturally lost frequency diversity. To combat this the Physical Channels used for LTE-M supports frequency hopping every 32 ms.

2.4.6 Handover

LTE-M has the same handover procedure as standard LTE and thereby maintains QoS while switching serving cell in connected mode.

2.5 Internet Protocol Suite

When designing communication systems, it is common practice to divide the system into different theoretical layers arranged in a stack. While this could be done in a multitude of ways there are two established models[18, Appendix. L], the OSI model and the internet protocol suite. The OSI model is purely conceptual and while it is not directly used in any real application it is used to characterize and standardize systems, to determine the responsibility for different parts of the system and the interaction between these. A layer in the model serves the layer above and is served by the layer below. The Internet protocol suite is used in the same way as the OSI model, but in addition to being a conceptual model, it is also the protocol which the Internet is built around.

The internet protocol suite consists of the following layers: the application layer, the transport, the internet layer, the network access layer and the physical layer. Fig. 2.9 illustrates the relationship between them.

Another name for the internet protocol suite is the TCP/IP model, named after 2 of the model's important protocols. The following sections will cover some of the important protocols for IoT, and how they fit into the TCP/IP model.

2.5.1 TCP

TCP resides in the transport layer of the TCP/IP model and is responsible for delivering data packets between hosts. Many applications in the application layer make use of TCP for its connection-oriented communication. The protocol establishes a connection between hosts through the means of a handshake procedure.

TCP provides reliable communication[19, s. 4.2]. Every packet contains a sequence number and acknowledgments packets are expected from the receiver by the sender after every delivered packet. This enables the sender to retransmit lost packets and the receiver to rearrange mismatched packets according to their sequence number. To further ensure reliability checksums enables TCP to detect erroneous packets, drop them and request retransmissions.

2.5.2 UDP

The main alternative to TCP is UDP. UDP is a minimal protocol that contrary to TCP, does not provide reliable communication[19, s. 4.1]. This means that an application layer process using UDP cannot be guaranteed that transmitted packets reach its destination. Reliability if needed has to be implemented by the application layer process itself. E.g, the constrained application protocol (CoAP) described below can optionally provide reliability for UDP based communication.

By having no inbuilt reliability, UDP exhibits a lower overhead and an enhanced speed compared to TCP, making it ideal for scenarios where speed is more important than ensuring no lost packages. For example, video streaming where attempting retransmission of lost packages would introduce jitter, impacting performance significantly more than a moderate number of lost packages.

2.5.2.1 CoAP

CoAP is an application layer protocol specifically designed for IoT and MTC[20]. This is evident in its low overhead and parsing complexity. In addition to its suitability to constrained environments, it is designed for easy integrating with web services. The ease of integration to web services stem from the use of the REST model in both HTTP and CoAP making designing a proxy between HTTP and CoAP trivial.

Central for CoAP is the concept of resources. A server can host multiple resources each identifiable with a unique URI. A resource can, for example, be a sensor value. This value can then be manipulated through the use of the basic REST methods: GET, POST, PUT, and DELETE. The PUT, POST, and DELETE methods are used to update, create and delete resources on the server while the GET is used to request the information associated with a resource. In the case of a sensor value, the sensor node would then send a POST request to the server updating the resource with a new reading. Then the value would be available at the central server through the GET method.

CoAP makes use of UDP and implements reliability. The use of reliability is optional and the sender indicates in its message if it wants its message to be confirmable or non-confirmable. In the case of a confirmable message, the server needs to respond with an acknowledgment packet on which it is possible to piggyback the response to the sender's request, further lowering overhead.

Security for CoAP is handled by the protocol DTLS. It is the UDP version of TLS and is designed to protect against attacks such as man in the middle and eavesdropping attacks[21].

3
Method

3.1 Hardware

The modem and the power analyzer used for evaluating the networks will be described in this section.

3.1.1 nRF9160 Development Kit

The evaluation of NB-IoT and LTE-M was conducted with the development kit nRF9160-DK[22] from Nordic Semiconductor. The development kit features a system in package (SiP) integrating an ARM processor and a modem supporting NB-IoT as well as LTE-M. During the time of writing this thesis, the SiP was under development and new firmware versions with new features and optimizations was released regularly. During the test period the SiP supported NB-IoT up to 3GPP release 14 and LTE-M up to release 13. Thus enabling the use of the release 14 feature release assistance indicator (RAI) for NB-IoT but not for LTE-M.

3.1.2 Power Analyzer

The current consumption measurements were done using an Otii Arc power analyzer[23]. The Arc was used as a power supply recording the current drawn by the measurement object. The Arc has an accuracy of $\pm(1\% + 0.5\mu\text{A})$ and a sample rate of 4 kHz in the lower current region and 1 kHz when the current is larger than 19 mA. Thus making it possible to get accurate measurements even when the current level switches fast, as in the nRF9160-DK SiP. The SiP which demands a voltage level in the region of 3 V to 5 V was supplied with 3.75 V for all measurements conducted with the power analyzer.

3.2 Tests

The configurations, parameters, and descriptions of the tests conducted are described in this section.

3.2.1 AT Commands

The nRF9160 device modems use the standard way of controlling modems. I.e, AT commands. Commands can be executed by firmware running in the SiP application

Command	Purpose
AT+CESQ	Returns reference signal received power (RSRP) value
AT%CESQ	Subscribes to changes in RSRP value
AT%XSYSTEMMODE	Changes system modes between NB-IoT and LTE-M
AT+CPSMS	Controls PSM requested values
AT+CEDRXS	Controls eDRX requested values
AT+CEDRXRDP	Reads requested values and received eDRX values
AT+CEREG	Subcripes to network status notifications
AT%XRAI	Sets the RAI flag

Table 3.1: Commonly used AT commands in this project.

core or through a serial interface with appropriate application core firmware[24]. AT commands allows the user to both retrieve network information such as signal strength, serving cell ID, frequency band in use as well as way to configure the modem in ways such as system mode and eDRX cycle length.

The syntax for AT commands is made up of the command line prefix AT, a command <CMD> for the type of information to read or parameters to set, and optional parameters [params]. Commands starting with + is standard AT control commands defined by 3GPP and commands starting with % is Nordic Semiconductor proprietary commands. These are examples of the generic AT command syntax for set and read commands:

- Set parameters: **AT+<CMD>=[params]**
- Read parameters: **AT+<CMD>?**

A list of commonly used AT commands in this thesis can be found in table 3.1. A complete list of AT commands for nRF9160-DK is specified in [24].

3.2.2 Signal Quality Values

When conducting tests involving signal quality measurements the nRF9160-DK is limited to RSRP as the only parameter. The RSRP measurements can be fetched via two different AT-commands, **AT+CESQ?** which requests an RSRP value when sent and **AT%CESQ=1** which subscribes to unsolicited RSRP value messages when signal quality changes. When judging the signal quality from the RSRP messages there exists several different estimates for when the quality is deemed excellent, good, fair to poor and when service loss can be expected. In table 3.2 estimates from 4 different sources are provided and will be used when judging results from tests. These sources are for standard LTE RSRP values and it must be kept in mind that both LTE-M and NB-IoT can provide coverage extensions of $\leq$ 20dB [10, pp. 199-200,298].

3.2.3 Configuring PSM

The value of the active timer and periodic tracking area update timer can be requested from the network. The network either accepts the requested values or re-

Source	[25],[26] RSRP [dBm]	[27]	[28]
Excellent	> -80	> -90	> -84
Good	-80 to -90	-90 to -105	-85 to -102
Fair to poor	-90 to -100	-106 to -120	-103 to -111
Signal loss	< -100	< -120	< -112

Table 3.2: Relation between RSRP value and signal condition.

bit			RPTAU t3412	RAT t3324
8	7	6	multiplier	
0	0	0	10 min	2 sec
0	0	1	1 hour	1 min
0	1	0	10 hours	6 min
0	1	1	2 sec	
1	0	0	30 sec	
1	0	1	1 min	
1	1	0	320 hours	
1	1	1	deactivated	deactivated

Table 3.3: Table for the three most significant bits of the octets for setting the PSM timer multipliers [1].

turns different values. The AT command **AT+CPSMS=1,"","","RPTAU","RAT"** is used to request values which are encoded as octets with the three most significant bits as multipliers, see table 3.3, and the 5 least significant bits corresponds to the values being multiplied.

While configuring PSM, RAT which stands for requested active time requests a value for the t3324 timer (a GPRS timer 2 as specified in [1]). The timer t3324 is responsible for how long the device should stay in RRC idle mode after RRC connected mode and is an integer value of $0 \rightarrow 11160$ s. The Requested Periodic TAU requests a value for timer t3412 (a GPRS timer 3 as specified in [1]) and controls the time between two successive TAU request messages and is an integer value of $0 \rightarrow 35712000$ s. The effect of these timers during a PSM cycle is illustrated in fig. 2.4.

For example requesting a PSM cycle with an active time of 1 minute and a 10 minutes interval of data transfer would be $RPTAU = 10101010$ and $RAT = 00100001$. In addition to using AT commands to request timer values, these can be provided in a project's configuration file using the Nordic Semiconductor software development kit.

3.2.4 Configuring eDRX

When configuring eDRX the **AT+CEDRXS=MODE,TECH,EDRX** command can be used where **MODE** enables and disables functionality. **MODE** = 0 disables

binary value	eDRX cycle [s]	Paging time window [s]	
		NB-IoT	LTE-M
0000	5.12 (only LTE-M)	2,56	1,28
0001	10.24 (only LTE-M)	5,12	2,56
0010	20.48	7.68	3,84
0011	40.96	10.24	5,12
0100	61.44 (only LTE-M)	12.8	6,4
0101	81.92	15.36	7,68
0110	102.4 (only LTE-M)	17.92	8,96
0111	122.88 (only LTE-M)	20.48	10,24
1000	143.36 (only LTE-M)	23.04	11,52
1001	163.84	25.6	12,8
1010	327.68	28.16	14,08
1011	655.36	30.72	15,36
1100	1310.72	33.28	16,64
1101	2621.44	35.84	17,92
1110	5242.88 (only NB-IoT)	38.4	19,20
1111	10485.76 (only NB-IoT)	40.96	20,48

Table 3.4: 4-bit eDRX cycle duration values and Paging Time Window values from network, values specified in [1].

eDRX, **MODE** = 1 enables eDRX, **MODE** = 2 enables eDRX and unsolicited result code, **MODE** = 3 disables eDRX, discards current eDRX parameters and resets to default manufacturer values if available. **TECH** is set as 4 when using LTE-M and 5 when using NB-IoT. **EDRX** is the requested eDRX cycle according to the half byte binary values provided in table 3.4. These parameters can alternatively be set in a configuration file using the Nordic Semiconductor software development kit. To see how the network responds to the request, unsolicited result codes should be enabled. The unsolicited messages provides the network provided eDRX cycle and the paging time window in the same half byte binary values as provided in table 3.4. Paging time window and the eDRX cycle with regard to the current consumption is illustrated in fig. 2.6.

3.2.5 Release Assistance Indicator Flag

The RAI flag can be used to tell the network to immediately drop connected mode right after a device has sent its last data packet of a transmission. The RAI flag is used when no downlink communication to the device is expected immediately following uplink communication. This is done for the nRF9160 by sending the Nordic Semiconductor proprietary AT command **AT%RAI=4**, enabling the RAI flag until turned off.

If no RAI flag is set the network will stay in the connected mode until no activity has been performed for the duration of the network configured inactivity timer. Through observation, it has been concluded that Telia uses an inactivity timer of 5 s for NB-IoT and 180 s for LTE-M.

3.2.6 Power Profile

For this thesis, the current drawn by the SiP on the development board is the relevant part for power profiling. The SiP consist of the ARM microprocessor, the LTE modem and its RF front end.

While conducting measurements the current to the SiP was supplied externally by the power analyzer Otii Arc while the rest of the development kit was USB powered. This enabled us to isolate the parts of the development kit relevant for making current consumption measurements.

Logging and UART functionality contributes to higher energy consumption in the nRF9160 SiP and was therefore turned off to get accurate results. Since measurements were done with only one modem from one company, and since the SiP was being developed during the project power profiling and current measurements must be seen only as an indication of the evaluated LPWANs performances.

3.2.7 Handovers

Tests for handover functionality were implemented by taking measurements on foot. The test routes were chosen such that several handovers could be triggered in a small area with known positions where handovers were likely. Application firmware was developed for TCP/IP and UDP/IP transmissions to an echo server at *http://tcpbin.org/* for TCP and a UDP echo server hosted on an AWS EC2 instance.

The TCP test application firmware relies on transmission and blocking receive until the echo is received, then waiting one second before transmitting the next message. The UDP test application firmware, on the other hand, relies on retransmission if the echo is not received within 20 seconds during which polling is conducted on the client socket file descriptor. The timeout of 20 seconds might seem excessive but was needed for stable operations due to rapid retransmissions leading to errors on the client-side with deadlocked sockets. There is no waiting time implemented for the UDP tests, it instead transmits the next message as soon as the echo is received leading to more data points. Trials were conducted for slower-paced transmissions but resulted in poor connections to the server.

AT-command functionality and serial output for logging were developed for the tests. The data collected was logged using a python script listening to the serial port and timestamping the outputs from the nRF9160-DK. Counter values which were iteratively increased were used such that transmissions and echo receptions could be matched. Calculating the time difference between the time stamps yielded round trip time (RTT) which was used as a measure of performance. Signal quality measurements were conducted via **AT+CESQ?** to get a RSRP measurement at the start of the tests and **AT%CESQ** to subscribe to unsolicited RSRP update

Measured Index	Cell ID	RSRP	Send	Receive	Calculated RTT
UTC-timestamp	Hexadecimal	dBm	integer	integer	seconds

Table 3.5: Table for the parameters measured and calculated during handover tests.

messages when signal quality changed during the tests. To map performance parameters to handovers **AT+CEREG=2** was used to get unsolicited messages when the nRF9160-DK connected to a new cell, these messages contain serving cell IDs. In table 3.5 the parameters measured and calculated for the tests are specified.

Regarding measuring the position while running handover tests, there was a problem with the hardware. For multiple version of the nRF9160-DK as well as for the version used in this project (v0.8.3) the matching circuits to the provided onboard GPS antenna was incorrectly implemented leading to no functionality for that part of the circuit. Thereby no GPS measurements could be conducted for the handover functionality tests.

3.2.8 Sensor Use Case

To further evaluate the low power characteristic of NB-IoT and LTE-M a sensor use case was constructed. The Python library aiocoap was used to develop a CoAP server, which was then deployed on an AWS EC2 instance. The server hosted a resource dedicated to the sensor data.

In this scenario, the nRF9160-DK sent a confirmable PUT request to the server every 30 minutes. The payload, 100 B of simulated sensor data was used to update the server's sensor data resource. The server responded with an acknowledgment packet as confirmation of the resource being updated. To facilitate this specific use case in an energy-optimized way PSM was used with an active time of 1 minute, ensuring delivery of the acknowledgment response from the server even when latency was higher than expected. eDRX was turned off since only solicited downlink data was expected.

In addition to this, the RAI flag was set for NB-IoT so that connected mode was dropped immediately after transmission, ignoring the inactivity timer. Since the nRF9160 did not support RAI functionality for LTE-M it was not possible to bypass the inactivity timer. The settings used are summarized in table 3.6.

Timer	**NB-IoT**	**LTE-M**
Inactivity timer	Disabled	≈180s (can not be disabled)
Active timer	60s	60s
DRX Cycle Length	10.24s (set by network)	2.56s (set by network)
eDRX	Disabled	Disabled

Table 3.6: Sensor use case settings.

4

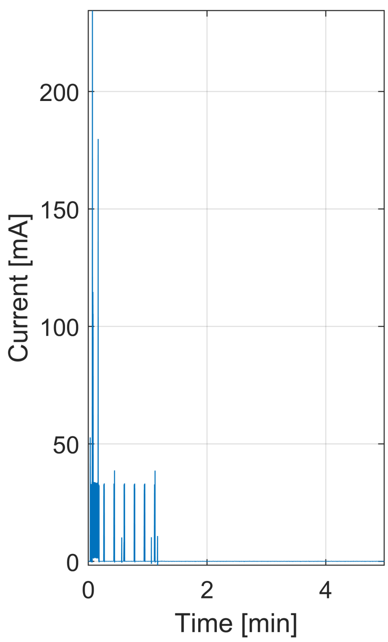
Results

4.1 Power Profile

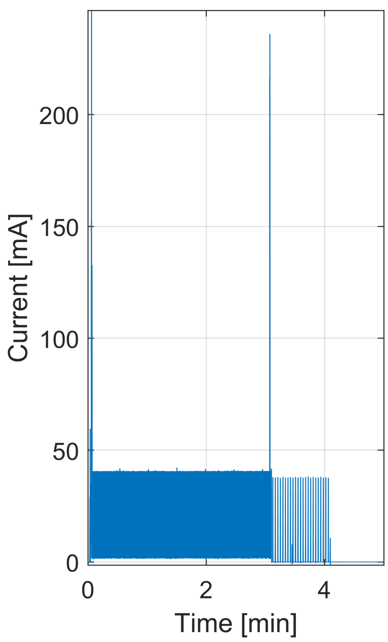
4.1.1 Power Save Mode

Fig. 4.1 illustrates the power profile of the SiP in a scenario with PSM activated, NB-IoT in fig. 4.1a and LTE-M in fig. 4.1b. The modem sends a UDP packet of data after which the inactivity timer starts, Telia's NB-IoT is configured to use a 5 s inactivity timer and Telia's LTE-M a 180 s inactivity timer. These values cannot be changed by the user.

When the inactivity timer is up the connected mode is released and the device goes into a configurable PSM active time, in this case, the active timer(t3324) is set to 1 min. In the active window, the device is reachable by the network through



(a) NB-IoT



(b) LTE-M

Figure 4.1: Illustration of a PSM cycle.

	100 B	1000 B
Avg. E/B	1.51 [mJ]	0.32 [mJ]
Ratio		0.21361

Table 4.1: Energy per Byte and ratio between 1000 B and 100 B transmitted, NB-IoT.

DRX cycles. The length of the DRX cycles is controlled by the network without input from the user, in this case, the cycle lengths are set to 10.24 s and 2.56 s, the maximum value for NB-IoT and LTE-M respectively.

Following the active time, the modem shuts down its RF capabilities. During this phase communication can only be initiated by the device itself. The SIM-card remained powered on during the whole active time. The average current drawn when the modem were sleeping was $\approx 6.3\ \mu$A for both LTE-M and NB-IoT. This is consistent with the nRF9160-DK specifications at the time of writing.

4.1.2 Uplink

4.1.2.1 Release Assistance Indicator

The graphs in fig. 4.2 illustrates the difference between setting **RAI=4** (fig. 4.2b) and the default behavior of the NB-IoT network (fig. 4.2a). Fig. 4.2b illustrates that the connected mode is dropped right after the transmission is done and idle mode is entered.

During the transmission interval of one 116 B UDP packet, setting the RAI flag decreased the energy consumption from 0.756 J to 0.292 J. I.e, a 61% decrease.

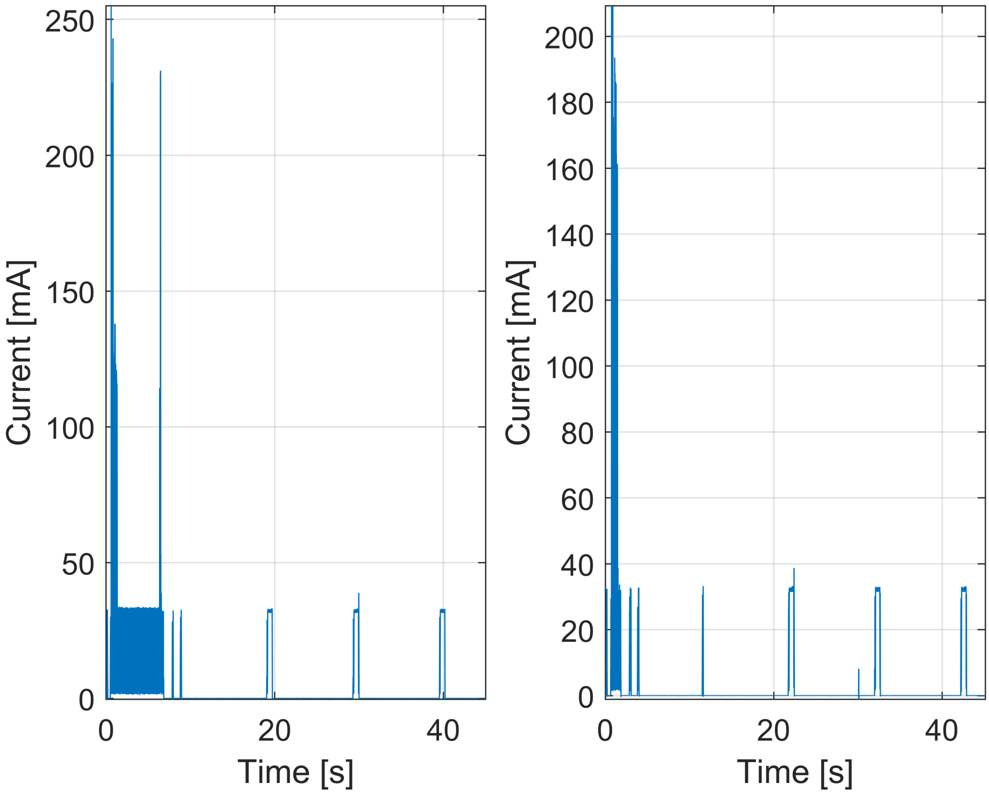
As mentioned in 3.1.1 the hardware used in this thesis did not support the RAI feature for LTE-M, thus making it impossible to skip the 3 min long inactivity timer for LTE-M. An example of energy consumption during such a window can be seen in the right graph of fig. 4.7b. The total energy cost during the inactivity timer was 20.52 J.

4.1.2.2 Uplink Transmission with NB-IoT

Fig. 4.3a illustrates 50 samples of the energy consumption for sending UDP 100 B packets. The cost of sending the majority of packets where ≈ 0.12 J, the variation was quite large, and the largest cost was more than three times the median.

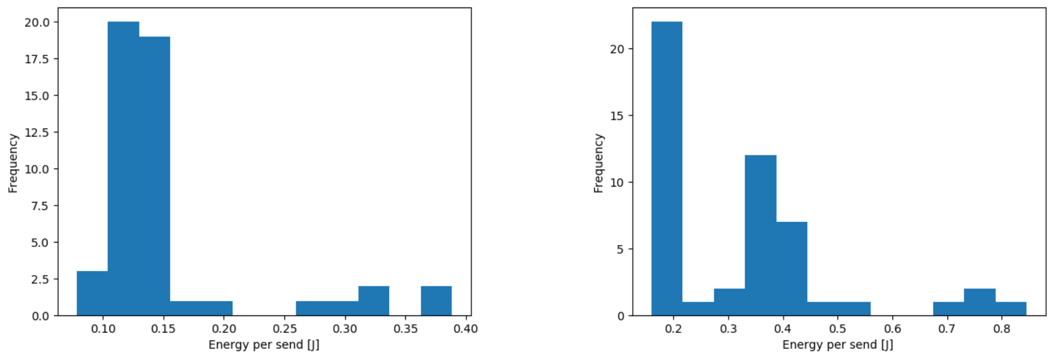
The same characteristic can be observed for the UDP 1000 B packets. The majority of the packets were as can be seen in fig. 4.3b sent using the energy consumption of ≈ 0.2 J, however, the largest cost was roughly four times the median consumption.

From table 4.1 it can be seen that the energy cost per bit was considerably lower for the 1000 B transmissions.



(a) No RAI flag set. **(b)** RAI flag set.

Figure 4.2: Difference between setting the RAI flag and the default behavior of the Telia network.

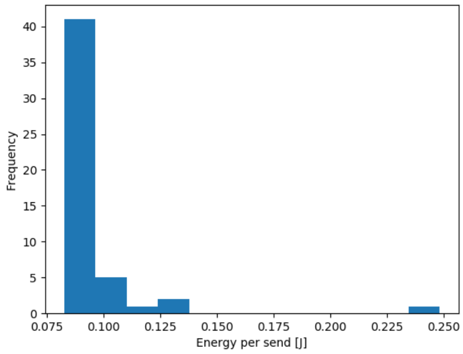


(a) 100 B transmission. **(b)** 1000 B transmission

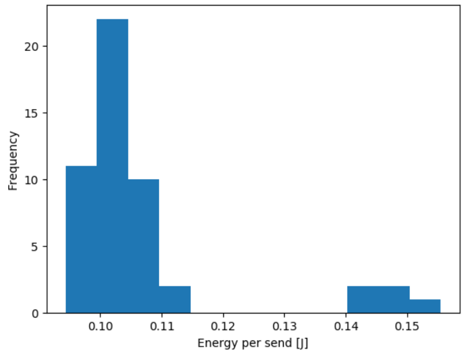
Figure 4.3: Transmission with NB-IoT, 50 samples each.

4.1.2.3 Uplink Transmission with LTE-M

The energy cost of sending UPD packets over LTE-M was overall less than for NB-IoT. In fig.4.4a and fig 4.4b it can be seen that the majority of the 100 B



(a) 100 B transmission



(b) 1000 B transmission

Figure 4.4: Transmission with LTE-M, 50 samples each.

	100 B	1000 B
Avg. E/B	0.96 [mJ]	0.11 [mJ]
Ratio		0.11065

Table 4.2: Energy per Byte and ratio between 1000 B and 100 B transmitted, LTE-M.

sized packages had an energy cost of ≈ 0.9 J, and the majority of the 1000 B sized packages had an energy cost of ≈ 0.1 J. The variance of LTE-M was lower than NB-IoT with the 100 B transmission only having one 50% larger outlier, and the 1000 B transmission 4 transmissions costing 150% more energy than the median.

4.1.3 Downlink

When using PSM there are 3 ways to enable downlink communication. Either through the use of eDRX or PSM, or a combination of the two.

4.1.3.1 eDRX

Fig. 4.5 illustrates the power profile of the SiP for a similar scenario as the PSM graph. UDP data is sent with a 15-minute periodicity over NB-IoT. The two largest current spikes in the graph is a result of data being sent. Between such spikes, smaller spikes can be seen with a period of ≈ 330 s. These smaller spikes represent eDRX paging cycles, were the modem checks for downlink data destined to the modem. One of these paging cycles exhibited an energy consumption of ≈ 0.073 J.

Between eDRX paging cycles, the modem shuts down all RF capabilities. During this time the modem still draws a current of ≈ 38 μA. The reason for the disparity between this value and PSM sleep current of 6.28μA is the current drawn by the SIM-card. The SIM-card is always turned off in PSM. For eDRX this varies depending on the configuration of the SIM-card [29]. In this case, Telia's SIM-cards were configured to remain active during the whole eDRX cycle.

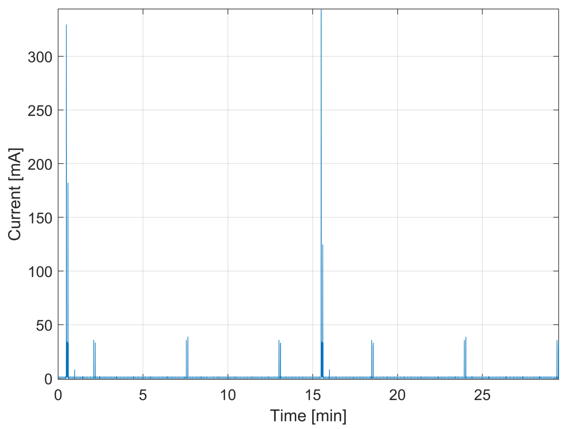


Figure 4.5: Illustration of NB-IoT using eDRX.

During the tests, eDRX did not work for LTE-M. Trials were done with Telia's own SIM-card and with another SIM-card provider, which were roaming on Telia's network. The reason for eDRX not working for LTE-M is unclear.

4.1.3.2 PSM and Downlink Communication

Fig. 4.6 illustrates the difference in current consumption between having a 30 s active time to facilitate downlink communication versus having no active time and going directly to PSM. The energy consumption in fig. 4.6b without an active window was 0.228 J. Fig. 4.6a with a 30 s active time had an energy consumption of 0.497 J, i.e a 118% increase.

A big part of the added energy consumption is keeping the SIM-card on for an extra 30 s. Instead of the SiP drawing ≈ 6 μA as in PSM sleep, it draws ≈ 35 μA during this time.

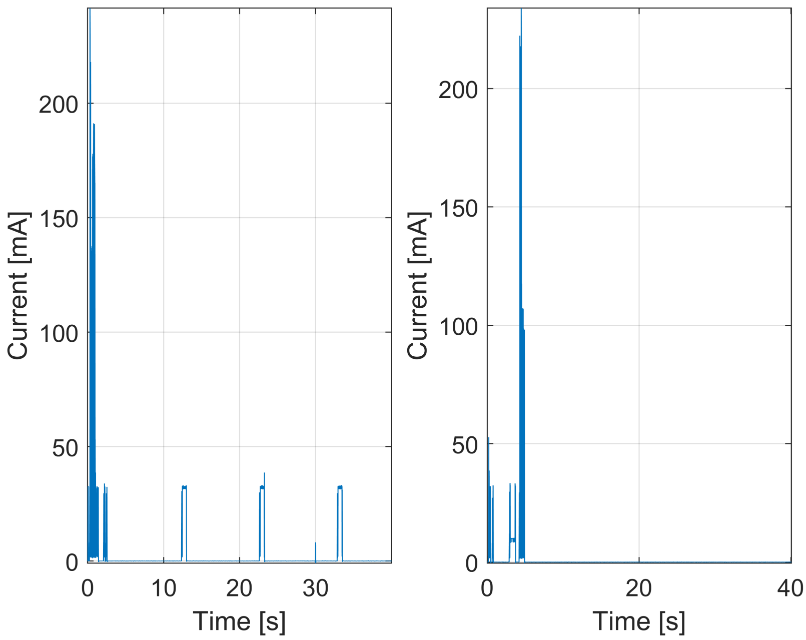
4.1.4 Sensor Use Case

The graphs of the power profile for the "realistic" sensor use case is shown in fig. 4.7 for NB-IoT and LTE-M. The scenario as described in 3.2.8 is that a CoAP message is sent, and to facilitate a response from the server an active time of 1 minute is used. For NB-IoT the RAI flag is set.

The energy consumption for one instance of a transmission of a CoAP message to the server and a response was measured to 1.062 J in fig. 4.7a and 21.276 J in fig. 4.7b for NB-IoT and LTE-M respectively.

4.1.5 Anomalies

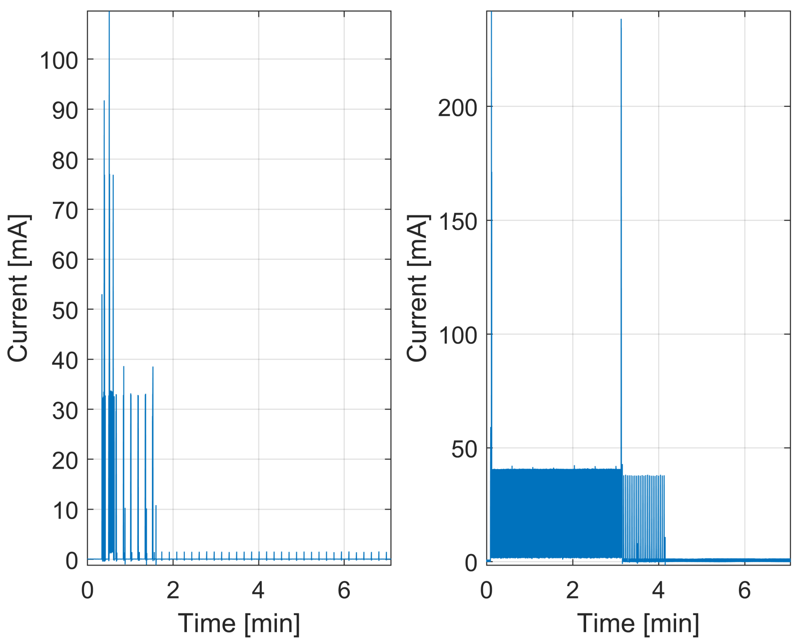
During the NB-IoT tests, the network connection dropped a number of times in a location where the coverage was good. One of these moments can be seen in fig. 4.8a where the connection dropped while trying to periodically send a UDP packet.



(a) 30 s active time.

(b) No active time.

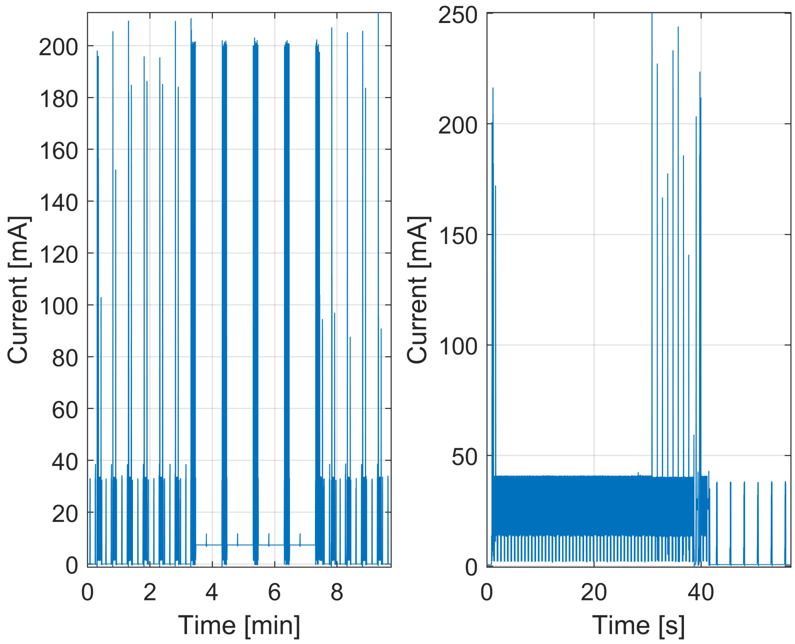
Figure 4.6: PSM active time.



(a) NB-IoT

(b) LTE-M

Figure 4.7: Sensor use case.



(a) NB-IoT anomaly. **(b)** LTE-M anomaly.

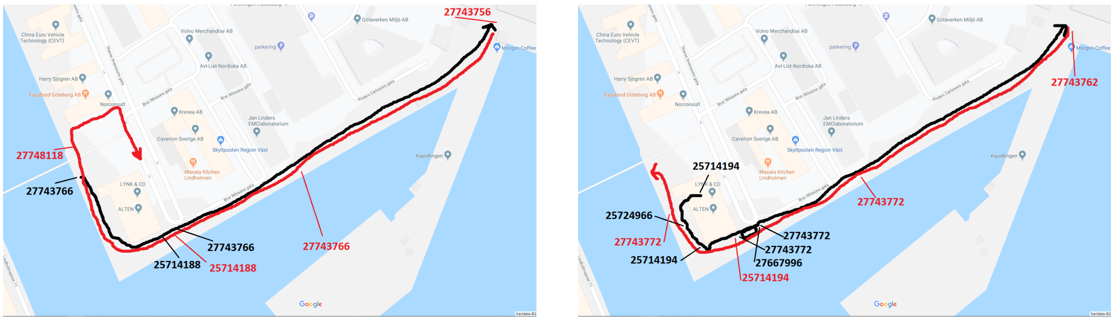
Figure 4.8: Encountered anomalies.

From the graph, it can be seen that the modem probably tries to reconnect and send the packet every minute. This occurrence might have to do with handovers which the device experienced even when stationary at this location. If this happens regularly it would heavily impact energy consumption.

LTE-M exhibited some very unexpected behavior seen in fig. 4.8b When trying to send data during the inactivity timer power spikes can be seen, indicating that the modem is trying to send data but is not succeeding. In these cases, no data was received at the recipient. In addition to this, when trying to do the opposite, receiving data during the inactivity timer, this did not work either. No indication of the modem receiving or trying to receive data could be seen from the current consumption. The expected behavior is that during the inactivity timer communication in both directions should be possible.

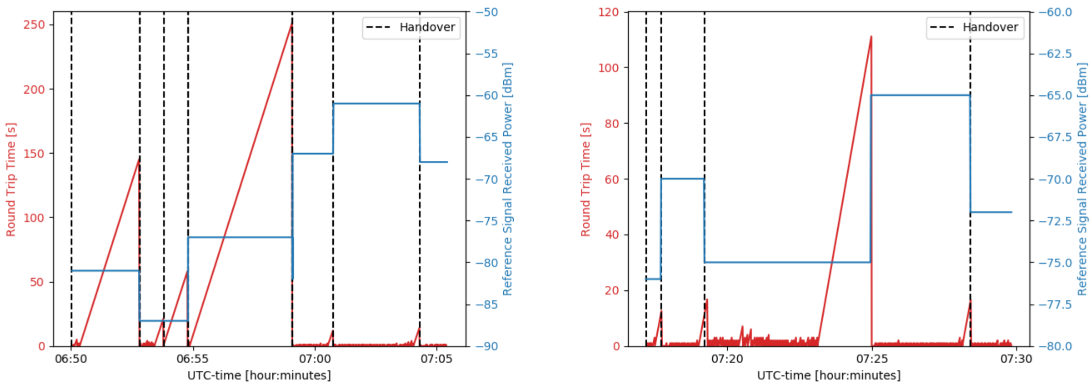
4.2 Handover functionality

Before conducting the field tests for handovers, locations where handovers between cells were triggered were found. In fig. 4.9, locations where handovers occurred with corresponding cell IDs are provided for both LTE-M and NB-IoT. The black line indicates the route taken and the red line is the route on the way back. Because of the large number of cells in the area, the field tests could be conducted on foot.



(a) LTE-M (b) NB-IoT

Figure 4.9: Handover locations with cell ID:s (Kartdata ©2019 Google).



(a) LTE-M (b) NB-IoT

Figure 4.10: Handover tests 2019-07-17 for TCP echo transmissions.

4.2.1 TCP echo handover field test

The results of the handover-functionality-test conducted on 2019-07-17 for LTE-M is illustrated in fig. 4.10a. The signal quality can be assessed by comparing table 3.2 to the row corresponding to the specific test in table 4.3. All signal quality measurements from tests will be judged in this manner henceforth. Signal quality during the test varied between -87 dBm and -61 dBm which is in the range of excellent too good. A maximum round trip time (RTT) of 252 s was recorded.

A test for NB-IoT was conducted on the same day and fig. 4.10b illustrates the results. The signal quality never dropped below -76 dBm throughout the test which is excellent by all estimations but incurs a maximum RTT of 111 s. An important point to make is that during the period where the maximum RTT was incurred there were no handover registered. This could be for two possible reasons. The most likely one is that the handover was initiated but before it could be completed the modem had regained significant signal strength from its original cell. The second option is that the handover was triggered but the modem failed to notify the new cell id. This could explain the marked increase in signal strength right after the maximum RTT.

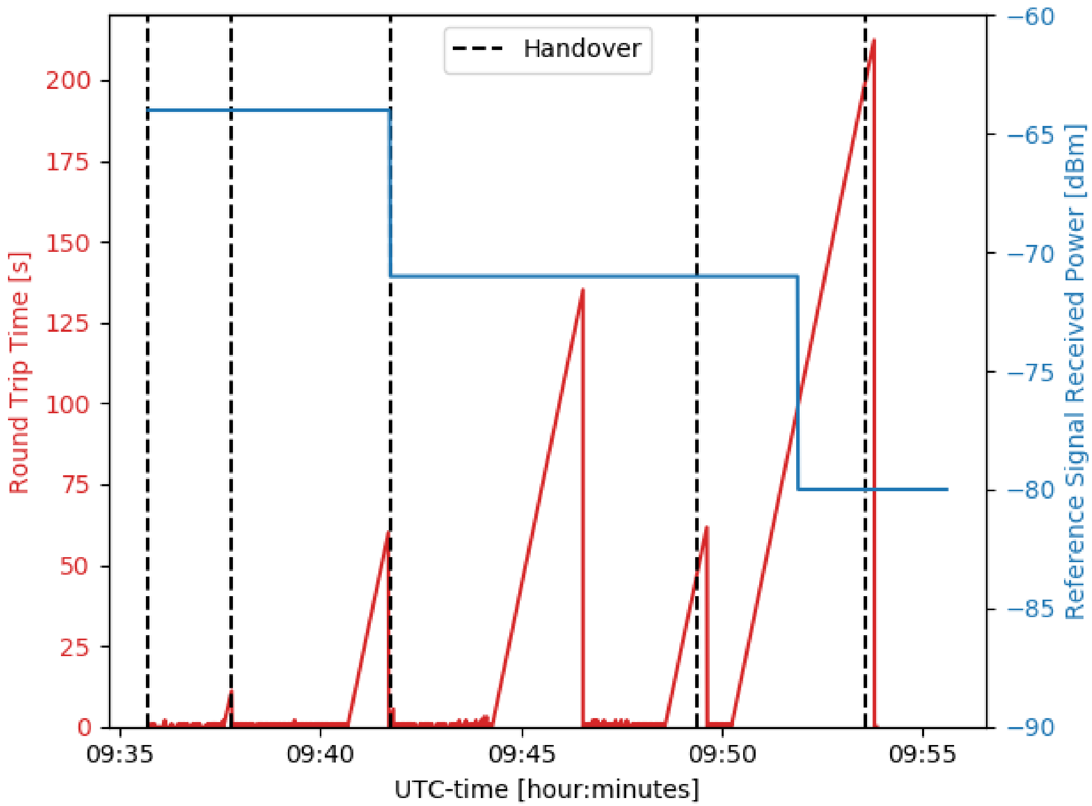
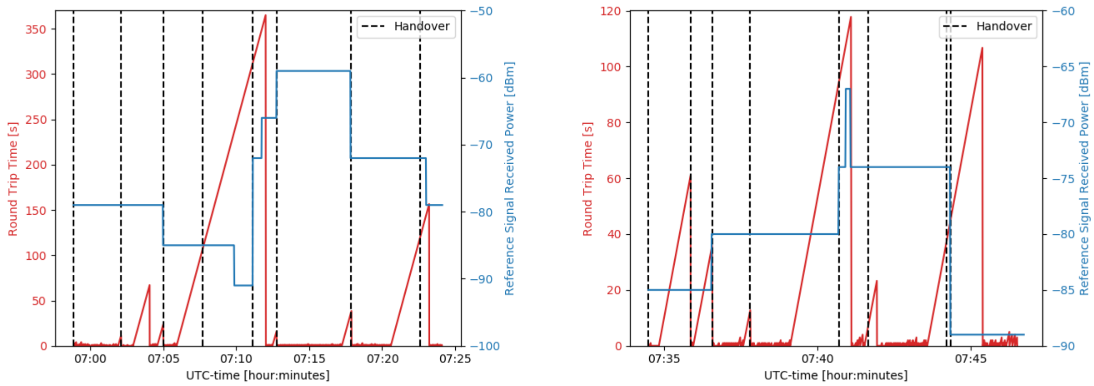


Figure 4.11: NB-IoT handover test 2019-07-18 for TCP echo transmissions.

On 2019-07-18 an NB-IoT test was conducted and is illustrated in fig. 4.11. A maximum RTT of 212 s was incurred with signal quality varying between -80 dBm and -64 dBm thus ranging in quality from excellent too good. In this test, there exists a large RTT spike in what seems like an unregistered or incomplete handover just as in the NB-IoT test conducted the previous day.

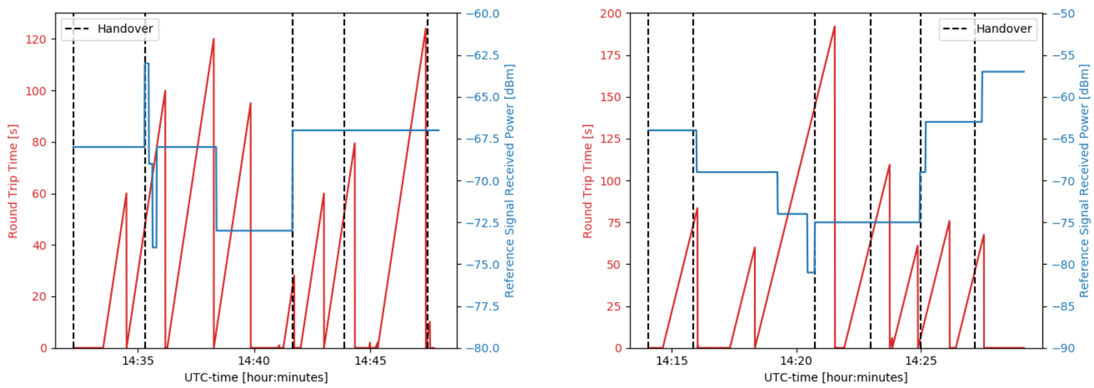
In fig. 4.12a the LTE-M test for 2019-07-19 is illustrated. RSRP values give an estimate of signal quality ranging from excellent to good or fair depending on the source, varying between -91 dBm and -59 dBm. The maximum RTT of 365 s during a handover is the worst performance measured for all TCP echo handover tests. The same day an NB-IoT test was conducted and is illustrated in fig. 4.12b with a maximum RTT of 118 s with signal quality ranging from excellent to good varying between -89 dBm and -67 dBm.

During the handover tests conducted for UDP, the performance was decreased when introducing waiting periods between a received message and transmission as described in section 3.2.7. Two new tests were conducted for TCP handovers with the waiting period removed to determine if the performance could be improved. The results are illustrated in figs. 4.13a and 4.13b and summarized in table 4.3. Both tests incurred multiple minute maximum RTT values with excellent signal quality. For LTE-M never dropping below -74 dBm and in the range of excellent too good



(a) LTE-M **(b)** NB-IoT

Figure 4.12: Handover tests 2019-07-19 for TCP echo transmissions.



(a) LTE-M **(b)** NB-IoT

Figure 4.13: Handover tests 2019-07-29 for TCP echo transmissions.

Date	Technology	Handovers total	RSRP [dBm] mean	max	min	RTT [s] max
July 17th	LTE-M	10	-72	-61	-87	251
	NB-IoT	3	-71	-65	-76	111
July 18th	NB-IoT	4	-70	-64	-80	212
July 19th	LTE-M	7	-74	-59	-91	365
	NB-IoT	7	-81	-67	-89	118
July 29th	LTE-M	4	-69	-63	-74	124
	NB-IoT	5	-65	-57	-81	192

Table 4.3: Table of TCP Handover test parameters.

for NB-IoT varying between -81 dBm and -57 dBm. The poor performance is maintained with or without waiting periods.

All in all handovers during TCP echo transmissions summarized in table 4.3 perform very poorly with maximum RTT in minutes, incurring latency values that is unacceptable in most use cases. This in spite of RSRP values most of the time ranging from excellent too good.

4.2.2 UDP echo handover field test

For the handover tests using UDP as the transport layer protocol, the same area was used for field trial as for TCP and can be seen in fig. 4.9. Signal quality ranges will be assessed for all tests according to the estimates provided in table 3.2.

One important thing to note regarding these results is that the timeout value for re-transmissions of 20 s is excessive. However, with shorter timeouts or slowly increasing timeouts, the application firmware send socket became deadlocked. Thereby the maximum RTT values should be regarded as within the latest 20 s interval as it can be seen that when a long RTT is resolved with a received echo back from the server it is always close to multiples of 20 s.

A LTE-M handover test using UDP conducted on 2019-07-25 is illustrated in fig. 4.14 and summarized in table 4.4. The maximum RTT value is 20 s. Handovers can thereby be resolved within 20 s. The RSRP values are in practice according to the estimates in table 3.2 excellent too good in most parts. One spike in RTT does not have a registered handover but coincides with the minimum RSRP value of -112 dBm which is estimated as fair to poor or even signal loss depending on the source. The poor signal strength could explain the long RTT.

The LTE-M test conducted on 2019-07-26 is illustrated in fig. 4.15a and summarized in table 4.4. Handovers are resolved within 21 s experiencing signal strengths ranging from good to fair varying between -97 dBm and -75 dBm. These results match the behavior of the previous LTE-M test. Illustrated in fig. 4.15b and summarized in table 4.4 are the results from a handover test for NB-IoT using UDP conducted on 2019-07-26. The signal quality values range from excellent to fair, varying between -82 dBm and -57 dBm incurring a maximum RTT value of 80 s. It can be seen that the handovers are resolved within anywhere from 20 s up to 80 s. A number of long RTT values do not coincide with handovers being registered by the modem.
Further handover tests for UDP were conducted on 2019-07-29 and the results are illustrated in figs. 4.16a, 4.16b and summarized in 4.4. In fig. 4.16a there are multiple instances with RTTs of 40 s showing that handovers being resolved within 20 s as in previous tests is not always the case for LTE-M. There are two instances of long RTT values during which no handover was registered by the modem. The signal quality is in the range of excellent to fair or poor varying from -104 dBm to -58 dBm.

The UDP test for NB-IoT illustrated in fig. 4.16b ends with failure as indicated by the black dashed-dotted line showing that the send socket can become deadlocked even with 20 s timeout between re-transmissions. The signal quality is in the excellent range throughout the test, never dropping below -78 dBm. The maximum RTT is 61 s but multiple handovers are resolved between 20 s and 40 s. There are also two instances of long RTTs without a registered handover.

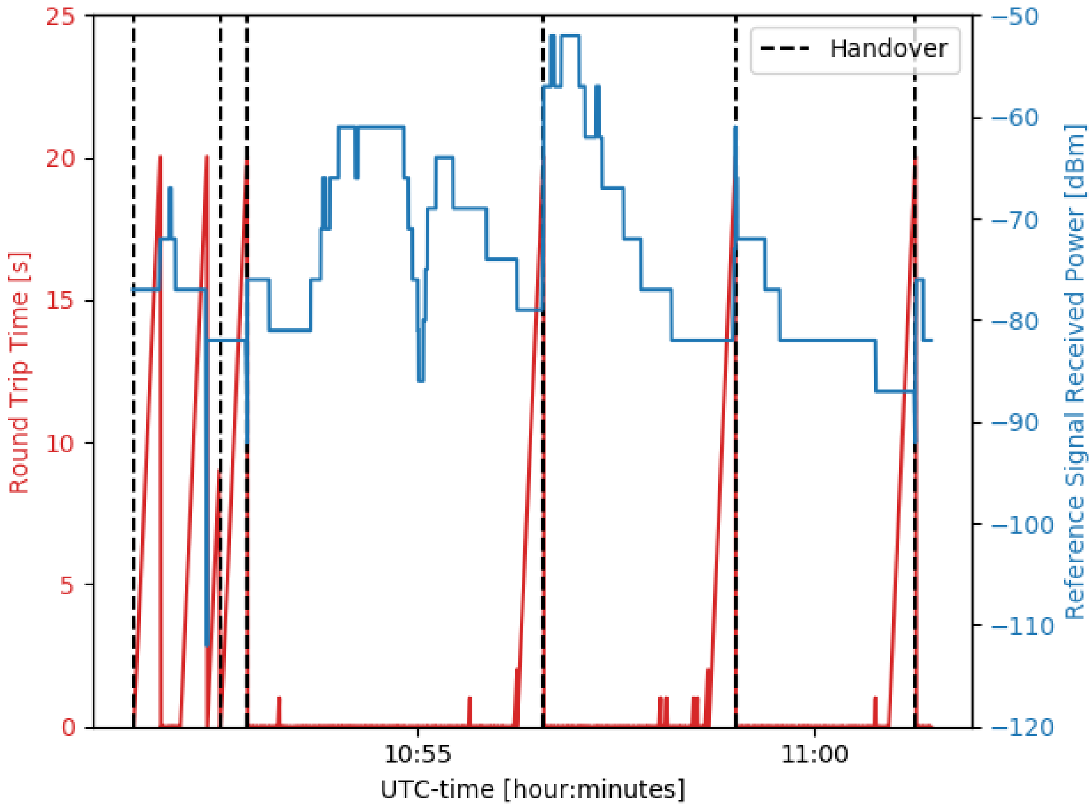
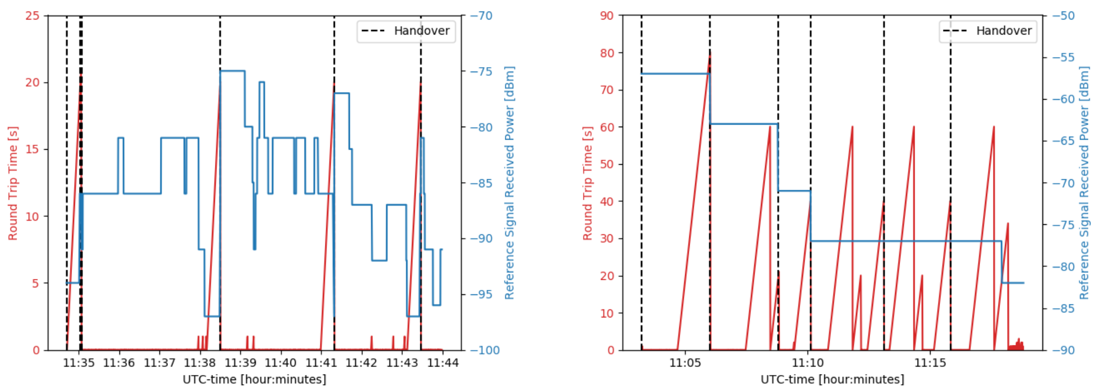


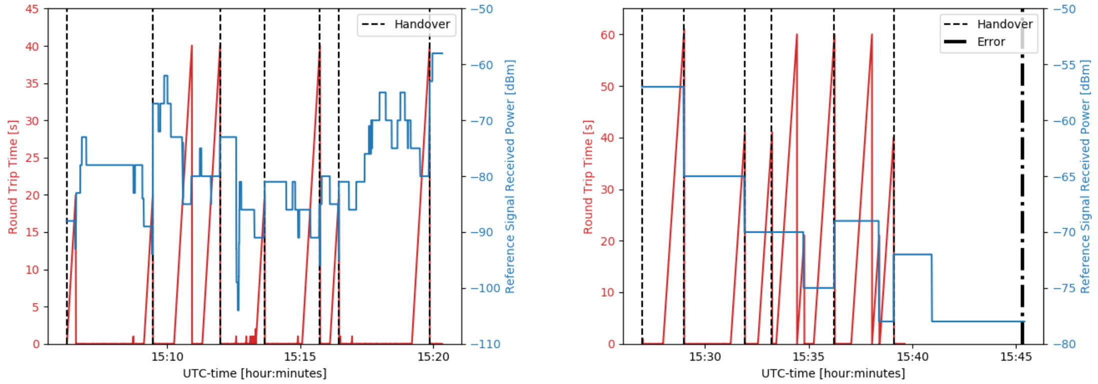
Figure 4.14: LTE-M handover test 2019-07-25 for UDP echo transmissions.



(a) LTE-M **(b)** NB-IoT

Figure 4.15: Handover tests 2019-07-26 for UDP echo transmissions.

Using UDP with re-transmissions as application layer protocol yields better handover performance as measured by RTT compared to TCP and especially for LTE-M.



(a) LTE-M **(b)** NB-IoT, with failure

Figure 4.16: Handover tests 2019-07-29 for UDP echo transmissions.

Date	Technology	Handovers	RSRP [dBm]			RTT [s]
		total	mean	max	min	max
July 25th	LTE-M	6	-72	-52	-112	20
July 26th	LTE-M	5	-84	-75	-97	21
	NB-IoT	5	-68	-57	-82	80
July 29th	LTE-M	7	-76	-58	-104	40
	NB-IoT	5	-67	-57	-78	61

Table 4.4: Table of UDP Handover test parameters.

5

Discussion

5.1 Power Optimization

To optimize the energy consumption of a device it is important to fully understand its use case. If it is crucial to be able to reach the device at all times, using eDRX is recommended. A suitable cycle length needs to be chosen, weighing the maximum allowed latency with energy consumption. However, one important fact to note regarding eDRX is if the SIM-card used allows for it to shut down during eDRX. If this is not the case the SIM-card will draw ≈ 35 μW during idle mode. To counteract this a combination of PSM and eDRX is needed. In such a case, PSM can be used with no active time since downlink communication is enabled through eDRX.

PSM can otherwise be used independently with a suitable active time if only solicited downlink communication is needed. To ensure delivery of the response from the network a suitable active timer could be ≈ 30 s to make room for latency.

The RAI flag should always be set in energy constraint scenarios to minimize the time spent in connected mode. Since the nRF9160 did not support this feature for LTE-M, this heavily impacted the energy consumption while using LTE-M. With the inactivity timer being set to 3 min for Telia's LTE-M network, every transmission cost an additional 20.52 J.

Part of the reason for the larger variance of the NB-IoT transmission can be explained with the fact that the device sometimes performed handovers during this test. A phenomenon not observed for LTE-M.

In general, the median energy consumption shows that LTE-M is still slightly more energy-efficient than NB-IoT while transmitting data. In both cases, it is preferable to send larger packets more seldom, than smaller packets more often.

NB-IoT's potential advantage of having the longer maximum DRX cycle of 10.24 s can be offset with the use of eDRX, however the disadvantage of not having RAI functionality for LTE-M is detrimental to its energy consumption. With this in mind, for energy-constrained devices 3GPP release 14 compatibility is essential.

During all of the power profile measurements, the coverage of the device can be considered to be good. This means that some of the advantages of NB-IoTs enhanced performance in bad coverage compared to LTE-M are not considered.

With one transmission of the sensor use case costing 1.062 J and the PSM current of 6 μA the average current is 161.5 μA. With a 2000 mAh capacity battery, this can with (5.1) be calculated to give a battery life of 12387 hours.

$$\frac{\text{ampere hour}[A \cdot h]}{\text{average current}[A]} = \text{time}[h] \tag{5.1}$$

I.e, a device in this scenario using NB-IoT would theoretically have slightly less than 1.5 years of battery life, disregarding self-discharge, assuming good coverage and no anomalous behavior of the modem or network. Using the same method for LTE-M this would give us a battery life of 26 days, making the negative impact of the 3 min inactivity timer evident.

While a battery life of 1.5 years and 26 days respectively is less than ideal for many applications, decreasing the transmission frequency impacts the battery life greatly. If the use case allows for a single transmission a day, using the same method as before, the theoretical battery life is $\approx$ 25 years for NB-IoT and $\approx$ 3 years for LTE-M.

One problem which would cause an increased average current is handovers. Handovers has been proven to occur even for a stationary device during this project. In a position where handovers are a regular occurrence the battery life would be impacted heavily.

5.2 Handovers

LTE-M and NB-IoT relying on TCP as application layer protocol places severe restrictions on mobility. The extensive RTTs (111 s to 365 s) incurred while transmitting and receiving during a handover in excellent to fair signal conditions as described in 4.2.1 is nowhere near tolerable for a wearable device. These results might be due to an error in implementation since LTE-M should be able to handle handovers significantly faster. When using UDP as application layer protocol with retransmissions, performance is improved but NB-IoT still experience up to 80 s RTT while LTE-M resolves handovers within 20 to 40 s which is possibly an indication that LTE-M relying on UDP can be an option for a wearable device after some optimization.

6 Conclusion

- Release assistance indicator
  - The RAI feature is an effective method for saving energy and should generally be used in energy constraint use cases.
- Power save mode
  - Given a scenario where no unsolicited downlink communication is needed the use of power save mode in combination with the RAI feature delivers the best performance in terms of energy consumption.
  - Care should be taken to set an appropriate active time.
- Extended discontinuous reception
  - eDRX is to be used when unsolicited is needed.
  - Care should be taken to set an appropriate cycle length, weighing acceptable latency against energy consumption.
  - A combination of power save mode and extended discontinuous reception is needed for energy optimization if the SIM-card remains active between paging windows.
- Energy per bit
  - Sending larger packets less often is preferable in terms of energy per bit transmitted.
  - LTE-M is slightly more effective than NB-IoT in terms of energy per bit in good coverage situations.
- Battery life
  - Energy consumption varies considerably, making battery life hard to predict. Handovers and coverage conditions are examples that introduces this variability.
  - Frequency of transmission impacts battery life heavily.
- Use cases
  - NB-IoT with release 14 compatibility has potential in energy constraint scenarios commonly found in IoT use cases. Although care has to be taken to manage factors introducing energy consumption variance.
  - LTE-M with release 13 is unsuitable for these scenarios.
  - The handover tests performed indicates that TCP with both NB-IoT and LTE-M is unsuitable for wearable devices due to the extensive RTTs of 111→365 s.
  - UDP with LTE-M showed indications of potential suitability for wearable use cases with handovers < 40 s.

7
Future Work

There are multiple options for future work in the field of cellular IoT. Some suggestions are listed here:

- Test and compare energy efficiency for different networks and devices
- Empirical tests with batteries to evaluate non-ideal conditions
- Trials using LTE-M with devices that supports 3GPP release 14 features
- Evaluate limited coverage condition effects on battery lifetime
- Retry the tests conducted using fully developed hardware and software

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