Energy Consumption of Low Power Wide Area Networks

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Spring 2018

Abstract

The market for low power devices is on the rise, as we move towards a more autonomous world by the day. A new type of wireless technology, Low Power Wide Area (LPWA), has been developed to ensure a longer battery lifetime combined with longer range. The increased interest in LPWA devices, which mostly consist of different types of sensors, leads to an increased amount of devices deployed on the field. The use of LPWA will allow for tens of thousands of sensors to connect to a single base station. There are two types of LPWA technologies available, those based on cellular technology and others that use proprietary technologies. The focus of the thesis will be on NarrowBand-IoT (NB-IoT), as well as LTE Cat M1 (enhanced Machine-Type Communication (eMTC)) and their respective energy consumption. Both technologies are standardized by the 3rd Generation Partnership Project (3GPP) and are based on Long Term Evolution (LTE) technology.

The beginning of the thesis will give an overview of Internet Of Things (IoT), energy consumption in computer systems and LPWA networks in general. In the last chapters, an experiment is done on the energy consumption of both NB-IoT and eMTC, together with the power saving features Power Saving Mode (PSM) and extended Discontinuous Reception (eDRX).

Keywords: Internet of Things, NarrowBand, Low Power Wide Area Networks, Energy consumption

Acknowledgements

I would like to thank Nextfour Group, for helping with the project and providing support when needed. Additionally, I would like to thank Turun AMK, for lending necessary cables used during the experiment and my supervisor Sébastien Lafond, for helping me to come up with ideas and taking the time to review my work. Finally I would like to thank all the device manufacturers and telecommunications service operators for their continuous support. This project would not have been successful without the help of all parties involved.

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CHAPTER 1

Introduction and background

We are moving towards a more autonomous world by the day. Nowadays we have devices, ranging from light bulbs to cars, gathering data which are sent to end-users or service providers. Often this happens without any interaction from the user. This phenomena is what we call the Internet of Things. To accommodate the surge of devices communicating with each other, we need a technology to support the increase in data traffic. Traditional technologies, such as Wireless Local Area Network (WLAN) and cellular technologies, are not efficient enough for these types of use cases. A sensor does not need as high data rates as a cellular phone, since it does not send as much data over the connection. Instead, long range, energy efficiency and scalability are more desired features.

Several technologies have been developed to help solve these problems. Some of which use the already-in-place infrastructure of LTE, while others rely on proprietary technologies. Technologies using the LTE infrastructure include NB-IoT and eMTC, while technologies such as Sigfox and LoRa need base stations equipped with proprietary technology. All of these technologies are categorized under the same label, LPWA networks.

1.1 Purpose of this thesis

The research in this thesis is done to evaluate the different LPWA technologies available today. LoRa and Sigfox are currently available in a broader scale, but technologies with backing from large companies, that are based on the the 3GPP standards, are looking to take over the space [8]. Despite large telecommunications service operators (TSP) have been developing the technology, the research done on NB-IoT and eMTC, regarding energy consumption in a real world environment, is lacking to date. An experiment on the energy consumption of NB-IoT and eMTC is done in Chapter 5. The end goal of this research is to give, both companies and researchers alike, more information about the possibilities of these new technologies.

1.2 Internet of Things

The term Internet of Things, was coined in 1999 by an innovator named Kevin Ashton [9]. Back then, the information technology (IT) infrastructure was nowhere near the levels of today, but the vision of connecting devices with each other was there. Ashton was working with radio-frequency identification (RFID) technology and while the technology is still used today, it is not what most people think about when they hear the term IoT. The early work on IoT is contributed to the research group Auto-ID center, where Ashton worked, and Massachusetts Institute of Technology (MIT) [10]. Since then, the trend has slowly risen and after 2010 it has been booming, as can be see in Figure 1.2.1.

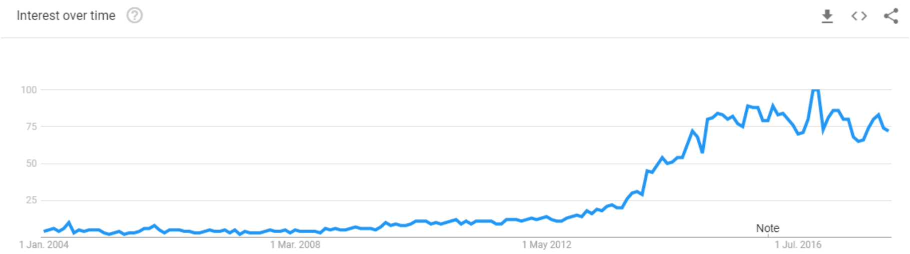


Figure 1.2.1: ”Internet of Things” search results on Google [1]

Most devices today will have some sort of internet connection. It is not unusual to be able to communicate with the fridge in the kitchen, or have security camera applications which can be monitored live through video streams. Most users are not aware of how these applications work, but expect them to help with their day-to-day lives. The IoT trend is slowly expanding from larger devices, such as kitchen appliances, towards smaller devices (e.g. sensors). For example, having a moisture sensor in your house can help prevent expensive renovations or allergic reactions to mold. An IoT application can be divided into three main categories [11]:

- Hardware
- Middleware
- Data visualization

Hardware

In this category, we have the hardware needed for an IoT application, which are sensors and embedded communication technologies. In this thesis we will not go into detail on how sensors work, instead the focus will be on the communication technology. This technology has evolved over the years, mainly because of the high demand on IoT devices. For example, if you own a summer cottage in a remote location, you might still want modern equipment at your disposal. To achieve this, the range of the signal must be able to reach the nearest base station. Instead of building numerous base stations, it would be easier and cheaper if most people could connect to a single one.

Middleware

The middleware, as the name suggests, is the middle man of the operation. Equipment such as data servers and tools for data analytics belong to this category. The vast surge of devices in recent decades, has forced companies to invest in ways to share and store their data efficiently. This can be achieved with cloud computing, which is an integral part of IoT. Without it, we would have a multitude of devices not being able to communicate with each other.

Data visualization

It is important for users of the application to be able to visualize and have access to their data. In technical terms, this component could be defined as the front-end. User experience (UX) has a high priority for companies nowadays. If the UX of an application is poor, the chances of customers repeatedly using the product are low. Especially if it is a niche product, or made by a smaller company, the consequences can be too severe to recover from.

1.3 Open issues for LPWA technology

LPWA technologies are still under development and have a few issues which need to be considered. The main two discussed in this section are *addressability* and *security*.

1.3.1 Addressability

The addresses on the internet are not like street addresses, each Internet Protocol (IP) address has to be unique. IP version 4 (IPv4) was first introduced in June 1978 [12], but this version uses a different header than the modern protocol. The IPv4 used today, was first described in the Request For Comments (RFC) document number 791 in the year of 1981 [13]. The lack of available IP addresses is a big issue that IPv4 is facing in the near future. It contains 32 bits and has thus a maximum of 2^{32}, or 4 294 967 296, possible unique addresses. Over 4 billion addresses sounded like more than enough 40 years ago, but due to recent surge in IoT devices they are quickly running out. Not to mention some of these addresses are not available as public addresses, instead they are classified as *reserved addresses* and are used for maintenance of routing tables, multicast traffic and unrestricted use on private networks. These addresses are listed in the RFC document number 5735 and can be seen in Table 1.1 [14].

Table 1.1: List of reserved IPV4 addresses

Address Block	Present Use
0.0.0.0/8	”This” Network
10.0.0.0/8	Private-Use Networks
127.0.0.0/8	Loopback
169.254.0.0/16	Link Local
172.16.0.0/12	Private-Use Networks
192.0.0.0/24	IETF Protocol Assignments
192.0.2.0/24	TEST-NET-1
192.88.99.0/24	6to4 Relay Anycast
192.168.0.0/16	Private-Use Networks
198.18.0.0/15	Network Interconnect Device Benchmark Testing
198.51.100.0/24	TEST-NET-2
203.0.113.0/24	TEST-NET-3
224.0.0.0/4	Multicast
240.0.0.0/4	Reserved for Future Use
255.255.255.255/32	Limited Broadcast

To solve the issue of the depleting resources of unique addresses, IP version 6 (IPv6) was introduced. Instead of a maximum of 32 bits, like the previous version, IPv6 has a maximum of 128 bits. This means the amount of available addresses jump from 2^{32} to 2^{128}. With LPWA technologies becoming more and more popular, the need for IPv6 is massive, but there are a few issues that need to be resolved. Mainly the header overhead introduced by the IPv6 protocol, which is at least 40 bytes. Without any optimization of the header, most LPWA technologies would need to use several frames just to send the header [15]. To solve these problems, The Internet Engineering Task Force (IETF) formed a working group in April 2016 to standardize the use of IPv6 in LPWA technology. The specifics of the standardization will be covered in more detail later in the thesis.

1.3.2 Security

Security is a very important aspect to take into consideration when discussing the use of IoT and LPWA devices. The amount of data sent, from a single LPWA device, is usually quite low depending on the use case. However, since the idea is to have numerous sensors, the total amount can increase exponentially. LPWA devices, or IoT devices in general, are vulnerable to both physical and software attacks. A lot of LPWA devices are left unattended for a long time, as the goal is to not need any maintenance during their lifetime. This leads to the possibility of physical attacks on the sensors themselves, which can be difficult to prevent. The cost of physical security cannot be too high, since the overall cost for LPWA modules need to stay low. The other type of attack on an IoT infrastructure is more technical. It focuses on stealing or manipulating the transmitted data. LPWA technologies can be vulnerable to this type of attack, mainly because of:

- Wireless communication
- Low data rates
- Low up-time

With wireless communication there is a risk of someone spoofing data between transmitters and receivers. One of these types of attacks is called a "man in the middle" attack. Figure 1.3.1 illustrates an example of how this type of attack could work in theory. The blue nodes, A and B, are the real devices on the network. The red nodes, A' and B', are placed in by the attacker to intercept the signal. Node A thinks it sends the data to the real node B, but it is in fact the attacker's node, B'. The message is transmitted from node B' to A', which then sends a copy of the data to the real node, B. The reply works the same way, but in reverse. This way, neither of the real nodes (A or B) have any idea that the data have been compromised and the attack can carry on without notice.

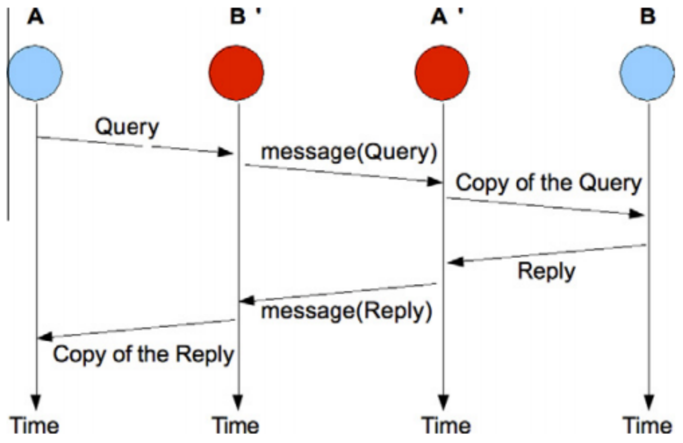


Figure 1.3.1: Example of a man in the middle attack [2]

The low data rates and low up-times of LPWA devices lead to other issues. For example, Transmission Control Protocol (TCP) is not a very suitable protocol for LPWA technologies, since it uses a three-way handshake to verify the integrity of the message. This would take too long for a device that is optimized for energy consumption, because it would need to be powered on for a long time each time it sends a message. For technologies such as Sigfox, which data rate might be as low as tens of bytes per second, it is almost impossible to use a heavy internet protocol such as TCP or User Datagram Protocol (UDP) [16]. LPWA technologies use different types of security protocols, some more secure than others. The security methods of both NB-IoT and eMTC, will be discussed in Chapter 2.

1.4 Cellular technology

When discussing LPWA technologies, it is important to understand the history of cellular technologies. There are three generations of cellular technologies in use today.

- Second generation (2G) - Global System for Mobile Communications (GSM)
- Third generation (3G) - Universal Mobile Telecommunications System (UMTS)
- Fourth generation (4G) - Long Term Evolution (LTE)

The fifth generation (5G) of cellular technologies is currently under development. The Finnish TSP Telia, is working with Ericsson and Intel to release a 5G network in Stockholm, Tallinn and Helsinki during the year of 2018. Exact dates have not yet been released [17].

The aforementioned technologies are still used today for IoT applications, but they were not developed for the types of use cases LPWA technologies aim to solve. Instead, the focus was on high data rates, mobility and overall convenience. Furthermore, as 5G will likely be used for the heavier applications in the future, for which 3G and 4G are used today, the TSPs had to either shut down old technologies or utilize their framework. This lead to the development of NB-IoT and eMTC, which do utilize the framework of 4G. It still remains to be seen what happens with the earlier generations. It is not easy to shut them down completely, since most devices today are still using them.

1.5 LPWA standards

There are a lot of standards available for LPWA technologies, some of which are listed in Figure 1.5.1. Multiple established organizations, such as Institute of Electrical and Electronics Engineers (IEEE), European Telecommunications Standard Institute (ETSI), IETF and LoRa Alliance, are putting in effort to standardize the field of LPWA and IoT. While most standards use propriety solutions and do not work well together, LPWA technologies are still in early stages of development. It is hoped that all of these standards can co-exist in the future. If co-existence is impossible due to technical reasons, the market will likely choose the most widespread and easiest technologies to implement [18].

The 3GPP standardized technologies have the major advantage of using an already-in-place infrastructure. NB-IoT will likely be one of the technologies used for sensors and stationary devices, while eMTC will be one of the leading technologies for devices that need higher data rates. Other standards will more likely be used for niche projects where:

- No cellular connections are available, or
- A certain technology is needed for its specifications

As it looks right now, standards that utilize proprietary technologies need to adapt or focus on very specific use cases, where they might have the edge. Having the choice of simply buying a sensor and installing it (NB-IoT), or needing to install a new base station first (LoRa), most companies would choose the former.

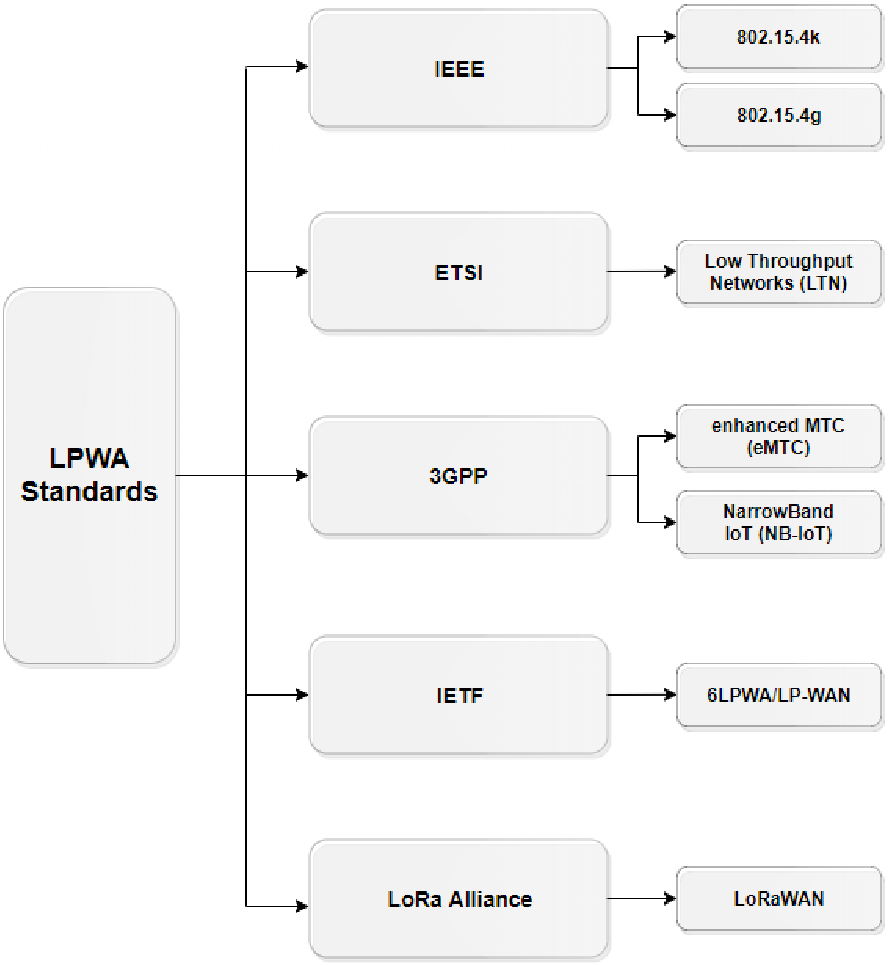


Figure 1.5.1: Main LPWA standards

1.5.1 IEEE

IEEE 802.15.4k

The 802.15.4k standard was developed by IEEE to support wide area networks with long range (up to 20 km), thousands of endpoints and where a maximum coupling loss (MCL), of up to 120 dBm, can be expected. The standard focuses on low energy critical infrastructure monitoring (LECIM) applications. To achieve this, two new physical layer (PHY) modes were implemented [19] [20]:

- Direct Sequence Spread Spectrum (DSSS)
- Frequency Shift Keying (FSK)

The 802.15.4k standard is designed to work on industrial, scientific and medical (ISM) bands with a frequency of sub-GHz or 2.4 GHz. The reasons for using low frequencies are mainly twofold, *range* and *density of LPWA devices*, which can be achieved by using the two aforementioned PHYs, DSSS and FSK.

Additionally, the standard describes amendments to the media access control (MAC) layer to support the implementation of the two new PHYs. It has two types of channel access methods to transmit messages, *normal* and *priority.* The normal channel access method uses either ALOHA or carrier sense multiple access with collision avoidance (CSMA-CA). The priority channel access method uses ALOHA with priority channel access (PCA), or CSMA-CA with PCA [21]. For IEEE 802.15.4k, as with most available LPWA standards, the devices are connected to base stations in a star topology.

IEEE 802.15.4g

IEEE 802.15.4g is a standard developed for Smart Utility Networks (SUN) and has a lot of similarities with the 802.15.4k standard. It also operates on the ISM band (sub-GHz or 2.4 GHz frequencies) and aims to solve the issues with range, energy consumption and density of devices. There are a few characteristics for the 802.15.4g standard [22]:

- Data rate between 40 kb/s and 1000 kb/s
- Frame size for PHYs need to be at least 1500 octets to avoid fragmentation of IP packets
- Need to be able to co-exist with other standards working on the same band

There are three new PHYs specified in this standard to support SUN [23]:

- Multi-rate and multi-regional-Frequency Shift Keying (MR-FSK)
- Multi-rate and multi-regional-Orthogonal Frequency Division Multiple Access (MR-OFDMA)
- Multi-rate and multi-regional-Offset-Quaternary Phase-Shift Keying (MR-O-OQPSK)

Each PHY has been defined for a specific reason. Factors such as speed, availability for geographical locations and pre-existing standards, have been taken into consideration. MR-FSK recognizes the fact that it is one of the most used modulations in the United States and MR-QFDMA was developed to support higher data rates. MR-O-OQPSK is similar to the corresponding PHY (O-OQPSK) defined by the base standard, 802.15.4. As O-OQPSK is already widely used in wireless sensor networks, the extended MR-O-OQPSK is easier to implement.

1.5.2 ETSI

Low Throughput Network

ETSI has standardized a technology called Low Throughput Network (LTN) and Sigfox is one of the LPWA technologies utilizing this standard. LTN focuses on low data rates and long battery lives and it operates on the sub-GHz ISM band (typically 868-915 MHz). The use cases for technologies based on LTN are very different compared to previously explained IEEE standards. The IEEE 802.15.4g standard was defined to have a frame size of at least 1500 octets, while the frame size for LTN is 12 octets (over 100 times smaller). Furthermore, the standard defines a maximum data usage of 5 kB per day. When developing devices and applications based on LTN, it is important to take this into account since the maximum data usage can cause problems. However, the usage of lower frequencies and low data rates help to attain an extremely long battery life with longer range. According to ETSI documentations, a 2.5 Ah modem using a 3 V battery, can last up to 20 years and achieve a range of up to 60 km in rural areas [24].

1.5.3 IETF

6LPWA/LP-WAN

IETF aim to develop a standard to support IP-based connectivity for LPWA technologies, since they noticed the need for IPv6 to solve the addressability issues mentioned earlier in this chapter. The organization has already developed an IP stack for IPv6 Low power Wireless Personal Area Networks (6LoWPAN), but this focuses mostly on IEEE 802.15.4 standardized networks, which support higher data rates and lower ranges than needed for LPWA technologies. There are a few problems to consider when developing a standard for LPWA [25]:

- Low data rates
- Tiny level two (L2) payload size
- Data rate constraints

LPWA technologies currently available, use different types of PHYs and MAC protocols to add to the difficulty of standardization. IETF developed 6LoWPAN further to work with all types of LPWA technologies. They developed numerous techniques to help fit the IPv6 stack in the small frame sizes of LPWA technologies. Most notable of these techniques are *header compression* and *fragmentation*. Because the payload size is so small in LPWA technologies, the header compression technique would help to fit the message into the payload. Additionally, most LPWA technologies do not support fragmentation at the L2 level, but it is needed since if the datagram does not fit into one L2 data unit, even after header compression, it has to be broken into fragments [26]. The techniques on how this is done is out of scope for this thesis, but the technical documentation by IETF can be found at [25] and [26].

1.5.4 LoRa Alliance

LoRaWAN

LoRa is a bidirectional technology and as with other LPWA technologies, the uplink has a higher priority. As opposed to IEEE and 3GPP, the technology behind LoRa is proprietary and how it works exactly is unknown to the public. However, similarly to the IEEE standards described above, it uses the ALOHA MAC protocol due to its simplicity. The PHY used by LoRa was developed by the company *Semtech* and operates on a sub-GHz ISM band [27]. Exact frequencies depend on the location, but they range from 433Hz to 928Hz [3]. The communication stack of LoRaWAN can be seen in Figure 1.5.2, where the green areas are made up of proprietary technology from Semtech.

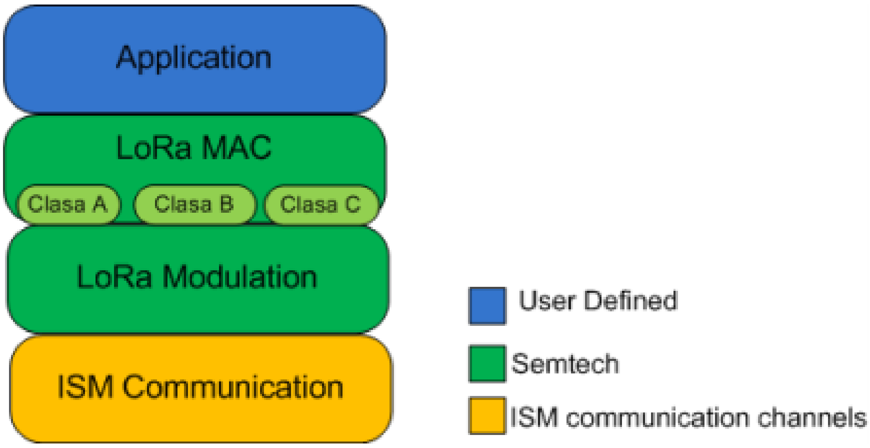


Figure 1.5.2: The LoRaWAN stack [3]

LoRaWAN has three different classes, each with a different type of use case: *Class A*, *Class B* and *Class C*. Class A is the most lightweight of the three.

While still being bidirectional, there are only two short downlink windows after a transmission. In other words, it cannot receive any data on the downlink without transmitting data first. In addition to the two short downlink windows, Class B has the possibility to open the windows at scheduled times without transmission of data, making it better for applications that require a more active use of the downlink. For both Class A and B, the modems are mostly in a sleep state, but with Class C the modem will be mostly powered on. The receiving window will be nearly always open, when not transmitting data [28]. The type of class used in an application has to be chosen by the developer, based on the requirements of the project.

1.5.5 The 3GPP standard

The 3GPP standard defines three technologies: *NB-IoT*, *eMTC* and *Extended Coverage GSM IoT (EC-GSM-IoT)*, but only the two first will be the focus in this thesis. While technologies, such as LoRa and Sigfox, are already available and deployed to some extent, the 3GPP saw the need for a standardization in the market. While the proprietary technologies utilize the ISM band, NB-IoT and eMTC are taking advantage of the already in place licensed LTE bands. The technical details of the 3GPP standard and how it is applied to NB-IoT and eMTC, will be discussed further in the next chapter.

CHAPTER 2

Overview of LPWA technologies

Technologies popular right now for Machine to Machine (M2M) communication are mostly done over short range technologies (e.g. WLAN and Bluetooth), or cellular networks in case there is a need for longer range. While this has been a working solution for a while, some of these technologies might be phased out by TSPs in the future [29]. Additionally, they are not optimized for neither range nor battery life, instead they are developed to carry high quality voice, text and data [30]. For low power devices such as sensors, this is a necessity and we can see that there is a market ready for new technologies.

LPWA technologies are often divided into two categories: standards taking advantage of the already-in-place cellular networks (3GPP) and other standards using proprietary technologies (e.g. LoRaWAN). Despite that LPWA networks, that use proprietary technologies, have a head start on the market, many people are interested in the 3GPP standardized technologies due to the broad and already-in-place infrastructure. This will help with a quick and cheap deployment of LPWA devices. In this chapter, LPWA technologies and their use cases will be explored with the focus on the 3GPP standardized technologies NB-IoT and eMTC.

2.1 LPWA networks

The growing trend of having sensors everywhere comes with a few problems LPWA technologies hope to solve. Issues such as range, penetrability of thick objects, long battery life, security and scalability. Using the aforementioned technologies (NB-IoT, LoRa etc.), the devices could theoretically have a battery life of over 10 years and a range of up to 22 km [31]. Currently none of these technologies are deployed worldwide, but it is projected there will be up to two billion active LPWA devices worldwide by the end of year 2019 [32]. It is still uncertain what technologies will be most used, but in Europe NB-IoT is focused on most while in the US they focus more on eMTC [33]. Most agree these are the LPWA technologies to break through worldwide, even if they are not commercially available yet and both LoRa and Sigfox are ready to be deployed. This is mostly due to the restrictions on infrastructure mentioned earlier, both NB-IoT and eMTC will be easier to deploy on a large scale and the use of them will not require installation of additional hardware. Instead, the TSPs simply need to apply a software update to their base stations to allow these technologies to work. As early as the summer of 2017 Telia, a major TSP in the Nordic countries, launched a successful test in Norway using NB-IoT to track sheep [34].

LPWA technologies use one of two types of spectrums: *narrowband* or *spread spectrum*. As can be seen in Figure 2.1.1, the narrowband technique uses a very small amount of the bandwidth. Thus, the overall bandwidth can be used more efficiently. The noise level inside a narrowband waveform, as seen in the same figure, is very low and while this makes it easier for the receiver to decode, this type of signal is also much easier to detect and intercept. The spread spectrum techniques will spread the same signal over a larger surface of the whole bandwidth, making it a ”noise-like” signal. This in turn, will require more processing power from the receiver but will also make it more difficult to intercept, because it has no clear peak in the spectrum, thus making it less distinguishable from the noise level [35]. Both NB-IoT and eMTC utilize a kind of narrowband operation.

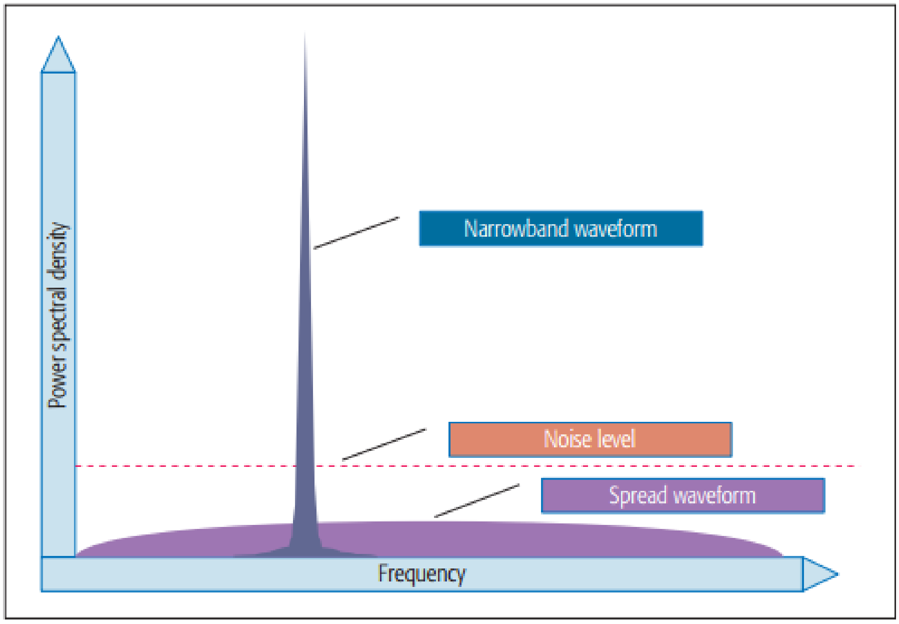


Figure 2.1.1: Narrowband vs Spread spectrum [4]

2.2 Goals of LPWA

Minimization of energy consumption is one of the main goals for LPWA technologies, which will be further discussed in Chapter 3. The other goals of LPWA technologies and how they can achieve these, will be discussed from the point of view of both NB-IoT and eMTC. The following aspects will be discussed:

- Range
- Security
- Scalability

The trade off for these perks of LPWA are in most cases low data rates and high latency (to different degrees, depending on technology used).

2.2.1 Range

LPWA networks can attain the previously mentioned range by applying a few different techniques. By using lower frequencies (often sub-GHz) than other technologies, the range and penetrability of objects increase and they can avoid congested frequencies, such as the one used by WiFi and Bluetooth (2.4 GHz). Additionally, both NB-IoT and eMTC has a increased tolerance for MCL (up to

164 dBm), which is achieved by repeating almost every signal, in every channel, by more than one subframe to accumulate enough energy. The amount of repetitions done in each channel is listed in Tables 2.1 and 2.2. These channels will be further explained in Section 2.3 [36][37].

Table 2.1: Maximum repetitions per channel for eMTC

eMTC channel	Repetitions
PBCH	5
MPDCCH	256
PDSCH	2048
PUSCH	2048
PUCCH	32
PRACH	128

Table 2.2: Maximum repetitions per channel for NB-IoT

NB-IoT channel	Repetitions
NPBCH	64
NPDCCH	2048
NPDSCH	2048
NPRACH	128
NPUSCH	128

This combined with the transmit power, of up to 23 dBm (Table 2.3), will ensure a longer range compared to legacy cellular technologies such as LTE. The MCL for NB-IoT and eMTC, as reported by 3GPP (Release 13), are 164 dB and 155.7 dB respectively. Compared with other technologies, such as LTE and General Packet Radio Service (GPRS) (144 dB) [38] [39], the difference between NB-IoT MCL and LTE MCL is as large as 20 dB.

2.2.2 Security

As was briefly discussed in Chapter 1, there are different types of security risks for LPWA devices (physical and software attacks), but in this section we will go into more depth on how LPWA technologies deal with software attacks. The difference between NB-IoT and eMTC, both being a part of the 3GPP standard, is small but each security aspect is important in order to understand how these LPWA technologies handle security risks. The security requirements for these technologies are as described in 3GPP TS 33.187 [40]:

- Secure provisioning and storage of device identifiers
- Device/Network mutual authentication
- Integrity- and replay protection
- Confidentiality protection

Secure provisioning and storage of device identifiers

There is a need to be able to identify each UE on the field. As with IP addresses, these identifiers given to equipment need to be unique, to reliably be able to identify the UE in question. There are two types of identifiers used in 3GPP networks (not only LPWA), *International Mobile Equipment Identity (IMEI)* and *International Mobile Subscriber Identity (IMSI)*. The former is attached to the UE during manufacturing and once connected to the network, the IMEI is stored in an Equipment Identity Register (EIR). If this device is reported stolen, it will show up in this register. While the use of IMEI is quite safe, the possibility of fake duplicates on the market will increase the risk of duplicate IMEIs. That is why both NB-IoT and eMTC also use IMSI, which is provided by the TSPs and where certification programmes provide secure storage for both IMEI and the associated subscriber authentication key [41].

Device/Network mutual authentication

For a mutual authentication between the device and the network, two types of technologies are implemented and required: *Universal Integrated Circuit Card (UICC)* and *Generic Bootstrapping Architecture (GBA)*. When the IMEI or IMSI is retrieved from the terminal, the UICC verifies the value, or range of values, it is configured with. If pairing check is verified *Good*, the UICC will set the status flag to "OK". In case of an unsuccessful pairing check, the status flag till be set to "KO". The GBA is used for key agreement and bootstrap authentication (specified in 3GPP TS 33.220 [42]) for application security and is based on the 3GPP standardized *Authentication and Key Agreement (AKA)*. While GBA is initiated from the UE, there is an extension called GBAPush (defined in TS 33.223 [43]), which is initiated from the network side. More detailed information about how these work can be found in 3GPP Technical Specifications [40] [42] [43].

Integrity- and replay protection

With integrity protection, a protocol can ensure the integrity of a message sent and thus can eliminate possibilities for attacks such as man in the middle (see Chapter 1). With replay protection, the protocol will deny any outside attack from inserting data into the communications link at a later stage and will also ensure that the data received at the other end are not tampered with. With a replay attack, the attacker could send the same data over and over to the base station, for example creating a loop on a video.

NB-IoT and eMTC deal with integrity protection by implementing *Temporary Mobile Subscriber Identity (TMSI)*. The TMSI is a local identifier, meaning it is tied to one location and hence needs to be updated when moving location. It needs to be accompanied by a Location Area Identification (LAI), to ensure the integrity. More technical documentation on how this is implemented can be found in 3GPP TS 43.020 [44]. As for replay protection, it shall be supported for received non-access stratum (NAS) messages, for both the UE and the MME. It will ensure that the same NAS message is received no more than once by the receiver. Technical documentations can be found in 3GPP TS 24.302 [45].

Confidentiality protection

There are two types of confidentiality, as described in 3GPP TS 33.401: *data confidentiality* and *device confidentiality*. It is as important to keep the identity of the device safe, as it is to keep the data safe from attacks. For device confidentiality, the UE can send the IMEI to the network, in case it requests it, in an integrity protected request. However, since the IMEI will be sent in the NAS protocol, it cannot be sent before NAS has been activated on the network. There are a few exceptions to the rule, which can be found explained on page 15 of TS 33.401.

Data confidentiality implements ciphering and key algorithms to keep the data safe. They use different EPS Encryption Algorithms (EEA), which are assigned a 4-bit identifier to each EEA (seen in list below). Important to note that all of these encryption algorithms are 128 bits, except for the *Null ciphering algorithm*.

- "0000_2" EEA0 Null ciphering algorithm

- "0001_2" 128-EEA1 SNOW 3G based algorithm
- "0010_2" 128-EEA2 AES based algorithm
- "0011_2" 128-EEA3 ZUC based algorithm

As stated in TS 33.401:

> *Communications between UEs and Evolved Node B (eNB) shall implement algorithms EEA0 through EEA2, and may implement EEA3. The eNB in a LTE network is the equivalent of a base station in a GSM network.*
> *Communications between UEs and MMEs shall implement algorithms EEA0 through EEA2, and may implement EEA3.*

More thorough technical details can be found in the 3GPP TS 33.401 [46].

2.2.3 Scalability

According to a theoretical analysis made by 3GPP in TS 45.820, up to 52 547 UEs can be connected to one cell using NB-IoT, or in other words 40 devices per household [47]. This is likely a more than ideal estimation of the NB-IoT network, since real world factors such as burstiness of the technology is not taken into account [48]. Burstiness means that numerous UEs are likely send their data at the same time, in bursts. No real world research has yet been done on this scale, hence there are still a lot of factors that are unknown. For example, will the TSPs select when UEs wakes up from PSM and thus being able to predict and account for the bursts in data. Further research on live networks is needed before exact numbers can be given.
The key aspect for scalability in NB-IoT, is the usage of multiple sub-channels. Each sub-channel carry a single carrier with individually pulse-shaped modulation. The bandwidth is divided into: 36 channels for the downlink and 12 for the uplink, as can be seen in Figures 2.2.1 and 2.2.2 (TS 45.820). By dividing the available sub-channels to different cells, the maximum amount of UEs per cell is higher (by re-using frequencies). Additionally, the usage of individual modulation for each sub-channel will enable communication with all types of UEs, also those with poor coverage and connection.

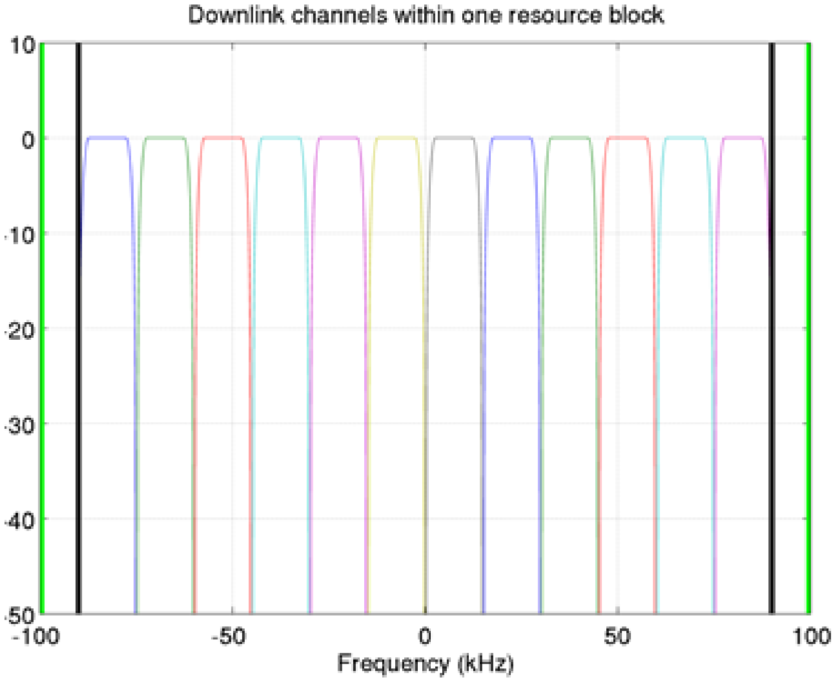


Figure 2.2.1: NB-IoT downlink channels

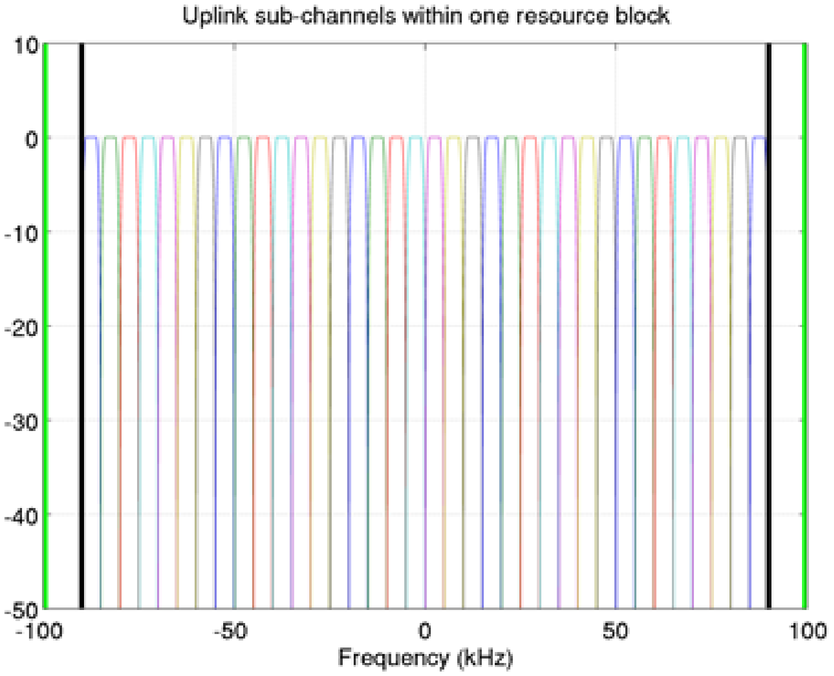


Figure 2.2.2: NB-IoT uplink channels

2.3 NB-IoT and eMTC technical specifications

In this section of the thesis the technical aspects of NB-IoT and eMTC will be discussed, with a focus on their physical layers and similarities with legacy LTE technology.

2.3.1 NB-IoT

Operation modes

NB-IoT uses one resource block in LTE transmission, which corresponds to a 180 KHz bandwidth. There are three deployments method that can be used:

- Stand alone operation, utilizes the GSM frequency which has a bandwidth of 200 kHz. This leaves a 10 kHz guard interval on both sides of the spectrum used. Additionally, it shall utilize scattered spectrum for potential IoT deployment.
- Guard band operation, utilizes the unused resource blocks within an LTE carriers guard band.
- In-band operation, utilizes the unused blocks within LTE carriers.

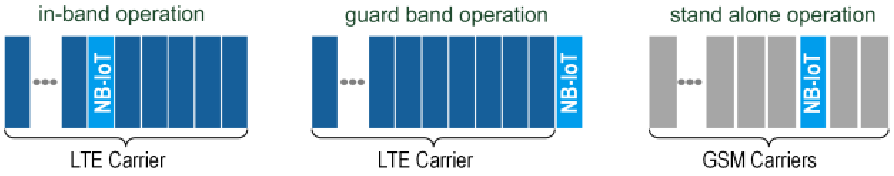


Figure 2.3.1: NB-IoT operation modes [5]

The choice of operation mode is up to the TSP, but this information needs to be available to the UEs. There are both positive and negative sides to each mode, hence this should be thoroughly thought out by the provider. *Stand alone operation* has higher initial cost, because antennas and RF systems need to be upgraded with new hardware and it takes a lot of effort to refarm GSM frequencies. On the upside, it has a larger MCL compared to the other methods [49]. *In-band* and *Guard band* have a lot of similarities, due to both utilizing the LTE carrier, but the biggest difference is the spectrum cost. Since guard band only uses the out-most physical resource blocks (PRB), the spectrum cost is nonexistent, while for in-band it has to co-exist with legacy LTE signals.

To cope with different radio conditions, three different coverage enhancement (CE) levels are introduced in NB-IoT: CE 0, CE 1 and CE 2, where CE 0 is for normal conditions and CE 2 is the for most extreme conditions. The MCL for these levels are 144 dB, 158 dB and 164 dB respectively [36]. It is up to the operator to choose which of these levels are implemented on the network. Furthermore, it is important to note that NB-IoT only supports Half Duplex (HD), meaning both uplink and downlink cannot transmit data simultaneously.

Downlink

The NB-IoT downlink scheme is based on Orthogonal Frequency-Division Multiple Access (OFDMA) with 15 kHz subcarrier spacing, same as for legacy LTE, and fully inherits the numerology from LTE. One NB-IoT carrier uses one LTE PRB on the spectrum, which is divided into twelve 15 kHz subcarriers, taking up a total of 180 kHz of the physical spectrum, as defined earlier. By inheriting the OFDMA numerology from legacy LTE, it ensures good co-existence on the downlink, which is important if in-band operation mode is chosen for deployment. To fit the new requirements, NB-IoT provides three new physical channels and two new signals on the downlink [50]:

- Narrowband physical broadcast channel (NPBCH)
- Narrowband physical downlink control channel (NPDCCH)
- Narrowband physical downlink shared channel (NPDSCH)
- Narrowband primary synchronization signal (NPSS)
- Narrowband secondary synchronization signal (NSSS)

Both signals, NPSS and NSSS, are used by an UE to perform cell search which includes frequency synchronization and cell identity detection. Only a few LTE PRBs are able to transmit NPSS and NSSS signals (subframe #5 for NPSS, #9 for NSSS). This means that the NPSS signal is transmitted every 10 ms and NSSS every 20 ms. Figure 2.3.2 shows how the subframes are allocated to the channels and signals of NB-IoT.

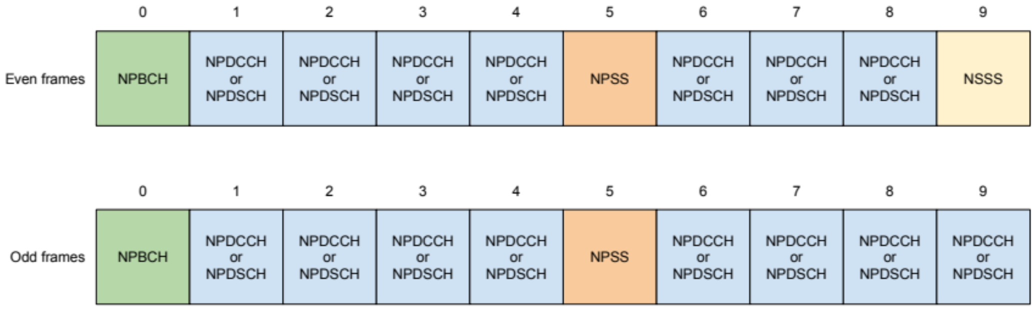


Figure 2.3.2: NB-IoT downlink subframe allocation [6]

NPBCH transmits one Narrowband Master Information Block (MIB-NB) in subframe #0 (see Figure 2.3.2), for a 80ms block, which repeats 8 times to endure extreme conditions. Therefore the MIB-NB remains unchanged during the transmission time interval (TTI), which equals 640 ms.

While NPDCCH carries scheduling information for both the uplink and downlink, NPDSCH carries the data from higher layers. The latter is scheduled by the former and there needs to be a 4 ms delay between the end of NPDCCH and the beginning of NPDSCH, to ensure that the UEs have time to decode NPDCCH [51]. As can be seen in Figure 2.3.2, both channels can be allocated to multiple subframes.

Uplink

The uplink of NB-IoT supports both multi-tone and single-tone transmissions. The multi-tone transmission is based on single-carrier frequency-division multiple access (SC-FDMA) and uses 15 kHz subcarrier spacing, same subcarrier spacing as legacy LTE. Similarly to the downlink, the use of 15 kHz subcarrier spacing comes with twelve subcarriers to make up the whole 180 kHz. Single-tone transmission supports both 3.75 kHz and 15 kHz subcarrier spacing. The 15 kHz spacing is the same as for multi-tone, but for 3.75 kHz spacing there are 48 subcarriers used to fill 180 kHz. The use of 15 kHz spacing will ensure best co-existence with legacy LTE, but 3.75 kHz spacing can ensure longer signal range because of higher power spectral density [52]. Release 13 introduces two new physical channels for NB-IoT uplink [50]:

- Narrowband physical random access channel (NPRACH)
- Narrowband physical uplink shared channel (NPUSCH)

NPRACH is a new physical channel similar to the legacy LTE physical random access channel (PRACH). The new physical channel is needed since the channel for legacy LTE uses a bandwidth of 1.08 MHz, which is higher than the total uplink bandwidth of NB-IoT. NPRACH only works with single-tone transmission, with a subcarrier spacing of 3.75 kHz. NPUSCH was designed to support longer range, scalability and longer battery life. The following features, and others not listed here, are supported to accomplish the aforementioned goals [51]:

- Single-tone transmission (both 3.75 KHz and 15 kHz spacing)
- Multi-tone transmission (15 kHz spacing)
- $\frac{\pi}{2}$ Binary phase shift keying (BPSK) and $\frac{\pi}{4}$ Quadrature Phase Shift Keying (QPSK) modulation

This physical channel has two formats, one for uplink data transmission and the other for signalling Hybrid Automatic Repeat Request (HARQ) acknowledgements for NPDSCH. For more information about uplink and downlink schemes, see research [50], [51] and [52].

2.3.2 eMTC

Operation modes

While NB-IoT had three operation modes, eMTC has only one:

- In-band operation

eMTC is similar to legacy LTE and utilizes most of its physical layer, while NB-IoT introduced all new channels and signals. Similarly to NB-IoT though, eMTC also uses a so called narrowband operation and operates on a bandwidth of 1.08 MHz. Instead of using only one LTE PRB, like NB-IoT, eMTC uses 6 PRBs and thus making the bandwidth the previously mentioned 1.08 MHz. By using a narrowband operation, eMTC can achieve lower costs and lower energy consumption compared to legacy LTE. Moreover, eMTC introduces two CEs similar to NB-IoT: *CE Mode A* and *CE Mode B*. The former supports full mobility while UE is connected to the network (similar to legacy LTE) and channel state information (CSI) feedback is supported. This mode is meant for normal coverage conditions. CE Mode B is meant for poor coverage conditions and it has no CSI feedback and only limited mobility is supported [53].

Downlink

Similarly to NB-IoT, the downlink of eMTC is based on OFDM and uses 15 kHz subcarrier spacing and uses identical numerology as LTE, thus it can co-exist with legacy LTE [54]. The following signals and channels are used:

- Primary synchronization signal (PSS)
- Secondary synchronization signal (SSS)
- Physical broadcast channel (PBCH)
- Physical random access channel (PRACH)
- Physical downlink shared channel (PDSCH)
- MTC Physical downlink control channel (MPDCCH)

All the channels and signals mentioned above, excluding MPDCCH, are inherited from legacy LTE. Further details and technical information about these channels can be found at [55]. MPDCCH was introduced in Release 13, because UEs could not monitor its legacy LTE counterpart, physical downlink control channel (PDCCH), since eMTC is a narrowband operation and PDCCH is wideband [53]. The new control channel will cover up to 6 PRBs on the frequency domain and is mainly used to control PDSCH and Physical uplink shared channel (PUSCH) resources on the side of the UE [37].

Uplink

The uplink of eMTC is also numerology identical to legacy LTE and is based on SC-FDMA with 15 kHz subcarrier spacing. The following channels are used for the uplink:

- Physical Uplink Shared Channel (PUSCH)
- Physical Uplink Control Channel (PUCCH)

These are both inherited from the legacy LTE physical layer, further information about these found at [55].

2.4 Use cases for LPWA networks

Extending the range, lowering energy consumption, maximizing scalability while maintaining a secure connection opens up new types of use cases for LPWA technologies. How eMTC and NB-IoT can achieve these goals have been discussed throughout this chapter. Now we can look at how these technologies can be applied in real life, for example in these types of areas [32]:

- Smart cities or buildings
- Agriculture
- Sensors deep underground
- Logistics

The choice between NB-IoT and eMTC has to be based on the type of application under development. For sensors in moving objects (e.g. cars), eMTC would be preferred due to its ability to support full mobility while connected similar to legacy LTE. The main difference between NB-IoT and eMTC can be seen in Table 2.3 [4].

Table 2.3: Comparison of 3GPP LPWA technologies

	NB-IoT	eMTC
Data rate up	65 kb/s	375 kb/s
Bandwidth	200kHz	1.08MHz
TX up	23 dBm	20/23 dBm
Duplex mode	Half duplex	Full/Half duplex
Band	GSM/LTE	LTE

Comparing this to the speeds of LTE Advanced, which has a peak downlink of 1000 Mb/s , one can see the clear difference [56]. From this alone, it can be deduced that LPWA technologies have different use than traditional cellular technologies. The latency aspect also plays a role in deciding whether you should use LPWA or not. For example, the accepted latency for NB-IoT uplink is 10 seconds [57], while the average latency for LTE is around 100ms [58].

CHAPTER 3

Energy consumption in computer systems

All components in a computer system need energy to function. In desktop computers there are Power Supply Units (PSU) and laptops mostly run on batteries. These are well known to the majority of people, but in this thesis we will focus on how LPWA technologies will optimize the usage of power. The microcontrollers and sensors used in LPWA networks are small computer systems, but instead of only thinking about the performance the focus is more on optimizing the usage of energy and thus achieving a longer battery life. In addition to components using power to do computations, some will also dissipate from the system. Dissipation of power is not the focus of this thesis, but to reach a basic understanding of why it happens the notion of energy (E) and power (P) will be briefly explained below.

We will first look at the correlation between *power* and *energy* and their effect on the consumption. Energy is commonly expressed as the property needed to perform work on an object and in physics there are two basic forms of energy, potential and kinetic. The law of conservation of energy states that the total energy in a closed system will remain constant. In other words, energy can neither be created nor destroyed, instead it will transform to other forms of energy. While energy used in computer systems is electrical, the law of conversation of energy applies here as well. The energy needed to perform tasks on a computer system will transform into other types of energy, which in the case of computer systems is mainly heat. Energy measures the amount of work done on an object per time unit, i.e the rate of energy consumption. When talking about electricity, we can calculate the energy as the factor of *power* (P) and *time* (s). In this thesis, the following units will be used:

- Voltage: Volt (V)
- Current: Ampere (A)
- Power: Watt (W)
- Energy: Watt hours (Wh)
- Time: Seconds (s)

To calculate these units we will use a base formula for calculating power and modify it as needed. In Equation 3.1, we calculate the average power by dividing the energy with time elapsed:

$$\overline{P} = \frac{E}{t}. \tag{3.1}$$

The voltage applied to a micro controller is often provided by a battery or other source with a constant value, hence by measuring the current we can calculate the power, as can be seen in Equation 3.2:

$$P(t) = V(t) \times I(t). \tag{3.2}$$

In a computer system the energy used is often calculated as Wh, in other words the amount of power used during an hour. From Equations 3.1 and 3.2, we can derive a function to calculate the energy consumption of a computer system based on the current, voltage and time elapsed:

$$E = \int_{t_1}^{t_2} V(t) \times I(t) \times dt = \int_{t_1}^{t_2} P(t) \times dt. \tag{3.3}$$

With these formulas we can calculate everything needed in this thesis. In Chapter 5, we will apply a known voltage to different modules and by measuring their currents we can calculate the energy consumption of that module.

3.1 Power management in the 3GPP standard

LPWA technology devices use a number of ways to maintain a low energy consumption while still providing a reliable connection:

- Low power mode
- Lightweight MAC protocols
- Topology
- Utilization of more complex base stations

First, the User Equipment (UE) does not need to send data continuously, like a mobile phone or similar. Instead, when the data are requested the device wakes up from its low power mode and sends the data. By doing this, it can save power by turning off the more power-heavy components and only use them for a short while between preparing to send and actually sending the message. Second, there is the need for new and more lightweight MAC protocols. Not only do the more standard protocols have more overhead, they are also too complex for LPWA UEs. Third, the topology of the networks are different. For normal cellular networks and WLAN, it is normal to use a mesh topology which helps with extending the range of a low range connection. UEs aim to connect straight to the base station to avoid any unnecessary jumps. Finally, unloading the complex operations on the base stations will greatly improve on the battery life of the UEs since they could be very simple devices. Only the first of these four options, low power mode, can be configured by the user for 3GPP standardized technologies. The rest are up to the TSPs to configure and hence the focus in this chapter will be on the ways NB-IoT and eMTC will apply low power modes.

3.1.1 Low power mode

A low power mode is nothing unique for LPWA technology. It is used by many IoT devices utilizing for example the cellular network, but it is nevertheless very important and has been optimized and further developed for LPWA technologies. The main idea, as explained above, is to have the device saving power while inactive. Powering down heavy components such as the processor can bring down the consumption drastically and will help to extend the battery life. Low power mode can be implemented in different ways depending on the application:

- Whether it uses uplink/downlink or both
- Frequency of data transfer

For example, a device only transferring data over the uplink can be scheduled to send data twice a day or by triggering send message manually. If the device also has to be able to receive messages through the downlink, it needs to be able to listen to the network for these messages. This can be done in different ways and the best way depends very much on the use case and how often it will be awakened from low power mode. If the device frequently sends messages, it can listen for messages on the downlink at the same time. However, if it is scheduled to send messages only once a week, this might not be an optimal solution as it would need to wake up from sleep just to listen to the downlink [59]. Low power mode is implemented slightly differently in eMTC and NB-IoT, but both use power efficient techniques called PSM and eDRX. The biggest difference between these techniques is that with eDRX the modem can listen to incoming signals, while with PSM the modem must wake up to send data before being able to receive data. Therefore, eDRX is better suited for applications where incoming data is important, but for applications only utilizing the uplink this would not be unnecessary.

PSM

PSM was first introduced in the 3GPP standard in release 12, and specified in 3GPP TS 23.682 and TS 24.301 [60][61]. The idea with the PSM method is to have the modem listen for incoming transmissions for a set period of time after being in *active mode*. This period is called the *idle mode*, during which the modem cannot transmit data, only receive. After idle mode, the modem can enter PSM where the modem essentially powers down completely but remains in contact with the network. When the modem becomes active again after PSM, it does not have to attach itself to the network or re-establish a public data network (PDN) connection again, since the connection to the network remains during PSM.

As can be seen in Figure 3.1.1 there are two timers, T3324 and T3412, in use with PSM. T3324 (or Requested Active Timer) determines the length of the idle mode previously mentioned. The T3412 (Periodic Tracking Update Area (TAU)) timer determines the time from when the modem leaves active mode until next active mode. The active mode does not necessarily include transmission of data, but can simply be thought of as a period when the UE begins any procedure towards the

Mobility Management Entity (MME). This can in some cases also happen before the end of T3412, if needed, which is important especially if the TSP manages the timers and your application needs to transfer data more frequently.

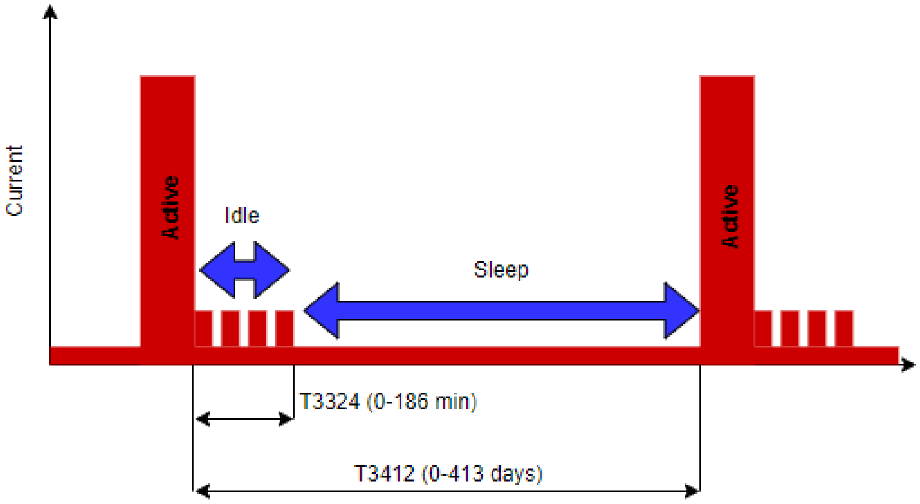


Figure 3.1.1: PSM illustration

Both T3324 and T3412 timers can be configured either on the UE or by the MME, depending on the configurations made on the MME. If the network is configured to accept UE configured timers, they will be sent during the Attach/TAU request. If T3412 timer value is not sent with the same request, the MME will use its own configurations for that timer. Additionally, sometimes the network will not accept as high T3412 values as the standard allows. If the UE tries to use a higher timer than allowed on the network, it might be denied and the UE will use the MME configurations instead. However, if the MME has configured T3324, the configurations made on UEs will not make a difference. In this case, the T3324 timer will start once the UE goes into idle mode and once this timer expires the UE enters PSM [62].

eDRX

This type of sleep mode was introduced in Release 13 of the 3GPP standard and specified in TS 23.682, TS 23.060 and TS 23.401 [63][64][65]. As was mentioned earlier, this method will allow for the modem to listen more frequently to the downlink, without going into active mode. Discontinuous reception (DRX), which is used in LTE, used sleep cycles of length up to 10.24 seconds. eDRX is an extended version of this, using hyper frames (HF) of 10.24 seconds. The UE will send the amount of HFs used to the network, making it known for how long the network should wait before sending any information to the UE. The definition used for this period of time varies. In this thesis we will use I-eDRX (idle eDRX) to describe the time from start of idle mode until the modem starts listening for transmissions again (see figures below). The maximum length of I-eDRX is approximately 44 minutes and 3 hours for eMTC and NB-IoT, respectively (see Figures 3.1.2 and 3.1.3). Exact definitions of and restrictions on these cycles can be found in TS 36.304 [66].

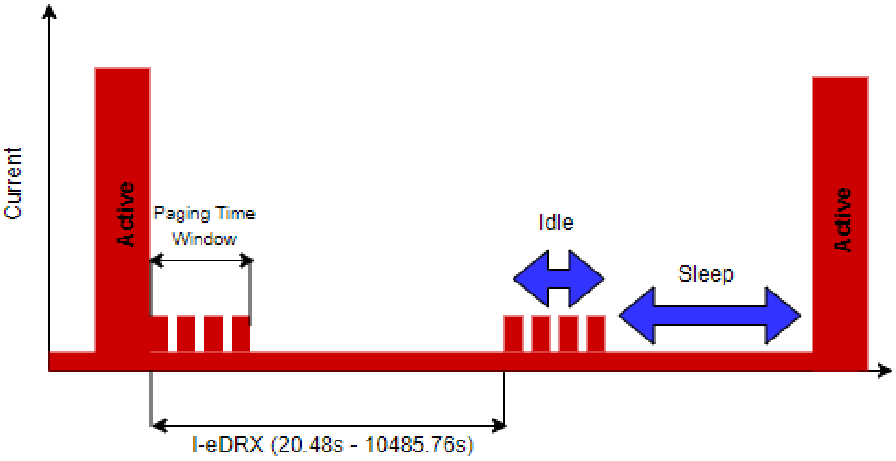


Figure 3.1.2: eDRX illustration (NB-IoT)

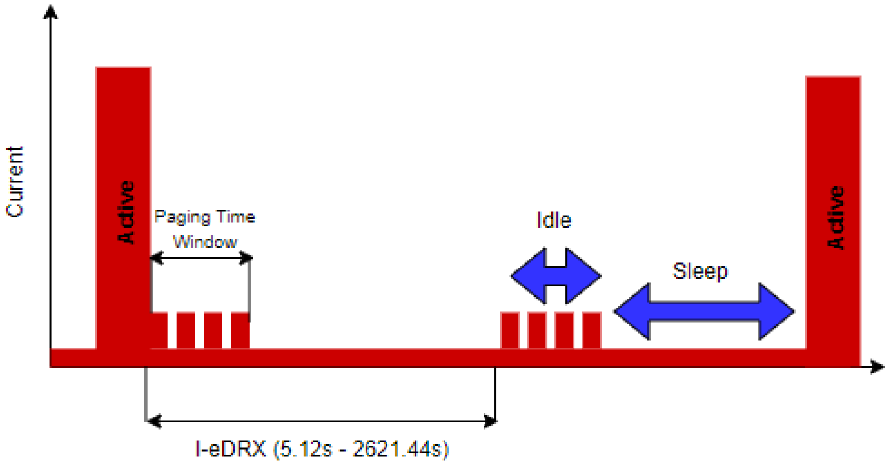


Figure 3.1.3: eDRX illustration (eMTC)

In Table 3.1, the exact lengths of I-eDRX cycles for both technologies are displayed. The length of eDRX cycle is based on DRX sleep cycles and is a power of two. All lengths, except for 5.12 seconds (eMTC), are N-hyperframes of length 10.24 seconds (see [66]).

Table 3.1: eDRX cycle lengths (seconds)

eMTC	NB-IoT
5.12	20.48
10.24	40.96
20.48	81.92
40.96	163.84
81.92	327.68
163.84	655.36
327.68	1310.72
655.36	2621.44
1310.72	5248.88
2621.44	10485.76

The use of eDRX requires support from the network and if no such support is available on the network, the UE shall use DRX instead, as stated in TS 24.301 (Release 13), if eDRX is used alone. It is possible for PSM and eDRX to co-exist and UEs can use both (if supported by the network). In such a case, the requirements are as stated in TS 24.301:

> *If the network accepts the use of both PSM (see subclause 5.3.11) and eDRX (see subclause 5.3.12), the extended DRX parameters IE provided to the UE should allow for multiple paging occasions before the active timer expires.*

The energy consumption also varies depending on the MCL, and according to simulated data done by M. Chen et al. in [7], a 5 Wh battery could last up to 12.4 years by using both PSM and eDRX with NB-IoT. The results from the simulations, measured in number of years, can be seen in Table 3.2. As these results are based on simulations they can only be indicative; real-life tests and results will be provided in Chapter 5 of this thesis.

Table 3.2: Simulation results using PSM and eDRX with NB-IoT [7]

Message size / message interval	Coupling loss =144 dB	Coupling loss =154 dB	Coupling loss =164 dB
59 bytes/2 hours	22.4	11.0	2.5
200 bytes/2 hours	18.2	5.9	1.5
50 bytes/day	36.0	31.6	17.5
200 bytes/day	34.9	26.2	12.8

CHAPTER 4

Experiment settings

Disclaimer

The technologies evaluated in this thesis are still new. Both the modems and the networks are still under development. All results will be attached to a date of when test was performed and the results may vary in the future.

4.1 Introduction to experimentation

All experiments were done in Turku, Finland starting at the 5th of April 2018. We are going to test a variations of power saving features, on both NB-IoT and eMTC. For the experiment, two different Finnish TSPs were used: *OperatorA* and *OperatorB*. OperatorA works on LTE Band 3, with support for both NB-IoT and eMTC. OperatorB works on LTE Band 20, with support for only NB-IoT at the time of the experiment. According to the TSPs used for these tests, these LTE bands are likely the ones that will be used in Finland. However, since the technology is still very new, this can still change.

Table 4.1: Power modes available on networks

	OperatorA NB-IoT	OperatorB NB-IoT	OperatorA eMTC
PSM	Yes	Yes	Yes
eDRX	Yes	No	No

The tests will be performed based on Table 4.1. This means that PSM will be tested on every network, while the tests for eDRX will only be done on the NB-IoT network of OperatorA. To evaluate these technologies, we have two different modules on test, both with different specifications. The *mangOH Red* module, developed by Sierra Wireless, is a bit more than only a modem. In addition to having LPWA capabilities, the module itself has an integrated application processor, making it easy for developers to build applications for it. Due to the application processor, the energy consumption of the modem alone cannot be measured. Instead, the energy consumption of the whole board will be measured using PSM, eDRX, normal mode and the module's own Ultra Low Power Mode (ULPM). Quectel's *BG96* does not have an integrated application processor and the energy consumption of the isolated modem can be measured, giving a more accurate reading of the LPWA technologies. Both the mangOH Red and BG96 are multiband modules, meaning they support multiple LTE Bands (multiple frequencies). Table 4.2 shows an overview of the modules used for these tests. More specific details regarding supported bands can be found at each respective manufacturer's homepage.

Table 4.2: Comparison of modules used during the research

	Bands supported	NB-IoT Support	eMTC Support
mangOH Red	Multiband	Yes	Yes
BG96	Multiband	Yes	Yes

4.2 Measuring setup

In addition to the modems, a precise measurement system has to be in place to be able to catch all the extremely quick current spikes. For this research, we used a *Keithley 2306 battery/charger simulator* because it can handle very fast sample rates and it can be operated from a PC. Before using this instrument we tested a normal multimeter, which was our first choice of measurement equipment. There were two flaws with it: it was too slow and the data had to be manually extracted (not programmable from a PC). The Keithley instrument accepts Standard Commands for Programmable Instruments (SCPI) commands. In essence, the developer can send commands to the instrument, commanding it to do certain operations. More on SCPI programming can be found at [67]. Instead of having to manually send SCPI commands to the instrument, a Python program was developed (see Appendix A). The output of the program is a graph, showing all the readings done during a period of time (modifiable by the developer) as a blue line and the average value as a red dashed line. Additionally, it saves the gathered data in an excel file, which can be used to calculate the energy consumption for certain intervals, check the highest recorded current etc. As was mentioned in Chapter 3, the voltage applied to all modules during the tests will be constant and we can thus calculate the average power and energy consumption by using Equations 3.2 and 3.3.

4.3 Modems used

In this section, a brief description of both modems is given together with the current readings of the modems, as presented by each manufacturer. The actual results from the research may vary a bit in regards to the manufacturers' results, since the network configuration used by them is unknown.

4.3.1 mangOH Red

As mentioned earlier, the mangOH Red board slightly differs from the BG96, in the way that is has an application processor integrated on the module. Due the fact that the current is measured over the whole board, it will have a higher energy consumption than the BG96 module. Sierra Wireless have reported current readings ranging from 7 μA to 50 μA when using ULPM, but no values for PSM or eDRX are given. The difference in current during ULPM depends on the interruption source. If the processor needs to listen to a button for interruptions, the consumption should be much higher, but so are the possibilities for the applications developed. If only a timer is applied as an interrupt signal, the current can be as low as 7 μA. More technical specifications of this module can be found in the Product Technical Specifications (PTS) document [68]. All power saving feature of the board and module will be tested, but the focus is going to be on PSM and eDRX, since these are not as thoroughly tested as UPLM. It is worth to note that no hardware modifications have been made to the board. The board is powered by the charger simulator from the battery connector and we can control the module using the USB interface. The module cannot be forced to a certain network, only preferences can be selected. Because of this, only NB-IoT was tested since it would not connect to the eMTC network of OperatorA. Furthermore, due to poor signal at the time of the experiment, the module would not connect to OperatorB, which is why the tests are not done on that network. The following tests are done on OperatorA's NB-IoT network:

- Normal mode 10min
- ULPM Timer 10min (Active average, sleep average)
- ULPM Button 10min (Active average, sleep average)
- PSM one hour (Active average, sleep average)
- eDRX 20min (Active average, idle average, sleep average)

4.3.2 BG96

BG96, which is developed by a company named Quectel, is a multiband module that supports both NB-IoT and eMTC. The BG96 is attached to an evaluation kit (EVK), provided by Quectel. The EVK, together with the module, can be operated by applying a 3.3 V -4.3 V to the EVK. For our research we had to do small modifications to the EVK, since we are interested in the energy consumption of the modem only. To accomplish this, we disconnected the R104 resistor and connected the charger simulator between the VBAT and GND pins. The EVK is still being powered by a separate power supply and is controlled via a RS232 DB9 connector. The current readings, according to Quectel reports, can be seen in Table 4.3.

Table 4.3: BG96 current readings - Quectel reports

	Average current
NB-IoT connected	65 mA - 89 mA
eMTC connected	124 mA - 190 mA
NB-IoT eDRX sleep	1.7 mA
eMTC eDRX sleep	1.1 mA
PSM	10 μA

More on these values and under what circumstances they were obtained, can be found in Quectel's specification sheet [69], or in the more detailed hardware design documentation (login needed to access the documentations) [70]. The current consumption varies mostly based on LTE band used, network parameters and transmit power of the module. The following tests were performed on both OperatorA (NB-IoT and eMTC) and OperatorB (NB-IoT):

- Normal mode 10min
- PSM one hour (Active average, idle average, sleep average)
- eDRX 20min (Active average, idle average, sleep average)

4.4 AT commands

To control and program a modem, you need to use commands called *AT commands*, which is short for ATtention commands. In addition to AT commands that are specific to a manufacturer, the modems used in this research also support 3GPP TS 27.007 standardized commands [71]. Apart from ping commands, which are manufacturer-specific, only 3GPP commands will be used in these experiments. See the list below for the most common 3GPP AT commands used. For the full list of commands, see [71].

- AT+CFUN
- AT+CSQ
- AT+CGDCONT
- AT+CGATT
- AT+COPS
- AT+CPSMS
- AT+CEDRXS
- AT+CEDRXRDP

CHAPTER 5

Results

Throughout this chapter, we will use Equations 3.2 and 3.3 when calculating the energy consumption and average power of the modules. The voltage applied to the module is defined in the beginning of each section and other parameters will be provided as needed. In the graphs, the blue lines represent the current readings and the red dashed line represents the average current over the measured time window. For graphs showing only one cycle, the red dashed line will still show the average of the whole test, not only for that specific cycle. According to the 3GPP standard, there should be one idle cycle (Figure 3.1.1) after an active cycle when using PSM. For some tests, there is no idle cycle present due to the configurations of the network. More experiments need to be done for these tests, with networks that are configured to have an idle cycle.

5.1 mangOH Red

A voltage of 3.7 V was applied to the module for every test in this section. The energy consumption and average power are calculated based on this voltage and the average current, for a certain time period. It is important to note that this module is still work in progress and not commercially available. The firmware installed on the module, when tests were run, was SWI9X06Y_02.14.04.00. All switches on SW401 were off (see [72]) and USB not connected to the board. The experiments were done on the 6th of April 2018, with a signal strength of -75 dBm. The command to check the transmit (TX) power of the board of LTE, is not yet implemented and cannot be determined for these tests. During the ULPM tests, the module was not connected to a network, but the tests were done to be able to compare ULPM with PSM and eDRX.

5.1.1 Normal mode

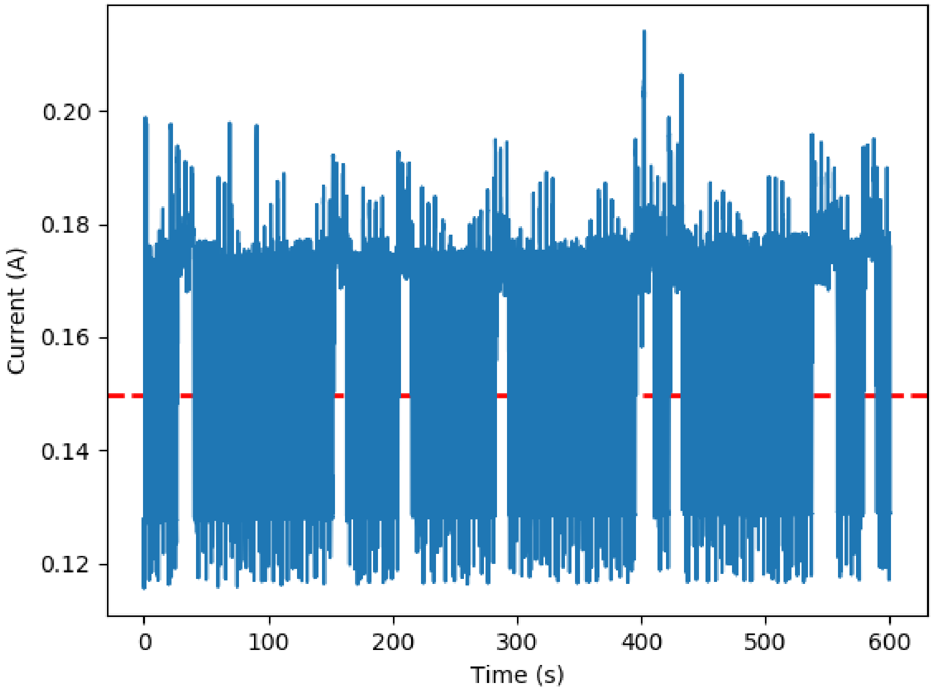


Figure 5.1.1: mangOH normal mode (OperatorA)

For this test the module was connected to the NB-IoT network for 10 minutes, without any user interaction. As can be seen in Figure 5.1.1, the current fluctuates between 0.12 A and 0.2 A. The results can be seen in Table 5.1.

Table 5.1: mangOH normal mode (OperatorA)

	Operator A
Total avg current	149.827 mA
Total avg power	554.358 mW

5.1.2 ULPM with timer

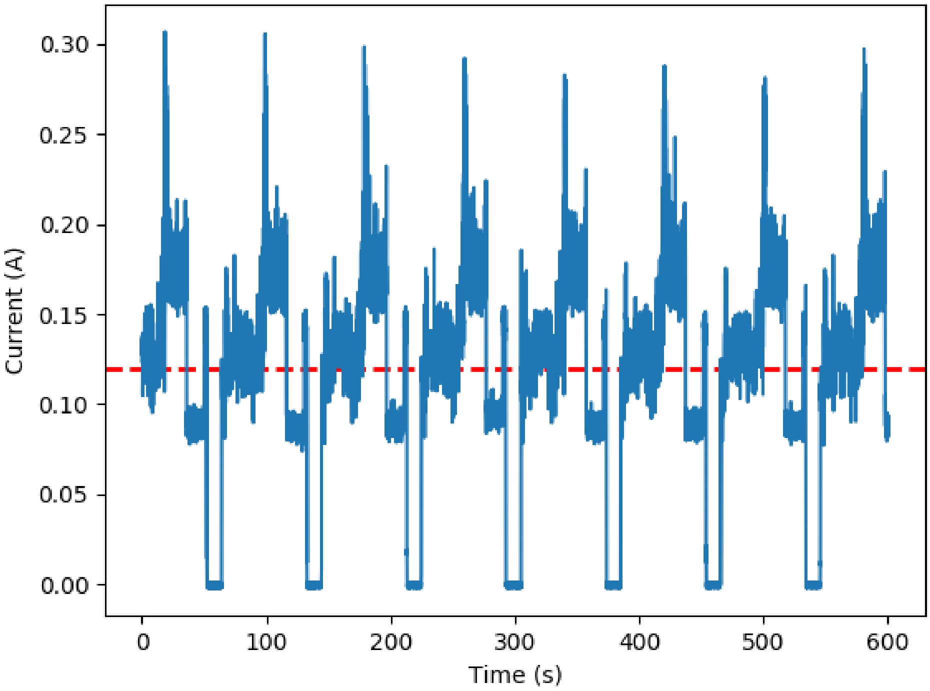
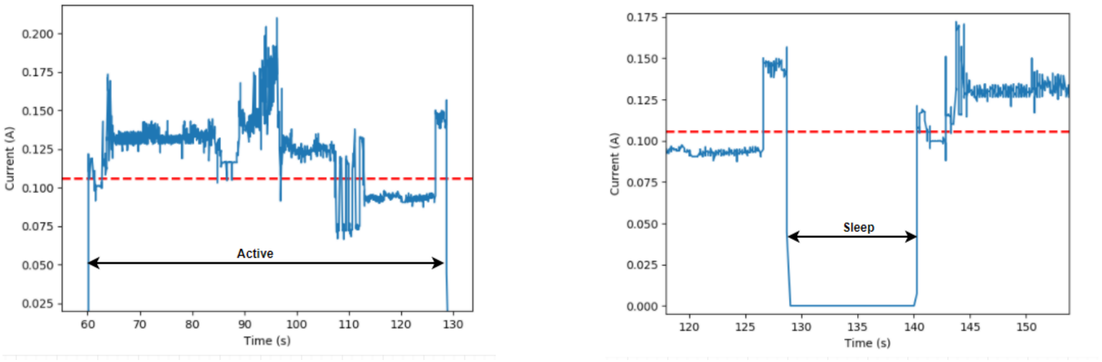


Figure 5.1.2: ULPM with timer

During a time period of ten minutes, the module was sent into ULPM at regular intervals and woken up by a timer, with no other interrupts active. This should lower the energy consumption even further, compared to having a button set as an interrupt signal, according to the manufacturer. Figure 5.1.2 illustrates the measured current during the test. During sleep mode, the current drops close to zero and during active mode it fluctuates between 0.07 A and 0.3 A.



(a) ULPM timer (active)

(b) ULPM timer (sleep)

Figure 5.1.3: ULPM timer - active and sleep cycles

Figure 5.1.3a and 5.1.3b show one active and one sleep cycle each. According to tests done by Sierra, the results for the sleep cycle should be around 7 μA. However, as can be seen in Table 5.2, our results are almost 20 times that. It is uncertain why our results are so different to theirs, but the most likely reasons are that either the board is configured incorrectly (e.g. SW401 switches), or there is a bug in the firmware. The configuration and firmware version of the board are available in the beginning of this section, if the reader want to do measurements of their own, with the same setup.

Table 5.2: mangOH timer active and sleep results

Active avg current	121.451 mA
Active avg power	449.368 mW
Sleep avg current	127.627 μA
Sleep avg power	472.218 μW

5.1.3 ULPM with button

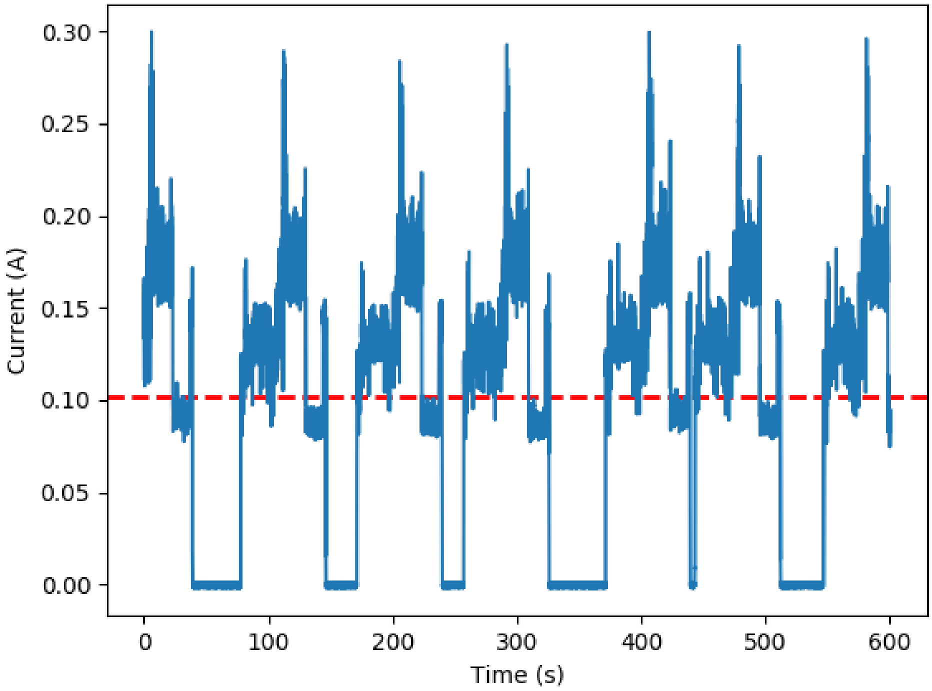
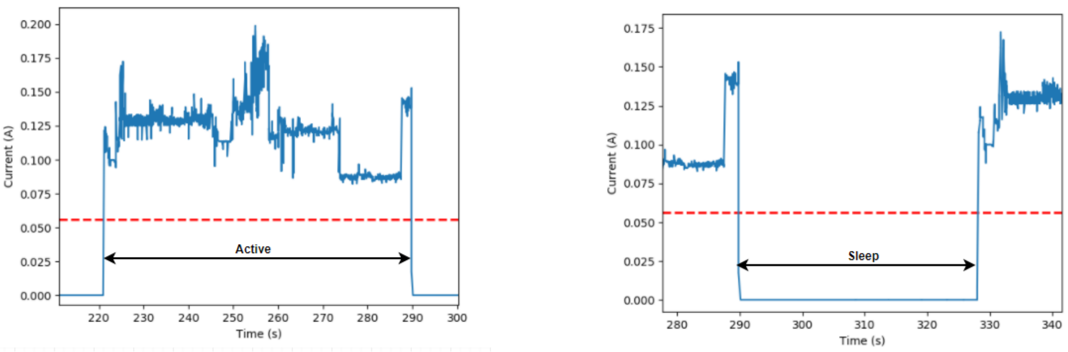


Figure 5.1.4: ULPM with button

Instead of using a timer as an interrupt signal for ULPM, this tests uses a button, which can wake up the module from sleep mode. Figure 5.1.4, which represents the ten-minute Button test, looks similar to the corresponding figure for the Timer test. The current drops close to zero during sleep and fluctuates between 0.07 A and 0.3 A during active mode. Because the sleep mode was interrupted by the push of a button, instead of using a timer, the lengths of the sleep cycle vary. This could cause the results of the test to be skewed, which is why we look at each cycle separately to determine the energy consumption.



(a) ULPM button (active)

(b) ULPM button (sleep)

Figure 5.1.5: ULPM button - active and sleep cycles

Table 5.3 shows the results of the individual cycles. Comparing these results, the average current of the Button test (120.3 mA and 128.6 μA) and the Timer test (121.5mA 127.6 μA), a small difference can be seen. While the average current of the Timer test was 1 μA lower during sleep mode, it was 1 mA higher during active mode. These differences are negligible compared to the results of Sierra, who measured a difference of up to 43 μA between Timer and Button tests during sleep mode.

Table 5.3: mangOH button active and sleep

Active avg current	120.261 mA
Active avg power	444.966 mW
Sleep avg current	128.626 μA
Sleep avg power	475.917 μW

5.1.4 OperatorA NB-IoT

PSM

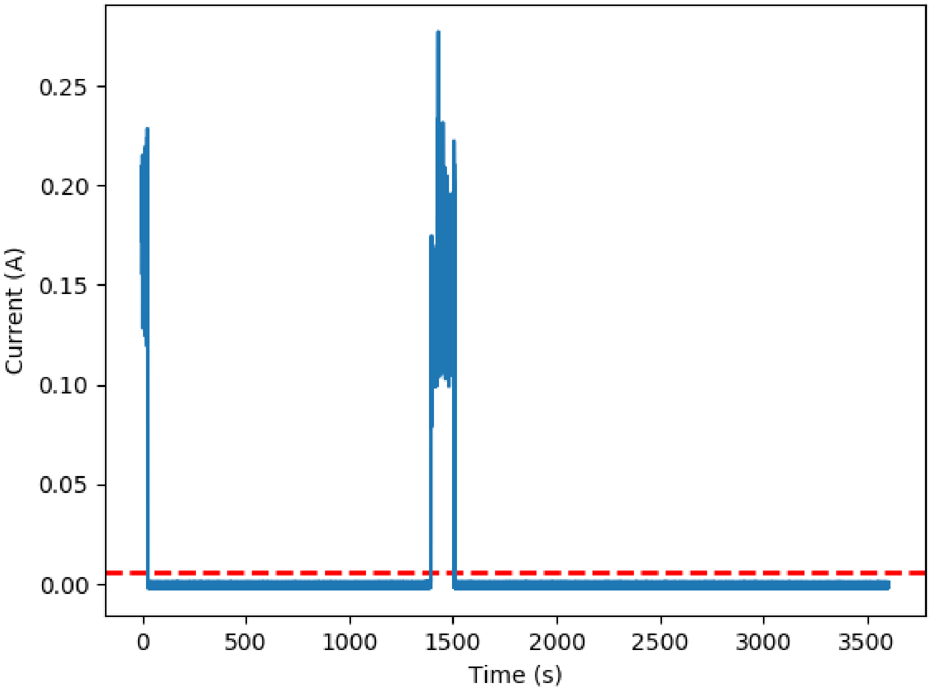
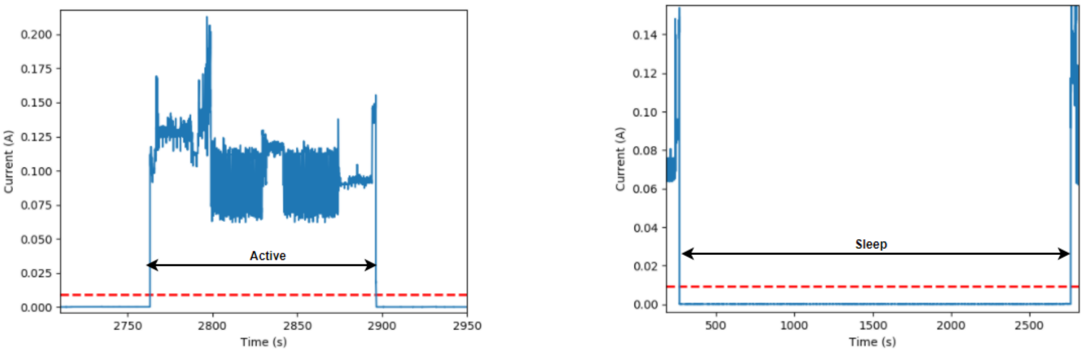


Figure 5.1.6: mangOH PSM (NB-IoT, OperatorA)

Figure 5.1.6 illustrates an one-hour PSM test. During this period, the module woke up from sleep once. The first spike in current was measured before the module had enter sleep mode the first time.



(a) PSM active

(b) PSM sleep

Figure 5.1.7: mangOH PSM active and sleep cycles (NB-IoT, OperatorA)

Similarly to the Timer and Button tests, we will look at the cycles separately to attain better results for both modes. As can be seen in Table 5.4 (illustrated in Figure 5.1.7), both the current and power drop significantly when entering sleep mode.

Table 5.4: mangOH PSM active and sleep (OperatorA)

	OperatorA
Active avg current	101.498 mA
Active avg power	375.544 mW
Sleep avg current	143.428 μA
Sleep avg power	530.684 μW

eDRX

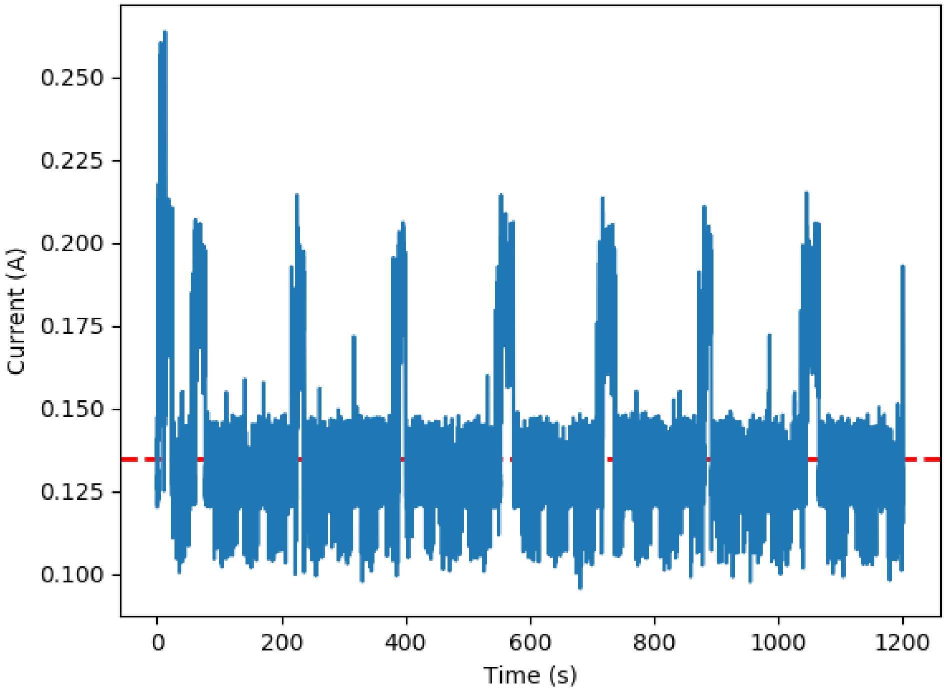
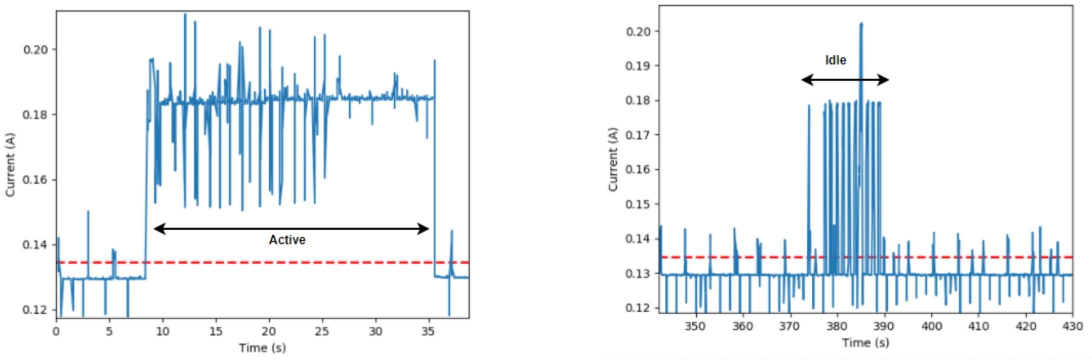


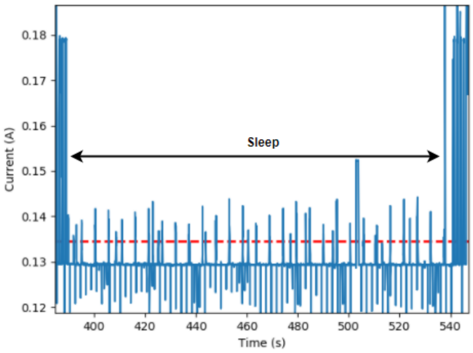
Figure 5.1.8: mangOH eDRX (NB-IoT, OperatorA)

Figure 5.1.8 shows the graph for the 20 minute eDRX test. In the beginning of the test, a ping command was sent to the module. This is reflected in the graph as the first spike in current, which reaches a peak of over 0.25 A. After the initial command, there were no external interactions and the module woke up at regular intervals to listen to the downlink, during which time the average current was around 0.2 A. Between idle cycles, the module was in sleep mode, where the current fluctuated between 0.1 A and 0.15 A.



(a) eDRX active

(b) eDRX idle



(c) eDRX sleep

Figure 5.1.9: mangOH eDRX active, idle and sleep cycles (NB-IoT, OperatorA)

As can be seen in Figure 5.1.9, during each cycle there are a lot of spikes in the current readings. These are likely due to the fact that the current is not measured from the modem alone and there are applications running on the application processor. The result of each separate cycle can be seen in Table 5.5.

Table 5.5: mangOH eDRX active, idle and sleep (OperatorA)

	OperatorA
Active avg current	183.313 mA
Active avg power	678.257 mW
Idle avg current	144.356 mA
Idle avg power	534.118 mW
Sleep avg current	129.786 mA
Sleep avg power	480.206 mW

5.1.5 Summary

Since the module has an integrated application processor, the mangOH Red cannot be compared to the BG96. Instead, the average power of each test done on the mangOH Red, were compared between themselves. A summary of the tests are shown in Figures 5.1.10 and 5.1.11. The former graph shows the average power during active mode and the latter shows the average power during sleep mode. Since the average power of eDRX during sleep mode was so much higher than the rest, it was not included in the second graph. See Appendix C for larger and more detailed graphs of the results.

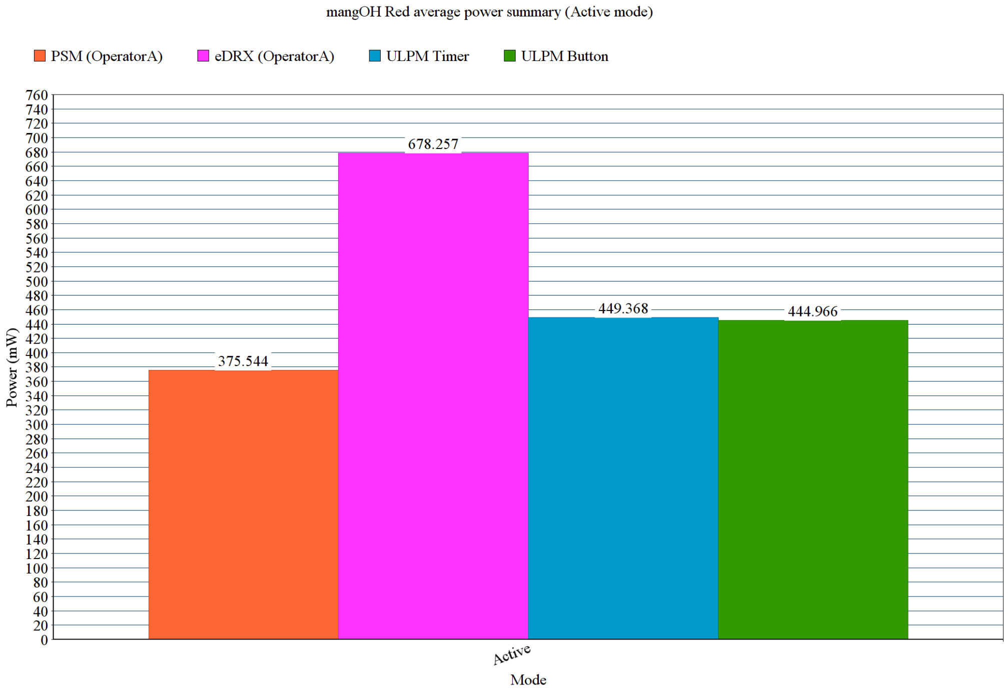


Figure 5.1.10: mangOH Red average power summary (active mode)

The results from the active cycles are all pretty similar, with the exception of eDRX. There is a slight difference between PSM and both ULPM modes, which is an interesting result. On one hand, it might be explained by the fact that both ULPM Timer and ULPM Button had an extra application running to control the sleep mode, while PSM was controlled by the modem. On the other hand, there was no network connection during either ULPM experiment, while PSM was always connected. These results are only indicative and need further research in a more controlled environment, to determine the actual differences.

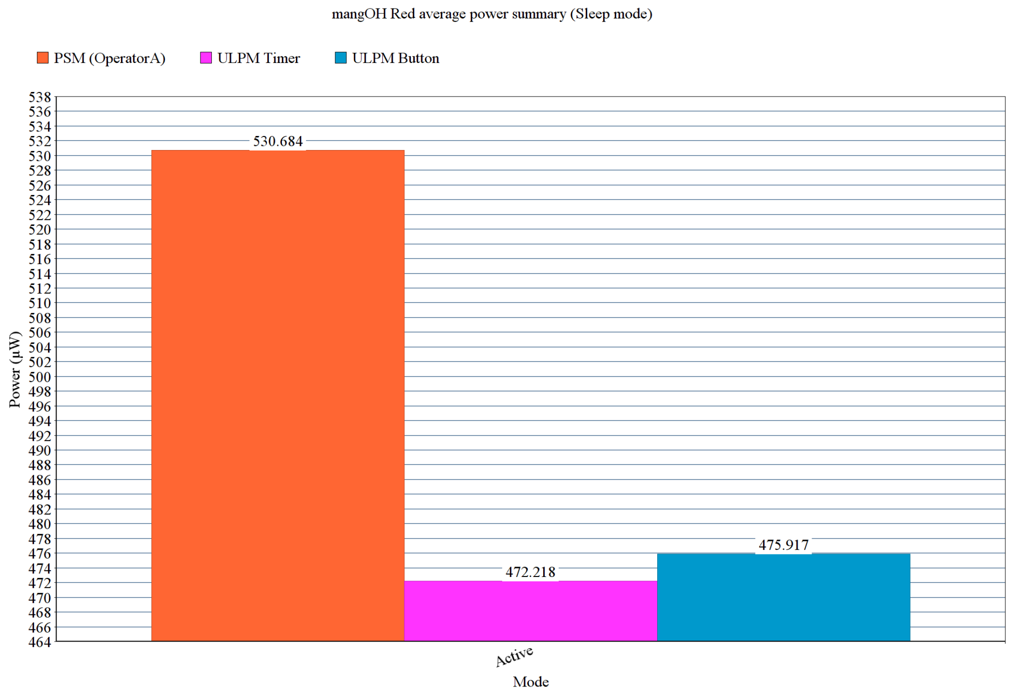


Figure 5.1.11: mangOH Red average power summary (sleep mode)

The average power, for both ULPM tests, is about 55 mW lower compared to PSM during sleep mode. This is likely due to the previously mentioned reason, that the modem stays attached to the network during PSM, while in ULPM it closes all connections. It is interesting to note, that during none of the sleep tests, were the desired ultra low powers achieved. The lowest average current was measured during the Timer test (127.627 μA), but this was not close to the desired 7 μA achieved by the manufacturer.

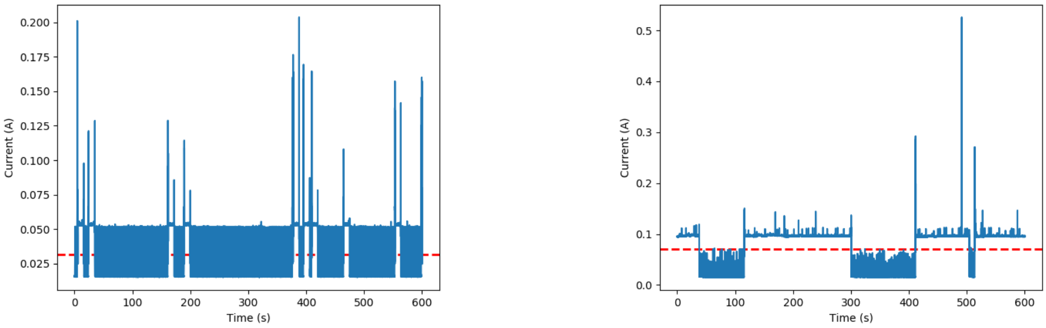
5.2 BG96

The tests for BG96 were done on 5th of April 2018. For all tests the TX power of the module was 23 dBm and voltage applied to the module 3.8 V. Table 5.6 shows the signal strengths of the module during the tests, which were aquired with AT+CSQ command. See [73] for more information about this AT command. As was mentioned in Chapter 4, both TSPs support PSM while only OperatorA supports eDRX (NB-IoT only). The initial tests for PSM were done during a one-hour period, which the end-results are based on, but on the 9th of April a second test was done for PSM (both OperatorA and OperatorB). The length of this test was doubled to show what the cycles look like during a longer period. Despite some small discrepancies in the the visual results, the average readings of both tests were similar. The figures from these two-hour tests are found in Appendix B.

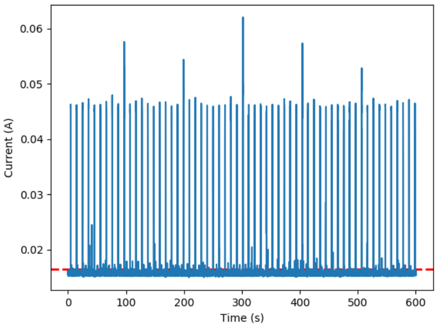
Table 5.6: Signal strength during test (BG96)

	RSSI
OperatorA NB-IoT	-91 dBm
OperatorA eMTC	-79 dBm
OperatorB NB-IoT	-105 dBm

5.2.1 Normal mode



(a) OperatorA NB-IoT (b) OperatorA eMTC



(c) OperatorB NB-IoT

Figure 5.2.1: BG96 normal modes

Figure 5.2.1 represents each network used during their normal mode, meaning the module was connected to the network, but no power saving feature was active. As can be seen in Table 5.7, the average current and power is lowest for

OperatorB (NB-IoT). The exact reason for this is unknown, but as can be seen in Figure 5.2.1a, there are a lot of current spikes which reach 0.2 A, in addition to the "normal" current of 0.05 A. The only known difference between these two networks is that OperatorB operates on 800 MHz, while OperatorA operates on 1800 MHz.

Table 5.7: BG96 normal mode results

	Average current	Average power
OperatorA NB-IoT	31.416 mA	119.380 mW
OperatorB NB-IoT	16.420 mA	62.398 mW
OperatorA eMTC	69.923 mA	265.708 mW

5.2.2 OperatorA NB-IoT

PSM

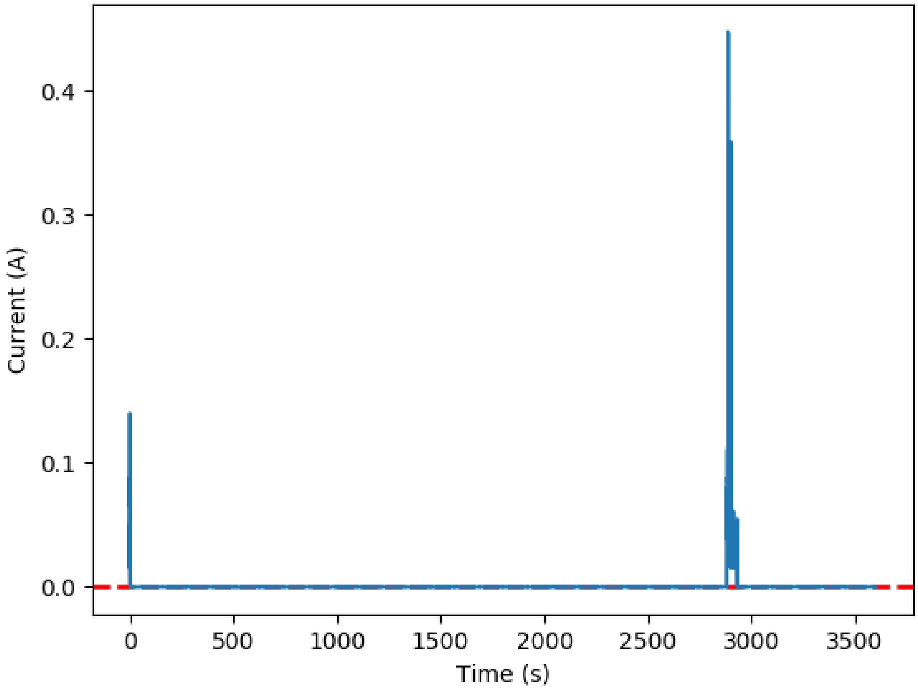
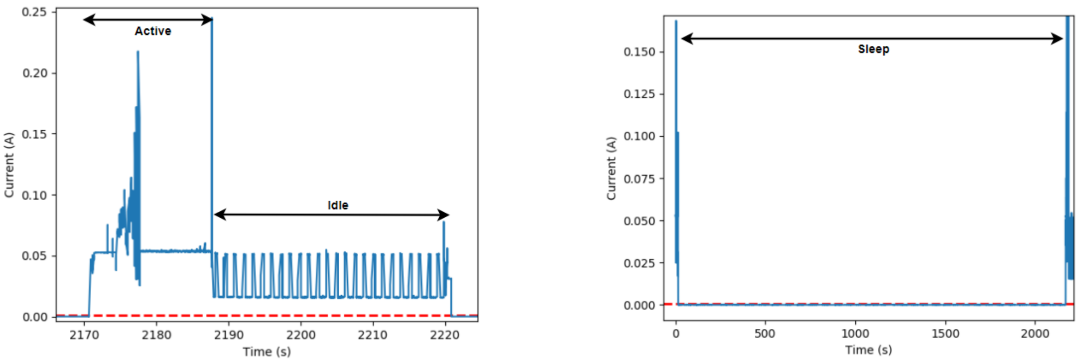


Figure 5.2.2: BG96 PSM (NB-IoT, OperatorA)

Similarly to PSM for mangOH red, the module woke up once during the one-hour test. Since this module does not have an application processor, the active time is much shorter as it does not need to start any applications. However, the maximum current during this period was much higher (almost 0.5 A), compared to mangOH Red.



(a) Active and idle mode

(b) Power saving mode

Figure 5.2.3: BG96 PSM active, idle and sleep cycles (NB-IoT, OperatorA)

Figure 5.2.3a shows what an active cycle looks like, when idle mode is enabled on the network. The graph is almost identical to the illustrated figure of PSM in Chapter 3. During the idle mode, the module listens on its downlink for incoming messages before going into sleep mode. As a result of the clear idle mode, we were able to measure the average power and current for all three cycles. See Table 5.8 for the results.

Table 5.8: BG96 NB-IoT PSM active, idle and sleep results (OperatorA)

	OperatorA
Active avg current	57.298 mA
Active avg power	217.730 mW
Idle avg current	26.881 mA
Idle avg power	102.148 mW
Sleep avg current	11.006 μA
Sleep avg power	41.821 μW

eDRX

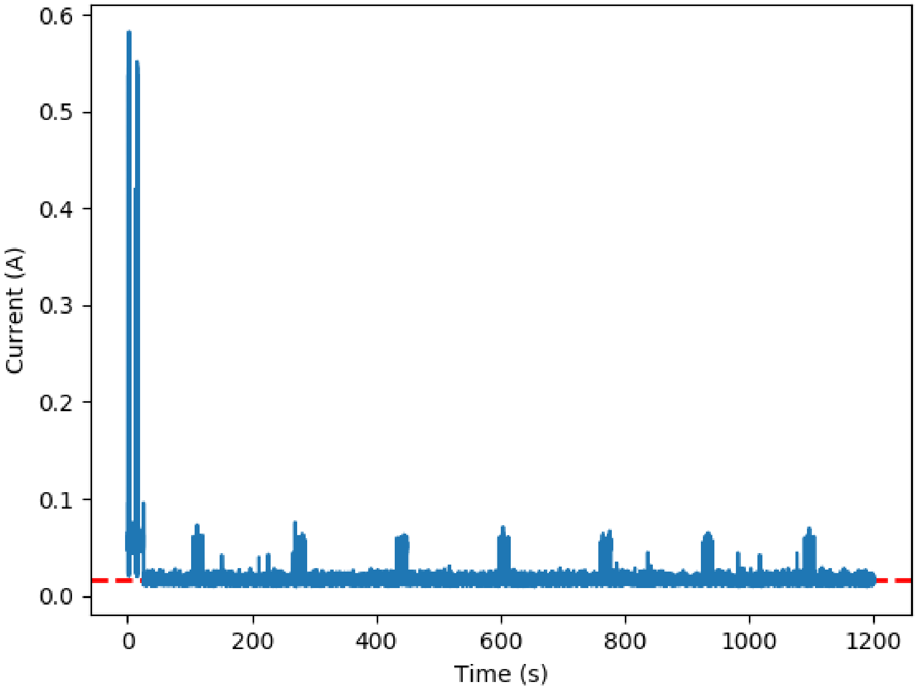
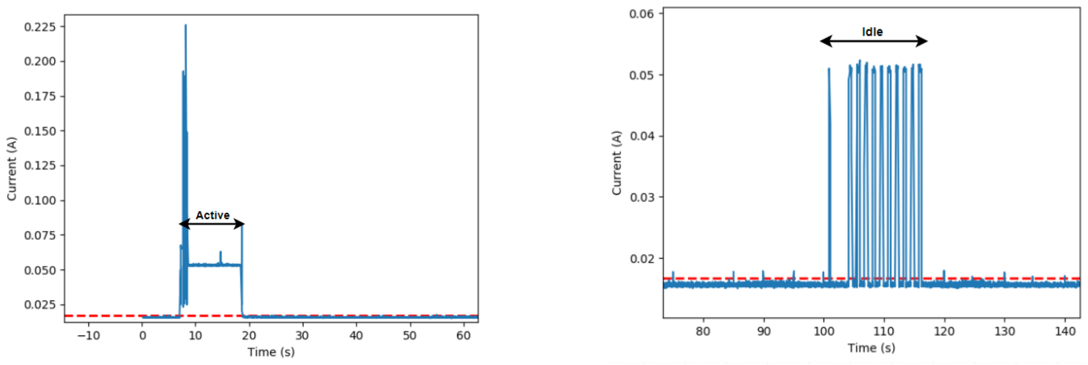


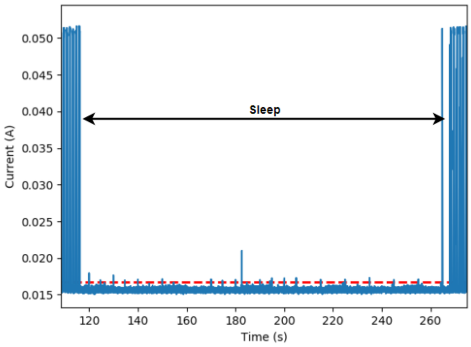
Figure 5.2.4: BG96 eDRX (NB-IoT, OperatorA)

Similarly to the test done on mangOH Red, a ping command was sent to the module in the beginning of the test, after which there were no user interactions. Comparing the results of BG96 to the corresponding results of mangOH Red (Figure 5.2.4 and 5.1.8), the peak current is again higher and has a shorter period during active mode. The average current of the idle mode cycles are however much lower for BG96 than they are for mangOH Red.



(a) eDRX active

(b) eDRX idle



(c) eDRX sleep

Figure 5.2.5: BG96 eDRX active, idle and sleep cycles (NB-IoT, OperatorA)

Figure 5.2.5 shows each cycle separately. The average current and power of each cycle can be seen in Table 5.9.

Table 5.9: BG96 eDRX active and sleep results (OperatorA)

	OperatorA
Active avg current	55.455 mA
Active avg power	210.729 mW
Idle avg current	25.286 mA
Idle avg power	96.088 mW
Sleep avg current	15.537 mA
Sleep avg power	59.039 mW

5.2.3 OperatorA eMTC

PSM

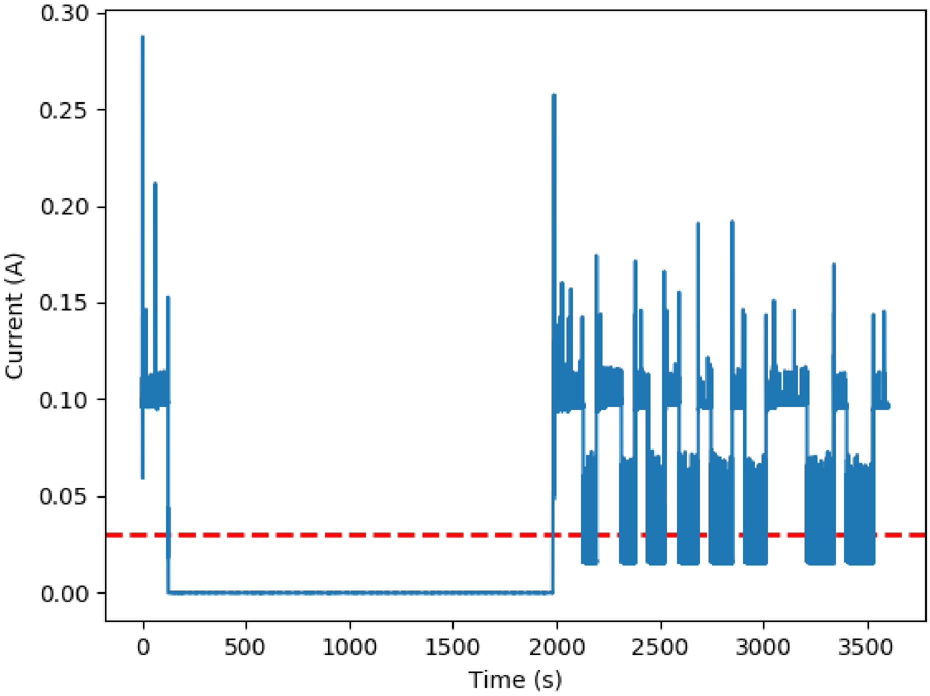
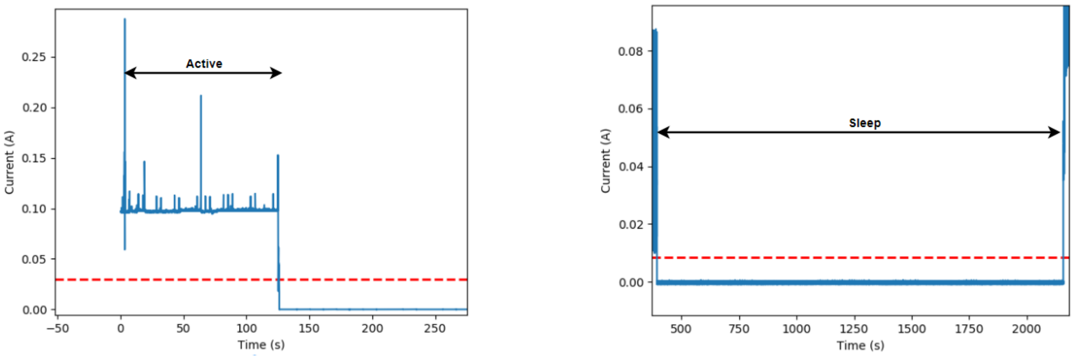


Figure 5.2.6: BG96 PSM (eMTC, OperatorA)

PSM for eMTC did not work the same way as for NB-IoT. After the module had woken up from its first sleep cycle, it would not go back to sleep mode. A two-hour test was done on the 9th of April, where the results were slightly different again (Appendix B, Figure B.0.3). During the two-hour test, there were clear cycles and the module would enter sleep mode normally after an active cycle. As was mentioned in the beginning of this chapter, the results of the one-hour and two-hour tests were almost identical, which is why the results are taken from the test one-hour test (illustrated in Figure 5.2.6). This was done to be able to compare the tests made on the same day and to avoid any changes in network configurations influencing the results.



(a) Active

(b) Sleep

Figure 5.2.7: BG96 PSM active and sleep cycles (eMTC, OperatorA)

Figure 5.2.7 shows both the active and sleep mode separately. Comparing the active cycle of eMTC, to the corresponding cycle of NB-IoT, there is a big difference in the active cycle. There is no clear idle mode, instead it enters sleep mode directly after the active cycle. Table 5.10 shows the results of both cycles.

Table 5.10: BG96 eMTC PSM active and sleep results (OperatorA)

	OperatorA
Active avg current	97.440 mA
Active avg power	370.272 mW
Sleep avg current	10.948 μA
Sleep avg power	41.604 μW

5.2.4 OperatorB NB-IoT

PSM

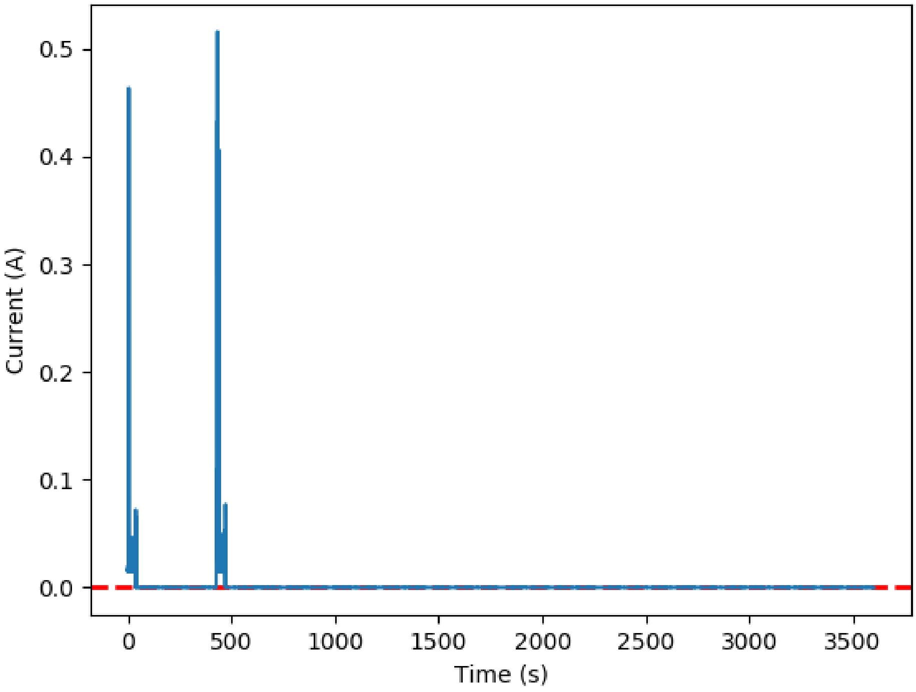
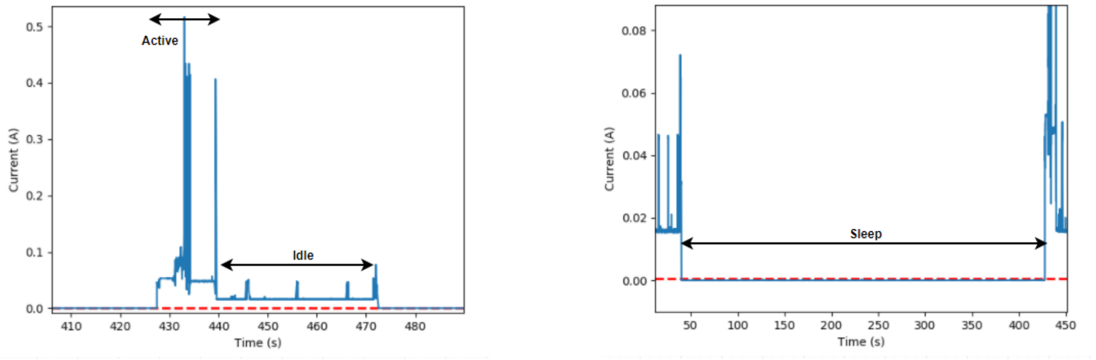


Figure 5.2.8: BG96 PSM (NB-IoT, OperatorB)

This test had almost identical results as the corresponding NB-IoT test done on OperatorA's network. The module woke up only once during the test (similar to OperatorA), despite it waking up almost immediately after its first sleep cycle. This is due to the difference in configurations on the TSPs networks. The illustrated results from the two-hour test can be found in Appendix B (Figure B.0.2).



(a) PSM active (b) PSM sleep

Figure 5.2.9: BG96 PSM active and sleep cycles (NB-IoT, OperatorB)

Similarly to OperatorA's PSM active cycle (NB-IoT), the idle mode is easily identifiable. However, there are a lot less current spikes and they are further apart (Figure 5.2.9a). The reason for this is not known, most likely reasons are either the bandwidth difference (800 MHz vs 1800 MHz), or differences in network configurations. Nevertheless, the idle mode was clear enough to be measured accurately. The results are available in Table 5.11.

Table 5.11: BG96 PSM active and sleep results (OperatorB)

	OperatorB
Active avg current	64.989 mA
Active avg power	246.959 mW
Idle avg current	17.277 mA
Idle avg power	65.654 mW
Sleep avg current	11.014 μA
Sleep avg power	41.854 μW

5.2.5 Summary

Unlike the mangOH Red module, for this module we will only compare the different 3GPP power saving features between each other, as the BG96 does not have a separate low power mode. The summary of the tests are illustrated in Figures 5.2.10 and 5.2.11. The results from sleep mode (PSM) was excluded from the first figure, due to the results being so much lower than the rest and a clear visual representation of the results could not be shown. Instead these results are available separately, in the latter figure.

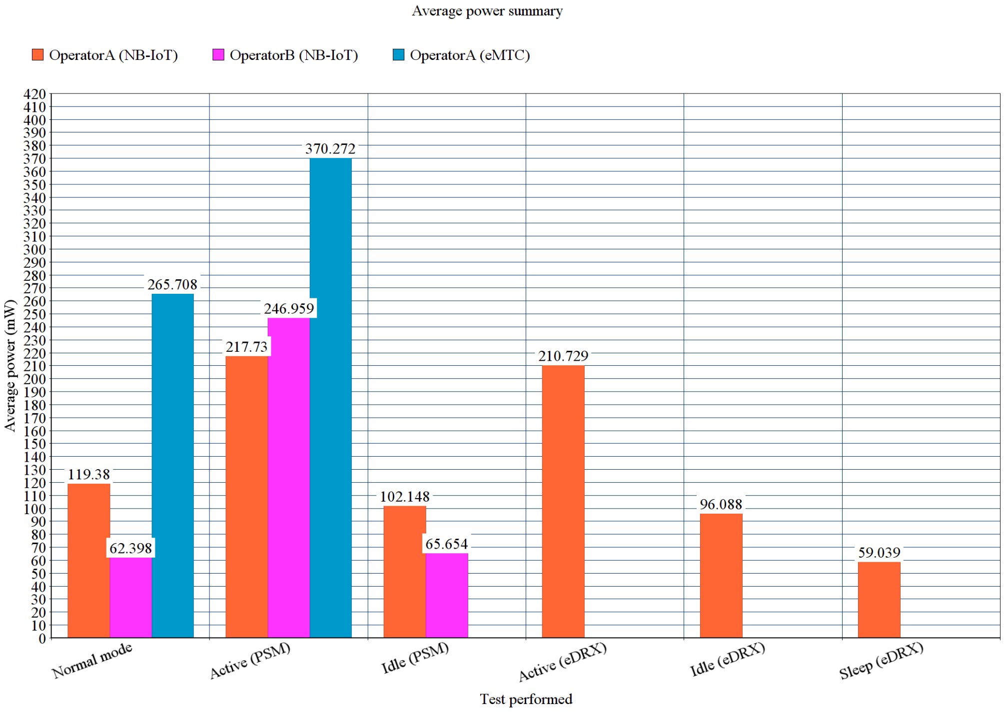


Figure 5.2.10: Average power of each test (PSM sleep excluded)

The fact that eMTC has the highest average power during normal and active modes, is a predictable outcome, as this technology is less focused on power saving than NB-IoT. What stands out during normal mode (as mentioned earlier in the chapter), is that the average power for OperatorB is almost half the value of OperatorA. This is something that needs more research with the help of TSPs. The results for eDRX (OperatorA, NB-IoT), are shown as the three last bars in the graph. Unfortunately these could not be compared to any other technology or TSP, but can be used as a baseline for further research.

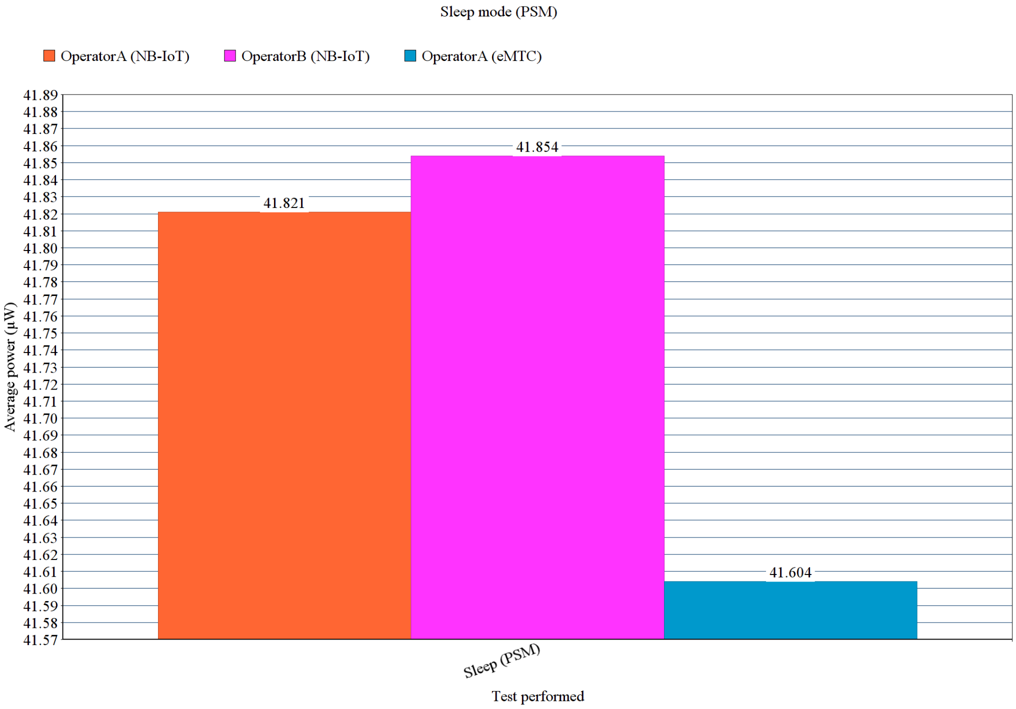


Figure 5.2.11: Average power of sleep modes

The average power, during PSM, is illustrated in Figure 5.2.11. What stands out is that eMTC had the lowest average power during PSM sleep, but the differences are very small between all three tests. The difference is so small, that it is most likely caused by small reading errors during the test. The average power should be the same for all technologies, as the modem is shut down during this period. Graphs for the average current and larger figures of the average power can be found in Appendix D.

CHAPTER 6

Conclusion and further work

6.1 Conclusion

The choice of technology, for a LPWA application, needs to be done on a case-to-case basis. For example, if the device under development is a sensor which only needs to send data once a month, PSM would most likely be the preferred technology. If however, the device would need to constantly listen to incoming messages, eDRX would be more suitable. In addition to the use case, this is also a question of the desired lifetime of the device and whether or not it has access to a power source that can charge its battery. The power saving feature used must be thoroughly thought out, since neither PSM nor eDRX is a one-fit-all type of technology. If we know the size of the battery and we know the network configurations, we can calculate the lifetime of a device. First we will do the calculations for PSM:

The battery has a total energy of 5 Wh. First we need to know how long the module is in sleep mode (T3412 timer). For this example, we will calculate the lifetime using four different timers: one hour, one day, one week and one month (30 days). Table 6.1 shows the average power of each cycle, paired with their respective times. The only variable is the T3412 timer, which will use the aforementioned times.

Table 6.1: Average power summary (PSM)

	Average power	Time
OperatorA NB-IoT (active)	217.730 mW	17.03 s
OperatorA NB-IoT (idle)	102.148 mW	32.91 s
OperatorA NB-IoT (sleep)	41.821 μW	T3412 timer
OperatorB NB-IoT (active)	246.959 mW	12.15 s
OperatorB NB-IoT (idle)	65.654 mW	32.62 s
OperatorB NB-IoT (sleep)	41.854 μW	T3412 timer
OperatorA eMTC (active)	370.272 mW	125.94 s
OperatorA eMTC (sleep)	41.604 μW	T3412 timer

The average power is calculated by first adding the total energy together. This result is then divided by the total elapsed time.

$$E_{tot} = E_{active} + E_{idle} + E_{sleep} \tag{6.1}$$

$$t_{tot} = t_{active} + t_{idle} + t_{sleep} \tag{6.2}$$

$$\overline{P_{tot}} = \frac{E_{tot}}{t_{tot}} \tag{6.3}$$

Finally, the lifetime of the battery is calculated by dividing the energy of the battery with the average power.

$$Lifetime = \frac{5Wh}{P_{tot}} \tag{6.4}$$

Table 6.2: Lifetime of 5 Wh battery (PSM)

	Once/hour	Once/day	Once/week	Once/month
OperatorA NB-IoT	2528 h (105 days)	40463 h (1686 days)	93449 h (3894 days)	112239 h (4677 days)
OperatorB NB-IoT	3443 h (143 days)	49351 h (2056 days)	99301 h (4138 days)	114060 h (4753 days)
OperatorA eMTC	398 h (17 days)	8614 h (356 days)	42130 h (1755 days)	83905 h (3496 days)

Table 6.2 shows the lifetime of a 5 Wh battery, when using PSM with NB-IoT and eMTC and changing the value of the T3412 timer. As expected, the lifetime is a lot shorter for eMTC compared to NB-IoT. It achieved a lifetime ranging

from 17 days to 3496 days, depending on the length of the sleep mode. The difference in lifetime is interesting, when comparing the two NB-IoT networks. Using OperatorB, the module could theoretically achieve a lifetime up to 4753 days, while the maximum for OperatorA was 4677 days. As can be seen from the results, it is more than possible to achieve a battery lifetime of over 10 years using a 5 Wh battery, it just depends on how long the application is allowed to sleep.

We can apply the same environment for eDRX as for PSM, except that the sleep time is also taken from the experiments done in this thesis. The average power readings for each eDRX cycle and their respective times, can be seen in Table 6.3.

Table 6.3: Average power summary (eDRX)

	Average power	Time
OperatorA NB-IoT (active)	210.729 mW	11.41s
OperatorA NB-IoT (idle)	96.088 mW	15.36s
OperatorA NB-IoT (sleep)	59.039 mW	148.56s

Using these values and the same 5 Wh battery as for PSM, we can calculate the lifetime of the battery. The calculations are based on the same equations used for PSM, but instead of having only one idle and one sleep cycle before the next active cycle, we will assume the application uses either 100 or 2000 consequent idle and sleep cycles. Using 100 consequent sleep and idle cycles means having a period of 4.5 hours between active cycles, for 2000 cycles that period would be 91 hours.

Table 6.4: Lifetime of 5 Wh battery (eDRX)

	100 cycles	2000 cycles
OperatorA NB-IoT	79.85 h	79.98 h

As can be seen in Table 6.4, the lifetime does not increase in the same manner as for PSM when increasing the period between active cycles. Comparing these results to the corresponding results for PSM, it is obvious that the use cases for eDRX and PSM are totally different. If it is important that the device listens to the downlink frequently, the battery also might also need recharging quite often.

6.2 Further work

There are still numerous uncertainties when it comes to new technologies such as NB-IoT and eMTC. As was mentioned in the beginning of Chapter 4, the networks used are only test networks and not commercially available, meaning they are still under development and might be configured differently once released. The exact configurations of the networks were unknown during the tests, which is why it is very difficult to draw accurate conclusions from the results. Sleep mode for PSM was the only test that gave the expected results, with around 10 μA for both NB-IoT and eMTC.

There are too many unknown factors (range, configurations etc.), to be able to give exact details on their energy consumption. Also, there were no experiments done on how the amount of data sent influences the energy consumption. This was unfortunately out of scope for this thesis, but is more than likely an interesting aspect for many stakeholders.

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Energiförbrukning för NarrowBand IoT och LTE Cat M1

Introduktion och bakgrund

Termen sakernas internet (Internet of Things) myntades redan i slutet på 1990-talet, men efterfrågan på enheter som använder sig av denna typ av teknik har ökat exponentiellt under de senaste 10 åren. Idén med sakernas internet är att enheterna (t.ex. sensorer) ska kunna kommunicera med varandra utan input från användaren. Under de senaste åren har den växande markanden för trådlöst kommunicerande sensorer skapat behovet av en ny trådlös teknik. Istället för höga hastigheter och låg latens ligger fokus på låg energiförbrukning, skalbarhet och räckvidd, eftersom simpla sensorer har andra användningsområden än t.ex. mobiltelefoner. En sensor behöver inte nödvändigtvis skicka data oftare än en gång i månaden, och även i sådana fall kan mängden ligga på kilobyte-nivå. Teknikerna som utvecklats för dessa användningsområden är antingen baserade på nuvarande infrastruktur eller på proprietär teknik, men båda typerna hör till kategorin för nätverk med låg strömförbrukning och lång räckvidd (LSLR). Fokus i denna avhandling ligger på teknikerna Narrowband IoT (NB-IoT) och LTE Cat M1 (eMTC), som båda använder sig av det nuvarande Long Term Evolution (LTE) nätverket. Nätverk baserade på proprietär teknik (Sigfox och LoRa) har funnits en längre tid än NB-IoT och eMTC, men nackdelen med dem är att de kräver installation av extra hårdvara i nätverket för att fungera, medan både NB-IoT och eMTC kan aktiveras av teleoperatörer genom uppdatering av mjukvaran vilket är enklare och signifikant billigare.

Eftersom denna teknik ännu är relativt ny finns det några problem som måste tas i beaktande, varav de två största är säkerhet och adressering. De nya sensorerna har en teoretisk livstid på över 10 år och idén är att de ska fungera hela denna tid oövervakade och utan underhåll, vilket betyder att adresserings- och säkerhetsmetod måste väljas noggrannt. Det är möjligt att uppdatera den fasta programvaran på modulerna över den trådlösa länken ifall det upptäcks att något måste åtgärdas i koden, men möjligheterna för vad som kan göras är begränsade. Till exempel måste enheterna ha support för internetprotokoll version 6 (IPv6), eftersom adresserna på internet med internetprotokoll version 4 (IPv4) kommer att ta slut. För att NB-IoT och eMTC ska kunna använda sig av IPv6 måste ramstorleken minskas på dessa paket p.g.a den begränsade bandbredden, vilket är något The Internet Engineering Task Force (IETF) arbetar på.

Energiförbrukning i datorsystem

Ett datorsystem använder sig av elektrisk energi för att utföra uppgifter. Den elektriska energi som förbrukas kan beräknas på basis av den applicerade spänningen, strömförbrukningen och tiden. Vid användning av inbyggda system användes ofta en konstant spänning, vilket betyder att energiförbrukningen kan beräknas genom att mäta tiden och den genomsnittliga elströmmen. Eftersom fokus ligger på låg energiförbrukning för LSLR har The 3rd Generation Partnership Project (3GPP) standardiserat två stycken nya lågenergi lägen, strömsparläge (Power Saving Mode (PSM)) och förlängd diskontinuerlig mottagning (extended Discontinuous Reception (eDRX)). I strömsparläge kan enheten inte bli kontaktad av nätverket, förutom under en kort tid efter att den har vaknat upp i aktivt läge. Tiden för strömsparläge är definierat av en timer (T3412), vilken är oftast styrs av nätverket. Vid användning av förlängd diskontinuerlig mottagning lyssnar enheten på nätverket med jämna mellanrum, ifall det finns meddelanden som behöver beaktas. På grund av att enheten aldrig går i djup sömn vid användning av förlängd diskontinuerlig mottagning är energiförbrukningen också signifikant högre jämfört med strömsparläget.

Översikt av LSLR-nätverk

Utöver att spara energi är målet för LSLR-nätverk att uppnå lång räckvidd och bra säkerhet i en miljö som tillåter ett stort antal enheter inom ett litet område. I LSLR-nätverk används två olika typer av spektrum, smalbandsspektrum och spridningsspektrum. Skillnaden mellan de två kategorierna är att i ett spridningspektrum är signalen spridd över hela bandbredden medan i smalbandsspektrum är signalen komprimerad till en mycket smal bandbredd. Signalen i ett spridningsspektrum är svårare att fånga upp av en oönskad tredje part eftersom den ligger under ljudnivån och signalen inte har någon klar topp, men däremot kräver denna typ av spektrum högre processeringsstyrka av mottagaren för att avkoda meddelandet. Både NB-IoT och eMTC utnyttjar en typ av smalbandsspektrum.

NB-IoT och eMTC kan uppnå lång räckvidd genom ett par olika tekniker. Först och främst använder de en låg signalfrekvens (ofta sub-GHz). För de lägre frekvenserna är räckvidden längre och genomträngligheten bättre än för högre frekvenser och på det sättet undviker man även frekvenser som är under hög belastning såsom trådlösa nätverk (WLAN) och bluetooth-nätverk med frekvensen 2.4 GHz. Utöver den låga frekvensen har dessa enheter en sändningseffekt på 23 dB och en hög tolerans av maximal kopplingsförlust (upp till 164 dBm). Denna typ av tolerans kan uppnås genom repetition av signalerna i dess kanaler. Den motsvarande toleransen för traditionella LTE är 144 dBm, vilket ger en skillnad i tolerns på 20 dBm.

Säkerhet för simpla enheter, såsom sensorer, är svårt att uppnå och en stor del av säkerheten sköts av nätverket. Varje enhet har en integrerad identifierare (International Mobile Equipment Identity (IMEI)) som appliceras vid tillverkning. Dessutom används ett SIM kort med en egen identifierare (International Mobile Subscriber Identity (IMSI)) och med hjälp av en av dessa (eller båda) kan enheten verifieras under kommunikation. Nätverket flaggar enheten antingen som ”OK” (godkänd) eller ”KO” (icke godkänd). Utöver IMEI och IMSI implementerar NB-IoT och eMTC en identifierare (Temporary Mobile Subscriber Identity (TMSI)) för att hantera integritetsskydd. Denna identifierare är bunden till en geografisk plats och måste uppdateras ifall enheten flyttas. För att säkerställa konfidentialitet av information använder NB-IoT och eMTC sig av olika typer av algoritmer baserade på EPS krypteringsalgoritmer.

Som nämndes, använder sig NB-IoT och eMTC av samma infrastruktur som LTE. Det finns tre sätt att distribuera NB-IoT. Antingen använder man de yttersta blocken av en LTE ram eller ett oanvänt block innanför ramen. Utöver LTE infrastrukturen kan NB-IoT använda sig av Global System for Mobile Communications (GSM) nätverket och även då används ett av de oanvända blocken innanför ramen. Det finns bara en möjlighet för eMTC, och det är att distribuera nätverket som en del av LTE där eMTC använder sig av sex stycken oanvända block innanför LTE ramen. Både NB-IoT och eMTC introducerar nya kanaler och signaler som måste användas i bägge teknikerna för att uppnå kraven för nätverket. Största skillnaden mellan dessa två tekniker är deras fysiska lager. Tekniken eMTC ärver största delen av LTE nätverkets specifikationer medan NB-IoT kräver stora förändringar.

Experimentets miljö

Mätningarna utförs på två stycken moduler, av två olika tillverkare, på två olika teleoperatörers nätverk (OperatorA och OperatorB). Både NB-IoT och eMTC testas, men på grund av att det handlar om testnätverk som fortfarande utvecklas, stöds inte alla lågenergi lägen på alla nätverk. Utöver detta har endast OperatorA stöd för eMTC. I tabellen nedan är en sammanfattning av lägen som stöds av nätverken.

	OperatorA NB-IoT	OperatorB NB-IoT	OperatorA eMTC
PSM	Ja	Ja	Ja
eDRX	Ja	Nej	Nej

Strömsparläge kommer att testas på alla nätverk medan förlängd diskontinuerlig mottagning endast på OperatorA NB-IoT nätverk.

Modulerna under test är mangOH Red som är tillverkad av Sierra Wireless samt BG96 som är tillverkad av Quectel. Förutom att båda stöder både NB-IoT och eMTC har de även stöd av flera frekvenser. OperatorA fungerar på LTE Band3 (1800 MHz) och OperatorB på LTE Band20 (800 MHz). Den största skillnaden mellan dessa två moduler är att mangOH Red har en integrerad programsprocessor på vilken man direkt kan köra olika program. På grund av detta är mätningarna gjorda för den modulen inte isolerade endast till modemet utan energikonsumtionen är för hela modulen. Programprocessorn gör att den även har ett eget lågenergi läge vilket kommer att jämföras med strömsparläget och förlängd diskontinuerlig mottagning. För BG96 mäts energikonsumtionen direkt från modemet och vi får då ett mer exakt resultat med tanke på NB-IoT och eMTC och det resultatet kommer i slutet att användas för att beräkna livslängden för ett 5 wattimmars batteri. Modulerna styrs med så kallade AT kommandon och med hjälp av dem kan vi ange vilket energisparläge modulen ska använda.

Själva mätningen av energiförbrukningen görs med hjälp av en Keithley 2306 som simulerar en strömkälla. Med den kan önskad spänning appliceras och samtidigt kan man mäta elströmmen. Simulatorn styrs av ett Python program som körs via datorn och resultatet sparas som en excel fil och illustreras i en graf. Programmet hittas i Appendix A.

Resultat

Resultaten för mangOH Red modulen är överraskande. Då tillverkaren av modulen lyckades åstadkomma ett läge där elströmmen var så låg som 7 μA var det lägsta i vårt test ungefär 473 μA. Detta beror förmodligen på fel i konfigurationen av modulen under testet eller problem med den fasta programvaran. Det motsvarande resultatet under strömsparläget var 530 μA, också mycket högre än det som förväntades. Då man jämför detta med resultatet av BG96, där den mätta strömmen under strömsparläget var 10 μA, kan man dra slutsatsen att något inte var korrekt under testet. Oavsett kan resultaten jämföras sinsemellan, och vi ser att energiförbrukningen är lite högre under strömsparläget jämfört med modulens egna lågenergi läge. Orsaken till detta är möjligtvis att under strömsparläget är modulen ännu ansluten till nätverket, medan i modulens lågenergi läge stänger den alla anslutningar.

Resultaten för BG96 ger en klarare bild över den egentliga energiförbrukningen med NB-IoT och eMTC. Under strömsparläget uppnåddes en elström på ungefär 10 μA för både NB-IoT och eMTC, men intressant är att energiförbrukningen för OperatorB var nästan hälften av OperatorA under normal användning (inget lågenergi läge). Orsaken till detta är okänd på grund av att nätverkens konfiguration också är okänd, men det är värt att göra mer undersökningar ifall frekvensen på nätverket kan ha en så stor inverkan på förbrukningen.

På basis av resultaten från BG96 testerna kan vi räkna ut livstiden för ett 5 wattimmars batteri. Tiden modulen var i strömsparläget var den enda variabeln i dessa uträkningar. Skillnaden mellan OperatorA och OperatorB med NB-IoT var signifikant. För OperatorA var livstiden 4677 dagar då modulen vaknade från strömsparläget en gång i månaden, för OperatorB var motsvarande resultat 4752 dagar. Vid användning av eMTC minskade detta resultat drastiskt till 3496 dagar.

Livstiden för ett likadant batteri då man använder sig av förlängd diskontinuerlig mottagning minskade ännu mer. Det som är intressant att lägga märke till är att resultatet inte ändras nämnvärt beroende på tidsperioden mellan aktiva skeden (då modulen skickar data). Då denna tidsperiod var 4.5 timmar var livslängden av batteriet 79.85 timmar, medan då tidsperioden ökades till 91 timmar ökades livslängden endast till 79.98 timmar.

Slutsats

Denna undersökning samt utförda experiment kan endast användas som en riktgivande grund för vidare forskning, eftersom testerna utfördes på testnätverk vilka vid testtillfället inte var färdiga för kommersiell användning. Det rekommenderas att ha tillgång till nätverkets konfiguration eller stöd av teleoperatörer vid fortsatt forskning, eftersom fler oklarheter som förekom i dessa experiment beror på att konfigurationerna var okända. Utöver detta sändes ingen data under aktivt läge och endast en modul var i användning under experiment, vilket kan ha en stor inverkan på energiförbrukningen. Det behövs fler experiment förrän det är klart hur mycket energiförbrukningen ökar med mängden data som sänds, och om mängden moduler har någon inverkan på nätverket.

Det finns ännu oklarheter angående vilken teknik som kommer att användas i framtiden, och hur nätverkena kommer att fungera då tiotusentals enheter samtidigt är i bruk. Mer forskning på verkliga nätverk med andra enheter rekommenderas före exakta slutsatser angående strömförbrukningen kan dras.

Appendices

APPENDIX A

Code for Keithley 2306 measurements

```
#Code for reading and saving current values from
#Keithley 2306 using GPIB–USB–HS cable.


import visa
import time
import matplotlib.pyplot as plt
import xlsxwriter

#Init Keithley 2306 simulator and set reading to Current
rm = visa.ResourceManager()
rm.list_resources()
keithley = rm.open_resource('GPIB0::16::INSTR')
keithley.write("SENS2:AVER 10")
keithley.write("SENS2:FUNC 'CURR'")
#Init writing to excel
book = xlsxwriter.Workbook("excel_file_name")
results = book.add_worksheet()
#Init values
```

```
x=0
curr = []
flist = []
time_tot = []
#Timeout on how long program should do polling
timeout = time.time() + 60*10

t0 = time.time()
while True:
        curr.append(keithley.query('READ2:ARR?').strip())
        ftlist += list(map(float, (curr[x].split(”,”))))
        x += 1
        for _ in range(10):
                time_tot.append(time.time()-t0)
        if time.time() >= timeout:
                break
y=0
while y<len(flist):
        results.write(y, 0, flist[y])
        results.write(y, 1, time_tot[y])
        y += 1
avg_current = sum(flist)/float(len(flist))
book.close()
plt.axhline(y=avg_current, color='red')
plt.plot(time_tot, flist)
plt.ylabel('Current (A)')
plt.xlabel('Time (s)')
plt.show()
```

APPENDIX B

BG96 PSM two-hour tests

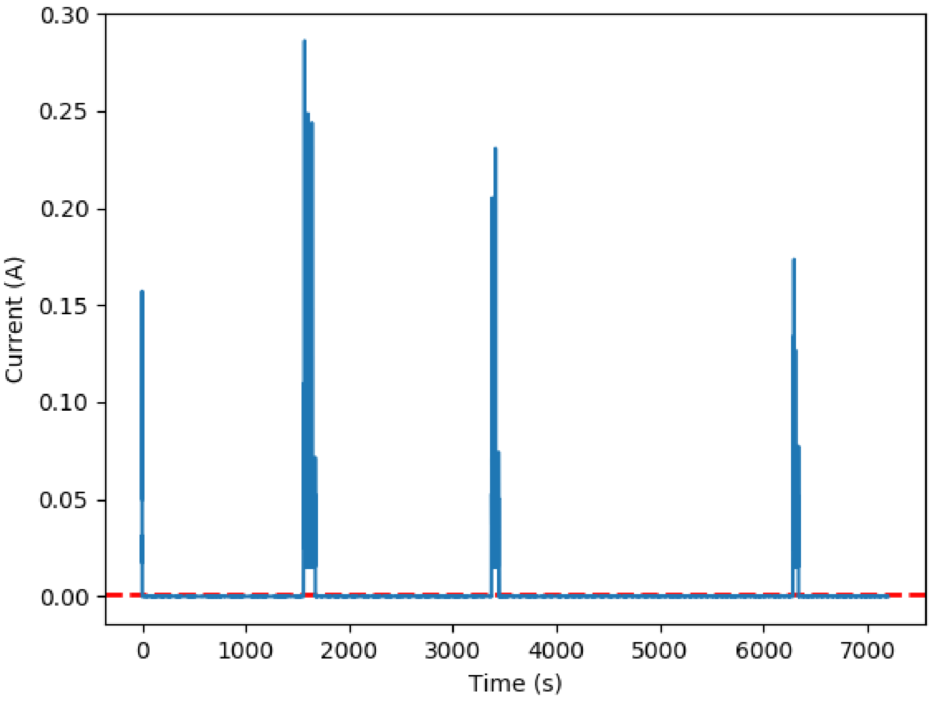


Figure B.0.1: NB-IoT PSM two-hour test (OperatorA)

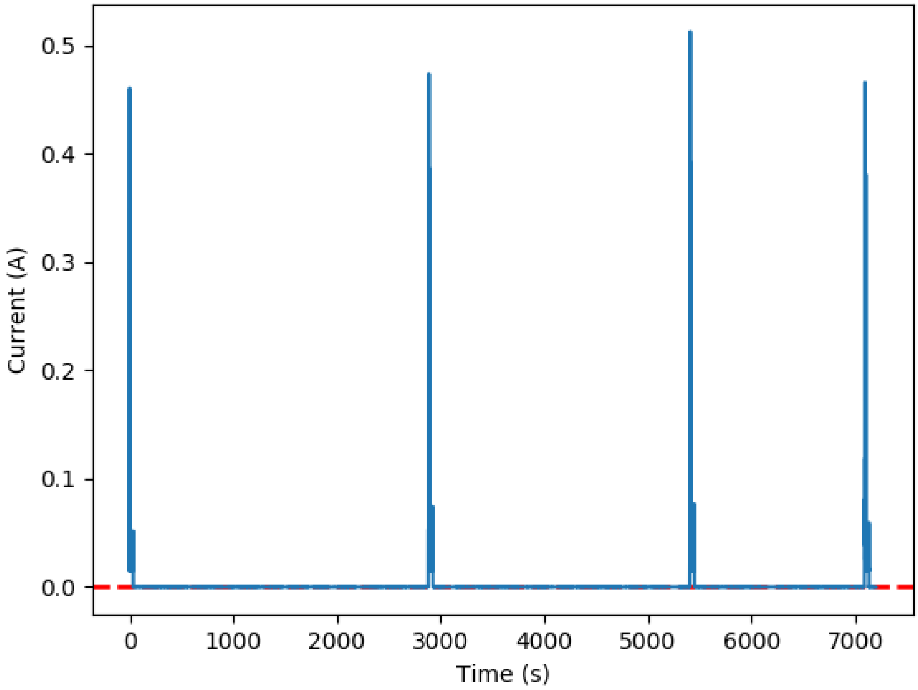


Figure B.0.2: NB-IoT PSM two-hour test (OperatorB)

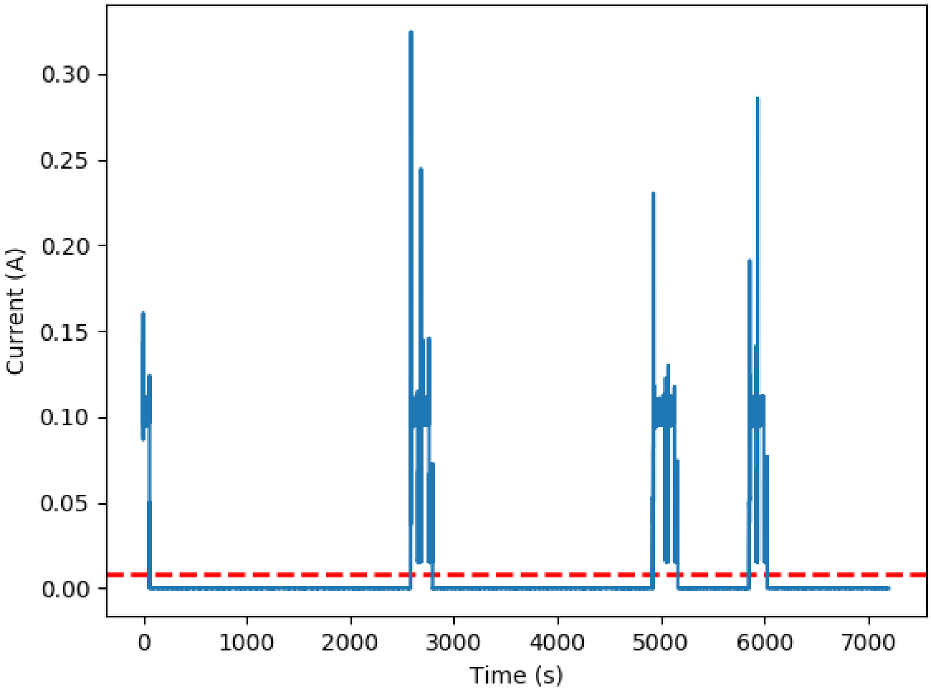
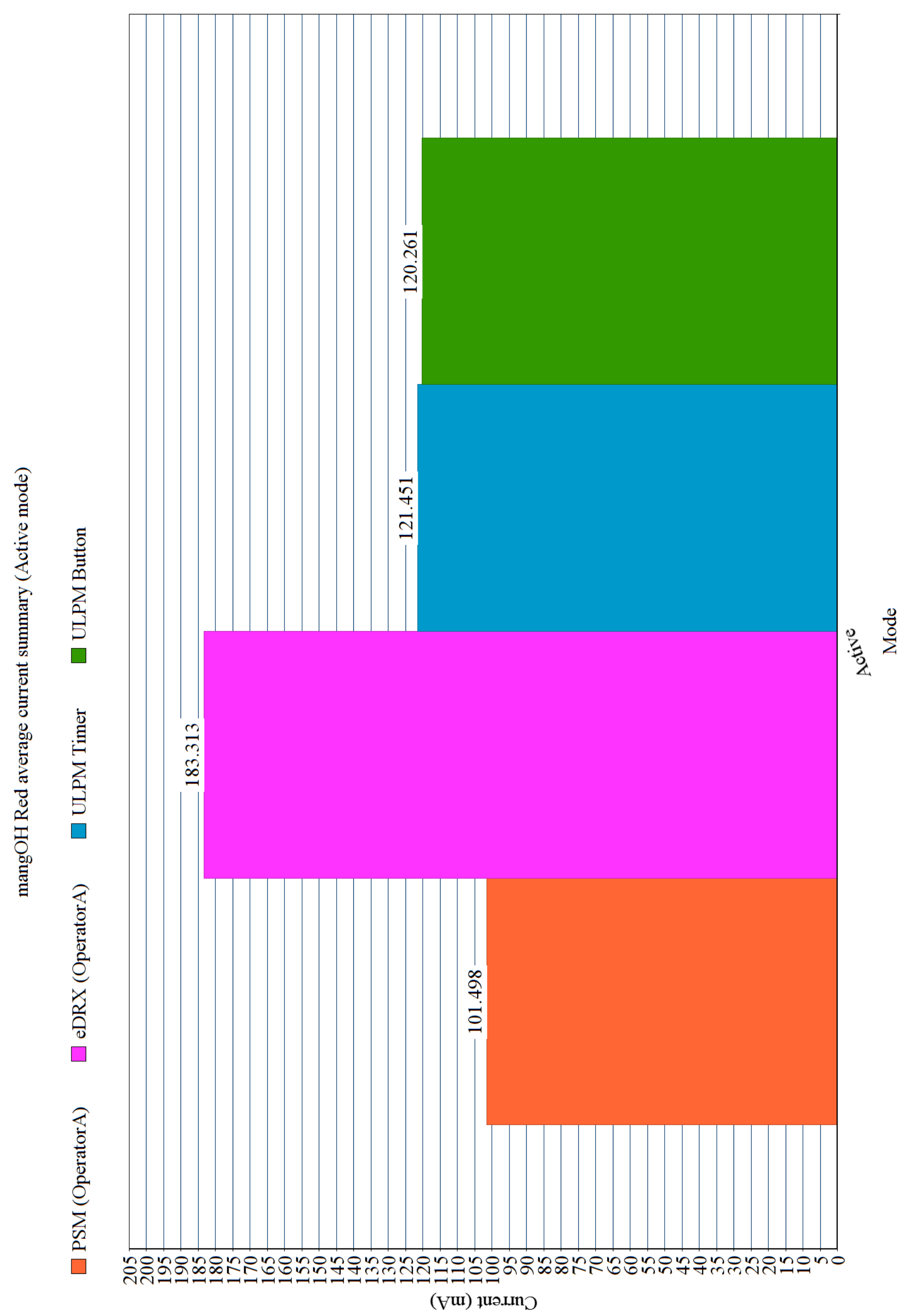
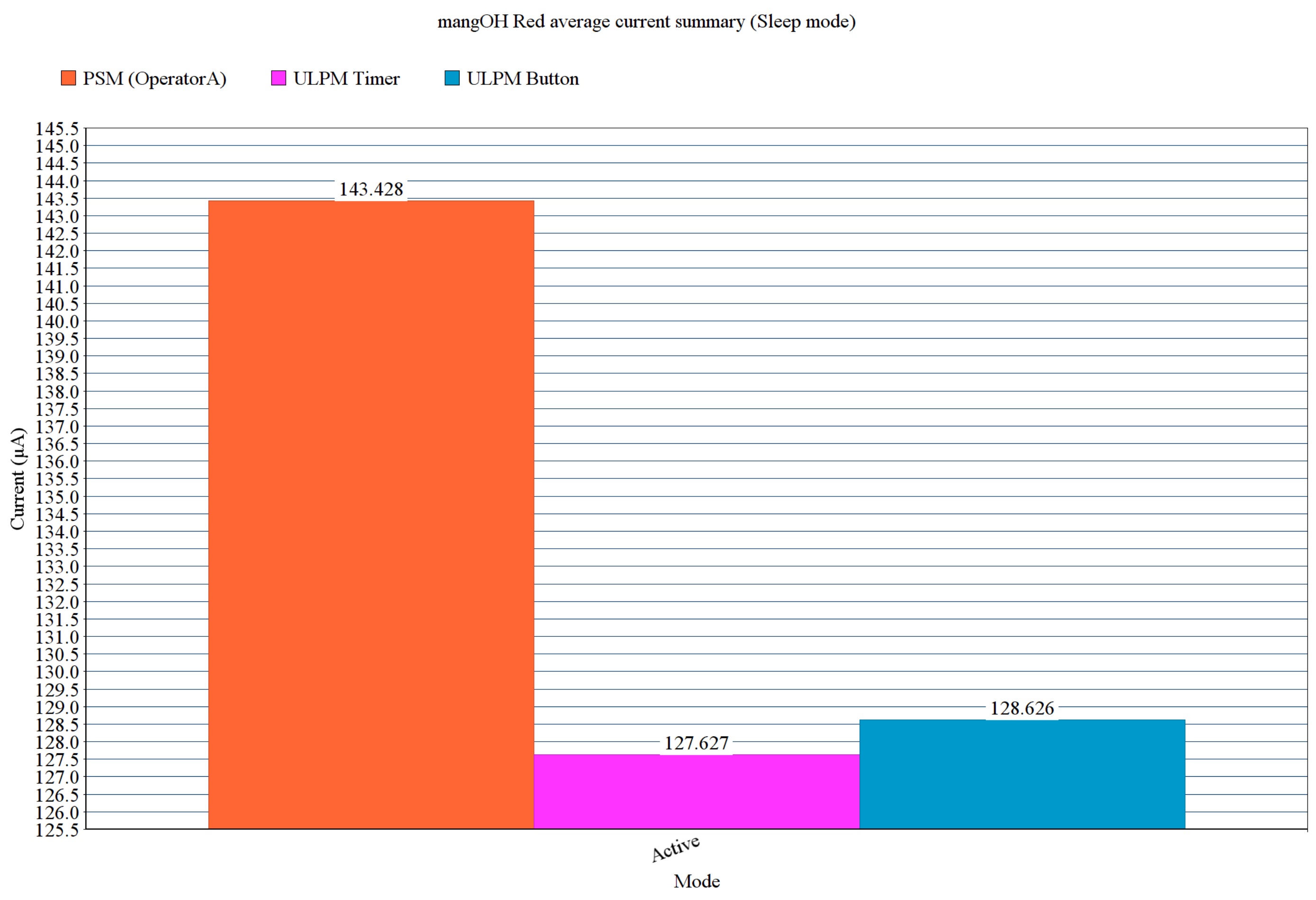


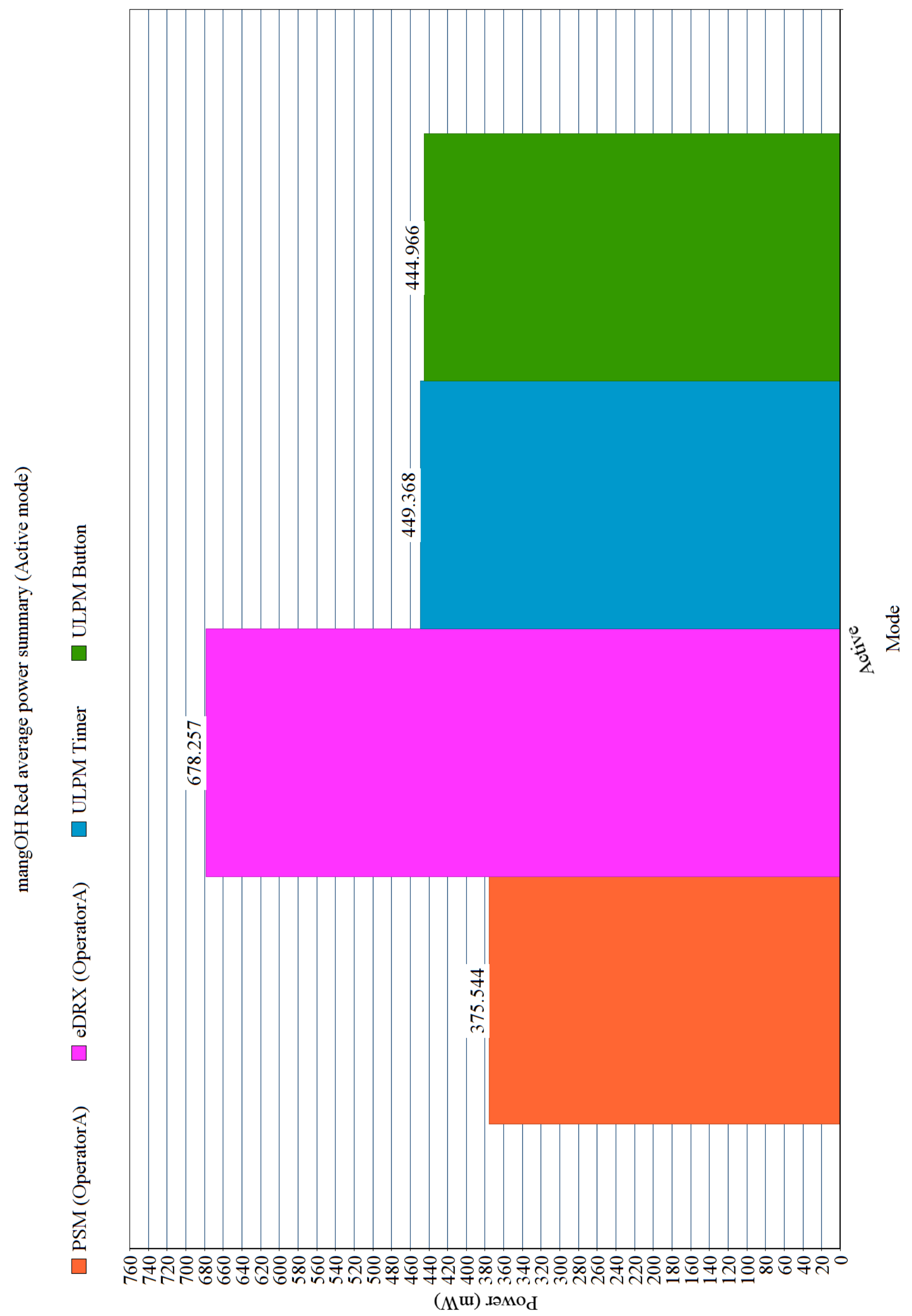
Figure B.0.3: eMTC PSM two-hour test (OperatorA)

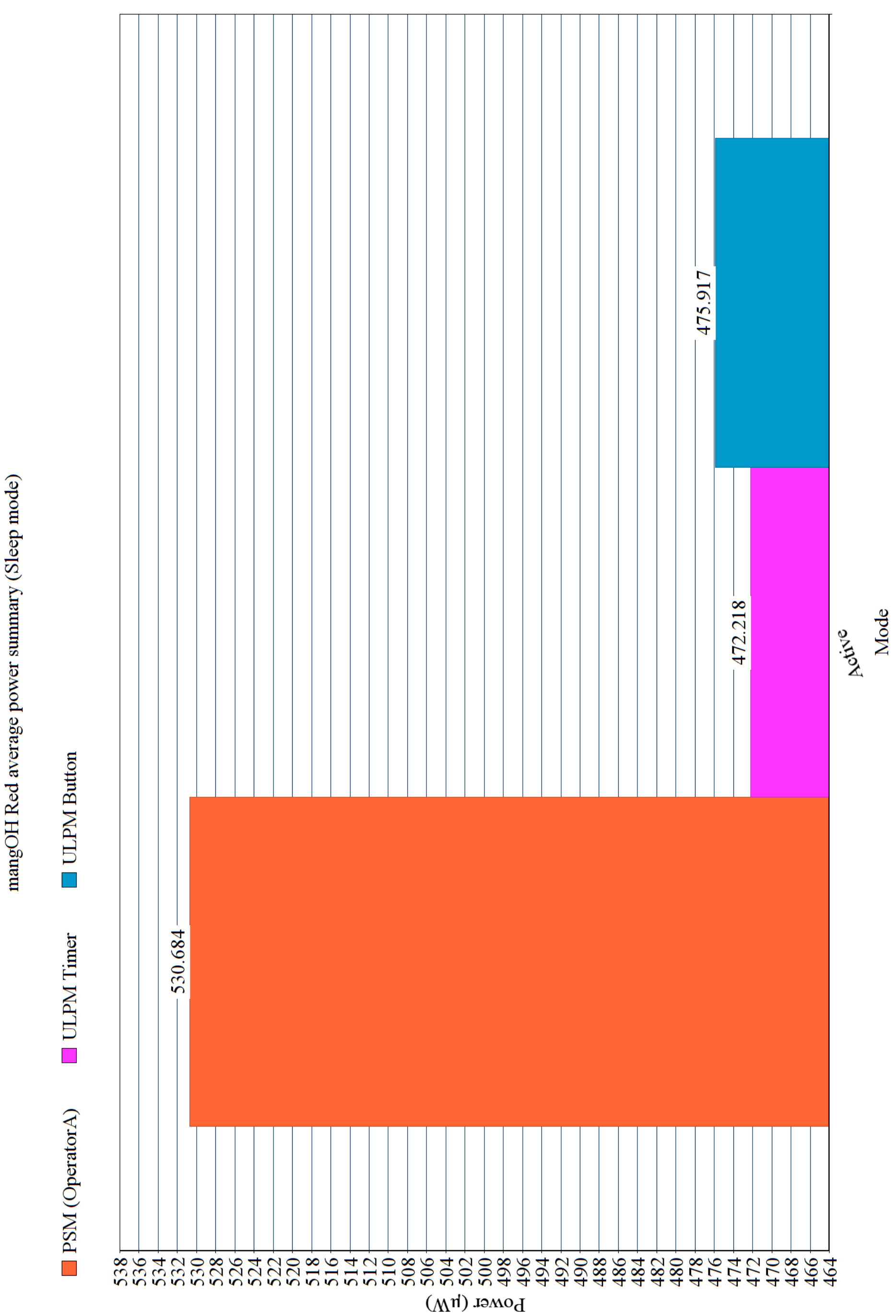
APPENDIX C

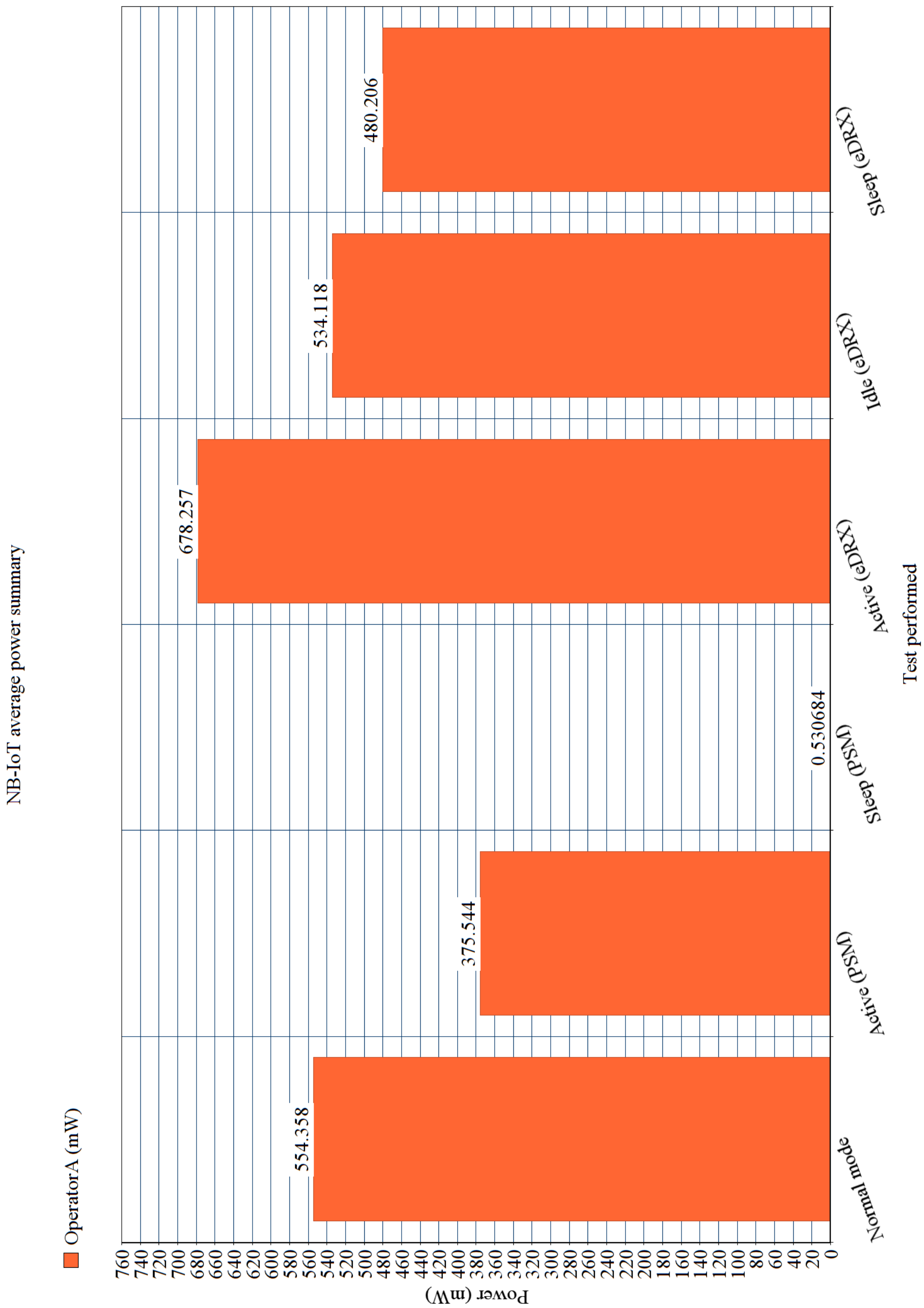
Average measurement readings for mangOH Red


mangOH Red average current summary (Active mode)
PSM (OperatorA)
eDRX (OperatorA)
ULPM Timer
ULPM Button
Current (mA)
205
200
195
190
185
180
175
170
165
160
155
150
145
140
135
130
125
120
115
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
101.498
183.313
121.451
120.261
Active
Mode

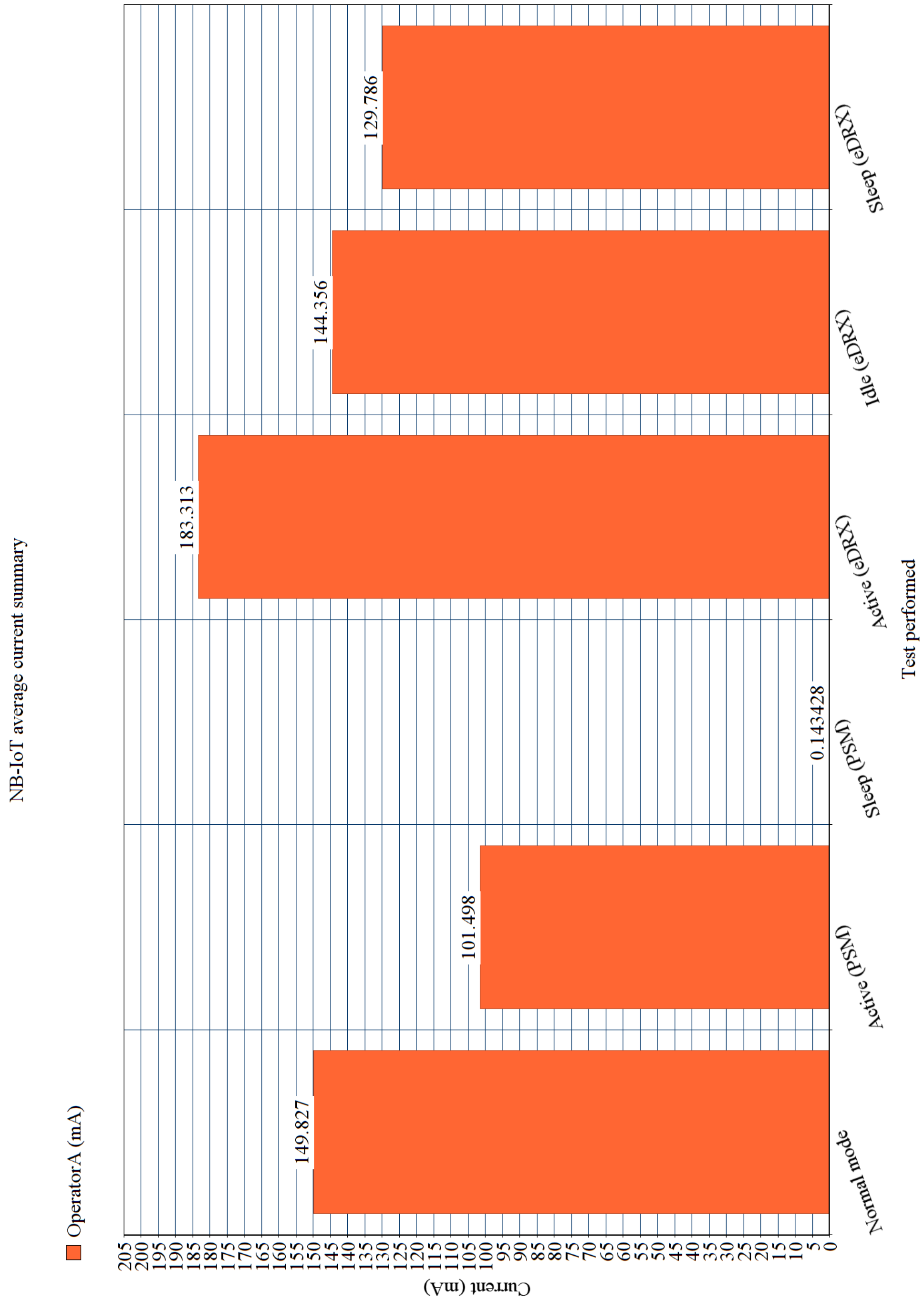

mangOH Red average current summary (Sleep mode)
PSM (OperatorA)
ULPM Timer
ULPM Button
Current (µA)
145.5
145.0
144.5
144.0
143.5
143.0
142.5
142.0
141.5
141.0
140.5
140.0
139.5
139.0
138.5
138.0
137.5
137.0
136.5
136.0
135.5
135.0
134.5
134.0
133.5
133.0
132.5
132.0
131.5
131.0
130.5
130.0
129.5
129.0
128.5
128.0
127.5
127.0
126.5
126.0
125.5
143.428
127.627
128.626
Active
Mode


mangOH Red average power summary (Active mode)
PSM (OperatorA)
eDRX (OperatorA)
ULPM Timer
ULPM Button
Power (mW)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
520
540
560
580
600
620
640
660
680
700
720
740
760
375.544
678.257
449.368
444.966
Active
Mode


mangOH Red average power summary (Sleep mode)
PSM (OperatorA)
ULPM Timer
ULPM Button
Power (µW)
538
536
534
532
530
528
526
524
522
520
518
516
514
512
510
508
506
504
502
500
498
496
494
492
490
488
486
484
482
480
478
476
474
472
470
468
466
464
530.684
472.218
475.917
Active
Mode

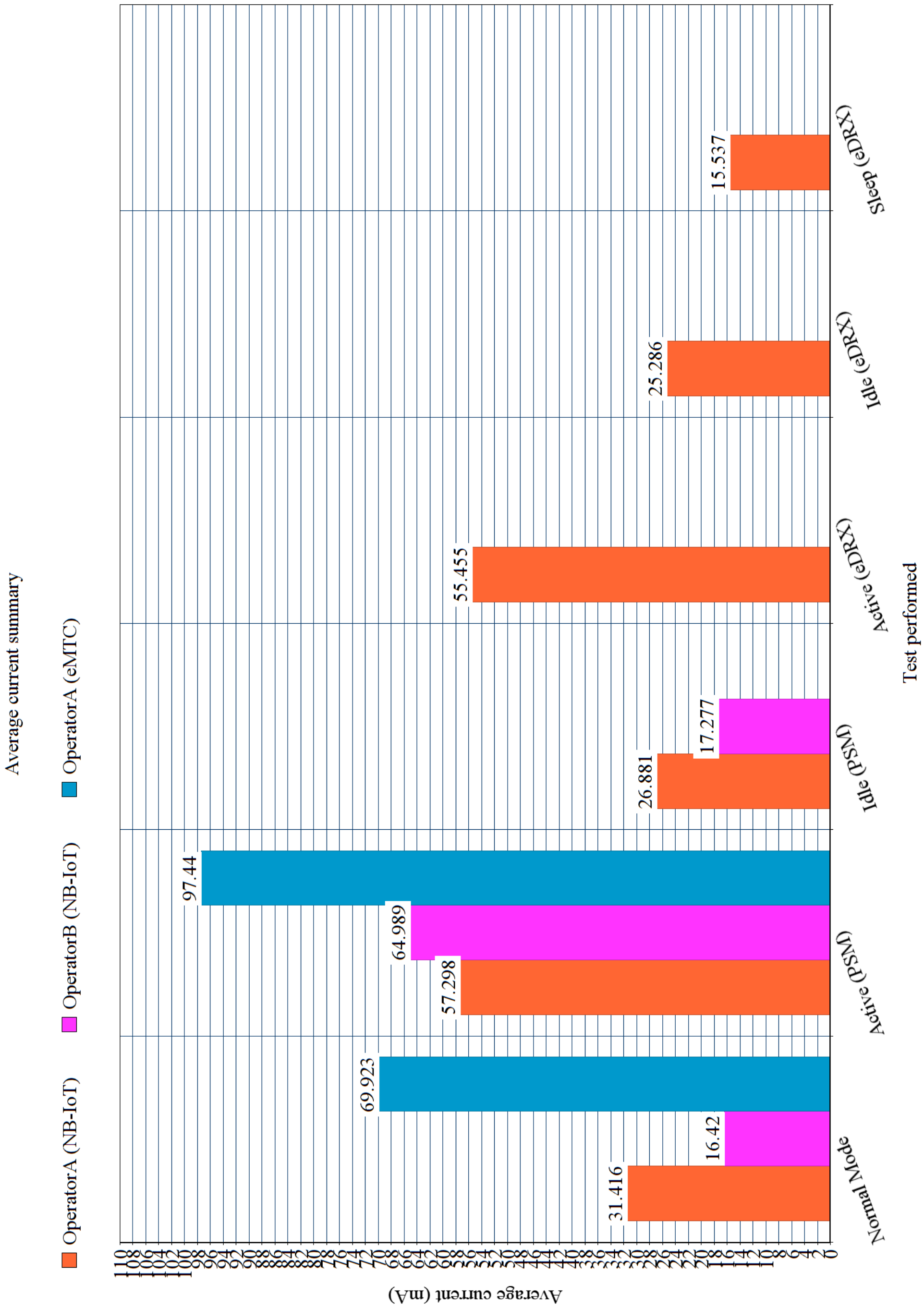


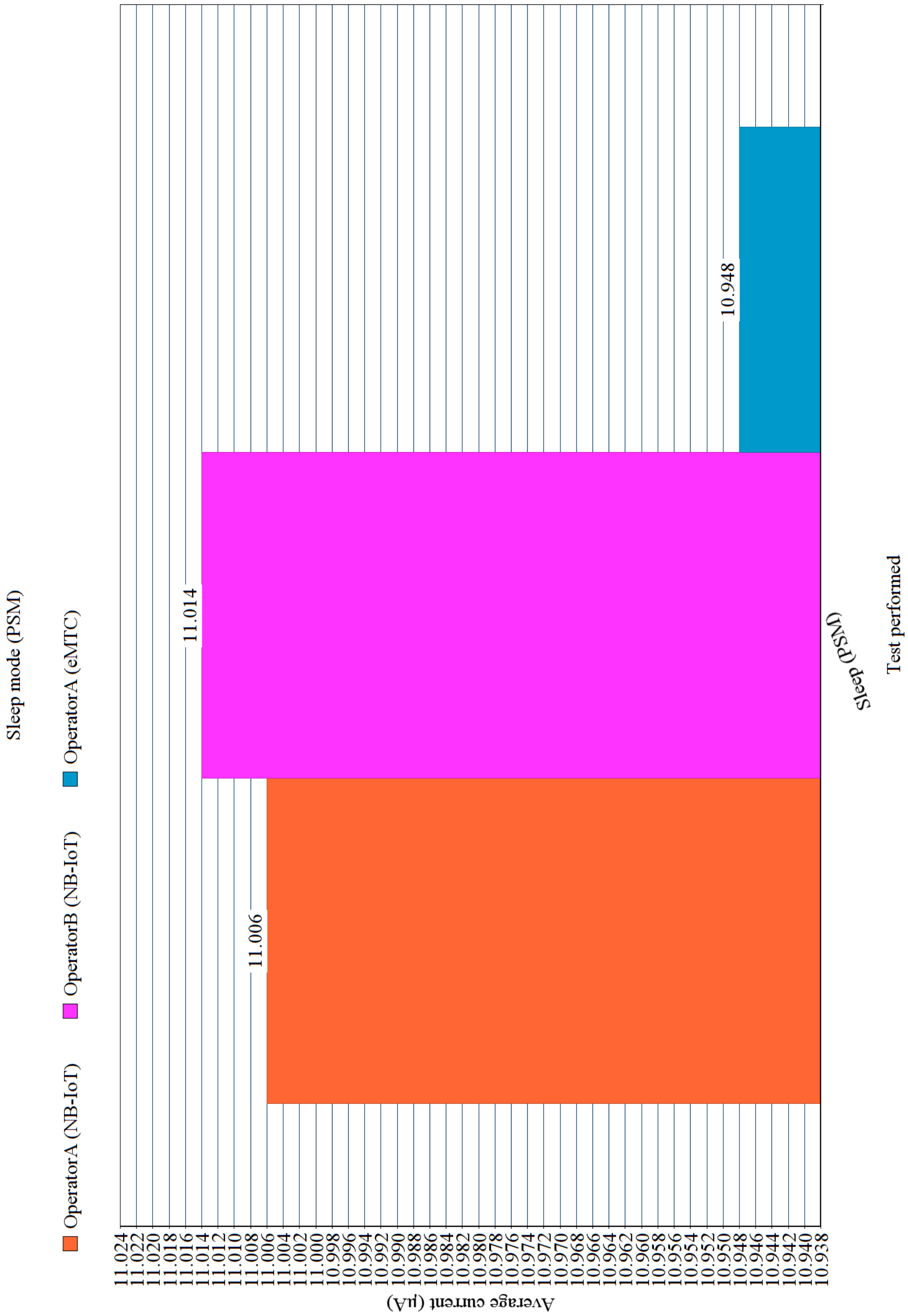
NB-IoT average power summary
🟥 OperatorA (mW)
Power (mW)
760
740
720
700
680
660
640
620
600
580
560
540
520
500
480
460
440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
554.358
375.544
0.530684
678.257
534.118
480.206
Normal mode
Active (PSM)
Sleep (PSM)
Active (eDRX)
Idle (eDRX)
Sleep (eDRX)
Test performed

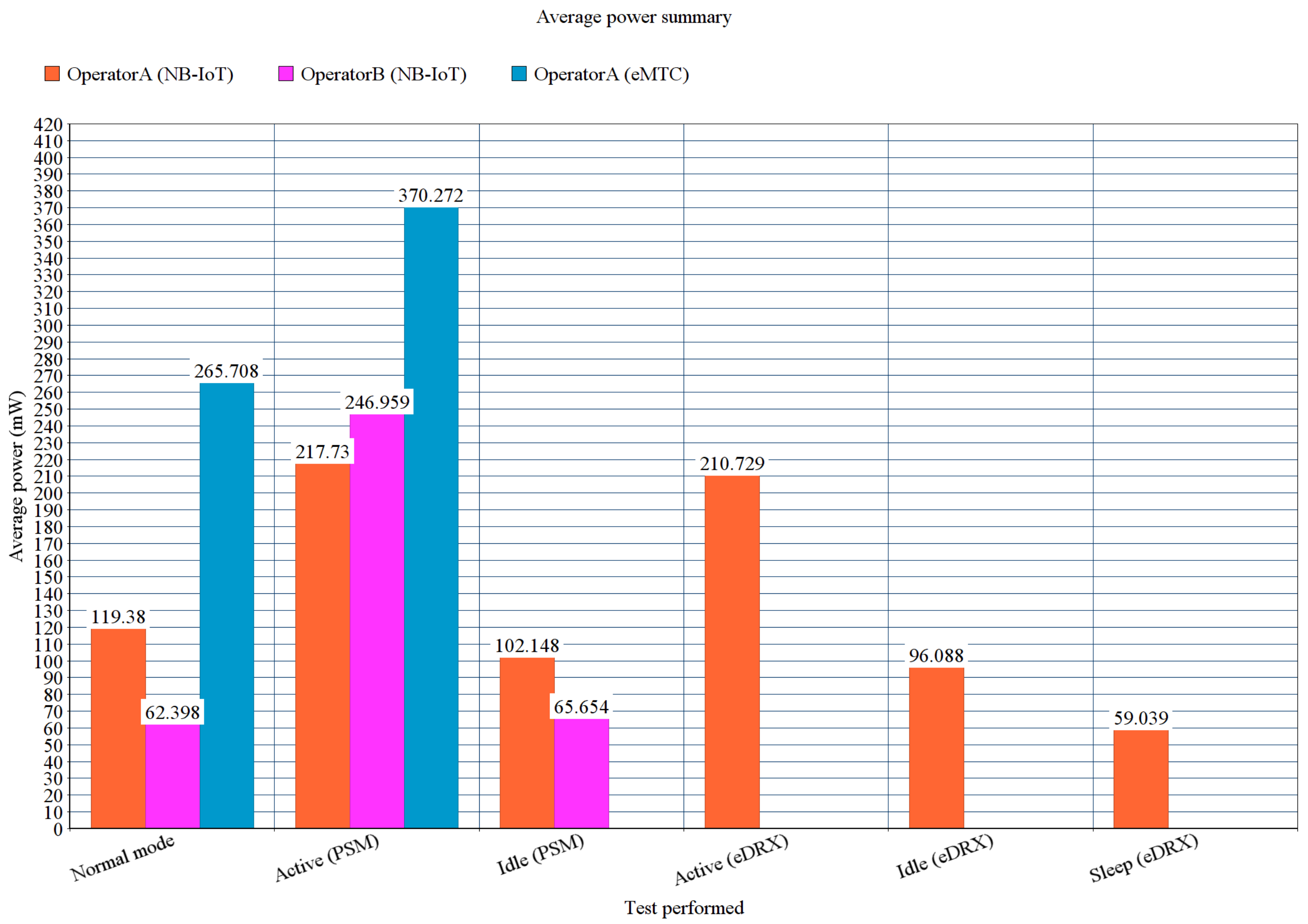

NB-IoT average current summary
OperatorA (mA)
Current (mA)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
155
160
165
170
175
180
185
190
195
200
205
Normal mode
149.827
Active (PSM)
101.498
Sleep (PSM)
0.143428
Active (eDRX)
183.313
Idle (eDRX)
144.356
Sleep (eDRX)
129.786
Test performed

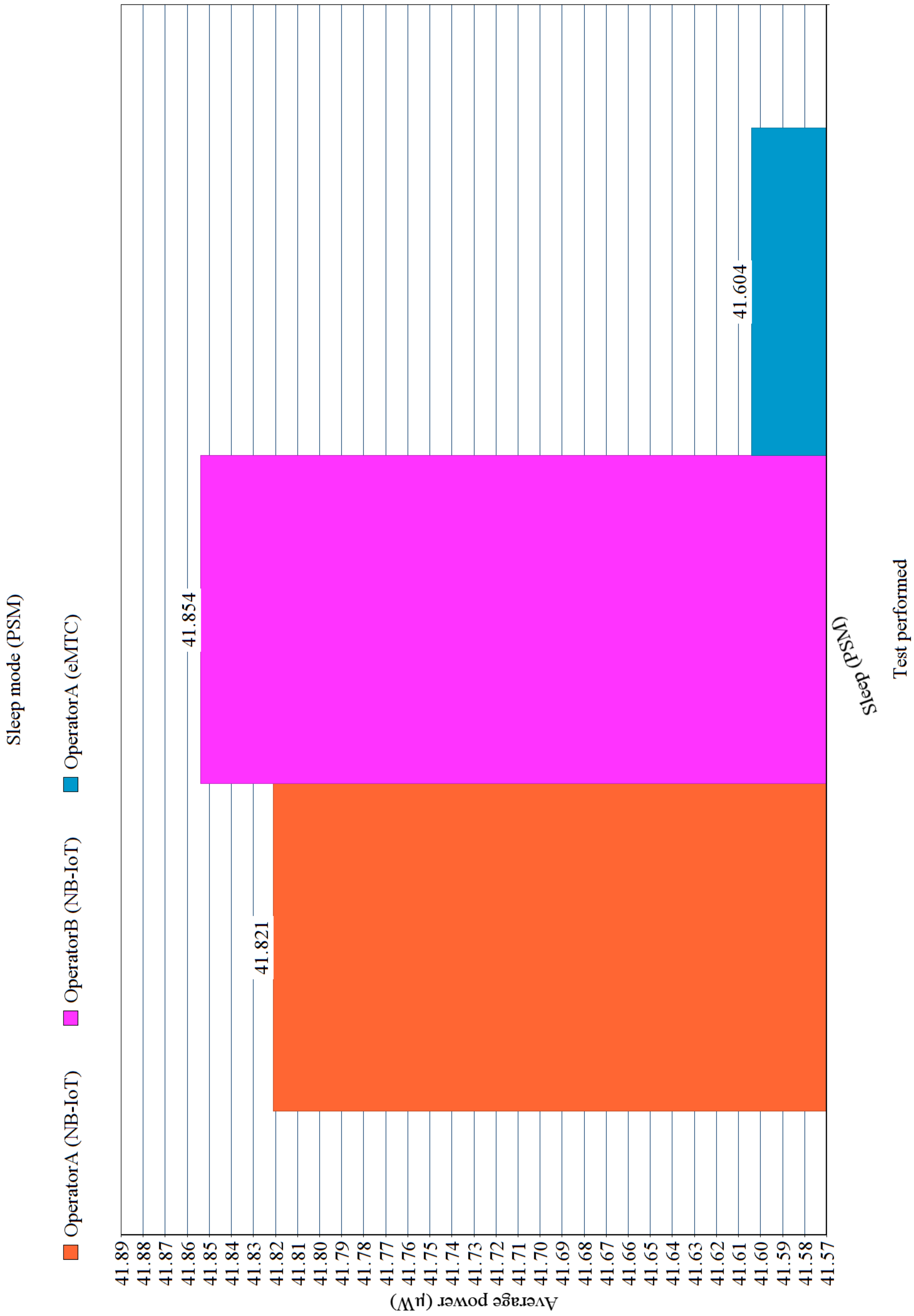
APPENDIX D

Average measurement readings for BG96


Average current summary
OperatorA (NB-IoT)
OperatorB (NB-IoT)
OperatorA (eMTC)
Average current (mA)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 100 102 104 106 108 110
Test performed
Normal Mode
31.416
16.42
69.923
Active (PSM)
57.298
64.989
97.44
Idle (PSM)
26.881
17.277
Active (eDRX)
55.455
Idle (eDRX)
25.286
Sleep (eDRX)
15.537


Sleep mode (PSM)
OperatorA (NB-IoT)
OperatorB (NB-IoT)
OperatorA (eMTC)
11.006
11.014
10.948
Average current (μA)
11.024
11.022
11.020
11.018
11.016
11.014
11.012
11.010
11.008
11.006
11.004
11.002
11.000
10.998
10.996
10.994
10.992
10.990
10.988
10.986
10.984
10.982
10.980
10.978
10.976
10.974
10.972
10.970
10.968
10.966
10.964
10.962
10.960
10.958
10.956
10.954
10.952
10.950
10.948
10.946
10.944
10.942
10.940
10.938
Sleep (PSM)
Test performed


Average power summary
OperatorA (NB-IoT)
OperatorB (NB-IoT)
OperatorA (eMTC)
Average power (mW)
420
410
400
390
380
370
360
350
340
330
320
310
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
119.38
62.398
265.708
217.73
246.959
370.272
102.148
65.654
210.729
96.088
59.039
Normal mode
Active (PSM)
Idle (PSM)
Active (eDRX)
Idle (eDRX)
Sleep (eDRX)
Test performed


Sleep mode (PSM)
OperatorA (NB-IoT)
OperatorB (NB-IoT)
OperatorA (eMTC)
41.821
41.854
41.604
Average power (μW)
41.89
41.88
41.87
41.86
41.85
41.84
41.83
41.82
41.81
41.80
41.79
41.78
41.77
41.76
41.75
41.74
41.73
41.72
41.71
41.70
41.69
41.68
41.67
41.66
41.65
41.64
41.63
41.62
41.61
41.60
41.59
41.58
41.57
Sleep (PSM)
Test performed