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NARROWBAND-IOT POWER SAVING MODES –

A COMPREHENSIVE STUDY

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Florian Gabelle
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ABSTRACT

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Exploring alternatives to LoRa for their liquid quality monitoring sensor, UROS started investigating narrowband technology. Regardless of the radio technology in use in the sensor, UROS wants to guarantee a specific battery runtime to the users of the device. The objectives of this thesis were to demonstrate how narrowband Internet of Things power saving features affect power consumption and provide guidelines on how to use them properly as well as measurement data to calculate runtime estimations. The work was commissioned by UROS.

All narrowband Internet of Things power saving features have been extensively tested using a Nordic Semiconductor nRF9160 development kit connected to the Finnish mobile network Elisa. Power consumption was recorded using a Qoitech Otii Arc power analyser.

A comprehensive analysis was performed to measure and document the effect of payload size, release assistance indicator, extended discontinuous reception cycle length, paging time window, tracking area update and power saving mode active time on power consumption.

Keywords: Narrowband IoT, Power saving features, Extended discontinuous reception, Power saving mode, Release assistance indicator, Nordic Semiconductor nRF9160

CONTENTS

VOCABULARY

BS	Base station
DUT	Device under test. In this document, DUT refers to the nRF9160 development kit in the context of power measurement.
DRX	Discontinuous reception
eDRX	Extended discontinuous reception
IoT	Internet of Things
LTE	Long-term evolution, sometimes referred as 4G.
MNO	Mobile network operator
NB	Narrowband
NB-IoT	Also known as Cat-NB, Narrowband Internet of Things is a radio technology standard allowing Internet of Things devices to operate on cellular networks. It first appeared in 3GPP Release 13.
PSM	Power saving mode
PTW	Paging time window
RAI	Release assistance indicator
RRC	Radio release control is a network layer protocol used on the Air interface between user equipment and base station.
RSRP	Reference signal received power
SiP	System-in-package
TAU	Tracking area update
UE	User equipment. In this document, UE refers to the nRF9160 development kit in the context of network connectivity.

1 INTRODUCTION

Founded in 2011 and headquartered in Oulu, UROS focuses on global connectivity and turnkey Internet of Things (IoT) solutions. UROS Sense, a key product of the company, provides customers with a liquid quality sensor allowing real-time remote monitoring for natural resources and industrial processes. The second generation of this sensor, which uses the LoRa radio technology, was reaching its final stages of development when this research work was initiated.

As an alternative to LoRa could be necessary in some regions, UROS wanted to investigate other wireless technologies, among which narrowband Internet of Things. Prior to performing the research presented in this thesis, several narrowband modems had been tested. Their power consumption was too high to meet a specific battery lifetime requirement or they did not work reliably. The purpose of this study was to perform a comprehensive analysis on how power saving features impact the power consumption of narrowband modems, provide data for battery runtime estimations as well as insights learned during this research work.

The Nordic Semiconductor nRF9160 system-in-package was selected for this study. Firmware was developed using the Zephyr real-time operating system and Nordic Semiconductor nRF Connect SDK. The current profile of the device and its associated energy consumption were recorded using a Qoitech Otii Arc power analyser. Recordings were performed while the device was connected to the Finnish operator Elisa narrowband Internet of Things (NB-IoT) network. All power saving related network parameters were tested and their effect on power consumption was evaluated.

2 THEORETICAL FOUNDATION

The purpose of this chapter is to introduce essential information about the topics inherent to the research performed during this thesis work. This presentation is kept at a high level and is not meant to expand on the technicalities of each introduced technology.

2.1 Narrowband Internet of Things

2.1.1 General description

Narrowband Internet of Things is a Long-Term Evolution (LTE) variety of low-power wide-area network (LPWAN), the purpose of which is to address “the IoT device requirements for low cost, low power, sparse transmission, and range extensions”. (1.) NB-IoT provides an alternative to traditional LPWAN technologies, such as LoRa or Sigfox, which is directly compatible with the cellular infrastructure.

Due to its characteristics, NB-IoT offers a wide coverage and deep signal penetration, allowing for previously unfeasible applications, such as indoor or underground. Modules making use of this technology have a low power consumption and are generally expected to work over ten years on battery. (2, p. 73.)

NB-IoT can be deployed according to three different models as shown in figure 1, either as standalone in which there is no cover with the LTE band, as guard-band using the edge band frequency or in-band within the LTE frequency band.

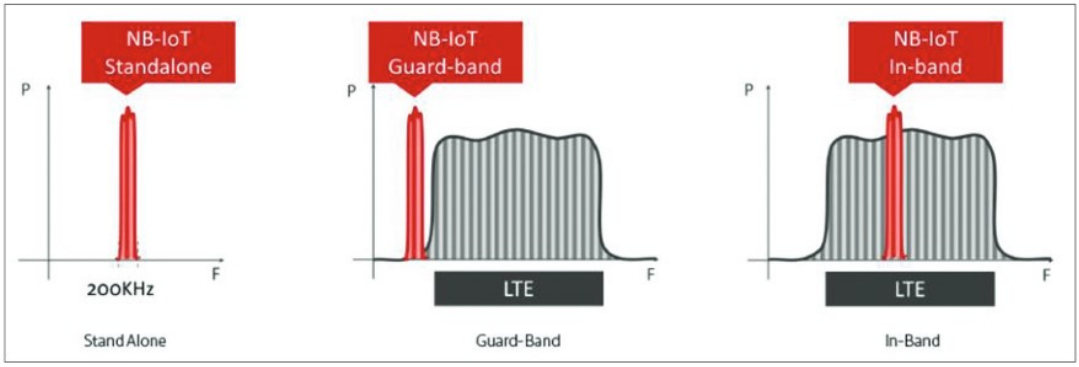

FIGURE 1. Deployments supported by NB-IoT (2, p. 76)

As its name implies, NB-IoT makes use of a narrow channel bandwidth at 180 kHz. Taking the previous example of in-band deployment, given the wide spectrum of the LTE bands, deployments of up to 200,000 devices per cell should theoretically be possible (1).

It should be noted that NB-IoT does not allow for mobility of the device as of Release 13. Once a device has been associated with a cell, it cannot transfer seamlessly to another one according to the process called handover. Moreover, NB-IoT is also missing the capacity for streams of data, such as voice or video. NB-IoT is therefore primarily targeted at stationary devices including connected sensors. (1.)

2.1.2 LTE power saving features for NB-IoT

A battery life of up to ten years can only be achieved thanks to power saving features present in the narrowband IoT standard. 3GPP Release 13 introduced several power saving features including power saving mode (PSM) and extended discontinuous reception (eDRX). Release 14 expanded on those features and added the release assistance indication (RAI). (3, p. 17.) Those three power saving features are independent from each other and can be used simultaneously.

Extended discontinuous reception

In order to save energy, cellular devices, such as smartphones, can momentarily switch off the receive section of the radio module for a fraction of second (3, p. 21) according to an LTE feature called discontinuous reception (DRX). During that time, the device cannot receive any data as it is not listening to the network.

In the case of NB-IoT devices, because they do not need to receive data often, extended discontinuous reception (eDRX) was introduced and allows for turning off the receive section of the radio module intermittently for greater lengths of time as illustrated in figure 2. Therefore, there is a trade-off between device reachability and energy consumption (4, p. 15). The duration of eDRX cycle length can vary from 5.12 seconds to as long as 10485.76 seconds and can be requested from the network upon attaching or routing area updating procedures (5, p. 157).

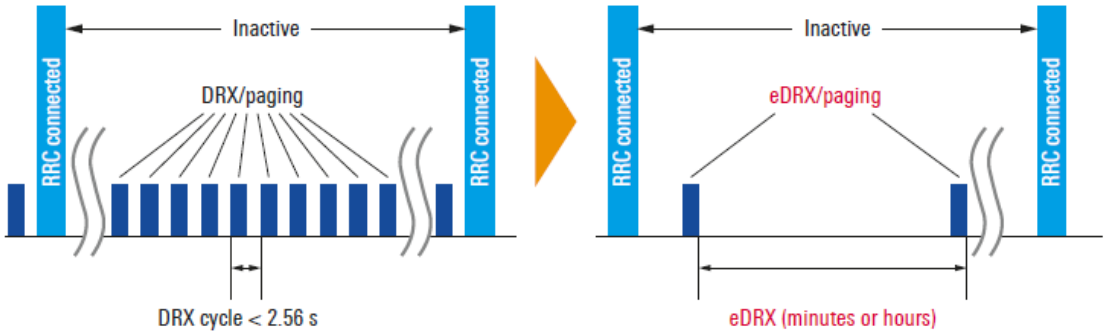

FIGURE 2. Comparison of DRX and eDRX (4, p. 15)

Power saving mode

Shutting down the NB radio module to save battery power is counter-productive because it involves reattaching to the network when it turns back on. The waste of energy caused by the reattach procedure would affect considerably the battery life of the device. Power saving mode (PSM) was designed to solve this issue. (3, p. 19.) When using PSM, the device enters a mode similar to power-off while remaining registered to the network.

Upon attaching to a base station or during routing area updating procedures, the device can request the use of power saving mode. According to 3GPP Release 16:

> *The network accepts the use of PSM by providing a specific value for timer T3324 when accepting the attach or routing area updating procedure. The MS may use PSM only if the network has provided the T3324 value IE during the last attach or routing area updating procedure with a value different from "deactivated". (5, p. 156.)*

When the device successfully attaches to the base station (BS) and its PSM request is accepted, the network provides two timers, T3324 and T3412. T3412 is the periodic tracking area update (TAU) timer. It defines how often the device must notify of its availability to the network. T3324 is the active timer which corresponds to how long the device must perform paging (listening for incoming data) before entering PSM. Consequently, PSM duration, which is illustrated in figure 3, is the difference between those two timers (3, p. 19).

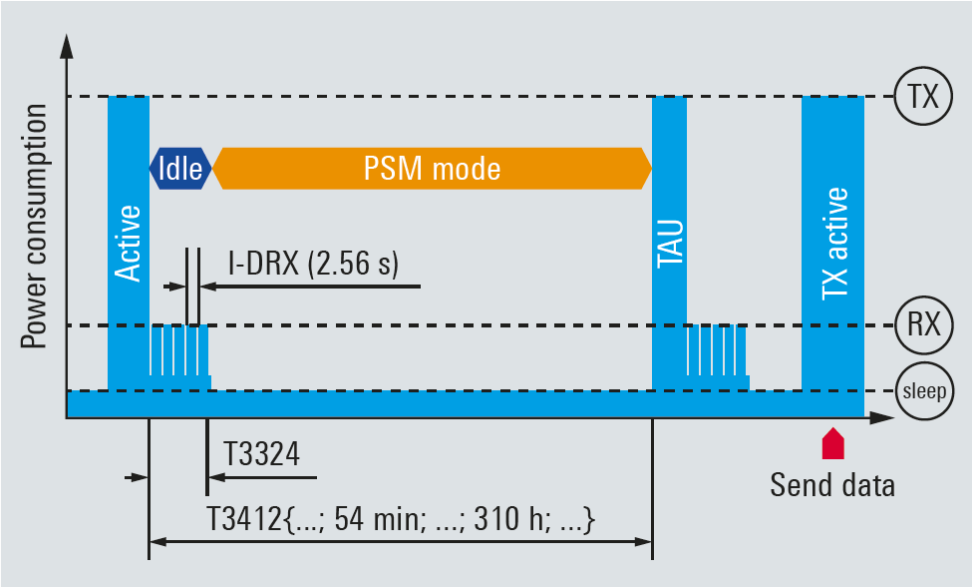

FIGURE 3. Principle of power saving mode (4, p. 20)

After waking up from PSM, the device can send data instantly without having to reattach to the network, hence saving the energy that would be spent searching for the network and performing an attach procedure. PSM is particularly suitable to devices that push data up to the network periodically (4, p. 21) without much downlink data transfers.

Release assistance indication

Release assistance indication (RAI) is the latest power saving feature introduced in 3GPP Release 14. Once the device is done transmitting data over the network, it can inform the network that it does not intend to send nor receive any more data. This allows for the connection to be released faster than if the device had had to wait for the network to release the connection on its own. (3, p. 36; 5, p. 22.)

2.2 Nordic Semiconductor nRF9160 system-in-package and nRF9160 development kit

For the purpose of this study, the Nordic Semiconductor nRF9160 was selected because of its advertised performance. The nRF9160 was also the latest LTE-M and NB-IoT modem to hit the market coming pre-certified for global operation (6, p. 1) as of 2020. It was expected to already be in a mature stage of development.

To simplify development and measuring tasks, the work was performed on an nRF9160 DK, which is the development kit for the nRF9160. It allows for flashing firmware and interfacing with the system-in-package (SiP) over the universal serial bus (USB).

2.2.1 Hardware

The nRF9160 is the smallest available cellular IoT chip on the market integrating an LTE-M/NB-IoT modem, an RF front end, a GPS module and power management as of 2020 (6, p. 1). Its architecture can be observed in figure 4. It features an Arm Cortex-M33 processor clocked at 64 MHz that supports Arm TrustZone and Arm Cryptocell, which are crucial to securing the client's intellectual property and wireless connections. On the memory side, there is 1 MB of flash and 256 KB allowing for complex applications to run on the module featuring full-fledged software stacks for various protocols, such as the LTE layers L1-L3, IPv4/IPv6, TCP/UDP and TLS/DTLS as well as the applications layers HTTP, CoAP, MQTT and LWM2M. (6, p. 2.)

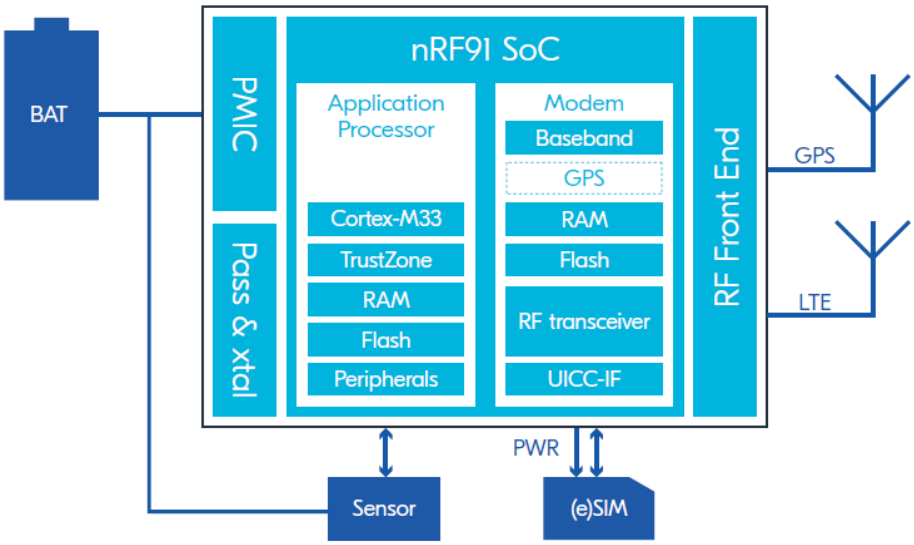

FIGURE 4. nRF9160 architecture (7, p. 2)

The nRF9160 DK includes both the nRF9160 SiP and the nRF52840 Bluetooth low energy (BLE) system on a chip which on top of providing basic Bluetooth functionalities serves as a controller for the nRF9160. Due to the dual technology present on this single board, prototyping Bluetooth gateways is possible.

In the context of this thesis work, one important feature present on this board is the connector P24 dedicated to measuring the current drawn by the nRF9160 as seen in figure 5. Moreover, there is a Segger J-Link on-board programmer/debugger which allows for using the Segger suite of software tools to help developing applications including Ozone for debugging purposes.

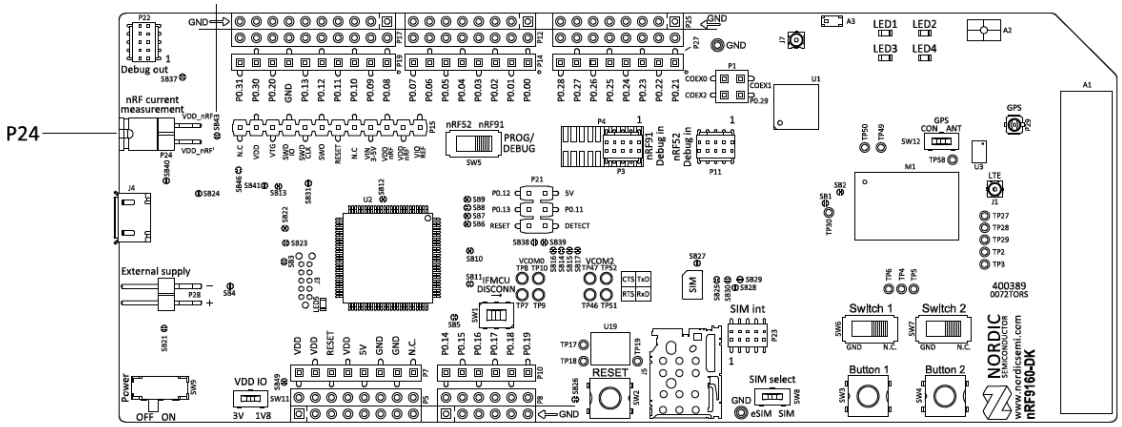

FIGURE 5. nRF9160 DK current measurement connector P24 (8, p. 36)

2.2.2 Software

Applications for the nRF9160 are built using the Nordic Semiconductor proprietary nRF Connect SDK which is publicly hosted in GitHub and also supports the nRF52 and nRF53 system-on-chips. It allows for developing applications using LTE wireless or short-range technologies including BLE, Bluetooth Mesh, Thread, Zigbee and near-field communication (NFC). (9.)

The nRF Connect SDK integrates the Zephyr real-time operating system, which is a Linux Foundation open-source collaborative project meaning to provide the "best-in-class small, scalable, real-time operating system -- optimized for resource-constrained devices, across multiple architectures" (10).

The most important concept while working with Zephyr is the manifest repository which combines multiple repositories, some of them including proprietary software, such as Nordic Semiconductor implementations of stacks for their own hardware, within a single one as illustrated in figure 6. All of these repositories are managed using a command line tool called "west".

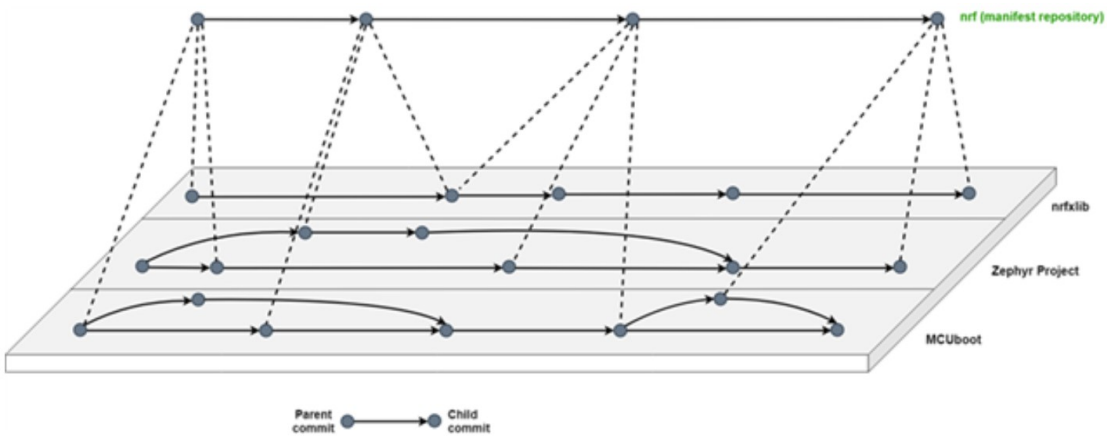

FIGURE 6. the nRF manifest repository (11)

In addition to allowing for managing the manifest repository, west offers options for configuring and building applications, flashing them to the selected target and debugging through either a debug console (GDB) or by attaching to the target and opening up a local network port (12). Alternatively, Nordic Semiconductor

offers access to a licensed version of the Segger Embedded Studio software for programming Nordic Semiconductor devices.

The west command line tool was selected for this work owing to its versatility and because it was more convenient to use a text editor, such as Microsoft Visual Code, to access library source code files which were hidden in Segger Embedded Studio.

2.2.3 Theoretical power consumption

According to Nordic Semiconductor, the nRF9160 is designed for low power solutions and it supports both PSM and eDRX power saving modes. It is expected to have a floor current as low as 2.7 µA in NB-IoT PSM and 9 µA in NB-IoT eDRX with a cycle length of 655.36 seconds (table 1).

TABLE 1. Current consumption of the nRF9160 in power saving modes (6, p. 2)

Current consumption (23 dBm TX power, 3.7 V supply)	
PSM floor current	LTE-M: 2.7 uA NB-IoT: 2.7 uA
eDRX, 655 seconds	LTE-M: 6 uA NB-IoT: 9 uA

Regarding the nRF9160 DK, Nordic Semiconductor announced that the average current for the device is 5.5 µA while uploading 1 KB every 12 hours in PSM mode (7, p. 2).

3 APPLICATION

3.1 Hardware setup

The device under test (DUT) in this study was the nRF9160 development kit version 0.9.0 featuring an nRF9160 SiP version 1. Measuring the power consumption of the DUT was performed using a Qoitech Otii Arc working simultaneously as a 3.6V power supply and as a power analyser. This all-in-one tool allows for displaying real-time data and statistics, wide dynamic range, recordings comparison and debug logs synchronization (14). The Arc was externally powered using an XP Power VER18US090-JA 9V AC/DC wall mount adapter.

To measure the current going through the SiP, Nordic Semiconductor recommends several setups including the following one presented in figure 7.

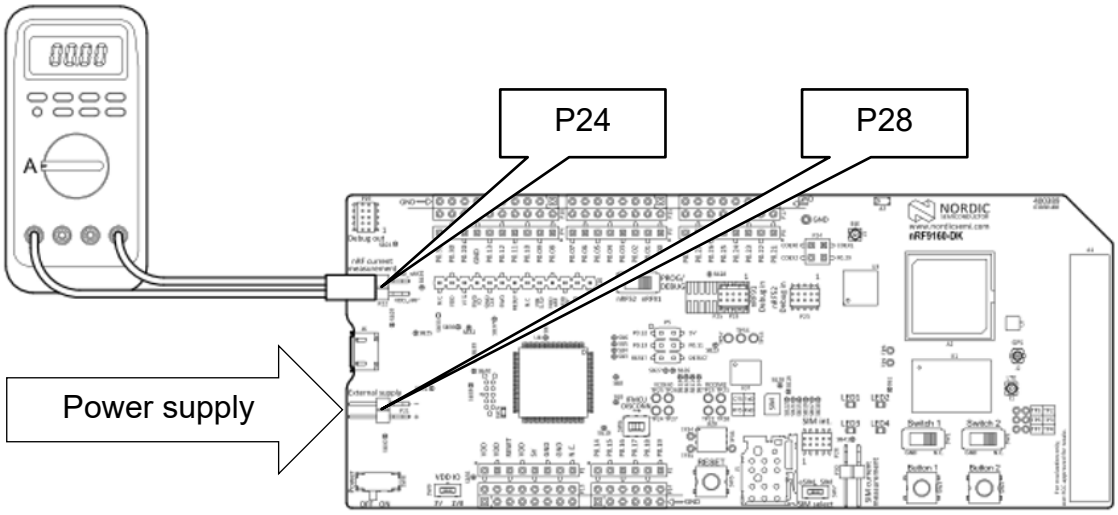

FIGURE 7. Current measurement with a current meter (14, p. 42)

The problem encountered was that the SiP is meant to be powered with an external power supply over P28 while measuring the current going to the SiP over the connector P24. The Otii Arc measures the current it sources itself, therefore this setup could not be used. Connecting it to P28 would make it measure the power consumption of the whole development kit including the peripherals, while connecting it to P24 does not allow to power peripherals.

Instead, based on information found in the Nordic Semiconductor DevZone support forum (15), the Arc was set up to source current to the SiP using both connectors P24 and P28 while the development kit peripherals were powered over the USB. Figure 8 presents the setup used for performing the measurements.

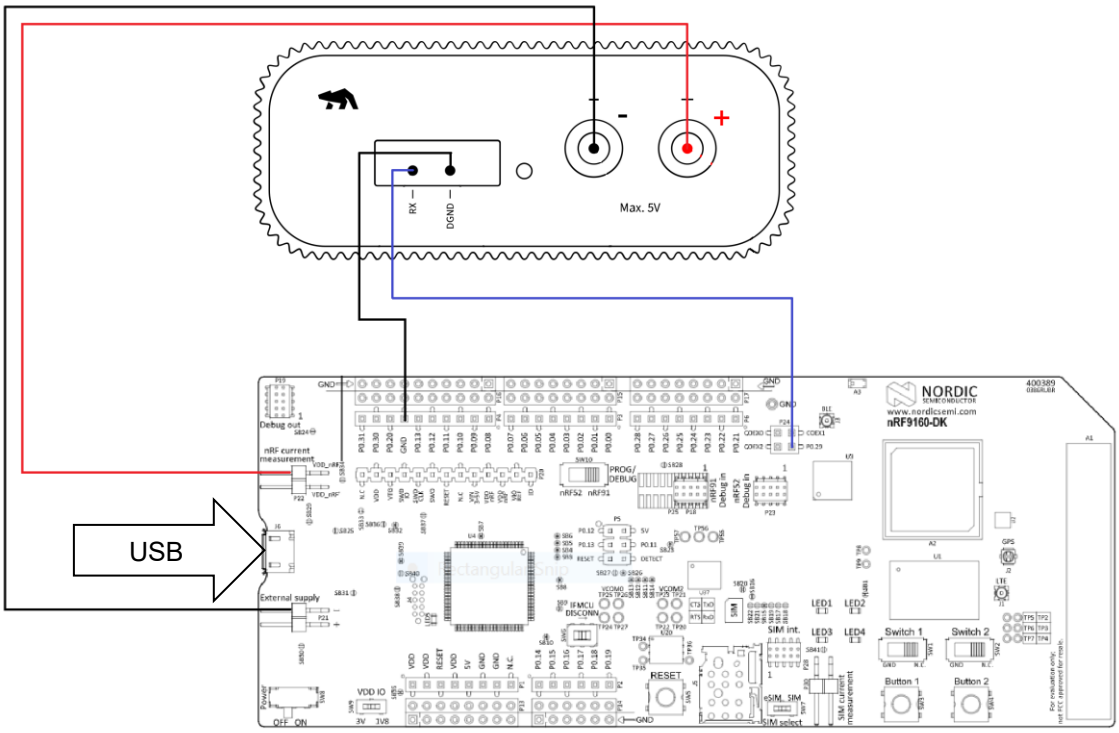

FIGURE 8. Setup allowing the Otii Arc to source current to nRF9160 SiP

An additional advantage brought by this setup is the possibility to flash the device firmware over the USB by actuating the SW1 switch and enabling the IFMCU, whereas serial logging is available on pin P0.29 once the IFMCU is disconnected.

3.2 Programming environment

Firmware for the modem was developed using Visual Studio Code complemented with Microsoft C/C++ and Kconfig for the Zephyr Project extensions. Manifest and repositories were managed using the West command line tool, which also allowed for configuring the project running “west build --target guiconfig” and finally building and flashing the application using respectively “west build” and “west flash”.

Debugging was performed using the Segger Ozone debugger v3.20g, thanks to the presence of the J-Link on-board debugger on the nRF9160 DK. Power measurements were performed with the Otii Arc on firmware 1.1.4 using software provided with the standard license on version 2.7.3.

3.3 Firmware development

The modem firmware and the nRF Connect SDK were updated whenever new versions were released during the course of this research. When performing the last measurements, the modem firmware was version 1.2.3 and the nRF Connect SDK was version 1.4.99 which later became the release 1.4.2. It should be noted that Nordic Semiconductor recommends the use of specific modem firmware versions which are certified for some mobile network operators (MNO) (17). Because Elisa is not part of those MNOs, the latest version was always used as per Nordic Semiconductor instructions.

The modem system mode was first set to LTE Cat-NB1 using the command %XSYSTEMMODE=0,1,0,0 (17, p. 67) and stored to non-volatile memory as a permanent hardware configuration by cycling the modem functional mode using the command AT+CFUN=0 (17, p. 23) running the AT Client sample application (18).

The modem was initially tested running the AT Client sample as applications previously developed to test other modems over AT commands could be reused. Once the nRF9160 had been confirmed to be working reliably, the test software had to be transferred to run internally on the nRF9160 in order to confirm its sleep and PSM current levels. Running the modem through AT command does not allow for such low currents because the UART connection adds almost 660 µA to the current draw.

It was decided to use the nRF9160: UDP sample application (19) which has been developed by Nordic Semiconductor to demonstrate the capabilities of this SiP. Changes were brought to the sample application, notably the addition of the Modem Information library (20) to monitor the reference signal received power

(RSRP) which indicates the network signal strength as well as configuration modifications and logging data output.

3.4 Modem location

The modem was located indoor on a table, in a room on the top floor of a house with a roof made of metal sheet. It would automatically connect to and switch between different Elisa base stations the locations of which are presented in figure 9. The base station 3213 was selected for this study.

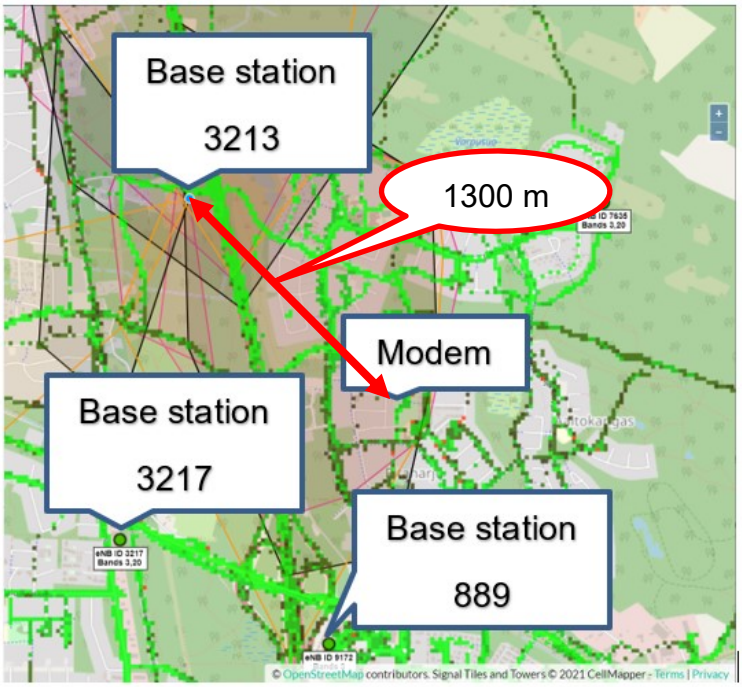

FIGURE 9. Modem location

Depending on what BS the UE was connected to, current profiles could vary drastically affecting overall power consumption. Figure 10 shows the current consumption of the nRF9160 sending the same payload while connected to two different base stations.

Legends for graphs generated with Otii Arc software can be difficult to see in some figures presented in this thesis. Legends were excluded from figures when they were not deemed necessary.

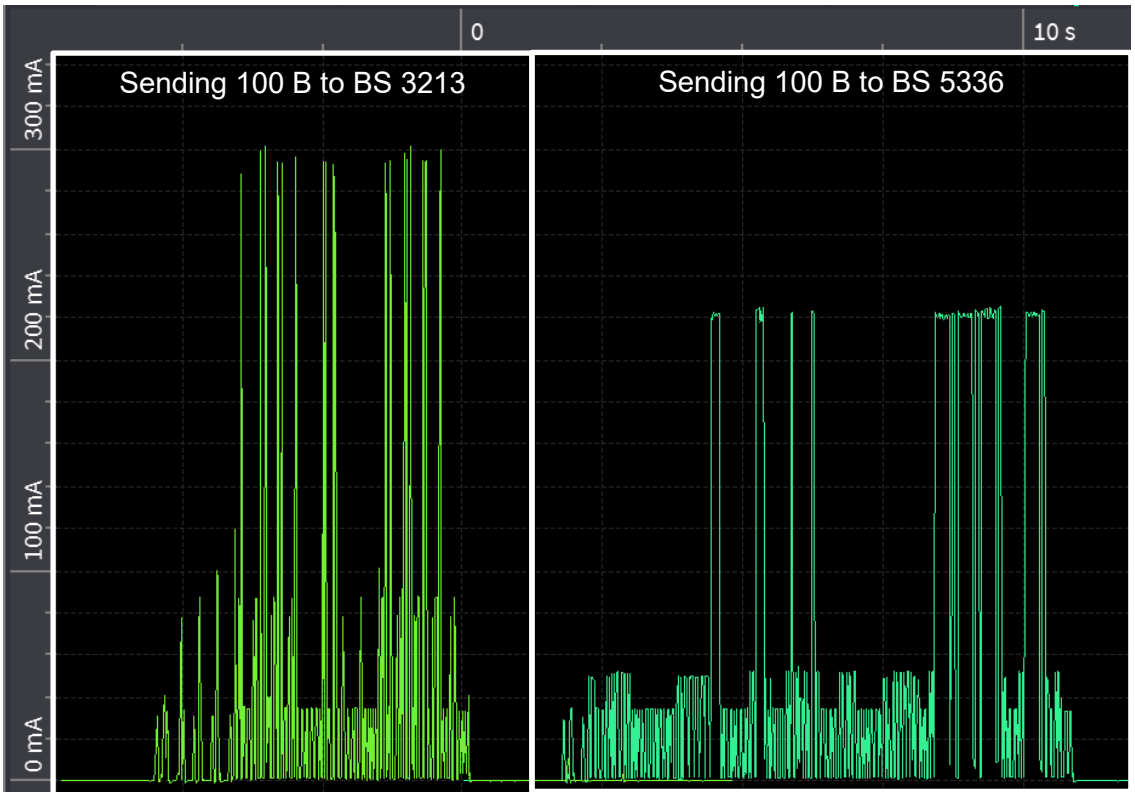

FIGURE 10. Sending the same payload to two different base stations

In order to ensure that all measurements performed during this study were comparable, it was decided to only compare events happening when connected to the same BS. The BS 3213 was selected because it was prioritized by the modem during cell selection.

The output power of the nRF9160, which can vary between -40 dBm and 23 dBm (21, p. 366), cannot be adjusted in firmware. Instead, it is driven by the BS based on the link budget (22). Figure 11 illustrates how the adjusted transmit power can affect resulting current levels. The UE was connected to the same BS and transmitted the same payload using different transmit power. There was a noticeable decrease in the maximum current from 226 mA to 53 mA after the BS had driven the UE transmit power down.

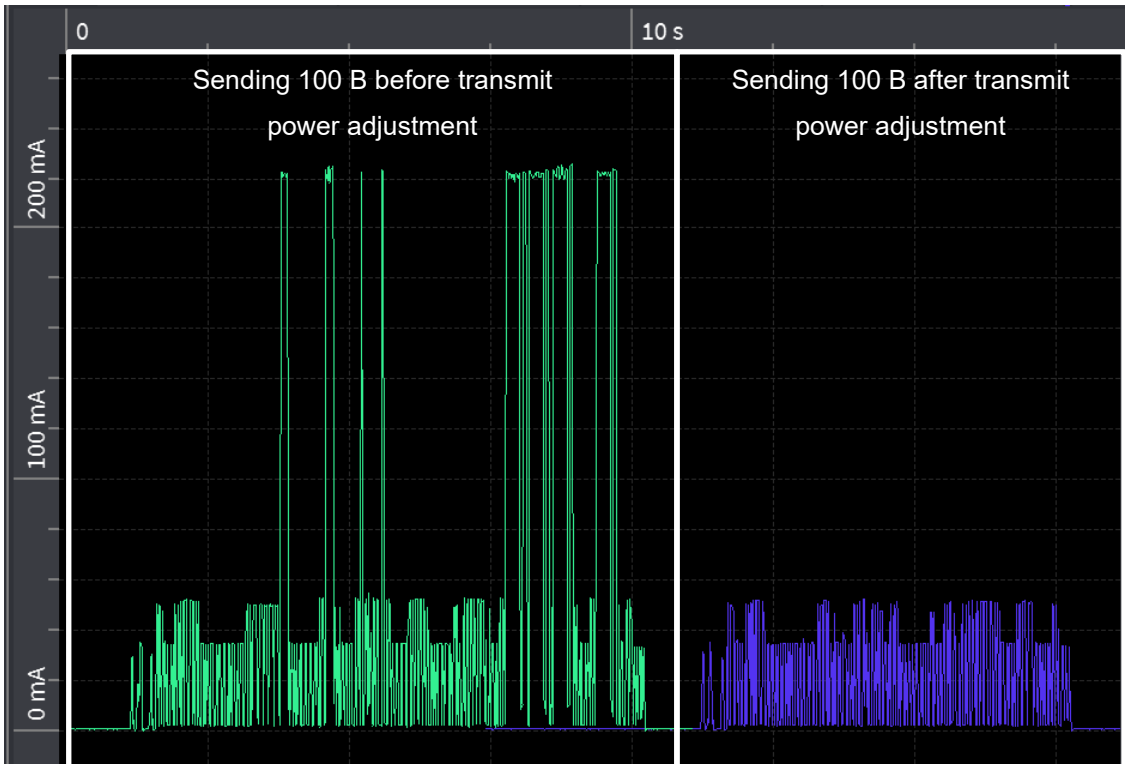

FIGURE 11. Transmit power and associated current levels

In addition to using a single BS, it was also decided to maintain a constant RSRP value during the measurements to isolate the effect of signal quality from the effect of the power saving modes. Because transmit power is dynamically adjusted on live networks based on the signal quality, a makeshift Faraday cage was installed around the modem whenever the reported RSRP value deviated from its original value of -87 dBm.

4 ANALYSIS

4.1 Power consumption overview

While running the UDP sample application, the modem first searches and attaches to the network. It then alternates between two states: the connected state during which it synchronizes with the network and transfers data over an UDP socket and either an idle state or power saving mode (PSM) depending if PSM is in use or not.

In both scenarios – PSM in use or not – the modem enters an inactivity state after it has sent its payload. The duration of that inactivity phase is set by the cellular operator. The release assistance indication (RAI) can be used to notify the network that either no downlink data or only one downlink packet is expected and allows for releasing the connection much faster.

When PSM is not in use, the modem enters an idle state after releasing the connection. Its floor current drops to a lower level (around 37 µA in case of the nRF9160 using an Elisa SIM), with the addition of discontinuous reception (DRX) or extended discontinuous reception (eDRX) paging windows of a set period and duration during which the modem listens for incoming data (figure 12).

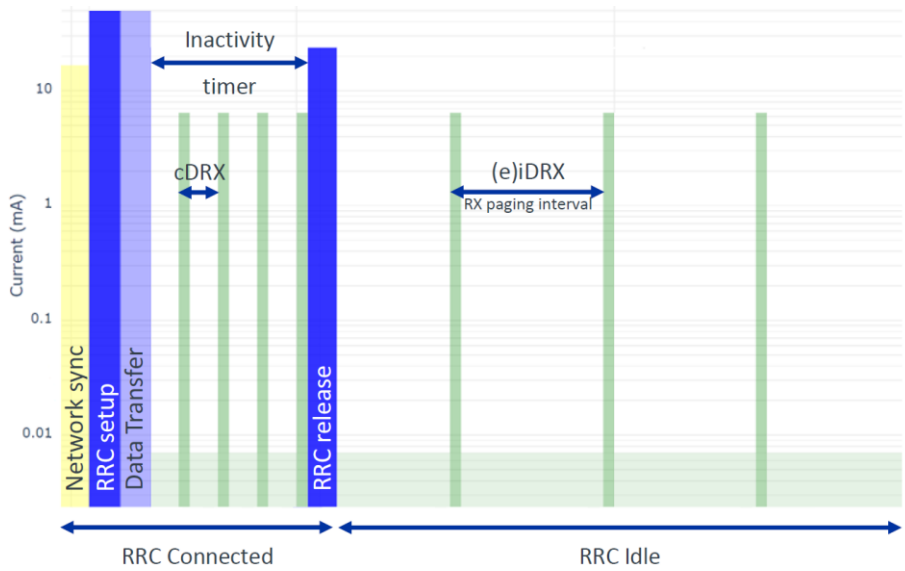

FIGURE 12. Connected and idle states – (extended) discontinuous reception mode (23, p. 11)

When PSM is used, additional steps take place after network synchronization, most importantly the tracking area update (TAU), which informs the network that the UE is still present and allows for negotiating the timers (T3324 and T3412) for the following PSM interval. Once the connection is released, the modem enters PSM, during which its floor current drops further to 7 µA. This low sleep current comes at the cost of latency as the modem cannot be reached until it wakes or until the end of the PSM interval (23, p. 12).

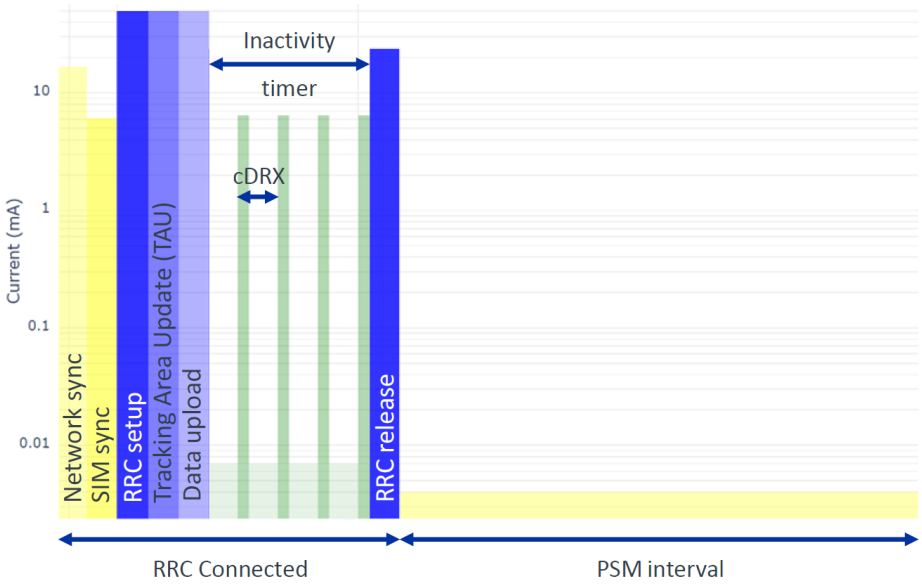

FIGURE 13. Connected and power saving mode states (23, p. 12)

4.2 Release assistance indicator

The release assistance indicator (RAI) is an important NB-IoT power saving feature introduced in 3GPP Release 14 considering it yields great power savings with no downsides, such as increased latency when using for example PSM. On Elisa network, it allowed for completely removing the 10-second-long inactivity state after informing the network that no downlink was expected. This introduced an energy saving of 204 µWh. Figure 14 features two measurements of the same event, sending 50 bytes, using RAI (yellow) and not using RAI (red).

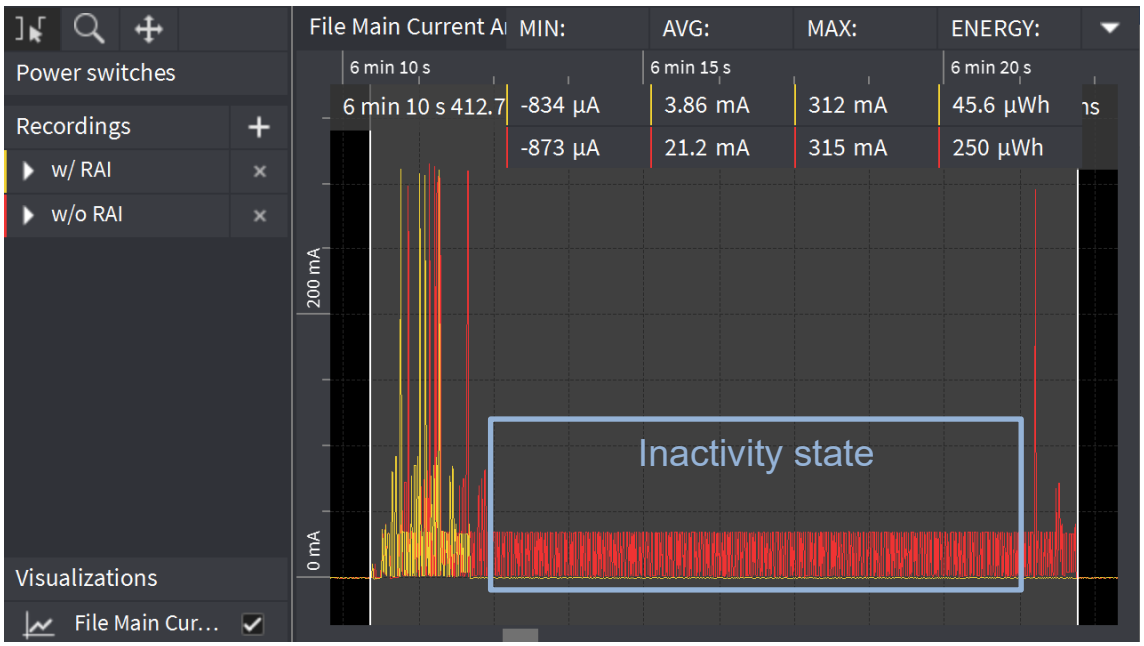

FIGURE 14. Release assistance indicator effect on inactivity state

Taking this sample for reference, the energy saved represents 82% of the total energy spent in the connected state as depicted in figure 15. In applications requiring a frequent upload of data and short periods of time spent in idle or PSM, the connected state can be responsible for most of the energy consumption of the device with an average current of 3.86 mA using RAI and 21.2 mA without RAI compared to 37 µA in idle mode without paging or 7 µA in PSM mode. Therefore, this proportion can in some cases almost directly translate to the DUT total energy consumption saving over time.

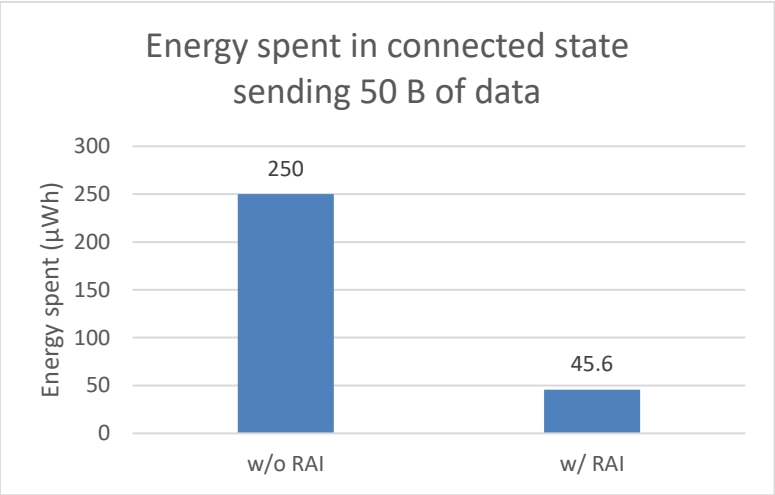

FIGURE 15. Influence of release assistance indicator on connected state energy consumption

Considering the gains offered by RAI and the absence of side-effects, there is no reason for not using it when having a device connected to NB-IoT networks. RAI has been used for the entirety of this study in order to emphasize how other parameters contribute to saving power, as their effect is considerably lower than that of RAI. Power savings would otherwise not show well in contrast to the increased consumption resulting from the inactivity period.

4.3 Payload size

The payload size is not a power saving feature but it contributes to power consumption. The developer can decide if it is worth it to send data more frequently or to store it in a buffer and transmit it at a lower upload frequency based on the application requirements.

Measurements showed that the payload size has little influence on the connected state power consumption. Tests presented in figure 16 were performed sending payloads with varying sizes: 10 B, 25 B, 50 B, 100 B and 1000 B. The total connected phase duration lasts from 1.5 s (sending 10 B) to 2.5 s (sending 1000 B).

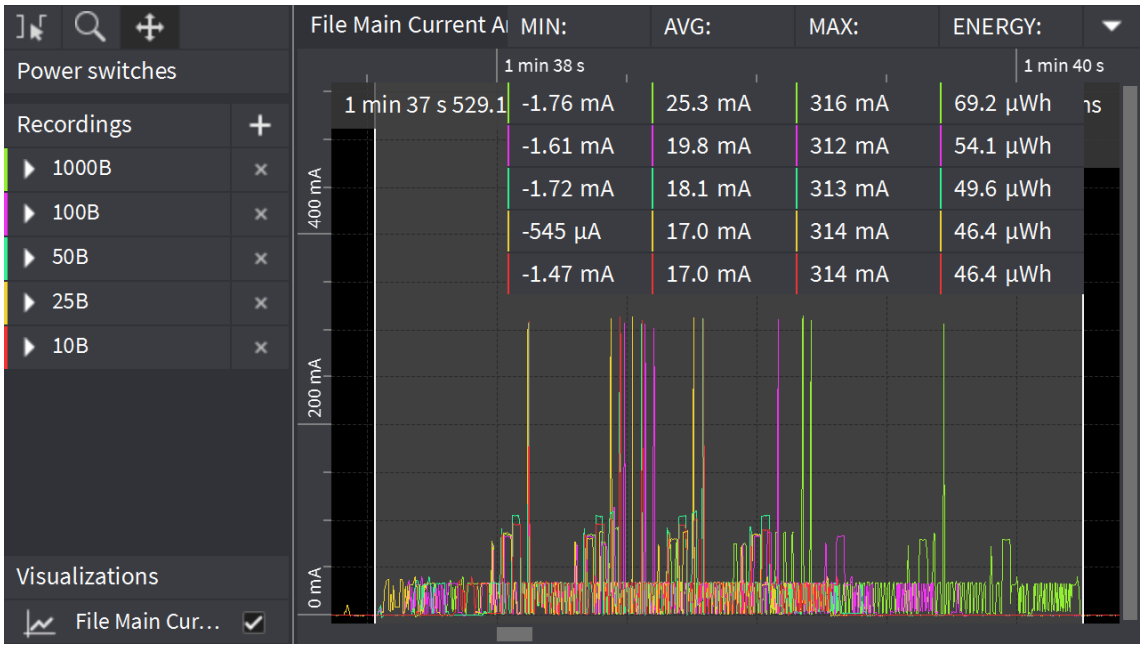

FIGURE 16. Sending various payload sizes

As can be seen in figure 17, the resulting energy spent while transmitting data does not increase significantly for smaller payload size increments, with a 17% increase for sending 100 B over 10B. On the other hand, sending a payload of 1000 B represents a 49% increase over 10 B and a 29% increase over 100 B.

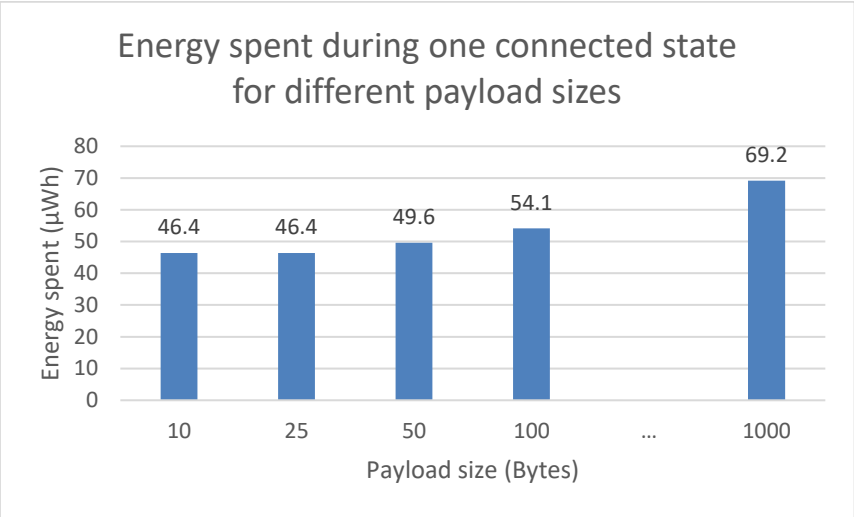

FIGURE 17. Energy consumption increases with the payload size

4.4 Extended discontinuous reception

4.4.1 Idle state

When the UE is not communicating with the network, it enters an idle state. In the case of the nRF9160, the modem enters sleep mode when entering idle. Its current consumption drops to 37 µA using an Elisa SIM.

4.4.2 Discontinuous reception

While in idle, if extended discontinuous reception is not in use, the UE listens to the network periodically using discontinuous reception (DRX). In the case of Elisa NB-IoT network, DRX cycle length is set at 10.24 s (figure 18). When the nRF9160 is in an DRX idle state, its average current consumption sits at 1.6 mA and its energetic consumption is 3.453 mWh per hour.

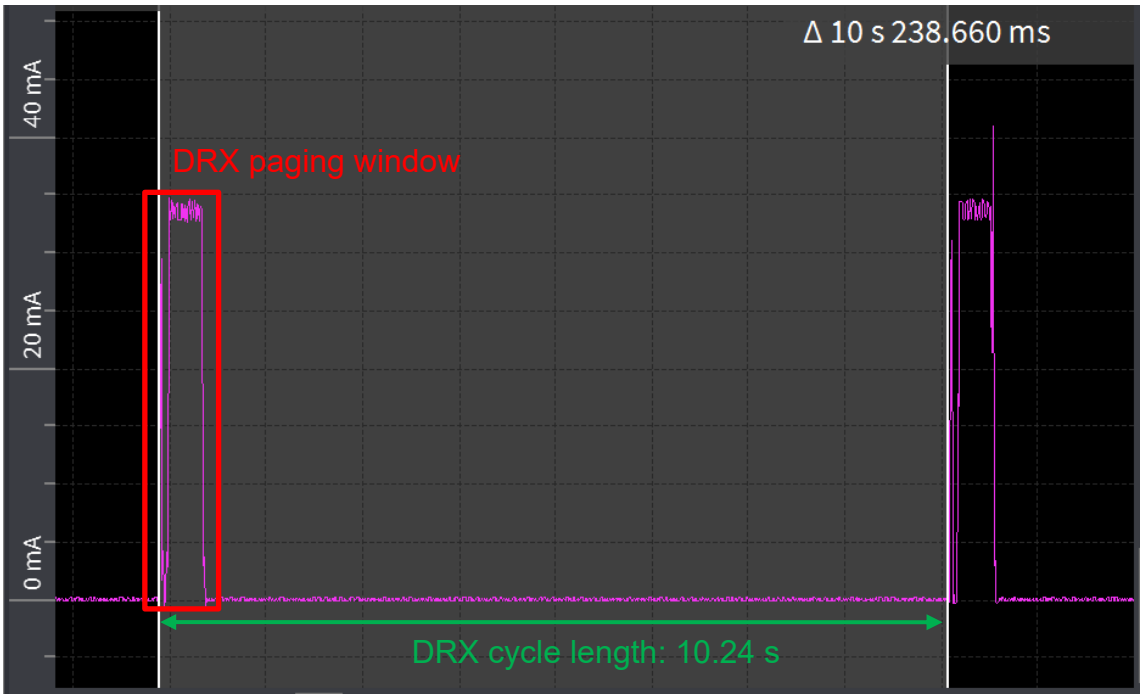

FIGURE 18. Discontinuous reception at 10.24 s

4.4.3 Extended discontinuous reception features

Extended discontinuous reception (eDRX) allows for longer periods of time between paging windows and consists of two components, the eDRX cycle length

and the paging time window (PTW). The eDRX cycle length defines the time duration between two paging windows. PTW corresponds to the duration of the paging windows.

Both those components affect the UE average current consumption while in an idle state. Two sets of measurements have been performed in order to measure their effect separately.

4.4.4 Extended discontinuous reception cycle length

Figure 19 illustrates how eDRX paging appears in current measurements. Two paging windows with a 5.12 s duration are seen at a 20.48 s interval. While the current amplitude during transmit events can reach values even higher than 320 mA depending on the RSRP value, its value is consistent at around 35 mA during receive events.

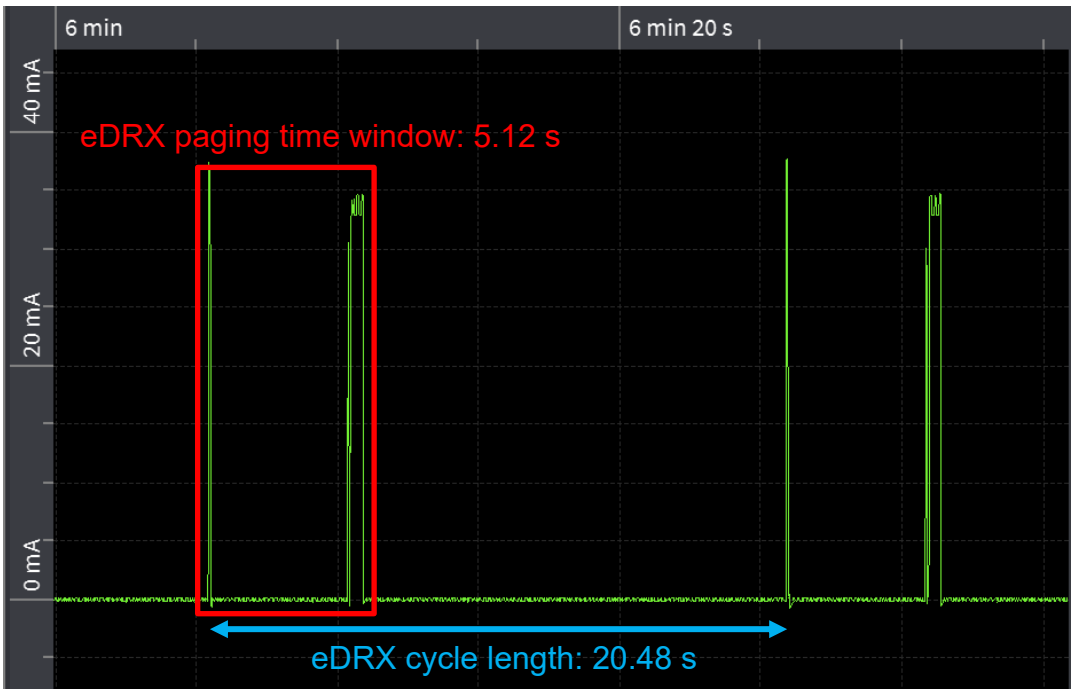

FIGURE 19. Two extended discontinuous reception paging windows

Possible values for the eDRX cycle length go from 20.48 s to 10485.8 s. Figure 20 presents idle current measurements performed at five different eDRX cycle lengths: 20.48 s, 40.96 s, 81.92 s, 163.84 s and 327.68 s. The default duration for PTW on Elisa NB-IoT network is set at 5.12 s.

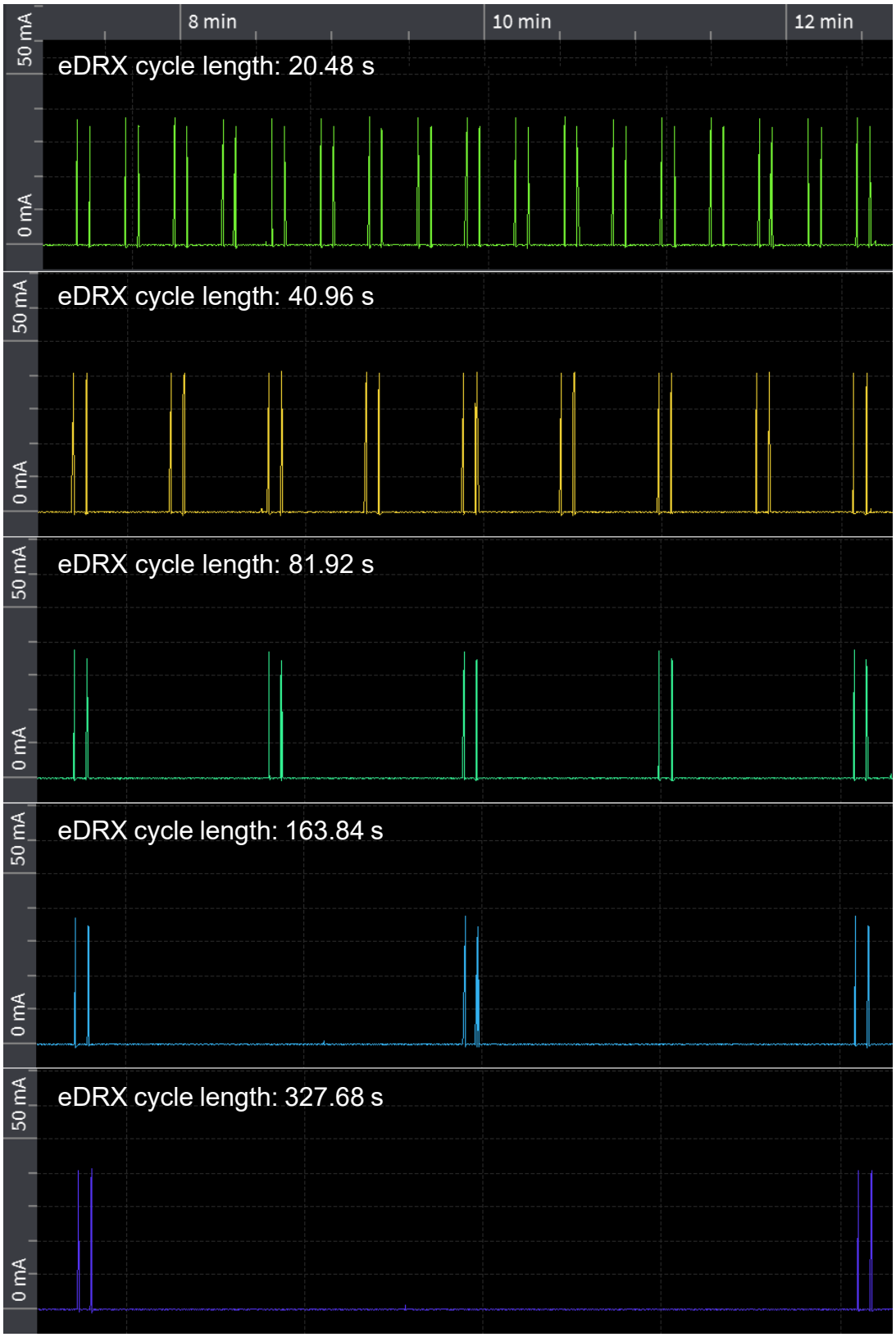

FIGURE 20. Five different extended discontinuous reception cycle lengths: 20.48 s, 40.96 s, 81.92 s, 163.84 s and 327.68 s

Increasing the eDRX paging cycle length leads to a decrease in power consumption in an idle state due to the lowered frequency of the paging windows. Figure 21 presents the measured energy consumption over one hour for the specified eDRX cycle lengths, with the addition of the calculated average hourly consumption for the longest possible eDRX cycle length duration of 10485.76 s.

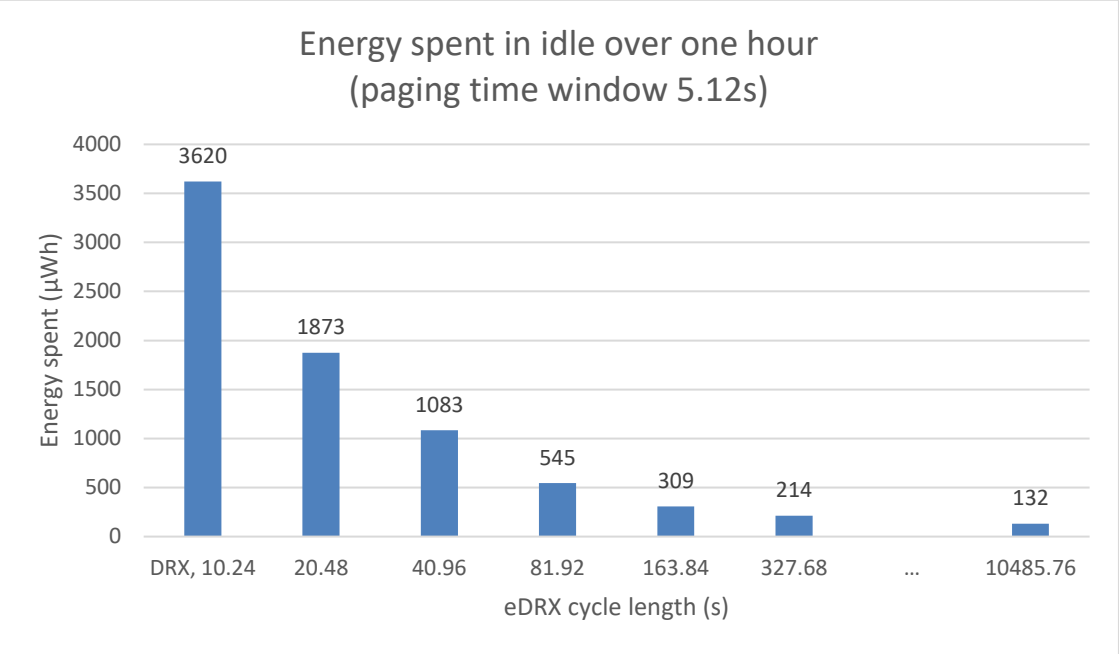

FIGURE 21. Increasing extended discontinuous reception cycle length decreases idle power consumption

The highest power saving can be obtained by using an eDRX cycle length value of 10485.8 s at the cost of the greatest latency regarding downlink transmissions.

4.4.5 Paging time window

Extending PTW allows the UE to listen to the network for greater lengths of time. Figure 22 features a paging window with a duration of 38.4 s. As can be seen, the paging window is not a single window but instead it consists of several successive paging windows.

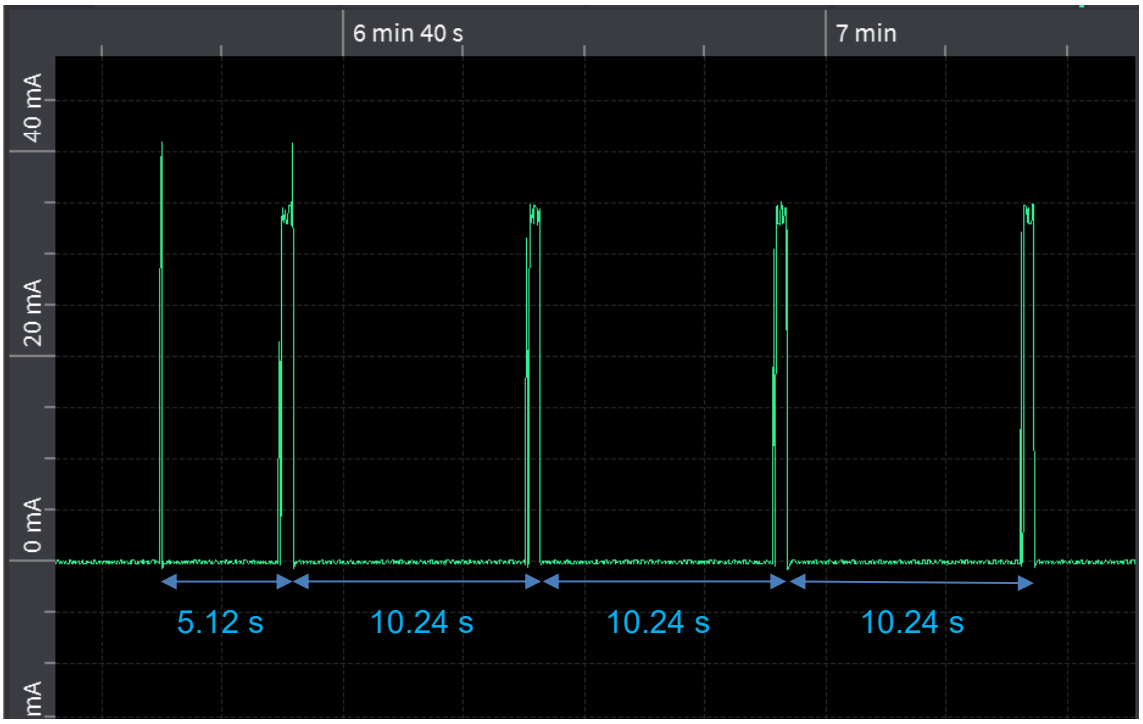

FIGURE 22. 38.4s paging time window comprises four paging windows

Measurements showed that despite PTW increments of 2.56 s being theoretically possible according to 3GPP technical specification 24.008 (5, p. 157), only increments of 10.24 s on top of a first 5.12 s window were noticeable in the nRF9160 current profile. The actual values for PTW could be determined using the formula 1, which was drafted based on those observations.

FORMULA 1. Actual paging time window durations for nRF9160 SiP

*PTW duration (s) = 5.12 + x * 10.24*, where

x is an integer between 0 and 3

When requesting PTW values in between those specific values, the resulting duration would be equal to the closest lower value issued from formula 1. For example, despite the network accepting the following requests, a PTW value of 7.68 s falls back to 5.12 s and a PTW value of 33.28 s results in a PTW of 25.6 s. The exception to this rule is the requested value of 2.56 s resulting in a 5.12 s PTW duration.

For this reason, it was decided that PTW values of 5.12 s, 15.36 s, 25.6 s and 35.84 s would be used in this analysis. The resulting current profiles can be seen in figure 23.

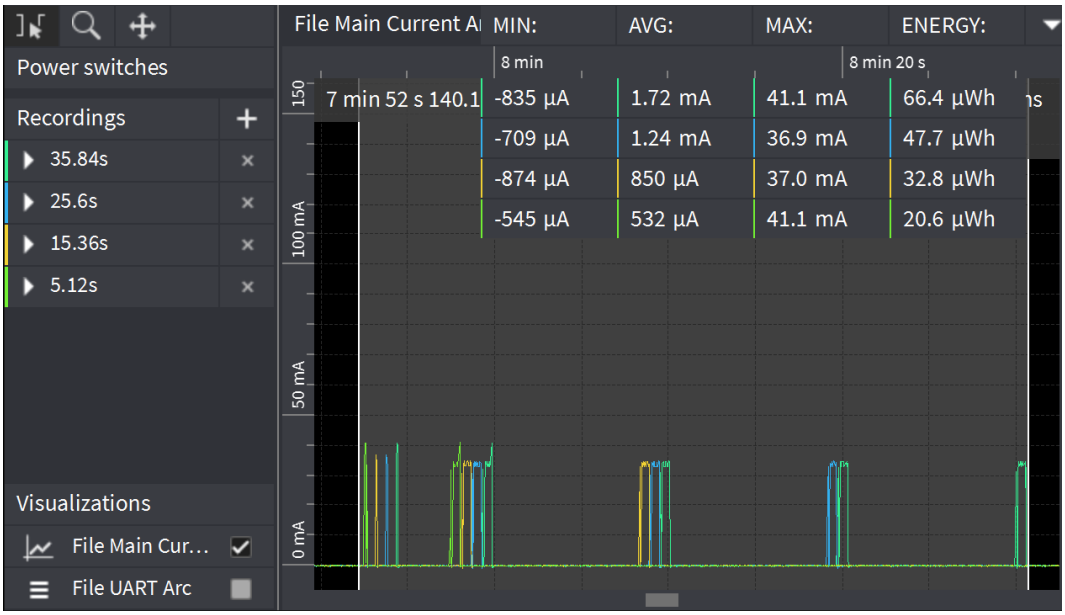

FIGURE 23. Paging time window duration comparison

Figure 24 summarizes the effect of paging window duration on power consumption. As with other NB-IoT power saving modes, PTW introduces a duality between power consumption and reachability. It should be noted that while PTW can be overlooked because it initially seems like a small energetic cost with low currents of 35 mA, its consumption is in fact comparable to the connected phase when sending a payload costs 50 µWh using RAI.

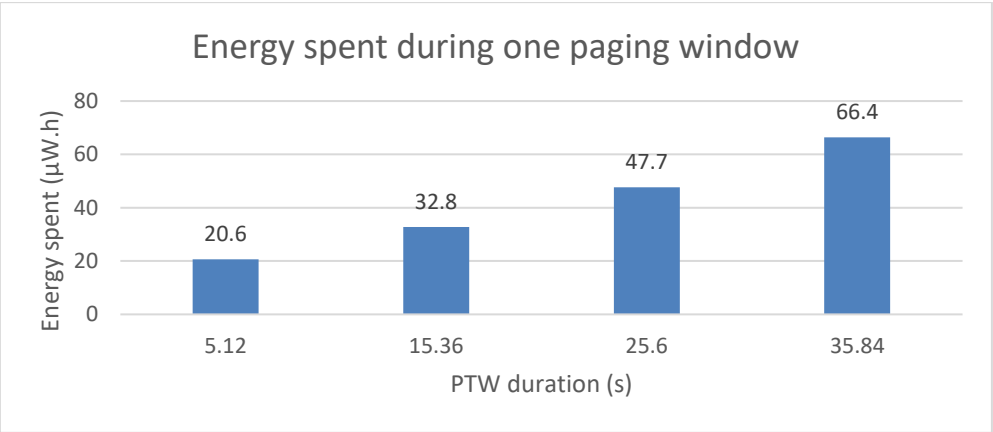

FIGURE 24. Paging time window energy cost

4.5 PSM

PSM allows the UE for entering a low-power mode while remaining registered to the network. PSM consists of two components, the tracking area update (TAU) period and the active time.

4.5.1 PSM state

While in PSM, the nRF9160 floor current was measured to be 7 µA. This brings the energy consumption of the nRF9160 to 26 µWh per hour, which represents an 80% saving over the longest available eDRX cycle length with a PTW of 5.12s, and a 99.3% saving over using the default DRX idle mode. Figure 25 presents the same data as figure 21 with the addition of PSM hourly energetic cost.

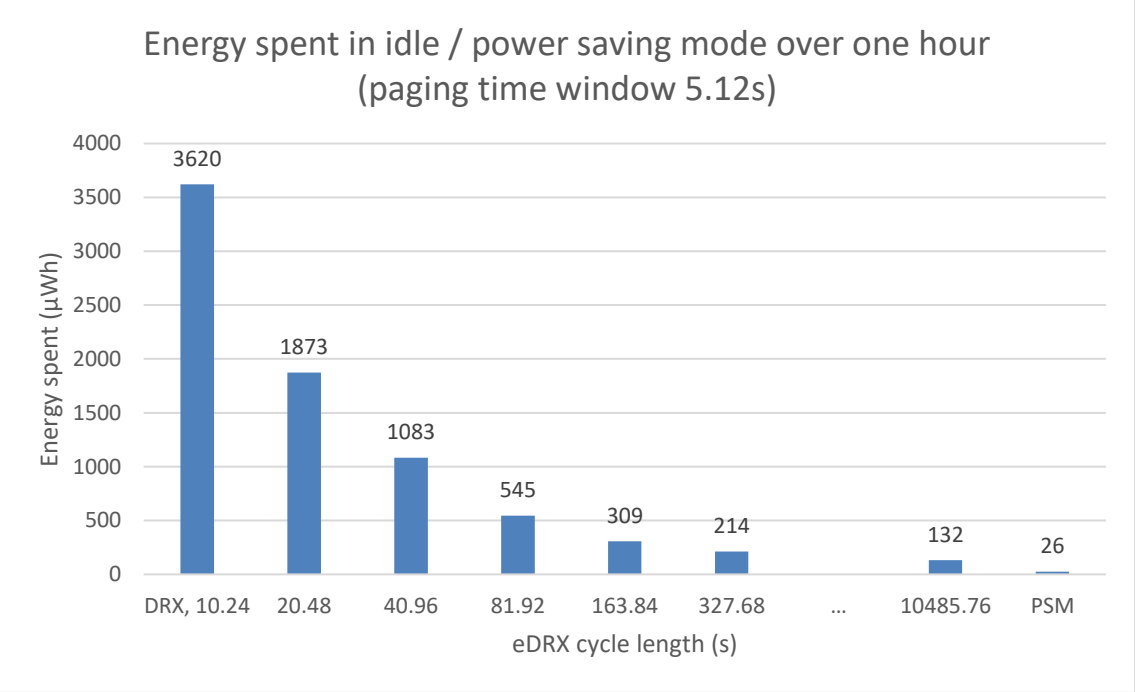

FIGURE 25. Power saving mode compared to (extended) discontinuous reception

4.5.2 Tracking area update

When using PSM, TAU must be performed at a periodic interval defined by the timer T3412 to inform the network that the UE is still present. Theoretically, the TAU period can go from 10 minutes to 413 days.

Trial and error showed that the lowest possible value that could be requested for T3412 on Elisa NB-IoT network was 250 minutes at the time this study was performed. Requesting a smaller value for T3412 resulted in PSM being deactivated.

It should be noted that while it is possible to request a particular value for T3412, it is actually the BS that determines the value for this timer based on that request. For example, requesting the minimum allowed TAU duration of 250 minutes from Elisa BS resulted in a T3412 duration of 260 minutes as depicted in figure 26.

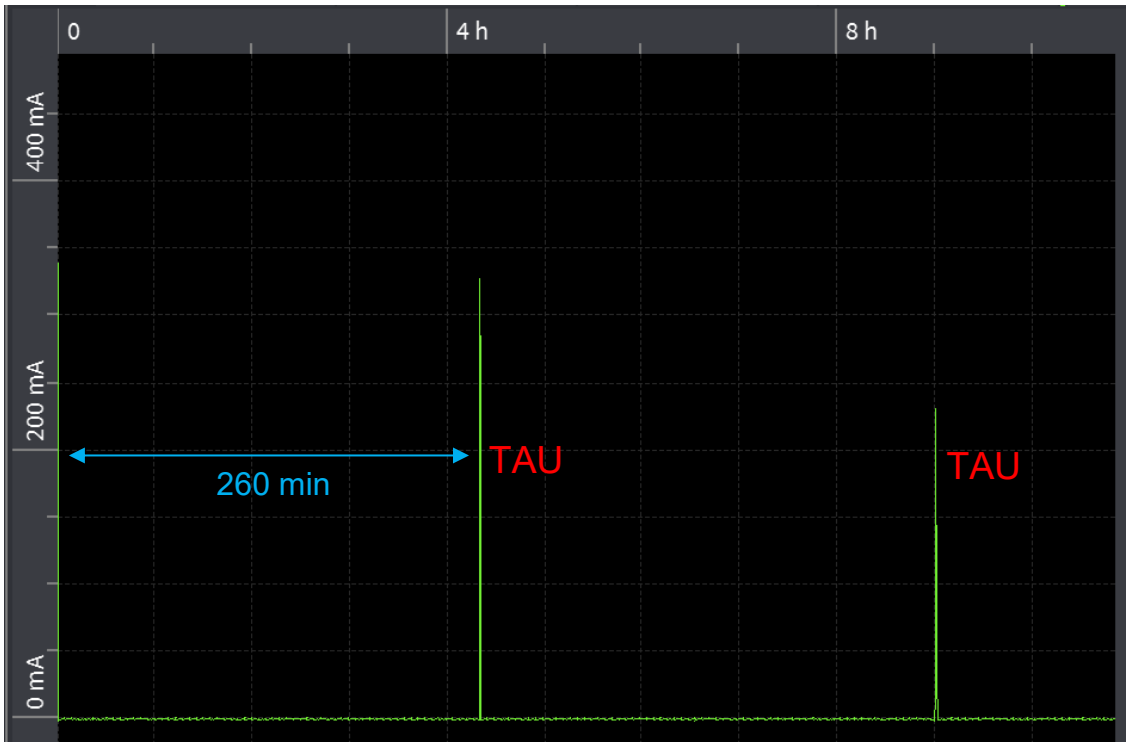

FIGURE 26. Power saving mode – T3412 of 260min

TAU has an energy cost of 297 µWh for an RSRP of -87 dBm (figure 27). This is six times the cost of sending a 50 B payload in the same conditions. Considering the high energetic cost of TAU, the gains in base current when comparing PSM (7 µA) to the eDRX idle state (37 µA) can rapidly be wasted if performing TAU too often.

It must be noted that RAI does not affect TAU. Using RAI simultaneously with PSM allows for reducing the duration of inactivity state after sending a payload when waking from PSM, but it does not affect the duration of the inactivity state when a TAU is performed. The first TAU event happening after 260 minutes in

figure 26 is presented in the following figure 27. Despite using RAI, the inactivity state last for more than 10 seconds.

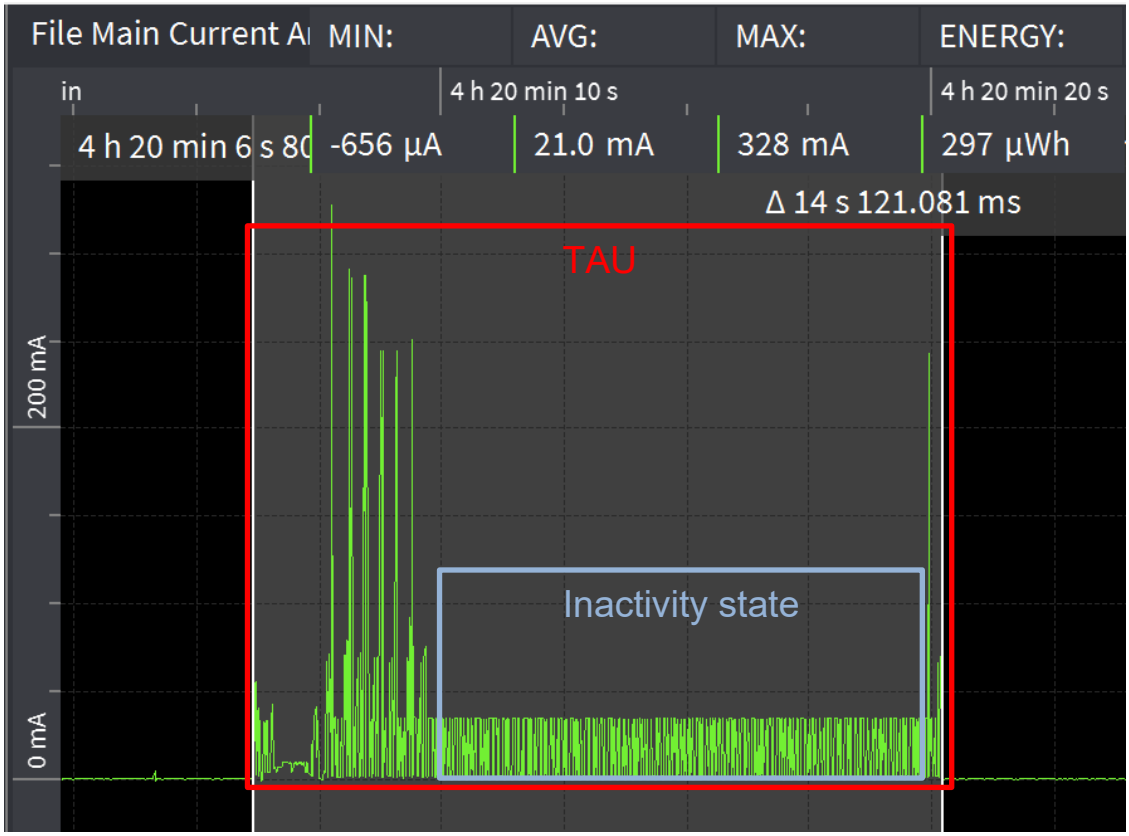

FIGURE 27. Tracking area update energy cost

4.5.3 Active time

When using PSM, it is possible to adjust the duration of time for which the UE remains listening for the network when going from the connected state to PSM. That change of state happens when a TAU takes place as well as right after the device has sent a payload when waking from PSM.

The active time is defined by the T3324 timer which can be requested during a TAU procedure. Theoretically, the active time can last from 2 seconds to 186 minutes.

Paging happening during active time works similarly to eDRX paging windows. It is composed of several listening windows lasting 10.24 s each (figure 28).

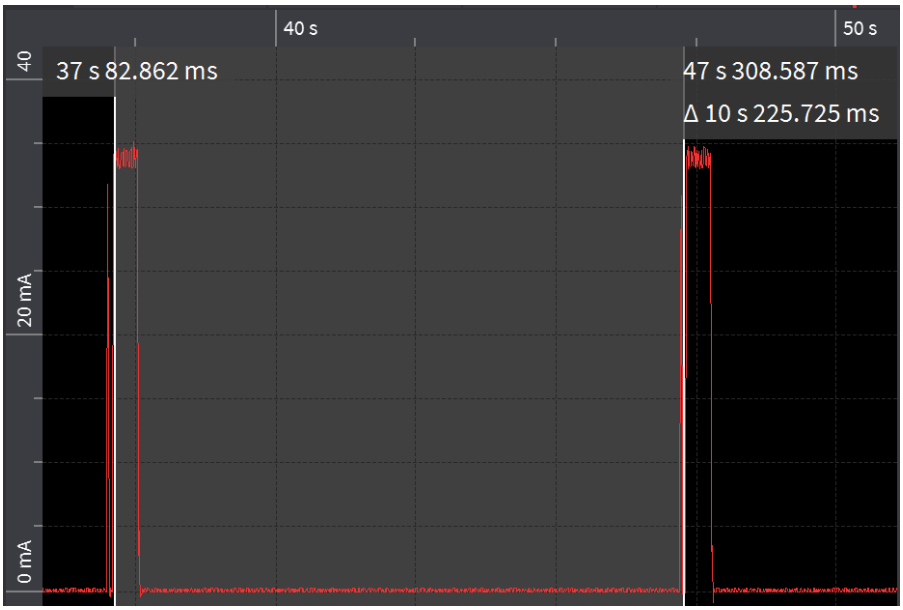

FIGURE 28. Paging windows during power saving mode active time

In a similar way to how PTW only allowed for specific values on Elisa network, T3324 could only be adjusted in increments of 30 seconds

Several values were tested in the set of measurements presented in figure 29: 30 s, 60 s and 120 s. It should be noted that the active time can be set to 0 s and effectively disable it altogether.

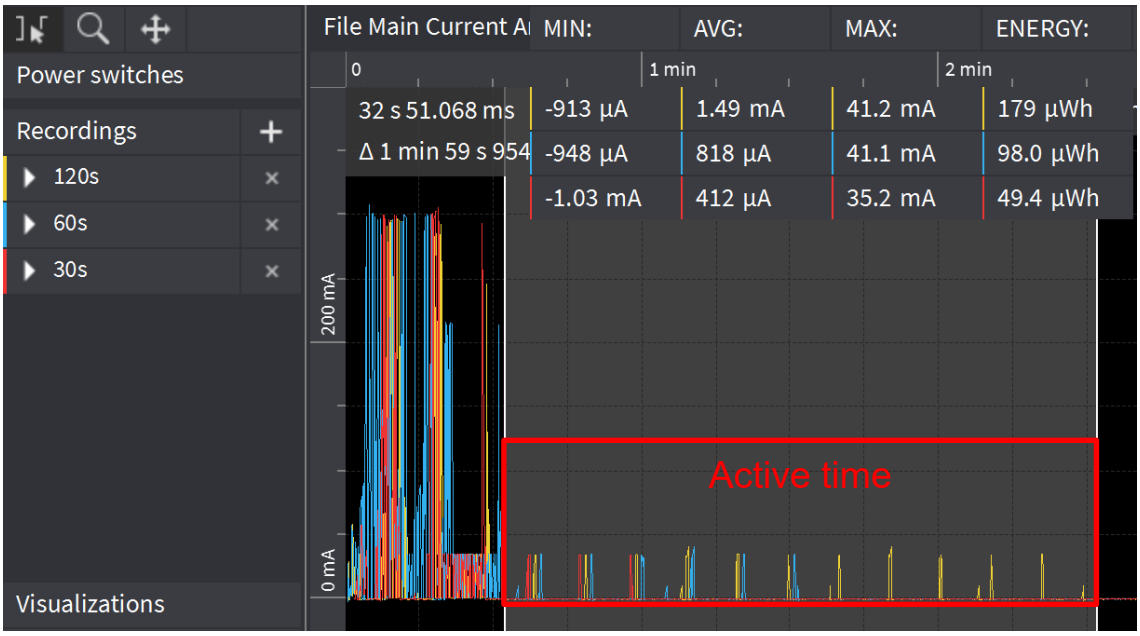

FIGURE 29. Varying active time durations

The energy spent during the active time is almost directly proportional to its duration as portrayed in figure 30. Once again, a direct analogy to eDRX PTW can be made regarding its high energetic cost. For every 30 seconds spent in the active time, the energy consumed is equivalent to sending one 50B payload with RAI at -87 dBm RSRP.

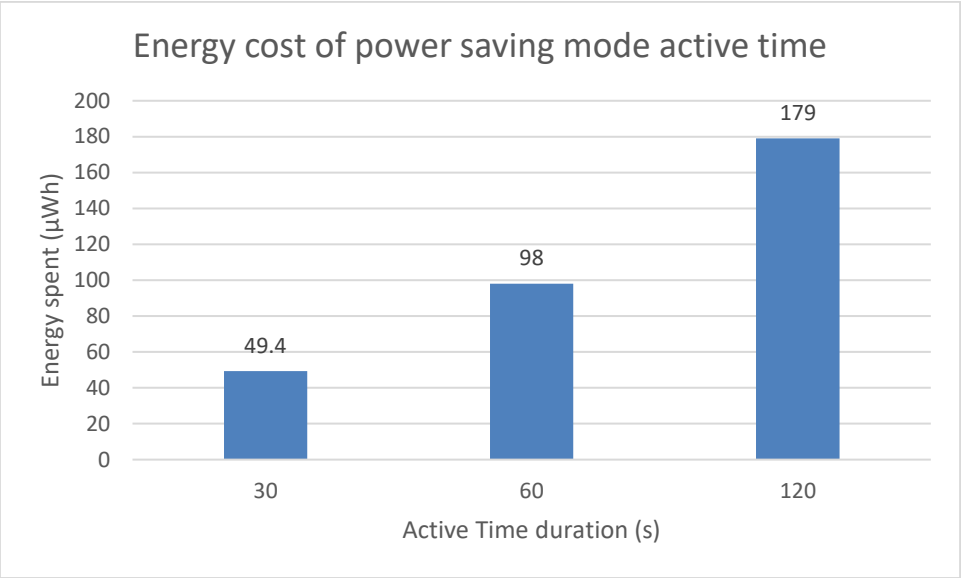

FIGURE 30. Energy spent during active time

4.5.4 Sending data in PSM

While in PSM, the UE has the possibility to wake and transmit data before T3412 expires. When doing so, its power consumption is defined by three factors: the payload size, the requested active time and the use of RAI.

For example, in figure 31, the nRF9160 wakes from PSM, sends a 50 B payload using RAI and remains active for 30 seconds before re-entering PSM. Power consumption is 55 µWh during the connected state and 33 µWh during the active time for a cumulated power consumption of 89.6 µWh.

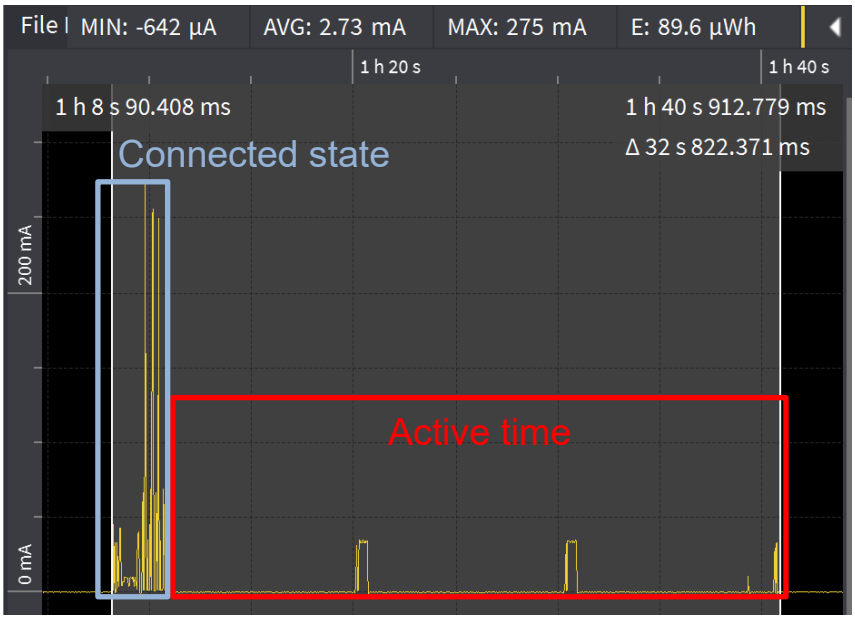

FIGURE 31. Using active time and release assistance indicator when sending a payload from power saving mode

The second possibility is to send the payload when TAU happens. In this case, the main contributing factor to energy consumption is the active time, because the payload size effect is negligeable compared to TAU energetic cost and RAI does not apply to TAU.

In figure 32, the nRF9160 performs its TAU and consecutively sends the 50 B payload. The active time was disabled. The energetic cost for connected state is 259 µWh, which is almost 5 times the amount of energy spent in the connected state when transmitting that payload outside of TAU.

While is seems inefficient to send data during TAU, this is actually the most efficient way to transmit data when using PSM considering TAU must be performed periodically. This strategy makes sense in applications that send data rarely and do not need to be reached often if at all.

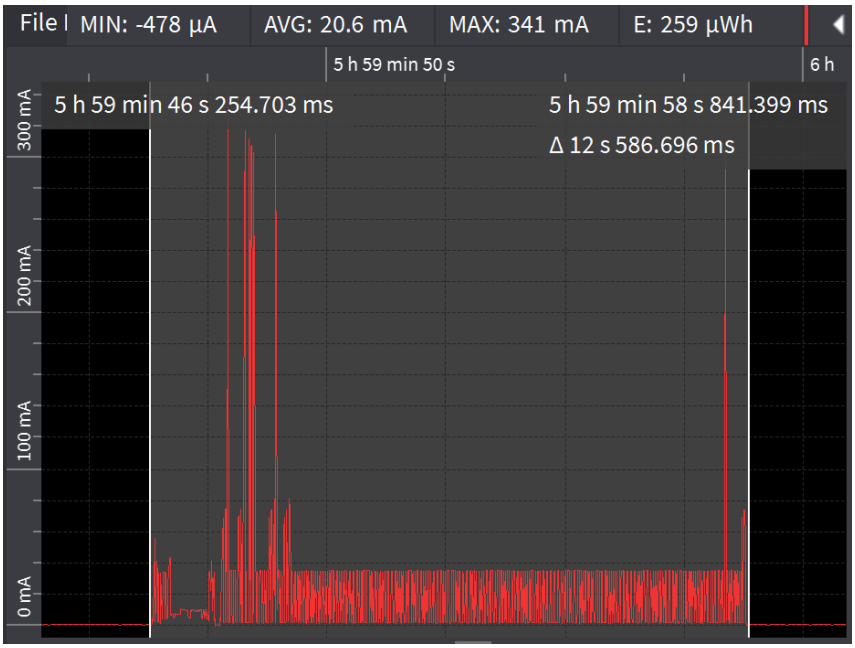

FIGURE 32. Sending a payload during tracking area update

5 SUMMARY OF RESULTS

Using narrowband-IoT power saving features in adequacy with the application uplink and downlink requirements allows for reducing power consumption. Those power saving features include release assistance indicator, extended discontinuous reception and power saving mode. In practice, increasing the battery runtime can be accomplished by reducing the value of the following parameters:

- payload size
- upload frequency
- paging frequency
- paging duration
- tracking area update frequency
- active time duration

Additionally, lowering transmit power by increasing the network signal quality effectively leads to a decrease in power consumption. During the course of this research, many parameters have been identified to affect the signal quality including antenna design, the distance to the base station, the location of the modem and the construction type of the building when it is located indoor, the presence of snow on the roof and its thickness, the altitude of the modem and the weather.

Table 2 summarizes the energetic cost of all events and power saving features measured during this research. The presented data can be used to calculate the battery runtime based on different scenarios for an RSRP of -87 dBm.

TABLE 2. NRF9160 power consumption during specific events at RSRP -87 dBm on Elisa NB-IoT network

eDRX				PSM			
Event	**Parameter tested**	**Value**	**Energetic cost (µWh)**	**Event**	**Parameter tested**		**Energetic cost (µWh)**
Transmit data (50B)	RAI	no	250	Transmit data (50B)	From TAU		259
		yes	46		Outside of TAU, using RAI		55
Transmit data using RAI	Payload size	10 B	46				
		25 B	46				
		50 B	50				
		100 B	54				
		1000 B	69				
Idle 1 hour	DRX	10.24 s	3620	PSM 1 hour			26
	eDRX cycle length (PTW 5.12s)	20.48 s	1873				
		40.96 s	1083				
		81.92 s	545				
		163.84 s	309				
		327.68 s	214				
		10485.76 s	132				
PTW 1 cycle	PTW duration	5.12 s	21	Active time 1 cycle		30 s	49
		15.36 s	33			60 s	98
		25.6 s	48			120 s	179
		35.84 s	66	TAU, 1 event		-	297

It can be noticed that transmitting 50 bytes of data had a different cost when analysing the effect of RAI and the one of payload size. This is a direct consequence of ever-changing signal quality and its resulting transmit power from one day to another as well as a consequence of the low sampling frequency of the power analyser. The measurements performed during this study were not meant to provide absolute consumption values but instead comparative data to understand how each power saving feature individually affects overall power consumption.

6 CONCLUSION

6.1 Power optimization

As depicted in the analysis chapter, optimizing the power consumption of the device relies on many parameters. Deciding on the upload frequency, using eDRX or PSM and selecting the correct timer values depends on the application requirements.

For example, an application which does not need a low uplink latency could store data in a buffer and send it all at once every hour or once a day instead of every few minutes. As it can be calculated from measurement data, increasing the payload size affects power consumption much less than sending several payloads.

In a similar manner, if a device sends data sporadically, does not need to be reached often if at all and aims for the longest possible runtime, using PSM could be more appropriate if TAU is not performed too often.

In a scenario where a device must be able to receive a payload quickly to perform sudden actions, PSM should be avoided in favour of eDRX which allows for constant monitoring of incoming data.

Lastly, unless unsupported by the mobile network operator, RAI should always be used to greatly reduce the amount of time spent in the inactivity state unless there is a specific reason not to do so.

6.2 Mobile network operators and power saving features availability

Mobile network operators do not necessarily support all NB-IoT power saving features. During this study, it was found that Elisa did not support TAU related T3412 inferior to 250 minutes, nor could an active time inferior to 30 seconds be possible. As this might not seem of prime importance, it actually greatly impacts overall power consumption of any device operating on the network.

For example, if an MNO does not support RAI, the greatest power saving feature regarding data transmission cannot be leveraged. The battery runtime can be divided by up to five before even considering the other settings.

Facing the inability to use specific timer values, Elisa was contacted and they investigated the issues encountered during this research. The operator performed modifications on the cellular network side which among other corrections allows NB-IoT devices to request shorter periods between TAU events.

Before deploying devices on a specific network, it is therefore of utmost importance to review if and how the operator implemented the power saving features necessary for an application battery runtime requirement.

6.3 Downlink latency and reachability

This study did not focus on the reachability of the deployed device but exclusively on its power consumption instead. Tests have not been performed to analyse how the eDRX cycle length, PTW duration or active time affect the capability of the device to receive downlink data.

Additionally, mobile network operators have varying specifications regarding network data retention, namely the amount of data it can temporarily store until the device listens for the network and for how long it is stored. In this study, data was only sent to the network and never received, therefore a further research would be necessary to comprehend the implications from using particular timer values for the eDRX cycle, PTW, TAU and PSM active time.

6.4 Sources of inaccuracies

6.4.1 Transmit power

Due to the impossibility of adjusting transmit power, the research was performed according to a worst-case scenario, having the modem set up in a location with a poor signal quality. The main drawback from this approach is an overall higher power consumption than what the modem could achieve in optimal conditions. Therefore, all figures presented in this document are not meant to exhibit the

absolute performance of the nRF9160, but instead they provide useful information to perform a comparative study of NB-IoT power saving modes.

Despite all efforts performed to ensure comparable current levels in each study, slight variations were noticed which may affect results. Additionally, single samples were used for visual comparison of current profiles. While it helped illustrating how each power saving feature works, accuracy would have improved working on average values of multiple identical events instead of single samples.

6.4.2 Measuring equipment

The Qoitech Otii Arc power analyser has a dynamic sampling frequency varying between 4kHz for current values inferior to 19 mA and 1 kHz when current goes above 19 mA. Figure 33 presents a current peak occurring during TAU when the device starts to communicate with the network. The samples taken by the Otii Arc are circled in red.

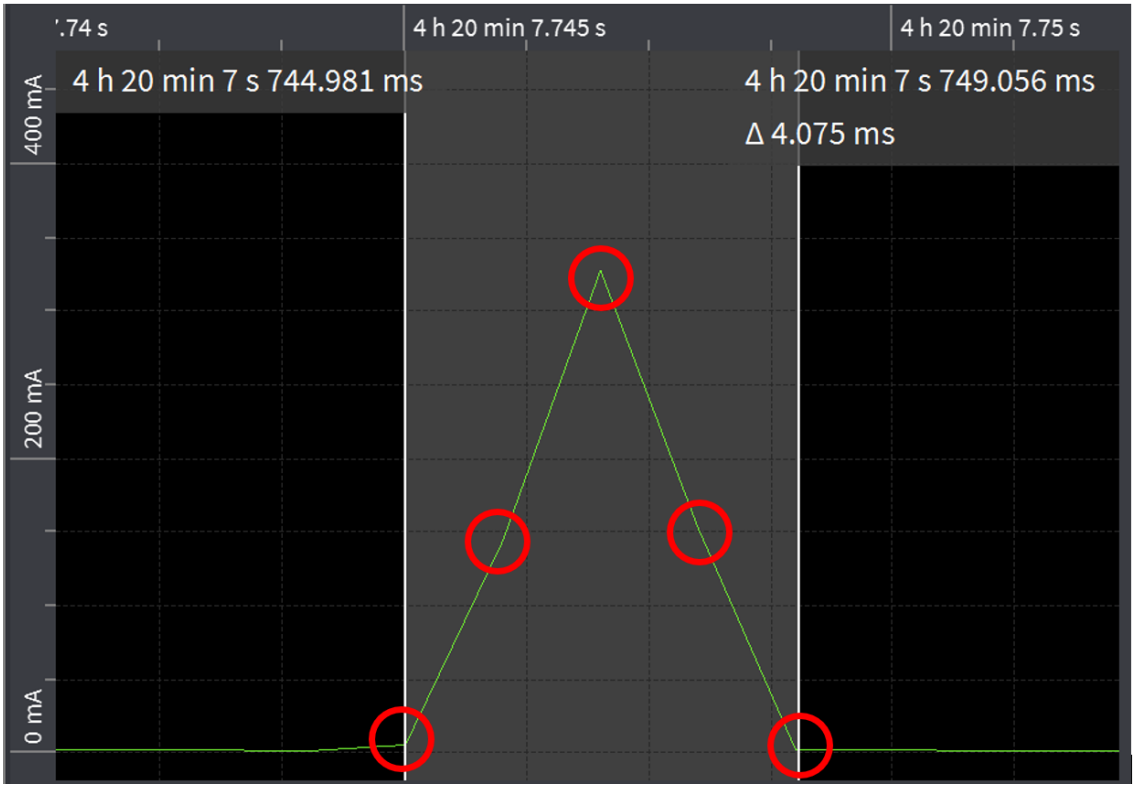

FIGURE 33. Otii Arc sampling of fast transients

While this rather low sampling frequency of 1 kHz does not pose a problem when recording slow and recurring events, such as eDRX paging cycles, it introduces a lack of precision during those fast transients. The resulting energy from the peak presented in figure 33 is computed based on three samples only. According to Qoitech, the error can amount to -6.4% for a 1 ms pulse of 25 mA with a standard deviation of 2.0%.

It can therefore be concluded that the power consumption of the device could have been underestimated during any event involving fast transients, such as transmitting data to the network. Despite this shortcoming, the Otii Arc proved to be a very powerful tool allowing for recording long events and comparing them effortlessly, provided that the lack of precision is taken into consideration when using its output data for battery runtime estimations.

7 DISCUSSION

7.1 Project review

The objectives for this research work were reached. NB-IoT power saving features were individually analysed and their effect on power consumption precisely measured. The output data can be used to calculate the resulting battery runtime when evaluating different scenarios.

The greatest success from this project is the learning process that contributed to reach the results. For example, much has been learnt about measuring equipment, considering that the recordings were originally all performed using other devices including the Agilent 34411A digital multi-meter which showed its limits when trying to record several TAU events. Limited with a memory of one million samples when retrieved remotely from volatile memory, recording several TAU events over a long period of time required to use a low sampling frequency which hid fine details from measurements. This problem led to acquiring better tools for power analysis. This also meant having to start over from the beginning in order to preserve comparability of recordings which must all be performed with the same measuring equipment.

Fundamentally, much was learnt about NB-IoT as well as Cat-M which shares the same power saving features. This resulting document can serve as an illustrated reference thanks to the way each feature is presented and its effect quantified.

7.2 Instructions for developing power efficient NB-IoT applications

The first step towards developing an energy efficient NB-IoT product is to define the absolute requirements for the uplink and downlink latencies as well as the battery runtime. The second step involves verifying that the selected modem supports all necessary features, for example waking from PSM with a built-in hardware timer. The third step is to request information about the supported power saving features and timer values from the targeted network operator.

Once all information is readily available, different scenarios should be evaluated. The first estimation of power consumption can be calculated using the data presented in this document.

Then comes the testing phase. Answers from the network should be monitored when requesting timer values to ensure that they are accepted or alternatively what are the actual timer values granted by the network. The possible values for the application will be determined through trial and error. Finally, power consumption can be measured after disabling logging and compared to the target battery runtime.

If the power consumption is too great to reach the battery runtime target, alternative scenarios should be considered based on the results and conclusion of this research.

7.3 Further development

What happens to T3412 when sending a payload from PSM before the timer expires remains unclear. In theory, the timer should be reset or renegotiated in the same active state as the payload is sent, but it was noticed during the measurements performed for the PSM chapter that this was not the case and TAU happened precisely when the initially negotiated duration for T3412 expired. This technicality affects how often TAU happens when using PSM, which in turn greatly influences power consumption.

More research is necessary to understand how the eDRX cycle length, PTW and active time affect reachability of the device in scenarios involving downlink messages.

All the measurements performed in this research should also be performed for different RSRP values to understand how the signal quality affects power consumption.

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