



Improving the Energy Efficiency of Cellular IoT Device

Muhammad Tahir Abbas

Faculty of Health, Science and Technology

Computer Science

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Faculty of Health, Science and Technology
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MUHAMMAD TAHIR ABBAS

Department of Mathematics and Computer Science

Abstract

Cellular Internet of Things (CIoT) has emerged as a promising technology to support applications that generate infrequent data. One requirement on these applications, often battery-powered devices, is low energy consumption to enable extended battery life. Narrowband IoT (NB-IoT) is a promising technology for IoT due to its low power consumption, which is essential for devices that need to run on battery power for extended periods. However, the current battery life of NB-IoT devices is only a few years, which is insufficient for many applications. This thesis investigates the impact of energy-saving mechanisms standardized by 3GPP on battery life of NB-IoT devices. The main research objective is to classify and analyze existing energy-saving solutions for CIoT and examine their limitations, to study the impact of standardized energy-saving mechanisms on the battery life of NB-IoT devices, both in isolation and combined, and to provide guidelines on how to configure NB-IoT devices to reduce energy consumption efficiently. The research aims to provide a deeper understanding of the effect of energy-saving mechanisms and best practices to balance energy efficiency and performance of NB-IoT devices. Applying the proposed solutions makes it possible to achieve a battery life of 10 years or more for CIoT devices.

Keywords: CIoT, 3GPP, energy saving, mMTC, NB-IoT, LTE-M, EC-GSM-IoT

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Karlstad, March 23, 2023

Muhammad Tahir Abbas

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List of Appended Papers

1. **Muhammad Tahir Abbas**, Karl-Johan Grinnemo, Johan Eklund, Stefan Alfredsson, Mohammad Rajiullah, Anna Brunstrom, Giuseppe Caso, Konstantinos Kousias, Özgü Alay. Energy-Saving Solutions for Cellular Internet of Things - A Survey. IEEE Access, vol. 10, pp. 62073-62096, 2022, doi: 10.1109/ACCESS.2022.3182400.
2. **Muhammad Tahir Abbas**, Johan Eklund, Karl-Johan Grinnemo, Anna Brunstrom, Stefan Alfredsson, Özgü Alay, Sándor Katona, Gergely Seres, Bela Rathonyi. Guidelines for an Energy Efficient Tuning of the NB-IoT Stack. 2020 IEEE 45th LCN Symposium on Emerging Topics in Networking (LCN Symposium), 2020, pp. 60-69, doi: 10.1109/LCN-Symposium50271.2020.9363265.
3. **Muhammad Tahir Abbas**, Johan Eklund, Anna Brunstrom, Stefan Alfredsson, Mohammad Rajiullah, Karl-Johan Grinnemo, Giuseppe Caso, Konstantinos Kousias, Özgü Alay. On the Energy-efficient Use of Discontinuous Reception and Release Assistance in NB-IoT. The IEEE 8th World Forum on Internet of Things (IEEE WFIoT) 2022, Yokohama, Japan, 26 October to 11 November 2022 - **2nd Place Best Paper Award**.

Comments on my Participation

Paper I Being a main author of this paper, I was responsible for conducting a comprehensive literature review of CIoT technologies and synthesized and summarized the findings to produce an organized and comprehensive analysis of the relevant research. Also, I consulted with other authors, particularly Karl-Johan Grinnemo who was responsible for developing the idea, to gain additional insights and develop a comprehensive understanding of the topic. Finally, I contributed to drafting the paper in terms of writing and editing.

Paper II As the lead author for the paper, I was responsible for designing the experiments, developing the simulator for the experiments with the help of Karl-Johan Grinnemo, conducting the experiments, and analyzing the resulting data. Additionally, I wrote the entire paper, while Karl-Johan Grinnemo and Johan Eklund was in charge of developing the idea and providing guidance and direction to the rest of the research team, ensuring that our research was completed in a timely and efficient manner. In order to ensure our findings were communicated effectively to the reader, every author contributed in reviewing and providing valuable feedback.

Paper III As the lead author of the paper, I developed and implemented the simulation experiments, analyzed the data, and wrote the paper. My co-

authors provided support and feedback on the data from the real-world experiments conducted by Konstantinos Kousias. Karl-Johan Grinnemo and Anna Brunström developed the idea and provided direction and guidance to the team, ensuring that the research was completed in a timely and efficient manner. To ensure our findings were communicated effectively to the reader, I wrote all the sections of the paper including introduction and conclusion of the paper.

Other publications

The following is the other publication I have authored that is not included in this thesis.

Muhammad Tahir Abbas, Johan Eklund, Karl-Johan Grinnemo, Anna Brunstrom. Impact of Tunable Parameters in NB-IoT Stack on the Energy Consumption. Proceedings of Fifteenth Swedish National Computer Networking Workshop (SNCNW). Presented at the 15th Swedish National Computer Networking Workshop (SNCNW 2019). Luleå, June 4-5, 2019.

Note: Some of the appended papers have been subjected to minor editorial changes.

Table of abbreviations

Abbreviation	Meaning
<i>2G</i>	Second-Generation cellular system
<i>3G</i>	Third-Generation cellular system
<i>3GPP</i>	3rd Generation Partnership Project
<i>4G</i>	Fourth-Generation cellular system
<i>5G</i>	Fifth-Generation cellular system
<i>ACB</i>	Access Class Barring
<i>ARM</i>	Advanced RISC Machines
<i>ARQ</i>	Automatic Repeat reQuest
<i>B-MAC</i>	Berkeley-MAC
<i>BLER</i>	BLock Error Ratio
<i>BS</i>	Base Station
<i>CC</i>	Coverage Classes
<i>cDRX</i>	connected mode Discontinuous Reception
<i>CE</i>	Coverage Enhancement
<i>CIoT</i>	Cellular Internet of Things
<i>CoAP</i>	Constrained Application Protocol
<i>CoCoA</i>	CoAP Congestion Control Advanced
<i>CP</i>	Control Plane
<i>CMM</i>	Connected Mode Mobility
<i>DRX</i>	Discontinuous Reception
<i>DTLS</i>	Datagram Transport Layer Security
<i>EAB</i>	Extended Access Barring
<i>EC-GSM-IoT</i>	Extended Coverage GSM IoT
<i>ECL</i>	Extended Coverage Levels
<i>EDT</i>	Early Data Transmission
<i>EPS</i>	Evolved Packet System
<i>eDRX</i>	extended Discontinuous Reception
<i>eGPRS</i>	enhanced General Packet Radio Service
<i>FACC</i>	Fast Associated Control Channel
<i>FI-TSFGP</i>	Further Improved-TSFGP
<i>GID</i>	Group ID
<i>GMSK</i>	Gaussian Minimum Shift Keying
<i>GSM</i>	Global System for Mobile Communications
<i>GP</i>	Group Paging
<i>HARQ</i>	Hybrid Automatic Repeat ReQuest
<i>HSS</i>	Home Subscriber Server
<i>IAT</i>	Interval Arrival Times
<i>iDRX</i>	IDLE mode Discontinuous Reception
<i>IETF</i>	Internet Engineering Task Force
<i>IoT</i>	Internet of Things
<i>IMM</i>	Idle Mode Mobility
<i>ITR</i>	Inactivity TimeR
<i>LAA</i>	Licensed-Assisted Access

Abbreviation	Meaning
<i>LTE</i>	Long Term Evolution
<i>LTE-M</i>	Long Term Evolution Machine Type Communication
<i>LoRaWAN</i>	Long-Range Wide-Area Network
<i>LPWAN</i>	Low-Power Wide-Area Network
<i>LwM2M</i>	Lightweight Machine-to-Machine
<i>MAC</i>	Medium Access Control
<i>MCS</i>	Modulation and Coding Scheme
<i>MCL</i>	Maximum Coupling Loss
<i>MME</i>	Mobility Management Entity
<i>MTC</i>	Machine-Type Communications
<i>mMTC</i>	massive Machine-Type Communications
<i>MQTT</i>	Message Queue Telemetry Transport
<i>MQTT_SN</i>	MQTT for Sensor Networks
<i>NR</i>	New Radio
<i>NAS</i>	Non-Access Stratum
<i>NB-IoT</i>	Narrowband - Internet of Things
<i>OFDMA</i>	Orthogonal Frequency Division Multiple Access
<i>PIE</i>	Packet Inspection Entity
<i>PPCH</i>	Packet Paging CHannel
<i>PPE</i>	Packet Prediction Entity
<i>PSM</i>	Power Saving Mode
<i>PTW</i>	Paging Transmission Window
<i>PGW</i>	Packet Gateway
<i>PDCCH</i>	Physical Downlink Control CHannel
<i>QoS</i>	Quality-of-Service
<i>QPSK</i>	Quadrature Phase-Shift Keying
<i>RAI</i>	Release Assistance Indicator
<i>RRC</i>	Radio Resource Control
<i>RTO</i>	Retransmission TimeOut
<i>RTT</i>	Round Trip Time
<i>REST</i>	REpresentational State Transfer
<i>S-MAC</i>	Sensor-MAC
<i>SCEF</i>	Service Capability Exposure Function
<i>SGW</i>	Serving Gateway
<i>SMS</i>	Short Message Service
<i>SR</i>	Service Request
<i>TAU</i>	Tracking Area Update
<i>T-MAC</i>	TimeOut-MAC
<i>TCP</i>	Transmission Control Protocol
<i>TCH</i>	Traffic CHannel
<i>TSFGP</i>	Traffic Scattering For Group Paging
<i>UE</i>	User Equipment
<i>ULLC</i>	Ultra-Reliable Low Latency Communications
<i>UDP</i>	User Datagram Protocol
<i>VoLTE</i>	Voice over LTE

Introductory Summary



1 Introduction

Recent studies by Ericsson [1] and Advanced RISC Machines (ARM) [2] found that the number of connected devices will exceed 50-100 times the world's population of 8 billion people by 2035. This significant increase in the number of connected devices is mainly due to a considerable growth of the Internet of Things (IoT) [3], which is as shown in Fig. 1 estimated to have 1 trillion devices by 2035. While most of these devices will be consumer-oriented, such as connected cars and wearable devices, a significant portion will be industrial devices, including connected machines and sensors.

Traditional IoT networks rely on short-range communication technologies such as Wi-Fi and Bluetooth, which are limited in range and speed, making them unsuitable for certain applications such as remote monitoring and control, as shown in Fig. 2. To address this, Cellular Internet of Things (CIoT) [4] (also termed as Low-Power Wide-Area Network (LPWANs) [5] technology) was proposed as a solution, combining the benefits of the existing cellular network infrastructure with the Internet of Things to provide wide coverage, reliability, security, scalability, and power efficiency. In further developments, 3GPP proposed Long Term Evolution-M (LTE-M) in release 12, also known as CAT-M1 and CAT-M2, and Narrowband Internet of Things (NB-IoT) in release 13 with the focus on extremely low data rates, narrow frequency band, and extended coverage for applications such as smart city infrastructure, smart agriculture, and remote monitoring. As an alternative to CIoT, technologies such as LoRaWAN (Long-Range Wide area Network) [6] and Sigfox [7, 8] offer a viable option. These networks can cover up to 10 kilometers or more and are power-efficient, making them well-suited for remote areas. Despite their advantages, these technologies require deploying new infrastructure that can be expensive and time-consuming and therefore is not a perfect solution in most scenarios.

Among all these LPWAN technologies, NB-IoT technology offers several advantages, as shown in Table 2. It is more efficient, providing greater range, lower power consumption, and improved security. It is also the most cost-effective option since it can be deployed in the current cellular infrastructure and require fewer resources. NB-IoT can be used in both licensed and unlicensed spectrum, making it more flexible and allowing it to be deployed in more places. Finally, NB-IoT can handle greater data speeds than other LPWAN technologies, making it suitable for more advanced applications.

The features of NB-IoT make it well-suited for a variety of applications, including: 1) Smart cities [9], where it can be used to connect a variety of devices and sensors in a city, such as traffic lights, parking meters, and air quality sensors, and in this way improve city planning and management; 2) Asset tracking [10], where it can facilitate tracking assets such as vehicles, containers, and in so doing improve supply chain management; 3) Environmental monitoring [11], where it can enable the monitoring of environmental conditions such as air and water quality, and thus improve environmental protection; 4) Industrial automation [12], where it can connect industrial machines and sen-

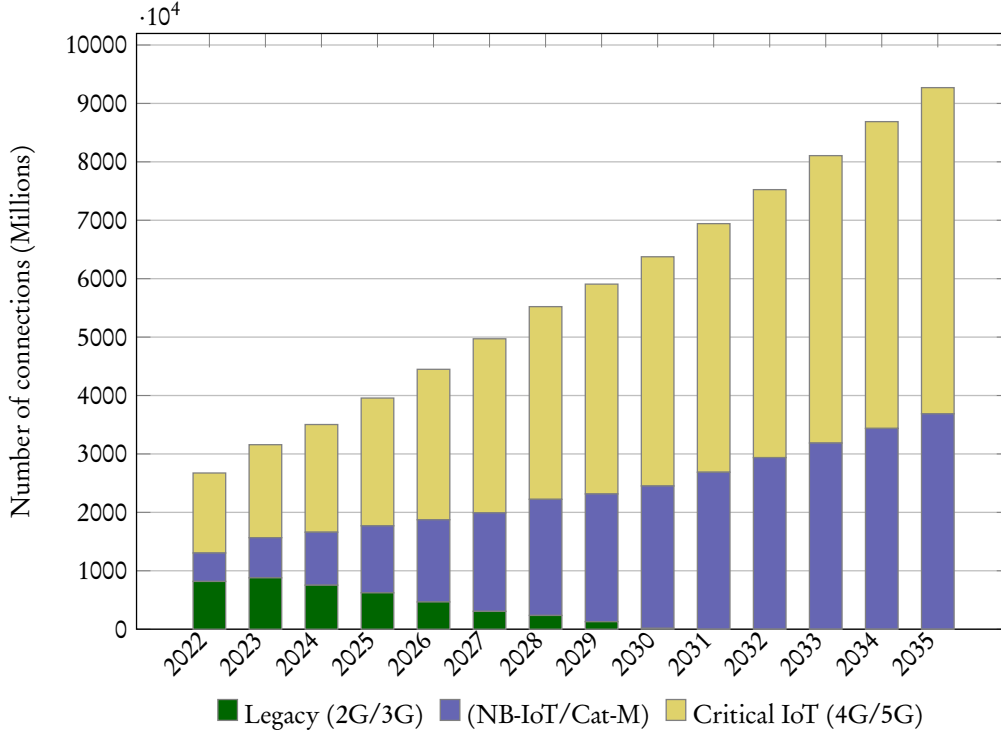


Figure 1: CIoT device connections forecast 2015-2027 by Ericsson (Ericsson Mobility Report) [1].

sors, and make the manufacturing process more efficient; 5) Healthcare [13], where it can be used to connect medical devices and sensors, and in this way improve patient care.

NB-IoT targets battery-powered devices and is designed for mass deployment; in fact, it is designed to support 100,000 or more devices per cell. Several NB-IoT applications involve deploying IoT devices in remote areas with tiny batteries as their only reliable power source. Since replacing batteries for many devices would be cumbersome and excessively costly, battery lifetime is a crucial concern for NB-IoT. The 3GPP standard determines the target battery lifetime in NB-IoT devices. This standard states that the minimum battery life for an NB-IoT device must be 10 years.

The longevity of a battery that charges an NB-IoT device depends to some extent on the technology used in the physical layer for transmitting and receiving data [14]; however, it depends to a greater extent on how efficiently the device can utilize various energy-saving mechanisms that allow large parts of the device to be powered down for extended periods [15, 16]. With NB-IoT technology, it is essential to ensure a long battery life of at least 10 years with non-rechargeable and non-replaceable batteries. Therefore, energy efficiency is of the utmost importance; to achieve this, it is essential to carefully select energy-saving parameters when deploying devices in deep indoor scenarios. This thesis, therefore, explores the impact of the energy-saving mechanisms standardized by 3GPP, both separately and in combination with each other, on the device energy consumption. Based on the conducted studies, guide-

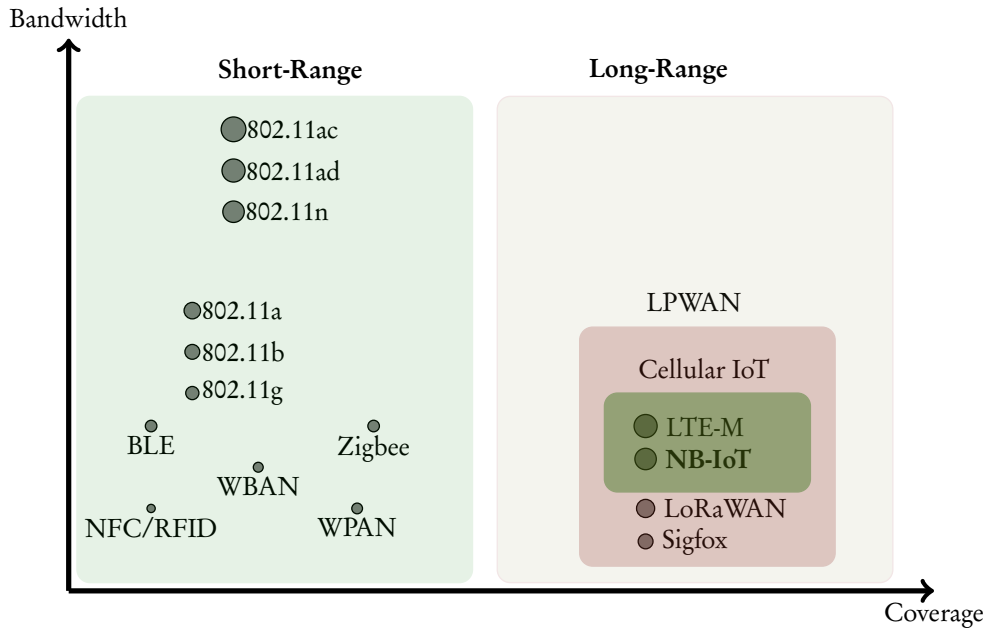


Figure 2: An approximate comparison of short-range and long-range IoT technologies

lines are provided that will significantly increase the battery life of NB-IoT devices. Although this thesis only considers NB-IoT, many of its findings apply to other CIoT technologies, not least CAT-M, which partly employs similar energy-saving mechanisms as NB-IoT.

3GPP has defined several methods to reduce the power consumption of NB-IoT devices. One method is to use low-power consumption modes for transmission and reception, which helps to reduce the overall power consumption of the device [17, 18]. Discontinuous reception (DRX) [19] is another important feature in NB-IoT networks as it allows devices to reduce their power consumption while still being able to receive data from the base station. The DRX mechanism is inherited from LTE and allows the NB-IoT device to shut down its radio transceiver for periods of time and then periodically wake up and check for incoming messages from the network. In addition, 3GPP has also defined various other power-saving methods for NB-IoT, including: Power Saving Mode (PSM): PSM is a power-saving mode that can be used by NB-IoT devices when they are not actively transmitting or receiving data; Extended DRX (eDRX): eDRX is an extension of the DRX power-saving feature that allows NB-IoT devices to enter a low-power state for an extended period, thereby further reducing power consumption; Connected Mode DRX (cDRX): cDRX is a power-saving method that is specifically designed for NB-IoT devices that are connected to the network but are not actively transmitting or receiving data; and Release Assistance Indicator (RAI): RAI [20] is used in NB-IoT to save power by allowing the network to release a connection when it is no longer needed. RAI can reduce battery drain by turning off the device radio and releasing network resources early.

Table 2: NB-IoT and CAT-M Comparison

Technology	NB-IoT	CAT-M
Data Rate	200 kbps (uplink)	1 Mbps (uplink and downlink)
Frequency Bands	Sub-1 GHz	LTE
Range (urban-rural)	1-15 km	1-10 km
Power Consumption	Low	High
Use Cases	Smart Homes	Automotive
Device Size	Small	Medium

This thesis aims to identify the crucial energy-saving mechanisms of CIoT technologies, and highlight the importance of various use cases. It is essential to understand that energy-saving mechanisms are interconnected and their configuration is critical. All energy-saving mechanisms must work together to reduce energy consumption and enhance battery life. This thesis studies the interdependence between energy-saving mechanisms and their configurations to maximize battery life and decrease energy consumption. It investigates the impact of 3GPP standardized energy-saving mechanisms on the battery life of NB-IoT devices, and provides guidelines on how to design and configure them to reduce energy consumption efficiently. It features a literature review on existing energy-saving solutions for CIoT, an analysis of each energy-saving mechanism's individual and combined impact on device battery life, and best practices to obtain a good balance between energy efficiency and performance.

The rest of the introductory summary is organized as follows. Section 2 delves into NB-IoT, its radio operations, and energy saving mechanisms. The main objective and the research questions addressed in this thesis are outlined in Section 3. Section 4 discusses research methods employed by the appended papers. Section 5 examines the main contributions of this work. A summary of the appended papers is provided in Section 6. Finally, Section 7 concludes the introductory summary and discusses future work.

2 Background

This section provides a comprehensive overview of the NB-IoT technology, including its use cases, deployment scenarios, radio operations, and energy-saving mechanisms that 3GPP has standardized. By leveraging these energy-saving mechanisms, the NB-IoT technology has the potential to provide low-cost, low-power, and reliable communication for a vast array of IoT applications, allowing for increased automation and improved efficiency across a variety of industries.

NB-IoT (Narrowband Internet of Things) is an LPWAN radio technology standard developed by 3GPP to enable a wide range of cellular devices and services. NB-IoT is designed to accommodate the massive growth of IoT devices by providing cellular connectivity to a wide range of devices with low power consumption and at a low cost. NB-IoT is an evolution of the LTE (Long Term Evolution) standard and is designed to operate in licensed spectrum. It

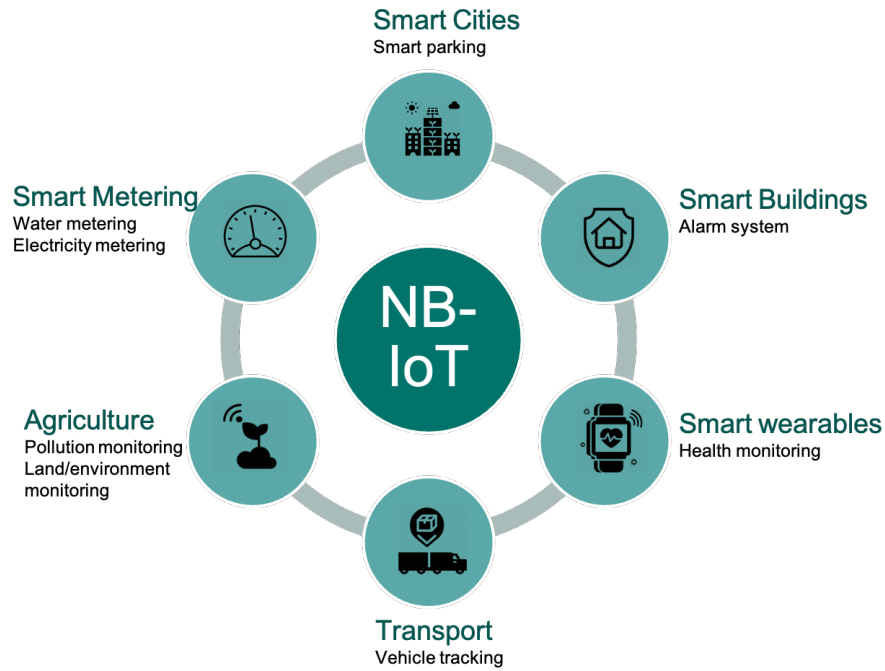


Figure 3: Multiple applications for NB-IoT technology.

uses a tinier version of the LTE radio interface and requires only a single narrowband carrier with a bandwidth of 180 kHz. The employed radio interface reduces power consumption and cost while still providing the same coverage and capacity as LTE [21]. In addition, NB-IoT also uses different modulation schemes than LTE; it uses Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink and Single-carrier FDMA (SC-FDMA) in the uplink, which gives an efficient use of the radio resources and results in low power consumption.

2.1 NB-IoT Use Cases

The use cases for NB-IoT technology are many and varied. The technology is used in various industries and applications to provide secure, efficient, and reliable data transmission over cellular networks. NB-IoT can be used for monitoring and tracking assets, for smart metering, for controlling and managing devices, for providing location-based services, and for other applications. It is particularly useful for applications that require low power consumption and robust data connectivity. An overview of some of the most common use cases for NB-IoT technology is provided below and also illustrated in Fig. 3.

Smart metering and energy management are among the most popular use cases for NB-IoT technology. NB-IoT-enabled devices monitor energy consumption in real-time, allowing utilities to manage their energy usage better and improve efficiency. This technology also allows for remote control and monitoring of energy usage, enabling consumers to save money by managing their energy consumption more effectively.

Another use case for NB-IoT is asset tracking and management. This technology can track the location and status of assets, such as vehicles, containers, or parcels. It allows companies to improve their supply-chain efficiency by ensuring that their assets are always where they should be. In addition, NB-IoT technology is often used for remote healthcare applications. These devices can monitor a patient's vital signs and medical conditions remotely, allowing healthcare providers to provide better care more efficiently.

NB-IoT offers several advantages over other LPWAN technologies, such as LoRaWAN and Sigfox, including higher data rates, lower power consumption, availability, Quality-of-Service (QoS), network security, and lower costs. Several major operators worldwide, including AT&T, Vodafone, and China Mobile, are currently deploying NB-IoT.

2.2 NB-IoT Deployment

The deployment of NB-IoT is vital for cellular operators as it enables them to extend their networks' coverage without needing additional infrastructure. The coverage extension is facilitated by reusing existing cellular spectrum bands and network elements, such as cell sites and base stations. The deployment of NB-IoT within the existing cellular infrastructure enables operators to provide a more reliable and secure connection for IoT devices. The increase in reliability and security is made possible through low-power transmission and a more sophisticated modulation scheme, which reduce interference and improve the reliability of the connection. NB-IoT supports the following four deployment scenarios:

1. **Standalone Deployment:** This deployment scenario involves deploying a dedicated network for NB-IoT, whereby a licensed spectrum is dedicated to the NB-IoT network. This type of deployment offers the most control and flexibility for network providers.
2. **In-Band Deployment:** This deployment scenario involves the deployment of NB-IoT in the same spectrum as other cellular technologies such as LTE. By leveraging existing infrastructure, the deployment cost and time are reduced. However, it has the potential to create interference between different technologies.
3. **Guard-Band Deployment:** This deployment scenario involves the deployment of NB-IoT in a spectrum separate from other technologies but adjacent to them. Guard-band deployment offers the flexibility of in-band deployment while reducing the risk of interference.
4. **NB-IoT and Licensed-Assisted Access (LAA)¹:** This deployment scenario involves the deployment of both NB-IoT and LAA in the same

¹Licensed-Assisted Access (LAA) is a technology used in 4G and 5G networks that allows unlicensed spectrum (such as WiFi) to be used in combination with licensed spectrum (such as cellular) to increase the overall capacity of a cellular network. It works by allowing users to access the unlicensed spectrum for short bursts of data traffic, while relying on the licensed spectrum for data throughput.

spectrum [22], and enables for the use of both technologies in the same area, allowing for more efficient spectrum use.

The power range of NB-IoT is from -40 dBm to +23 dBm. This range covers various applications, from residential and consumer scenarios to industrial applications. The wide range of power levels allows for more flexibility in coverage and capacity, making it ideal for various applications. At the lower end of the range, signals are more secure and reliable but require more power to transmit. Conversely, signals are weaker at the higher end of the range but require less power to transmit. Additionally, the low-power nature of the technology allows for longer battery life in devices, allowing for more extended deployments.

2.3 Radio Operation of NB-IoT

The Radio Resource Control (RRC) layer is a crucial component in the NB-IoT technology stack, responsible to configure, monitor, and release radio resources. In particular, the RRC protocol provides several key functions, such as connection establishment and release, RRC connection re-establishment, radio bearer setup and release, mobility management, paging, and security. As shown in Fig. 4, NB-IoT devices can be in two major RRC states: *RRC_CONNECTED* and *RRC_IDLE*. In the *RRC_CONNECTED* state, the device has an active RRC connection and can transmit and receive data. In the *RRC_IDLE* state, the device does not have an active RRC connection and thus cannot send or receive data.

The RRC uses several timers to control the various aspects of radio resource management: 1) The *RRC_CONNECTED* state timer or the Inactivity Timer (ITR) controls the duration of an idle RRC connection between the Base Station (BS) and the User Equipment (UE), 2) The *RRC_IDLE* state timer or the Tracking Area Update (TAU) timer controls the time that the mobile device remains in the *RRC_IDLE* mode, 3) Finally, the RRC Active Timer controls the time that the mobile device remains in the RRC Active mode.

2.4 NB-IoT Energy-saving Mechanisms

To reduce the power consumption of NB-IoT devices, using energy-saving techniques defined by 3GPP is essential. Some of the most common energy-saving techniques for NB-IoT include: Power Saving Mode [23], Discontinuous Reception [24], and Release Assistance Indicator [25]. By using these energy-saving techniques, it is possible to reduce the power consumption of CIoT devices by up to 90%. We detail the energy-saving mechanisms, particularly for NB-IoT, which are critical in achieving a long battery life, below.

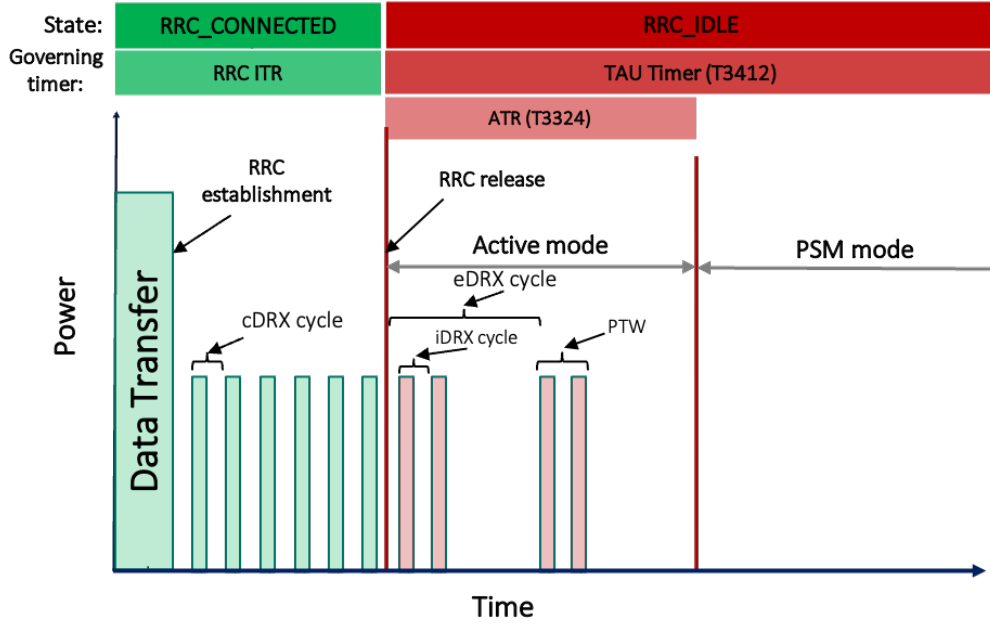


Figure 4: NB-IoT RRC states with energy-saving features, such as: *cDRX*, *eDRX*, *PSM*, etc.

2.4.1 Discontinuous Reception

Discontinuous Reception, or DRX, is one of the key energy-saving mechanisms of NB-IoT. DRX allows the NB-IoT device to power down its radio receiver during inactivity, reducing power consumption, as shown in Fig. 4. DRX can be further optimized by using a longer on-duration or a shorter off-duration or both and reducing the number of active RX slots per DRX cycle. DRX allows devices to reduce their power consumption in both the *RRC_CONNECTED* and *RRC_IDLE* states. In the *RRC_CONNECTED* state, connected DRX (*cDRX*) enables a device to enter a low-power state for a period of time after it has transmitted data. During this time, the device will not actively listen for incoming messages from the base station, thus reducing its power consumption. When the device leaves the low-power state, it will resume listening for messages from the base station.

In the *RRC_IDLE* state, DRX makes it possible for a device to enter a low-power state for a period without actively listening for incoming messages from the base station. When the low-power state is left, the device will resume listening for messages from the base station. Again, during this time, the device will not transmit or receive any data, thus reducing its power consumption. However, this time the listening is done more sporadically compared to *cDRX* and is called extended DRX or *eDRX*.

2.4.2 Paging and Paging Time Window

Paging in NB-IoT is done by the base station sending a broadcast message to devices in a cellular network. The process initiates communication with a spe-

cific device and informs the device about incoming data. The device responds to the message only if it is the intended recipient. NB-IoT technology uses a specific protocol and message structure to carry out this type of communication. This protocol is optimized for low-power devices, allowing the paging process to be conducted even when limited power is available. The paging process initiates communication between a base station and a device, and the message sent can contain data or instructions. This process is essential to ensure efficient communication between the base station and the device and that the device is kept up-to-date.

The Paging Time Window (PTW) in NB-IoT is a feature that allows the network to send paging requests to a target device during a specific time interval rather than sending them continuously. It reduces the power consumption of the device. It increases battery life since the device will only need to receive and respond to a paging request during the PTW instead of constantly monitoring incoming requests. The length of the PTW and the paging interval are configurable by the network so that it can be optimized for specific use cases.

2.4.3 Power Saving Mode

Power Saving Mode (PSM) is transparent to the application and the end user and does not require any changes to the existing NB-IoT network. PSM is supported by all major NB-IoT chipsets and modules and is already deployed in NB-IoT networks worldwide. PSM is based on the principle of discontinuous reception, where the NB-IoT device only periodically wakes up to receive data, as shown in Fig. 4. The wake-up and sleep period lengths are configurable and can be optimized for different applications. For example, a device that only needs to receive data once an hour can be configured to wake up for a few seconds every hour and remain in sleep mode for the rest of the time. The sleep periods result in a significant reduction in energy consumption without sacrificing the quality of service. PSM also supports the mechanism of Tracking Area Updates (TAU). The TAU timer saves power by reducing the time a device needs to update its location. It works by allowing the network to keep track of the location of a device for a certain amount of time. After the timer expires, the device must send a TAU request to the network to update its location.

2.4.4 Release Assistance Indicator

The Release Assistance Indicator (RAI) was standardized by 3GPP in release 14 and is an essential feature of NB-IoT. RAI enables the network to efficiently manage its resources by releasing unneeded radio resources, as shown in Fig. 5. Moreover, it allows the network to ensure that it is used effectively and that a device saves its battery resources. The RAI is sent from the network to the device to inform the device that it is time to release its allocated resources. The RAI is typically sent as part of an uplink grant message and indicates the type of resources the device should release, including the radio resource blocks allocated to the UE.

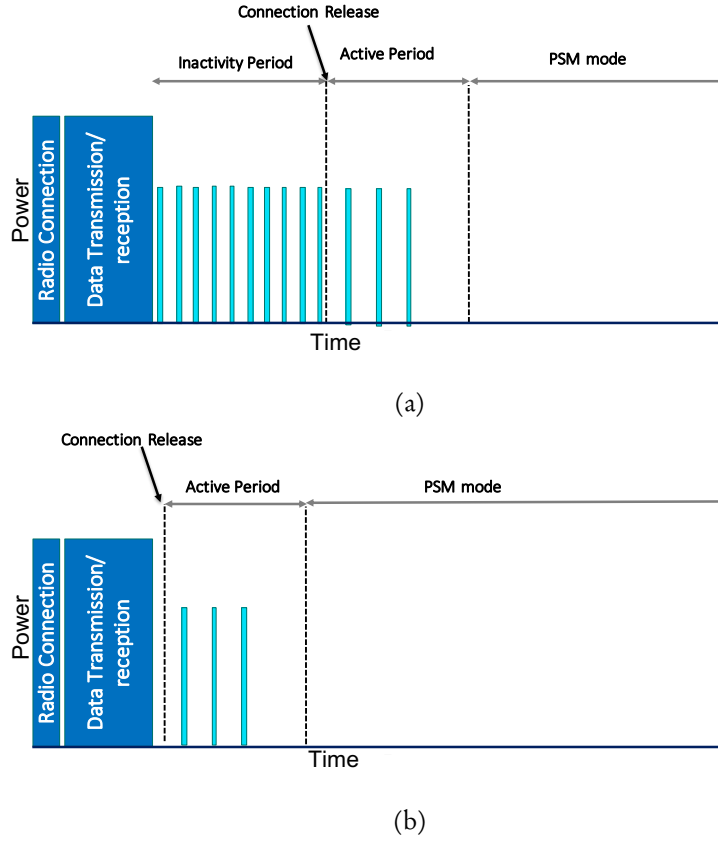


Figure 5: The graph illustrates how energy consumption depends on when the radio connection is released. Fig. (a) illustrates the energy consumption when the connection is released after the Inactivity Timer expires, and Fig. (b) shows the energy consumption when the connection is released due to a request from the UE (RAI).

Once the NB-IoT device has received a RAI, it will start releasing allocated resources: The device sends a Release Request to the network. The network responds with an acknowledgment message confirming that the resources have been released. Once the resources have been released, the network can reallocate them to other devices. In this way, RAI effectively manages the network's resources and helps NB-IoT device release radio connections and save battery.

3 Research Objectives

This thesis focuses on extending the battery life of NB-IoT devices. In particular, the main research objective of this thesis is:

To examine the impact of the standardized energy-saving mechanisms by 3GPP on the energy consumption of NB-IoT devices, both individually and in combination, and provide guidelines on how to configure the mechanisms in order to minimize the energy consumption of these devices.

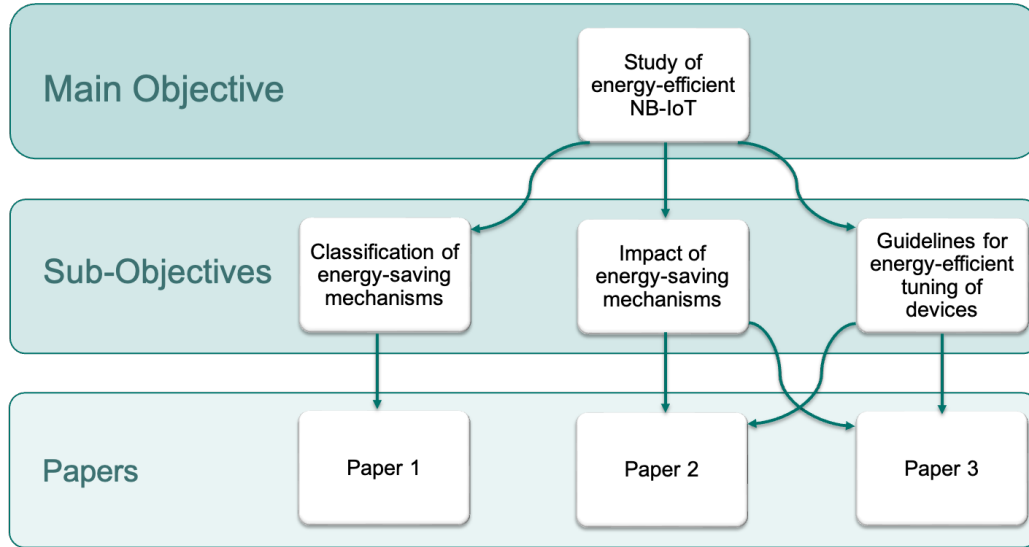


Figure 6: A diagram showing the mapping between the appended papers and the research objectives.

The main objective is divided into the following three sub-objectives:

- (O1) *To classify and analyze existing energy-saving solutions for CIoT.*
We study existing energy-saving mechanisms for CIoT, proposed by 3GPP and others [26, 27], to understand their limitations and shortcomings. Examining these mechanisms allows us to gain in-depth knowledge about the extent of each mechanism's impact on device battery life. We also aim to classify existing energy-saving mechanisms and provide a literature study.
- (O2) *To study the impact of standardized energy-saving mechanisms on the battery life of NB-IoT devices.*
Several studies try to evaluate the NB-IoT energy-saving mechanisms standardized by 3GPP [25, 28]. However, only some offer a detailed investigation of the impact of each mechanism under a broad spectrum of conditions. We aim to study the extent to which the major energy-saving mechanisms standardized by 3GPP extend the battery life of NB-IoT devices, both in isolation and combined.
- (O3) *To provide guidelines on how to configure NB-IoT devices to reduce their energy consumption efficiently.*
We provide guidelines on how to efficiently reduce the energy consumption of NB-IoT devices. We also aim to provide best practices to obtain a good balance between the energy efficiency and performance of these devices.

Figure 6 illustrates how the three appended papers relate to the three different objectives.

4 Research Methods

Computer Science is an ever-evolving field requiring new and innovative research approaches. Scientists must constantly find new ways to study and analyze data to advance the field. The scientific research methods in computer science are varied and often depend on the research question or project. Generally, the methods can be divided into three main categories: quantitative, qualitative, and empirical.

Quantitative methods involve using mathematics and statistics to measure, analyze, and compare data. Examples of quantitative methods include surveys, experiments, and simulations. Qualitative methods involve using descriptive methods to gain insight into the research question or project. Examples of qualitative methods include interviews, focus groups, and participant observation. Finally, empirical methods involve using both quantitative and qualitative research methods. This approach allows researchers to take an integrated approach to research and comprehensively understand the research question or project. This approach allows researchers to gain a more comprehensive understanding of the research question or project. Additionally, the empirical scientific method can help researchers identify patterns and trends in the data.

This thesis revolves around computer science and follows the empirical scientific method, which includes several steps, as shown in Fig. 7. The following steps can summarize the empirical scientific method:

- 1) **Problem Statement:** The first step in the scientific method is to identify a problem or question to be investigated and answered, i.e., the problem statement. The problem statement should be clearly stated and provide a framework for the scientific method.
- 2) **Hypothesis Building:** The next step is to create hypotheses explaining the problem and providing a basis for experimentation. Hypotheses should be well-defined, testable, and measurable.
- 3) **Experiment Design:** The experiments should be designed to test the hypotheses accurately and efficiently.
- 4) **Hypothesis Testing:** The experiments should then be performed and the results should be compared to the hypotheses.
- 5) **Analysis:** The results should be analyzed in order to draw conclusions. The outcomes of this step should be used to support or refute the hypotheses.

Hypothesis testing in computer science can involve a variety of experimental setups. Analytical modeling involves evaluating the system with theoretical and often mathematical models. Simulation, meanwhile, uses models of the system and its environment that are more accurate and life-like than those used in analytical modeling. Emulation combines simulation and real-world experimentation, wherein only some parts of the system and environment are

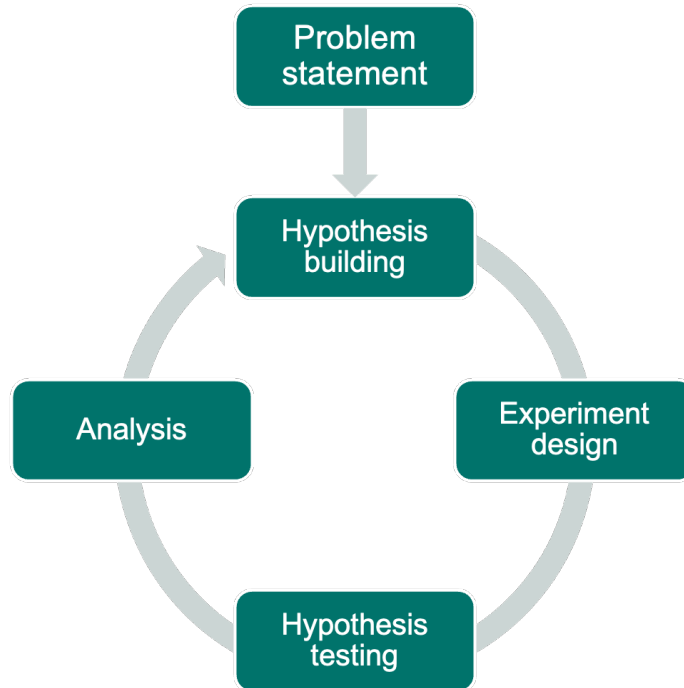


Figure 7: An overview of the iterative, scientific method.

modeled while the rest are actual components. Finally, real-world experimentation involves experiments conducted in the real world.

Analytical modeling, simulation, emulation, and real-world experiments all present their own advantages and disadvantages. Analytical modeling can enable researchers to understand the core mechanisms of a system's behavior and does not necessitate using many resources. Similarly, simulation is flexible and allows full control of the environment without buying or setting up expensive and intricate infrastructure. However, the results produced by both analytical modeling and simulation many times deviate from reality and include several assumptions and simplifications. Emulation, on the other hand, produces results much closer to the real world while still allowing full control of the environment, and real-world studies provide the most accurate results but limit the control a researcher has over the environment. To this end, real-world experiments reduce the ability to repeat an experiment and verify its results. Consequently, great caution should be taken to limit the effect of noise on the measurements, which can be done by running multiple experiments.

Simulated environments are an important tool for studying the energy consumption of CIoT devices because they provide a controlled platform for researchers and engineers to analyze the energy consumption of UEs. By creating a simulated environment, researchers can accurately measure the energy consumption of a device under different conditions, allowing them to identify areas of energy consumption that can be improved. Using a simulated environment is also beneficial because it allows researchers to study the energy consumption of a device without having to physically construct the device or have access to the actual environment. This can save valuable time and

resources, as well as reduce the cost of testing. Additionally, simulated environments can be used to test scenarios that would otherwise be impractical or impossible to replicate in the real world.

Simulated environments can be incredibly useful for researchers, as they can help them better understand their devices' behavior and troubleshoot any issues that arise under certain conditions. Furthermore, data collected from these simulated environments can be utilized to create energy efficient models that optimize a device's energy consumption. It should be noted, however, that the effectiveness of these simulated environments is often limited by the power of the computer they are operating on, the simulations' complexity, and the computer scientists' knowledge. These limitations can lead to a decreased amount of data available and a decrease in the accuracy of the simulation.

This thesis presents a comprehensive literature review and classification of energy-saving mechanisms, providing a strong foundation for further research. Furthermore, detailed studies of energy-saving mechanisms and results from both simulated and real-world environments are presented. This is because simulations provide a controlled environment for testing and exploring ideas, but real-world experiments provide data from a physical system, which can validate simulations and add to the overall understanding. Paper I provides the literature review, while papers II and III present the results of NB-IoT energy consumption in a simulated environment. At the same time, Paper III also includes measurements conducted in a real-world commercial networks located in Oslo.

5 Contributions

The main objective of this thesis is to comprehensively analyze the energy consumption of NB-IoT devices when using one or several of the energy-saving mechanisms standardized by 3GPP. To do so, this thesis provides a detailed study of various energy-saving mechanisms, their advantages, and their limitations, both used separately and combined. Moreover, the thesis provides comprehensive guidelines on configuring an NB-IoT device to gain extended battery life. These contributions are further detailed as follows:

1. *Classification of energy-saving mechanisms employed by CIoT.*

Several previous studies [25, 29, 30] have considered a selection of the energy-saving mechanisms proposed for a specific CIoT technology; however, only some studies attempt to compile and classify the key energy-saving solutions offered for all significant CIoT technologies in terms of their ability to reduce the device energy consumption. To address objective O1, we provide a classification of currently used energy-saving solutions for CIoT. Notably, the thesis reviews and classifies contemporary CIoT studies and compiles the reported effects of presently used energy-saving mechanisms on device energy consumption. The thesis also discusses the limitations of these energy-saving mechanisms

and avenues for future research. These contributions are provided in **Paper I**.

2. *A summary of the effects of the energy saving mechanisms standardized by 3GPP for NB-IoT on the energy consumption.*

The extent to which individual energy-saving mechanisms standardized by 3GPP for NB-IoT reduce the energy consumption of IoT devices has been investigated in several studies [31, 32, 33]; however, how these energy-saving mechanisms interact and their combined impact on energy consumption have received much less attention. To address objective **O2**, we show how the key NB-IoT energy-saving mechanisms behave under various circumstances and how they separately and combined contribute to the reduction of the energy consumption of an NB-IoT device such as: DRX, RRC timers, PSM, RAI and transmission power. These contributions are provided in **Paper II** and **Paper III**.

3. *Provide guidelines on how to energy-efficiently configure NB-IoT devices.*

Some previous works considered studying the effects on energy consumption of specific NB-IoT protocol-stack parameters [26, 34, 35, 36, 37, 38, 39, 40] and how they should be tuned to reduce the energy consumption of an NB-IoT device. Still, these papers omit to consider interaction effects between different protocol-stack parameters in the NB-IoT stack and how this affect the tuning of these parameters. To this end, this thesis address **O3** and not only consider the interaction effects between key protocol-stack parameters, e.g., DRX and RRC timers, and PSM settings but also provide guidelines and recommendations on how to configure these parameters in such a way that the battery life of an NB-IoT device is 10 years or more, i.e., complies with the battery life prescribed by 3GPP. These contributions are provided in **Paper II** and **Paper III**.

6 Summary of Appended Papers

Paper I – Energy-Saving Solutions for Cellular Internet of Things - A Survey

CIoT is an emerging technology that promises to revolutionize how we interact with the physical world. It has the potential to connect billions of devices and enable new applications in areas such as healthcare, transportation, and smart cities. However, CIoT faces several challenges, including high energy consumption, which limits its adoption. This paper addresses the challenge of high energy consumption and classifies currently used energy-saving solutions for CIoT. We provide a comprehensive overview of energy-saving solutions for CIoT and survey energy-saving techniques proposed for CIoT components, including network infrastructure, devices, and applications. We

also provide insights into several protocol layers, including the physical, radio-resource management, network, and application layers. Moreover, we discuss the reported effects of presently used energy-saving mechanisms on device energy consumption, their limitations, and avenues for future research.

Paper II – Guidelines for an Energy Efficient Tuning of the NB-IoT Stack

This paper discusses the importance of energy efficiency in NB-IoT systems and provides an overview of the NB-IoT stack. It delves into the energy efficiency of the stack and provides guidelines for optimizing it for energy efficiency. It describes the different energy-efficiency optimization techniques that can be applied to the NB-IoT stack and provides guidelines for choosing the most appropriate technique for a given application. It also summarizes the energy-efficiency optimization techniques to gain a battery life of 10 years and more. The paper suggests that the key to saving energy for NB-IoT devices is the use of Discontinuous Reception (DRX), including the use of connected-mode DRX (cDRX). It explains that energy consumption is largely dependent on the intensity and burstiness of the traffic and can be significantly reduced if data is sent in bursts with less intensity. Furthermore, it discusses the impact of the RRC inactivity timer, CoAP retransmission timer, and other parameters on energy consumption, and provides guidelines on how to configure an NB-IoT device to conserve energy and prolong the lifetime of its battery.

Paper III – On the Energy-efficient Use of Discontinuous Reception and Release Assistance in NB-IoT

Paper III further extends the findings of paper II and discusses the use of the DRX, RAI, and PSM energy-saving mechanisms to improve the energy efficiency of NB-IoT devices. Through a real-world measurement campaign and simulations, we demonstrate that cDRX and RAI are essential energy-saving mechanisms to reduce the energy consumption of NB-IoT devices. We show that a battery life of 10 years is achievable by correctly configuring and using these mechanisms. Furthermore, the detailed analysis of cDRX and RAI shows that it is possible to save 70%-90% in energy consumption by correctly tuning these mechanisms. Additionally, this paper examines the effect of PSM on an NB-IoT devices' energy consumption and conclude that it is crucial to enable PSM to extend the battery life to 10 years.

7 Conclusions and Future Work

NB-IoT is a promising technology for the massive deployment of IoT due to its wide coverage, high data rate, and low cost. However, the high energy consumption of NB-IoT devices is a significant challenge due to devices being deployed at remote locations with non-rechargeable batteries. The research presented in this thesis provides a comprehensive overview of CIoT technologies and energy-saving mechanisms, particularly for NB-IoT. The thesis shows

that energy efficiency is essential for low-throughput applications requiring an extended battery life and can only be achieved provided the energy-saving mechanisms are correctly configured. By analyzing the impact of several parameters, such as DRX, RAI and transmission power, on the device energy consumption, this thesis provides guidelines on configuring an NB-IoT device to prolong the battery life.

As CIoT technology becomes more widely used and accepted, understanding the trade-off between latency and energy consumption becomes increasingly important for specific applications, e.g., industrial automation. There is a growing need to minimize latency while maintaining a low energy consumption. In our future work, we intend to study the trade-off between latency and energy consumption for CIoT technologies.

It is worth noting the limitations of the studies conducted in our thesis. While the studied parameters are essential to ensure optimal battery performance and are the focus of this thesis, further study of physical layer parameters, early data transmission, congestion control mechanisms, enhanced paging mechanisms incorporating group paging, and the impact of wake-up signal calls for NB-IoT devices could be equally important. The thesis also suggests potential research directions to improve energy efficiency, such as the influence of enhanced application-layer protocols.

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Improving the Energy Efficiency of Cellular IoT Device

Cellular Internet of Things (CIoT) has emerged as a promising technology to support applications that generate infrequent data. One requirement on these applications, often battery-powered devices, is low energy consumption to enable extended battery life. Narrowband IoT (NB-IoT) is a promising technology for IoT due to its low power consumption, which is essential for devices that need to run on battery power for extended periods. However, the current battery life of NB-IoT devices is only a few years, which is insufficient for many applications. This thesis investigates the impact of energy-saving mechanisms standardized by 3GPP on battery life of NB-IoT devices. The main research objective is to classify and analyze existing energy-saving solutions for CIoT and examine their limitations, to study the impact of standardized energy-saving mechanisms on the battery life of NB-IoT devices, both in isolation and combined, and to provide guidelines on how to configure NB-IoT devices to reduce energy consumption efficiently. The research aims to provide a deeper understanding of the effect of energy-saving mechanisms and best practices to balance energy efficiency and performance of NB-IoT devices. Applying the proposed solutions makes it possible to achieve a battery life of 10~years or more for CIoT devices.

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