Muhammad Tahir Abbas

Improving the Energy Efficiency of Cellular IoT Devices

Improving the Energy Efficiency of Cellular IoT Devices

Muhammad Tahir Abbas

Faculty of Health, Science and Technology

Computer Science

DOCTORAL THESIS | Karlstad University Studies | 2025:15

Improving the Energy Efficiency of Cellular IoT Devices

Muhammad Tahir Abbas

DOCTORAL THESIS | Karlstad University Studies | 2025:15

Improving the Energy Efficiency of Cellular IoT Devices

Muhammad Tahir Abbas

DOCTORAL THESIS

Karlstad University Studies | 2025:15

urn:nbn:se:kau:diva-103638

ISSN 1403-8099

ISBN 978-91-7867-562-3 (print)

ISBN 978-91-7867-563-0 (pdf)

https://doi.org/10.59217/cmon1505

Distribution:
Karlstad University
Faculty of Health, Science and Technology
Department of Mathematics and Computer Science
SE-651 88 Karlstad, Sweden
+46 54 700 10 00

Print: Universitetstryckeriet, Karlstad 2025

WWW.KAU.SE

Improving the Energy Efficiency of Cellular IoT Devices

Muhammad Tahir Abbas
Department of Mathematics and Computer Science
Karlstad University

Abstract

The rapid rise of Cellular Internet of Things (CIoT) technology is expected to connect over 6 billion devices by 2029. Many of these devices, often deployed in remote, urban, or hard-to-reach areas, operate on limited battery resources and are expected to last up to 10 years. However, current battery limitations challenge the long-term operation required by many applications. Ensuring low energy consumption is therefore crucial for avoiding frequent recharging or battery replacements.

This thesis addresses the challenge of enhancing the energy efficiency of Narrow-Band Internet of Things (NB-IoT) devices by examining and optimizing the energy-saving mechanisms standardized by the 3rd Generation Partnership Project (3GPP). Specifically, the research classifies and evaluates existing energy-saving solutions for CIoT— particularly for NB-IoT—by identifying their limitations and studying the impact of mechanisms such as Discontinuous Reception (DRX), Release Assistance Indicator (RAI), Power Saving Mode (PSM), Early Data Transmission (EDT), and Preconfigured Uplink Resources (PUR) on battery life. While improved energy efficiency is essential, it often comes at the cost of increased latency. This thesis evaluates these effects on both energy consumption and latency, offering insights into the trade-offs between the two.

Based on these findings, we propose guidelines for configuring NB-IoT devices to achieve an optimal balance between energy efficiency and performance. A significant contribution of this research is the development of a machine learning-based optimization approach that dynamically adjusts configurations based on network conditions, such as signal quality, packet loss, and data transmission frequency. By integrating advanced energy-saving mechanisms with optimization techniques, this work deepens our understanding of the interplay between device configurations and battery life. Although energy-saving measures may reduce performance (e.g., increased latency or reduced throughput), further investigation into these trade-offs is essential. The proposed guidelines and strategies aim to extend NB-IoT devices' battery life to 10 years or more, enhancing their usability across diverse CIoT deployments.

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

Förbättring av energieffektiviteten för cellulära IoT-enheter

Muhammad Tahir Abbas
Institutionen för matematik och datavetenskap
Karlstads universitet

Sammanfattning

Den snabba utvecklingen av Cellular Internet of Things (CIoT)-teknologi förväntas koppla samman över 6 miljarder enheter till år 2029. Många av dessa enheter, som ofta placeras i avlägsna, urbana eller svårtillgängliga områden, drivs av begränsade batteriresurser och förväntas fungera i upp till 10 år. Dock utgör nuvarande batteribegränsningar en utmaning för långvarig drift i många applikationer. Därför är låg energiförbrukning avgörande för att undvika frekventa laddningar eller batteribyten.

Denna avhandling adresserar utmaningen att förbättra energieffektiviteten hos NB-IoT-enheter genom att undersöka och optimera de energibesparande mekanismer som standardiserats av 3rd Generation Partnership Project (3GPP). Specifikt klassificerar och utvärderar forskningen befintliga energibesparande lösningar för CIoT, särskilt för Narrowband Internet of Things (NB-IoT), genom att identifiera deras begränsningar samt studera effekterna av mekanismer såsom Discontinuous Reception (DRX), Release Assistance Indicator (RAI), Power Saving Mode (PSM), Early Data Transmission (EDT) och Pre-configured Uplink Resources (PUR) på batteritid. Förbättrad energieffektivitet kommer dock ofta till priset av ökad latens. Denna avhandling utvärderar dessa effekter på både energiförbrukning och latens och erbjuder insikter i de avvägningar som krävs.

Baserat på resultaten föreslås riktlinjer för att konfigurera NB-IoT-enheter så att en optimal balans mellan energieffektivitet och prestanda uppnås. Ett betydande bidrag från detta arbete är utvecklingen av en maskininlärningsbaserad optimeringsmetod som dynamiskt justerar konfigurationer beroende på nätverksförhållanden, såsom signalstyrka, paketförlust och dataöverföringsfrekvens. Genom att integrera avancerade energibesparande mekanismer med optimeringstekniker fördjupar detta arbete förståelsen för samspelet mellan enhetskonfigurationer och batteritid. Även om energibesparande åtgärder kan minska prestanda (t.ex. ökad latens eller reducerad genomströmning), krävs ytterligare undersökningar kring dessa avvägningar. De föreslagna riktlinjerna och strategierna syftar till att förlänga NB-IoT-enheternas batteritid till 10 år eller mer, vilket förbättrar deras användbarhet i olika CIoT-implementeringar.

Nyckelord: CIoT, 3GPP, energibesparing, mMTC, NB-IoT, LTE-M, EC-GSM-IoT, maskininlärning.

Acknowledgements

First and foremost, I would like to express my deepest gratitude to my parents, whose unwavering love, prayers, and support have been my greatest strength throughout this journey. My father, in particular, has been a source of inspiration for me. I vividly remember how, during my childhood, he expressed his dream of seeing me as a doctor. Today, as I earn this doctorate, I feel proud to fulfill his dream, and I dedicate this achievement to him. This is not just my success, but his too—a testament to his belief in me and the values he instilled in me. I also congratulate him for seeing his dream realized. To my mother, whose constant prayers and boundless love have always guided me, I owe my deepest gratitude.

I would like to extend my heartfelt gratitude to my main supervisor, Karl-Johan Grinnemo, who has been an exceptional mentor, guide, and friend throughout my PhD journey. Karl-Johan has always been there for me, guiding me through professional challenges, personal struggles, and moments of doubt. His kindness, immediate assistance, and unwavering support during my difficult times, including when I faced health issues, have left an indelible mark on me. He not only helped me become a better researcher but also inspired me to grow as a person. I cannot thank him enough for being the kind of mentor who goes beyond academic guidance to provide emotional and moral support.

I am also deeply thankful to my co-advisors—Johan Eklund, Stefan Alfredsson, Mohammad Rajiullah, and Anna Brunström—for their valuable feedback, guidance, and encouragement throughout my PhD. Their expertise, patience, and insights have been critical to shaping my research and helping me navigate through the complexities of this journey. I also owe special thanks to Stefan Alfredsson for his compassionate support during one of the most challenging periods of my life. When I faced personal challenges, he and others in the department provided emotional support and understanding that helped me persevere during those tough times.

My heartfelt thanks go to my collaborators at Ericsson Sweden and Hungary. I am especially grateful to Bela Rathonyi from Ericsson Sweden, whose expertise in radio technology was instrumental in completing several experiments, and Sándor Katona from Ericsson Hungary, who provided crucial assistance during our meetings and research activities. Their willingness to help and their invaluable insights made a significant impact on my work. I also extend my gratitude to Simula Research Laboratories in Oslo, Norway, for providing real-world experimental data for NB-IoT, which proved critical in our simulations and experiments. Furthermore, I would like to thank Pascal Jörke from TUM University in Germany, whose collaboration added immense value to my research. Your contributions are deeply appreciated.

I am sincerely thankful to my colleagues and friends at the university, especially my fellow PhD students, for their support, productive discussions, and camaraderie. The fika sessions we shared every Friday at 2:30 PM were moments of joy and relaxation that brought us closer together. These informal

gatherings provided not only a platform for exchanging ideas but also a sense of community and belonging. I will always cherish these memories, including the cultural diversity we explored through fika and the friendships we built.

I would also like to express my gratitude to my fellow countrymates, whose sense of community and support during hard times gave me strength and encouragement. Their assistance and solidarity have been a significant part of my journey, and I am truly thankful for their presence.

In reflecting on this journey, I am reminded of the profound words from the Quran that have guided me through the hardships of PhD life:

> *"So verily, with the hardship, there is relief."*
> (Quran, 94:6)

These words have been a source of comfort and a reminder that perseverance and faith lead to success, even in the face of challenges.

Finally, I thank Allah for granting me the strength, patience, and guidance to achieve this milestone. Without His blessings, none of this would have been possible.

Karlstad, March 25, 2025 Muhammad Tahir Abbas

Contents

Paper IV: Evaluating the Impact of Pre-configured Uplink Resources in NB-IoT 131

Paper V: Dynamic NB-IoT Configuration: A Machine Learning-Driven Optimization Framework 157

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. LCN Symposium, 2020, pp. 60-69, DOI: 10.1109/LCNSymposium50271.2020.9363265.
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. IEEE WFIoT 2022, Yokohama, Japan, 26 October to 11 November 2022, DOI: 10.1109/WF-IoT54382.2022.10152235 - **2nd Place Best Paper Award**.
4. **Muhammad Tahir Abbas**, Karl-Johan Grinnemo, Anna Brunstrom, Pascal Jörke, Johan Eklund, Stefan Alfredsson, Mohammad Rajiullah, Christian Wietfeld. Evaluating the Impact of Pre-configured Uplink Resources in NB-IoT. Sensors 2024, 24(17), 5706, DOI: 10.3390/s24175706.
5. **Muhammad Tahir Abbas**, Yurong Li, Karl-Johan Grinnemo, Anna Brunstrom, Johan Eklund, Mohammad Rajiullah. Dynamic NB-IoT Configuration: A Machine Learning-Driven Optimization Framework. IEEE Internet of Things Journal
(Under submission).

Comments on my Participation

Paper I As the primary author of this paper, I conducted an extensive literature review on CIoT technologies and was primarily responsible for synthesizing and summarizing the findings. I also wrote the majority of the manuscript and collaborated with Karl-Johan Grinnemo on organizing and structuring the paper to ensure coherence and clarity. Additionally, Karl-Johan Grinnemo and I worked closely on reviewing the manuscript to enhance its quality. My co-authors provided valuable support and constructive feedback throughout the process, contributing insights that strengthened the overall contribution of the paper.

Paper II As the primary author of this paper, I was responsible for writing the manuscript in its entirety. Together with Johan Eklund, I conceptualized and designed the experiments, and took the lead in developing the simulator with valuable guidance and technical support from Karl-Johan Grinnemo. I conducted all experiments, performed thorough data analysis, and interpreted the results to draw meaningful conclusions. Additionally, I synthesized the insights from the analysis to ensure alignment with the research objectives and maintained the coherence and scientific rigor of the paper. Throughout the process, my co-authors provided valuable support and constructive feedback, particularly in contextualizing the findings.

Paper III The original idea for this research was conceived by Karl-Johan Grinnemo and Anna Brunström. I took the lead in designing and conducting the simulation experiments, performing in-depth data analysis, and drafting the manuscript. My co-authors provided valuable support and constructive feedback throughout the process, particularly in contextualizing the findings. Additionally, the real-world experimental data, collected and analyzed by Konstantinos Kousias, played a critical role in complementing the simulation results, and my co-authors offered insights to integrate these findings cohesively into the paper.

Paper IV As the primary author of this paper, I conducted the simulation experiments, performed comprehensive data analysis, and wrote the manuscript. I collaborated with Karl-Johan Grinnemo on the organization, structuring, and thoroughly reviewing the paper to ensure clarity and coherence. The development of the simulator was supported by Pascal Jörke, who provided valuable feedback and technical insights. My co-authors contributed constructive feedback throughout the research and writing process, further enhancing the paper's quality and impact.

Paper V As the lead author, I developed the research idea and implemented the machine learning optimization framework. Yurong Li conducted extensive experiments to validate the model's performance. My responsibilities also included analyzing the results and writing the manuscript. Throughout the process, I received ongoing support and constructive feedback on technical details and simulation approaches from all co-authors.

Other Publications

The following is a list of other publications that I have authored and co-authored, that are 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. Presented at the 15th Swedish National Computer Networking Workshop (SNCNW 2019). Luleå, June 4-5, 2019.
- **Muhammad Tahir Abbas**, Karl-Johan Grinnemo, Anna Brunstrom, Johan Eklund, Mohammad Rajiullah, Stefan Alfredsson. Boosting NB-IoT Battery Life: Analyzing the Impact of Pre-configured Uplink Resources. Presented at the Nineteenth Swedish National Computer Networking and Cloud Computing Workshop (SNCNW 2024). Linköping, June 11-12, 2024.
- **Muhammad Tahir Abbas**, Karl-Johan Grinnemo, Guillaume Ferré, Philippe Laurent, Stefan Alfredsson, Mohammad Rajiullah, and Johan Eklund. Towards Zero-Energy: Navigating the Future with 6G in Cellular Internet of Things. Article id 103945, Journal of Networking and Computer Applications, June 25, 2024.
- Jameel Ali, **Muhammad Tahir Abbas**, Giuseppe Caso, Anas Saeed Al-Selwi, Foivos Michelinakis, Karl-Johan Grinnemo. Optimizing Energy Consumption in NB-IoT Networks through Enhanced Cell Selection and Reselection Strategy. Presented at the 26th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM), May 27-30, 2025.

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

Table of Abbreviations

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

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

Abbreviation	Meaning
VoLTE	Voice over LTE
WBAN	Wireless Body Area Networks

Introductory Summary

1 Introduction

The Internet of Things (IoT) is revolutionizing our interaction with the world by connecting billions of devices across various sectors, including smart cities, industrial automation, healthcare, and environmental monitoring [1]. Recent studies by Ericsson forecast that by 2029 [2], the number of Cellular Internet of Things (CIoT) devices will reach over 6 billion, as shown in Fig. 1. While most of these devices will cater to consumer needs—such as connected cars, wearables, and smart home devices—a significant portion will be used for industrial applications, including manufacturing machinery, remote monitoring systems, and smart infrastructure [3, 4, 5].

Traditional IoT networks typically rely on short-range communication technologies like Wi-Fi and Bluetooth [6]. However, these technologies have limitations in terms of coverage, and power efficiency, making them unsuitable for specific applications, as shown in Fig. 2. CIoT has emerged as a promising solution to overcome these challenges, utilizing existing cellular networks to provide wide-area coverage, robust security, scalability, and low power consumption [7, 8, 9]. Key advancements in CIoT include Low-Power Wide-Area Network (LPWAN) [10] technologies such as Long Term Evolution Category M1 (LTE-M) [11] and NB-IoT [12], which are standardized by the 3rd Generation Partnership Project (3GPP) in releases 12 [13] and 13 [14]. A detailed comparison of these two technologies is provided in Table 2, highlighting their differences in data rates, frequency bands, power consumption, and typical use cases. Alternative LPWAN technologies like LoRaWAN [15] and Sigfox [16] also offer extended range and low-power capabilities but necessitate separate infrastructure deployment, which can be expensive and time-consuming. Among all LPWAN technologies, NB-IoT stands out due to its extended range, low power consumption, improved security, and cost-effectiveness, as shown in Fig. 2. It operates on both licensed and unlicensed spectrum bands, allowing for flexible deployment within existing cellular infrastructure. These features make NB-IoT suitable for a wide variety of applications, including smart cities, asset tracking, environmental monitoring, industrial automation, and healthcare.

Given its broad applicability, one of the critical challenges for NB-IoT is ensuring energy-efficient operation, particularly for battery-powered devices often deployed in remote or hard-to-reach locations. The aim is to achieve a battery life of up to ten years or more, as specified by the 3GPP standards. However, long battery life requires effective management of power consumption during various operational states, such as transmitting, receiving, and idle states.

To address the challenge of energy efficiency, 3GPP has standardized several energy-saving mechanisms for CIoT. These include Power Saving Mode (PSM), extended Discontinuous Reception (eDRX), connected Discontinuous Reception (cDRX), and Release Assistance Indicator (RAI), which are designed to balance network connectivity with reduced energy usage [12, 17, 18]. In releases 15 and 16, advanced mechanisms such as Early Data

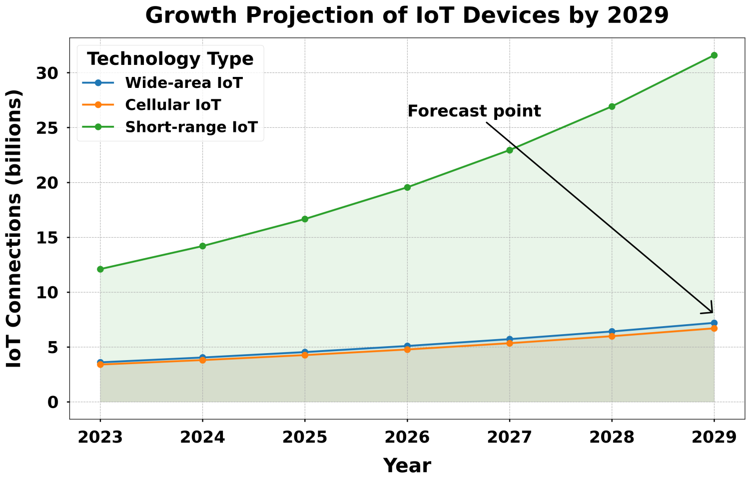


Figure 1: CIoT device connections forecast 2023-2029 by Ericsson (Ericsson Mobility Report) [2].

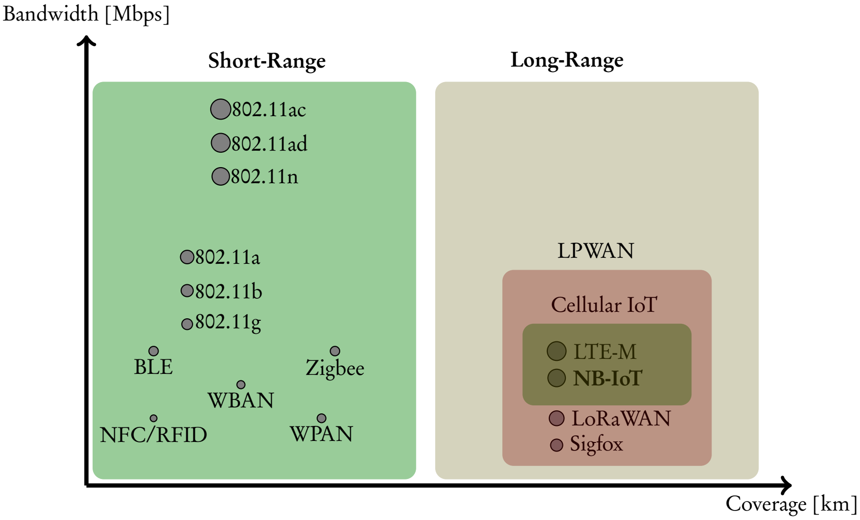


Figure 2: Approximate comparison of short-range and long-range IoT technologies in terms of coverage and bandwidth.
Note: Positions of circles are approximate and illustrative, showing general trends in coverage and bandwidth rather than exact values.

Table 2: NB-IoT and LTE-M Comparison

Technology	NB-IoT	LTE-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

Transmission (EDT) and Pre-configured Uplink Resources (PUR) were introduced to optimize energy consumption further and reduce latency in CIoT devices [19, 20]. These strategies enable efficient uplink transmissions and minimize energy use during the Random Access Procedure (RAP).

Despite the availability of various mechanisms, deploying billions of devices across diverse environments presents significant challenges in energy optimization. A static configuration of devices might not be practical, particularly given the varying signal conditions and the need to balance performance with energy efficiency. Therefore, an adaptive approach that allows for dynamic Over-The-Air (OTA) configuration of NB-IoT devices is essential for ensuring their optimal performance and longevity. Machine Learning (ML) provides a powerful tool to enable such adaptive configurations. By leveraging real-time environmental data—such as signal quality, packet loss, and traffic conditions—ML can predict and recommend optimal configuration settings for energy-saving mechanisms like PSM, Discontinuous Reception (DRX), and RAI.

This thesis aims to explore the interactions between the different energy-saving mechanisms used in CIoT technologies and to develop guidelines for maximizing battery life in NB-IoT devices. It focuses on analyzing the impact of each mechanism, both individually and in combination, and proposes methodologies for optimizing their configuration across various operational scenarios. While these mechanisms significantly enhance energy efficiency, they often come at the cost of reduced performance, such as increased latency, decreased data throughput, or potential functionality trade-offs. Recognizing and addressing these trade-offs is critical to ensure that the proposed optimizations achieve a balance between energy savings and system performance. The research builds upon a comprehensive review of the existing literature on CIoT energy efficiency. This thesis introduces an ML-based adaptive framework that not only maximizes energy savings but also addresses trade-offs related to performance, including latency, data throughput, and functionality. The proposed methodologies aim to bridge the gap between static configurations and the dynamic requirements of large-scale IoT deployments, contributing to more sustainable CIoT operations.

The rest of this introductory summary is organized as follows. Section 2 delves into NB-IoT, covering its radio operations, energy-saving mechanisms, and the role of ML. The main objectives and research questions addressed in this thesis are outlined in Section 3. Section 4 discusses the research methods employed in 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 potential future work.

2 Background

This section offers a detailed overview of NB-IoT technology, covering its use cases, deployment scenarios, radio operations, and the energy-saving mechanisms standardized by 3GPP. By utilizing these energy-saving features, NB-IoT technology can deliver low-cost, low-power, and reliable communication for a wide range of IoT applications. This capability promotes increased automation and enhanced efficiency across various industries.

NB-IoT 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 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 benefits applications requiring low power consumption and robust data connectivity. An overview of some of NB-IoT technology's most common use cases is provided below and illustrated in Fig. 3.

Smart metering and energy management are among NB-IoT technology's most common use cases. NB-IoT-enabled devices monitor energy consumption in real time, allowing utilities to manage their energy usage better and improve efficiency.

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 their assets are always where they should be. In addition, NB-IoT technology is often used for remote healthcare applications. These devices can remotely monitor a patient's vital signs and medical conditions, allowing healthcare providers to provide more efficient care.

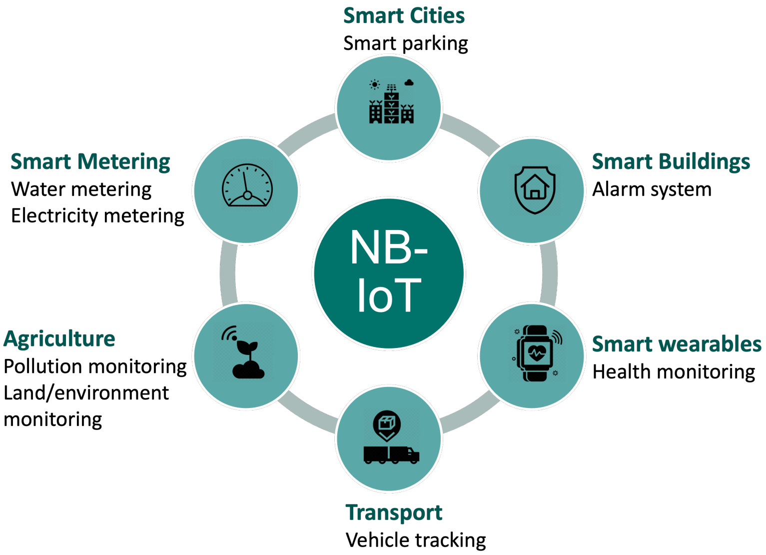


Figure 3: Multiple applications for NB-IoT technology.

NB-IoT offers several advantages over other LPWAN technologies like LoRaWAN and Sigfox. These include 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 [22].

2.2 NB-IoT Deployment

NB-IoT deployment is vital for cellular operators, enabling them to extend their networks' coverage without additional infrastructure. The coverage extension is facilitated by reusing existing cellular spectrum bands and network elements, such as cell sites and base stations. NB-IoT deployment 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 risk of creating 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 spectrum [23]. It enables 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 energy to transmit. Additionally, the low-power nature of the technology allows for longer battery life in devices, allowing for more remote 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 for configuring, monitoring, and releasing 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 operate 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* state, 3) Finally, the RRC Active

---

[1] Licensed-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 allows users to access the unlicensed spectrum for short bursts of data traffic while relying on the licensed spectrum for data throughput.

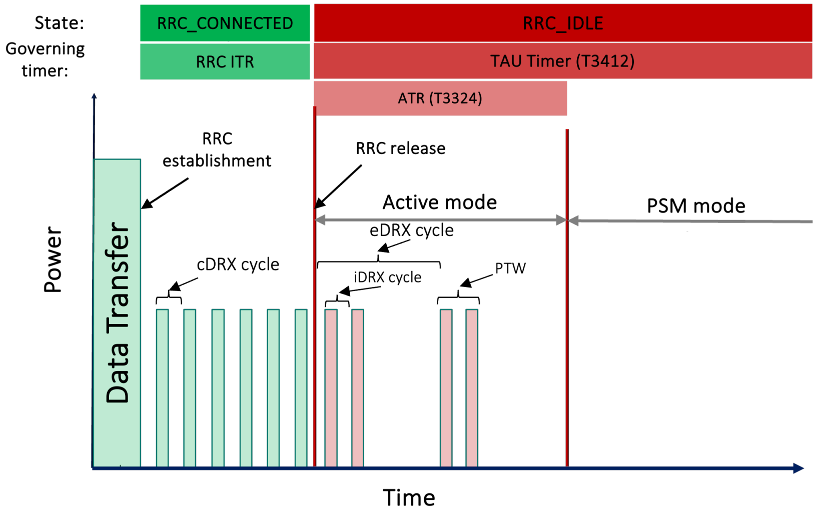


Figure 4: NB-IoT RRC states with energy-saving features, such as: *cDRX*, *eDRX*, *PSM*, etc.
Note: Axes units (time and power) are indicative; scales are illustrative and not exact.

Timer controls the time that the mobile device remains in the RRC Active state.

2.4 NB-IoT Energy-saving Mechanisms

To reduce the power consumption of NB-IoT devices, it is essential to implement energy-saving techniques defined by 3GPP. Some of the most common techniques include Power Saving Mode [24], Discontinuous Reception [25], and Release Assistance Indicator [26]. By adopting these methods, the power consumption of CIoT devices can be reduced by up to 50% [26]. Below, we provide details on the energy-saving mechanisms, some of them designed explicitly for NB-IoT, which are crucial for achieving long battery life.

2.4.1 Discontinuous Reception

DRX is a crucial energy-saving feature of NB-IoT. It enables NB-IoT devices to power down their radio receivers during periods of inactivity, significantly reducing power consumption. This is illustrated in Fig. 4.

DRX can be optimized further by extending the on-duration, shortening the off-duration, or both, as well as reducing the number of listening slots per DRX cycle. This feature helps devices minimize power usage in both the *RRC_CONNECTED* and *RRC_IDLE* states.

In the *RRC_CONNECTED* state, cDRX allows a device to enter recurring low-power states, several cDRX cycles, for a specified period after data transmission. During this time, the device does not actively listen for incoming messages from the base station, resulting in lower power consumption. Once the low-power period ends, the device resumes listening for messages.

In the *RRC_IDLE* state, DRX similarly allows a device to enter a low-power states without actively monitoring incoming messages. When the device exits this low-power state, it will return to listening for messages from the base station. However, the listening intervals during this state are more sporadic compared to cDRX and are referred to as eDRX.

2.4.2 Paging and Paging Time Window

Paging in NB-IoT occurs when the base station broadcasts a message to devices within a cellular network. This process establishes communication with a specific device and informs it about incoming data. A device will respond to the message only if it is the intended recipient. NB-IoT technology employs a particular protocol and message structure tailored for this type of communication, optimized for low-power devices, allowing the paging process to function even with limited power availability.

The paging process is crucial for ensuring efficient communication between the base station and the device and keeping the device updated.

The Paging Time Window (PTW) in NB-IoT is a feature that enables the network to send paging requests to a target device during a designated time interval rather than continuously. This approach reduces the device's power consumption and extends its battery life since the device only needs to monitor the network and respond to paging requests within the PTW rather than constantly checking for incoming messages. The network can configure both the length of the PTW and the paging interval to optimize performance for specific use cases.

If the UE receives a paging request during the PTW, it processes the message and, if necessary, transitions to the RRC_CONNECTED state. In this state, the device establishes a connection with the network to handle the incoming data or perform tasks such as acknowledging the message or initiating further communication. This selective monitoring and transition mechanism balances efficient power use during idle periods with maintaining network connectivity when required.

2.4.3 Power Saving Mode

Power Saving Mode (PSM) is designed to be transparent to both applications and end users, requiring no modifications to existing NB-IoT networks. All major NB-IoT chipsets and modules support PSM, and it has already been widely deployed in NB-IoT networks across the globe. PSM allows the device to enter an ultra-low-power state for extended periods, where it effectively powers down most of its functionalities while maintaining registration with the network. Unlike DRX, the device in PSM does not wake up periodically to receive data. Instead, it wakes up only when triggered by specific events, such as scheduled Tracking Area Update (TAU) updates or when it needs to initiate data transmission.

The sleep and active periods in PSM are highly configurable and can be optimized for different applications. For example, a device that needs to transmit data only once per day can remain in the low-power PSM state for the majority of the time, waking up briefly to perform a scheduled TAU or send data. This approach significantly reduces energy consumption, ensuring that the device conserves battery power without compromising its functionality.

PSM is crucial for enabling the long-term operation of battery-powered NB-IoT devices, especially those deployed in remote or hard-to-reach locations where battery replacement is not feasible. By allowing devices to spend the majority of their time in PSM, the technology helps achieve the 10-year battery life target specified by 3GPP for NB-IoT devices, making it an essential energy-saving mechanism for a wide range of IoT applications.

Additionally, PSM includes support for Tracking Area Updates (TAU). The TAU timer conserves power by minimizing the time a device needs to update its location. This mechanism allows the network to track the device's location for a specified period. Once the timer expires, the device must connect to the network and send a TAU request to the network to refresh its location information.

2.4.4 Release Assistance Indicator

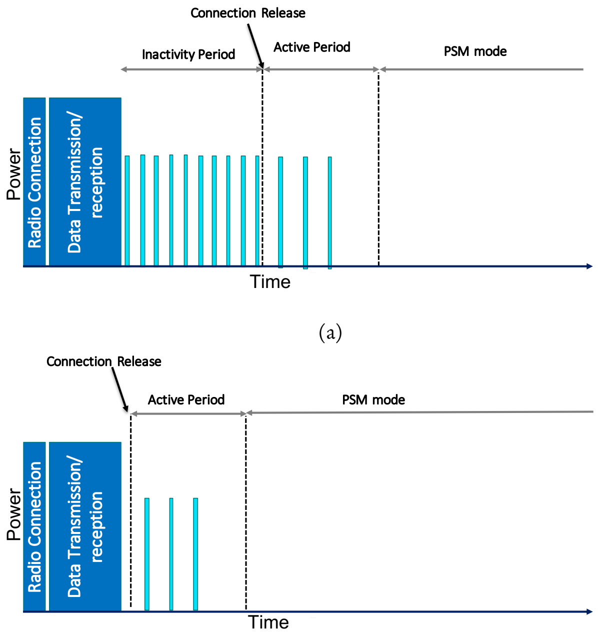
RAI was standardized by 3GPP in release 14 and is a crucial feature of NB-IoT. RAI enables the network to efficiently manage its resources by releasing unnecessary radio resources, as illustrated in Fig. 5. Additionally, it helps ensure effective network usage while allowing devices to conserve battery life.

RAI can be transmitted both from the network to the device or from the UE to the network. When sent by the network, RAI signals the device that it is time to release the allocated resources. This indicator is typically included in an uplink grant message and specifies the types of resources the device should release, such as the radio resource blocks assigned to the UE. Conversely, the UE can include RAI in its uplink message to proactively inform the network that it no longer requires certain resources. This capability allows the network to manage resources more efficiently, reducing unnecessary allocation and optimizing overall system performance.

Upon receiving RAI, the NB-IoT device will release its allocated resources by sending a Release Request to the network. The network then replies with an acknowledgment message, confirming that the resources have been successfully released. Once the resources are freed, the network can reallocate them to other devices. In this way, RAI effectively manages the network's resources and assists NB-IoT devices in releasing radio connections early to conserve battery power.

2.4.5 Early Data Transmission

EDT is a crucial mechanism introduced in 3GPP release 15 to improve en-



(a)

(b)

Figure 5: The graph demonstrates how energy consumption varies based on the timing of the radio connection release. Fig. (a) depicts energy consumption when the connection is released after the Inactivity Timer expires, while Fig. (b) illustrates energy consumption when the connection is released upon a request from the UE (RAI).

ergy efficiency and reduce latency for NB-IoT devices. Designed for infrequent small data transmissions, EDT enables devices to send data during the Random Access Procedure (RAP), optimizing power consumption and operational efficiency.

EDT modifies the traditional multi-step RAP, as illustrated in Fig. 6, by allowing data to be sent directly during the early stages, specifically during the Msg3 transmission, which typically handles signaling.

In the typical EDT process, the UE sends a preamble to the eNodeB to initiate the RAP (Msg1) and then receives a Random Access Response (RAR) from the eNodeB, which includes timing advance and uplink grant information (Msg2). Subsequently, the UE transmits the small data payload and necessary signaling information during Msg3. This integration of data transmission with initial signaling is central to EDT, allowing the eNodeB to process this combined message and send an acknowledgment back to the UE (Msg4).

EDT incorporates Control Plane (CP) and User Plane (UP) solutions. The Control Plane (CP) EDT utilizes Non-Access Stratum (NAS) signaling messages to carry user data, effectively reducing signaling overhead for small

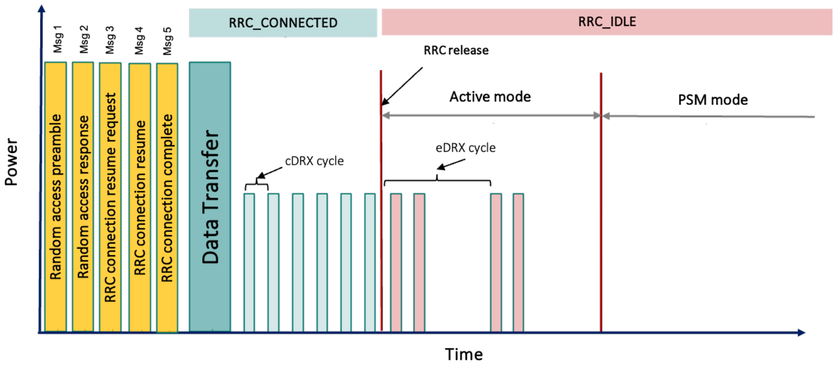


Figure 6: The operational states of NB-IoT, showcasing the stages of the random access procedure and connection setup highlighted in yellow (to the left), the data transmission phase and the CONNECTED state in cyan (in the middle), and the IDLE state depicted in red (to the right).

data packets. UP EDT, on the other hand, allows the UE to resume a suspended data bearer, enabling data transmission with the necessary security contexts, which benefits applications requiring higher data integrity and security.

EDT significantly lowers power consumption by decreasing the number of signaling exchanges needed before data transmission. This allows devices to quickly send data and return to a low-power state, thus extending battery life. Additionally, reducing signaling steps decreases latency, making EDT suitable for applications that require timely data updates. Furthermore, EDT simplifies network procedures by combining signaling and data transmission, minimizing complexity and overhead.

Security measures must be integrated within Msg3 for data transmissions using EDT to ensure data integrity and confidentiality. The mechanism is optimized for small data packets, while larger data transmissions may require traditional methods or segmentation across multiple EDT cycles. Effective implementation of EDT requires network support for the modified RAP and signaling procedures, including updates to eNodeB functionalities to handle the combined signaling and data transmission.

2.4.6 Preconfigured Uplink Resources

PUR is a mechanism introduced in 3GPP release 16 to enhance the efficiency of NB-IoT by pre-allocating uplink resources for data transmission. This approach reduces signaling overhead and improves energy efficiency and latency. PUR eliminates the need for the initial steps of the RAP by allowing the UE to transmit data directly using pre-assigned resources.

In the PUR process, the UE completes an initial synchronization phase

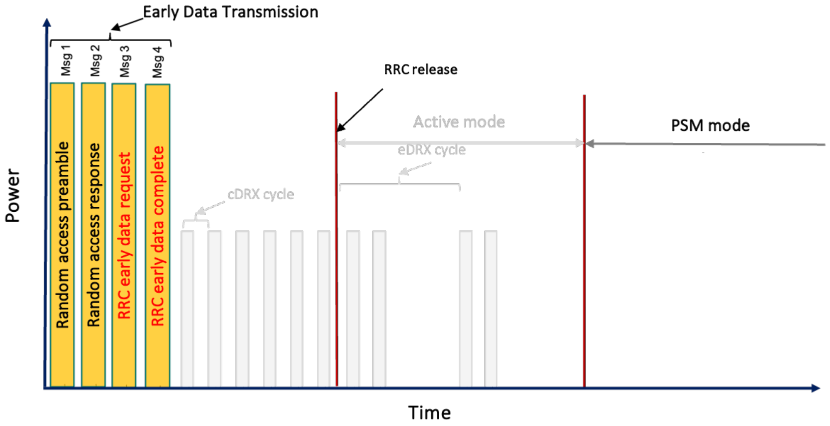


Figure 7: The NB-IoT Early Data Transmission procedure, as outlined in Release 15, highlights the transmission of data in Msg3 and the reception of acknowledgment by the User Equipment in Msg4.

to acquire a valid Timing Advance (TA) from the eNodeB. This phase involves Msg1 and Msg2, which establish synchronization and resource allocation. Following this, Msg3 facilitates the first scheduled uplink transmission by combining RRC signaling with the uplink data payload. Msg4, the final message, serves several purposes: it acknowledges the data transmission, addresses any contention issues, and may also include downlink data payloads or instructions that transition the UE to the CONNECTED state, as illustrated in Fig. 8.

PUR supports both dedicated and shared resource schemes. Dedicated PUR allocates specific uplink resources to a single UE, making it suitable for periodic uplink transmissions. On the other hand, shared PUR allows multiple UEs to utilize the same resources, differentiated by orthogonal demodulation reference signal sequences. This flexibility enhances network scalability, especially in environments with periodic traffic patterns.

By preconfiguring uplink resources, PUR reduces the need for dynamic resource scheduling, leading to lower energy consumption and reduced latency. Dedicated resources enable immediate data transmission without network authorization, significantly decreasing latency. Shared PUR boosts resource utilization but is most effective in low Signal to Interference and Noise Ratio (SINR) conditions to mitigate excessive interference.

Before initiating a PUR transmission, the UE must evaluate the validity of the TA to ensure accurate synchronization. This evaluation includes checking for changes in the serving cell, the expiration of the PUR TA timer, and variations in Reference Signal Received Power (RSRP). Successful uplink transmissions via PUR can be acknowledged through layer-1 signaling if no downlink data is pending or through layer-2/3 signaling for acknowledgments, configu-

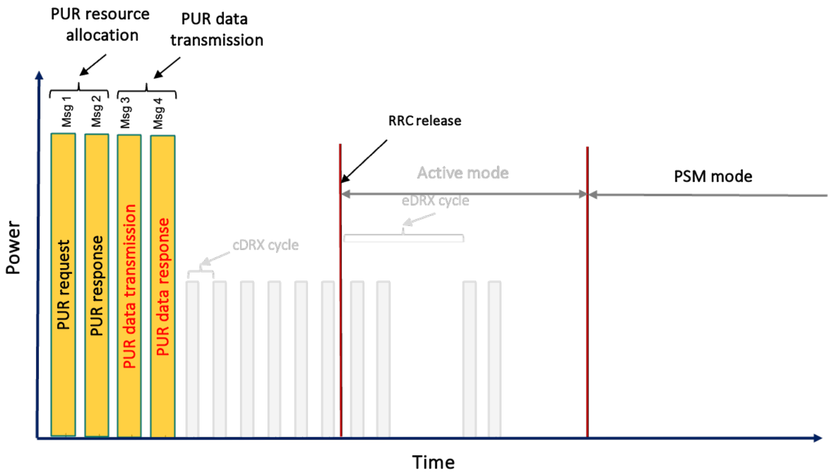


Figure 8: The NB-IoT PUR process, as outlined in 3GPP release 16, is a simplified two-message protocol: Msg3 (PUR data transmission) sends data, while Msg4 (PUR data response) confirms receipt of that data.

ration adjustments, and state transitions.

2.4.7 Effectiveness of Default Configurations in Energy-Saving Mechanisms

The energy-saving mechanisms standardized by 3GPP, including PSM, eDRX, cDRX, RAI, EDT, and PUR, are designed to optimize the power consumption of NB-IoT devices. However, the effectiveness of these default configurations can vary depending on the specific use case and application requirements.

Power Saving Mode (PSM): PSM configurations are generally effective for applications with low communication frequency, such as smart metering or environmental monitoring. The default settings allow devices to achieve significant energy savings by entering deep sleep states for extended periods. However, they may not be optimal for applications requiring higher responsiveness, as long PSM durations can delay updates. Fine-tuning parameters like the TAU timer can improve the performance of PSM for specific use cases.

Discontinuous Reception (DRX): Default DRX configurations effectively reduce energy consumption by allowing devices to power down their radio receivers during inactivity. However, longer DRX cycles can introduce latency, making them unsuitable for latency-sensitive applications like industrial automation. In contrast, shorter DRX cycles improve responsiveness but increase energy consumption. Optimizing DRX parameters for application-specific needs is therefore critical.

Extended Discontinuous Reception (eDRX): The default eDRX settings provide substantial energy savings for periodic data transmissions by increasing the intervals between listening cycles. While effective for use cases such as logistics tracking or smart agriculture, longer eDRX intervals may not suit applications requiring frequent updates or real-time communication. Configuring parameters like the PTW can help balance energy efficiency with responsiveness.

Release Assistance Indicator (RAI): RAI is effective for applications with sporadic uplink communication needs, as it allows devices to signal the network to release unused resources. However, its benefits are less pronounced for use cases requiring continuous data streams, where connections are rarely idle. Customizing RAI settings can further enhance its effectiveness for latency-sensitive scenarios.

Early Data Transmission (EDT): Default EDT settings work well for infrequent, small data transmissions, such as sensor readings. By reducing the number of signaling exchanges, EDT lowers power consumption and latency. However, for applications requiring high throughput or frequent updates, traditional Random Access Procedure (RAP) methods may still be necessary.

Preconfigured Uplink Resources (PUR): PUR configurations are particularly effective for periodic uplink transmissions, as they eliminate the need for dynamic resource scheduling. However, shared PUR schemes may require adjustments in high-interference environments to ensure optimal resource utilization. Dedicated PUR schemes work best for predictable communication patterns with stationary devices, such as environmental monitoring.

Overall, while these default configurations provide robust energy-saving capabilities for general use cases, fine-tuning them for specific operational scenarios is often necessary to balance energy efficiency with application performance.

2.4.8 Energy Efficiency using ML

ML provides a transformative approach to address energy challenges by enabling dynamic and intelligent adjustments in device configurations. Unlike traditional methods that depend on manual setups, ML techniques can adapt device operations to environmental changes, optimizing energy use without compromising performance. In my research, I employ ML models such as Gradient Boosting [27], Random Forest [28], and Neural Networks [29] to predict the energy consumption of NB-IoT devices under various configurations. These models capture complex relationships between device settings—like transmission power and data rate—and network conditions, establishing a solid foundation for more accurate and adaptive energy management.

To enhance this approach, I integrate these ML models with optimization algorithms like Particle Swarm Optimization (PSO) [30] to develop a framework for real-time, energy-efficient configuration adjustments. This hybrid methodology reduces energy consumption while improving the longevity and reliability of NB-IoT deployments. Additionally, energy-saving mechanisms such as PSM and DRX are incorporated, allowing NB-IoT devices to alternate between active and low-power states based on demand.

To contextualize the results of this research, the proposed ML-based optimization framework can be viewed as an enhancement to the default configurations of NB-IoT energy-saving mechanisms. While the default settings of PSM and DRX, as defined by 3GPP, provide a baseline for energy efficiency across standard applications, they are often static and not tailored to dynamic network conditions or specific use cases. By contrast, the ML-based approach dynamically adapts device configurations, such as sleep intervals and transmission settings, based on real-time environmental factors like signal quality and traffic patterns.

The results demonstrate that the proposed framework not only reduces energy consumption compared to default configurations but also maintains or enhances device performance, addressing the trade-offs typically encountered in static setups. This highlights the potential of ML-based solutions to further optimize NB-IoT deployments, bridging the gap between standardization and application-specific requirements.

3 Research Objectives

This thesis focuses on improving the battery life of NB-IoT devices. Specifically, 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 to minimize the energy consumption of these devices.*

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 [31, 32], 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 [26, 33]. However, only some offer a detailed investigation of the impact of each mechanism under a broad spectrum

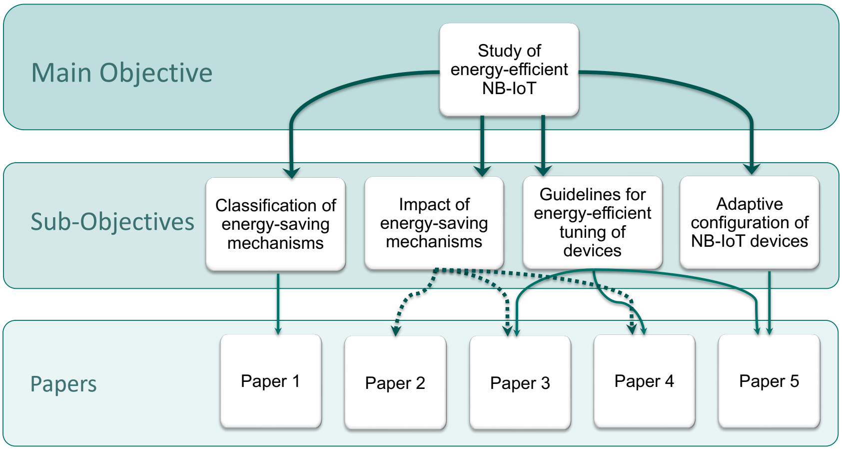


Figure 9: A diagram showing the mapping between the appended papers and the research objectives.

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 efficiently reducing NB-IoT devices' energy consumption. We also aim to provide best practices to balance these devices' energy efficiency and performance.

(O4) *To develop and evaluate a machine learning-based optimization framework for the Over-The-Air (OTA) adaptive configuration of NB-IoT devices.*
Given the expected large-scale deployment of billions of NB-IoT devices, managing their configurations dynamically to ensure energy efficiency is critical. This objective focuses on designing a framework that utilizes machine learning models to predict and adapt the optimal energy-saving configurations, such as PSM, cDRX , eDRX, and RAI, in response to changing environmental conditions like signal quality, packet loss, and data transmission needs.

The illustration in Fig. 9 shows how the five appended papers correspond to the four objectives.

4 Research Methods

Computer Science is a constantly evolving field requiring innovative research approaches. Researchers must continually find fresh ways to study and analyze data to advance the discipline. The scientific research methods used in

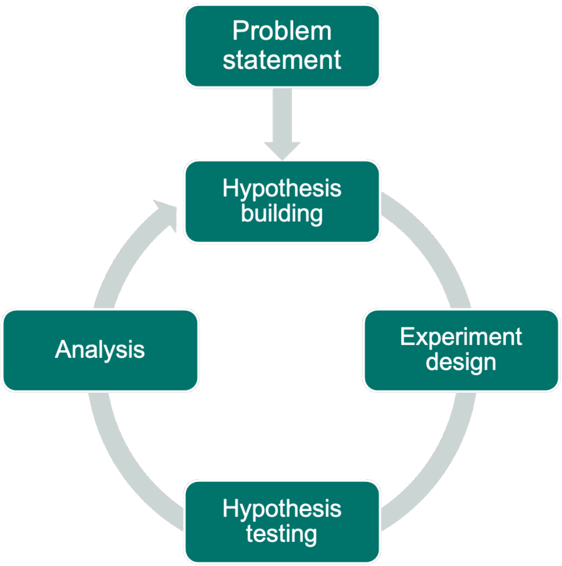


Figure 10: An overview of the iterative, scientific method.

computer science are diverse and often depend on the specific research question or project. Generally, these methods can be categorized into three main types: 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, on the other hand, focus on descriptive techniques that provide insights into the research question or project. Examples of qualitative methods include interviews, focus groups, and participant observation. Lastly, empirical methods incorporate both quantitative and qualitative approaches, allowing researchers to adopt an integrated strategy to understand the research question or project comprehensively. This approach enables researchers to uncover patterns and trends in the data more effectively.

This thesis focuses on computer science and follows the empirical scientific method, which encompasses several steps, as illustrated in Fig. 10. The empirical scientific method can be summarized in the following steps:

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 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 more accurate and lifelike models of the system and its environment than those used in analytical modeling. Emulation combines simulation and real-world experimentation, wherein only some parts of the system and environment are 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 complete control of the environment without buying or setting up expensive and intricate infrastructure. However, the results produced by analytical modeling and simulation often 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 complete 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 and by repeating the same experiment several times.

Simulated environments are an essential 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 benefit 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[2].

This thesis presents a comprehensive literature review and classification of energy-saving mechanisms, providing a solid 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, III, IV, and V 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.

5 Contributions

The primary objective of this thesis is to thoroughly analyze the energy consumption of NB-IoT devices that utilize one or more energy-saving mechanisms standardized by 3GPP. To achieve this, the thesis presents an in-depth study of various energy-saving mechanisms, highlighting their advantages and limitations when used individually and in combination. Additionally, it provides comprehensive guidelines for configuring an NB-IoT device to extend its battery life. The contributions of this thesis are detailed as follows:

1. *Classification of energy-saving mechanisms employed by CIoT.*
   Several previous studies [26, 34, 35] 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**, this thesis provides a comprehensive classification of currently used energy-saving solutions for CIoT, focusing on their reported effects on reducing energy consumption and their applicability to various use cases.

   This classification achieves two key goals: (1) it enables a clearer understanding of the range of mechanisms available for improving energy efficiency across CIoT technologies, and (2) it highlights their limitations and areas for improvement, which inform the subsequent objectives of this thesis. By reviewing and categorizing contemporary CIoT studies, this work establishes a foundation for evaluating energy-saving mechanisms in more depth. Additionally, the thesis identifies gaps in the existing literature and discusses potential avenues for future research. These contributions are provided in **Paper I**.

---

[2] 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.

2. *A summary of the effects of the energy-saving mechanisms standardized by 3GPP for NB-IoT on 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 [36, 37, 38]. However, less attention has been given to understanding how these mechanisms interact and their combined impact on energy consumption in real-world scenarios.

   To address objective **O2**, this thesis provides a detailed analysis of the behavior of key NB-IoT energy-saving mechanisms under a variety of conditions. Mechanisms such as DRX, RRC timers, PSM, RAI, and transmission power are examined individually to highlight their specific contributions to reducing energy consumption. Furthermore, the thesis investigates how these mechanisms interact when combined, providing insights into their cumulative impact on the overall energy efficiency of NB-IoT devices.

   By studying these mechanisms under diverse circumstances, the thesis contributes to a better understanding of their trade-offs and synergies, offering guidance on how they can be configured together to optimize energy consumption. These findings are particularly valuable for practical deployments, where multiple mechanisms often operate simultaneously. These contributions are provided in **Paper II** and **Paper III**.

3. *Provide guidelines on how to configure NB-IoT devices energy-efficiently.*
   Some previous works have studied the effects of specific NB-IoT protocol-stack parameters on energy consumption [31, 39, 40, 41, 42, 43, 44, 45] and proposed methods for tuning these parameters to reduce the energy consumption of NB-IoT devices. However, these studies typically focus on individual parameters in isolation and do not account for the interaction effects between different protocol-stack parameters in the NB-IoT stack. This limitation is significant because the combined impact of these parameters can influence their optimal configuration and, ultimately, the battery life of the device.

   To address objective **O3**, this thesis not only examines key protocol-stack parameters—such as DRX, RRC timers, EDT, PUR, and PSM settings—but also explores how their interactions affect energy efficiency. By studying these interactions, the thesis provides a comprehensive understanding of how multiple parameters work together and influence the overall energy consumption of NB-IoT devices.

   Additionally, the thesis offers specific guidelines and recommendations for configuring these parameters to achieve a battery life of 10 years or more, as prescribed by 3GPP standards. These recommendations are particularly valuable for practical deployments, where parameter tuning must account for both individual effects and interaction effects to optimize energy efficiency without compromising performance. These contributions are provided in **Paper II**, **Paper III**, and **Paper IV**.

4. *Develop and validate an ML framework for OTA configuration of NB-IoT devices.*
   While previous research has explored the use of machine learning for optimizing parameters in NB-IoT networks, these efforts often focus on isolated features or single layers of the communication stack. Such a narrow focus overlooks the potential benefits of a holistic, multi-layered approach that accounts for the complex interactions between different parameters and layers. To address this limitation, objective **O4** introduces a comprehensive framework that utilizes machine learning models to predict and optimize the energy-saving mechanisms of NB-IoT devices dynamically.

   This framework leverages real-time environmental data, such as signal quality, packet loss, and traffic patterns, to facilitate adaptive configuration across multiple layers of the network stack. By dynamically adjusting energy-saving mechanisms, such as PSM, DRX, and RAI, the framework enables energy-efficient operation while maintaining device performance. The scalability of the approach allows thousands of devices to be reconfigured simultaneously over the air, making it particularly suitable for large-scale NB-IoT deployments.

   A key innovation of this framework is its use of the Gradient Boosting algorithm, identified as the most accurate model for predicting energy consumption, in combination with PSO to achieve optimal configurations. This hybrid approach ensures that configurations are not only adaptive but also optimized for energy efficiency in diverse scenarios.

   The results demonstrate significant energy savings and extended battery life, validated through extensive testing across a range of use cases and deployment conditions. These findings contribute to a deeper understanding of how machine learning can be harnessed for automated, adaptive configuration, paving the way for sustainable and scalable CIoT deployments. These contributions are primarily presented in **Paper V**.

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 limit 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 and combining the most appropriate techniques for a given application. It also summarizes the energy-efficiency optimization techniques to gain an expected battery life of 10 years and more. The paper suggests that the key to saving energy for NB-IoT devices is the use of DRX, including the use of cDRX and longer PSM. 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, Constrained Application Protocol (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.

Paper IV – Evaluating the Impact of Pre-configured Uplink Resources in NB-IoT

Paper IV further investigates the effectiveness of EDT and PUR in enhancing the energy efficiency and reducing latency of NB-IoT devices. By exploring the LENA-NB simulator in the ns-3 environment, we demonstrate that PUR significantly reduces energy consumption by over 2.5 times and increases battery life by 1.6 times compared to the default RAP. Furthermore, PUR reduces latency by 2.5-3.5 times, making it especially beneficial in high-density environments. Ultimately, PUR shows potential to extend the battery life of NB-IoT devices, supporting the goal of achieving a 10-year lifespan and advocating for its widespread adoption in future IoT deployments.

Paper V – Dynamic NB-IoT Configuration: A Machine Learning-Driven Optimization Framework

Paper V investigates the application of machine learning (ML) techniques to dynamically optimize the energy efficiency of CIoT devices by predicting and configuring energy-saving mechanisms. Through the analysis of over 20 ML models, the study identifies Gradient Boosting (GB) as the most accurate predictor of energy consumption, and Particle Swarm Optimization (PSO) as the optimal method for configuring NB-IoT device parameters. The framework leverages these techniques to adjust device configurations dynamically in response to environmental factors like signal quality, packet loss, and data transmission requirements. This approach enables CIoT devices to maintain energy efficiency while adapting to real-time conditions, reducing energy consumption by 30% to 75% compared to default configurations. This framework has significant implications for network operators by facilitating large-scale, automated OTA configuration of thousands of devices, leading to extended battery life and more sustainable NB-IoT deployments.

7 Conclusions and Future Work

NB-IoT is a promising technology for the large-scale deployment of IoT due to its extensive coverage, high data rates, and low costs for devices combined with the integration with existing infrastructure. However, a significant challenge lies in the high energy consumption of NB-IoT devices, especially since they are often deployed in remote locations with non-rechargeable batteries. This thesis provides a comprehensive overview of CIoT technologies and energy-saving mechanisms, explicitly focusing on NB-IoT.

Target applications for NB-IoT generally generate infrequent low-throughput, latency insensitive traffic. The findings confirm that for battery powered devices, energy efficiency, based on appropriate configuration, is crucial to reach the target of up to ten years battery life time. This efficiency can only be achieved if the energy-saving mechanisms are configured correctly. By analyzing various parameters such as DRX, RAI, and transmission power, this thesis offers guidelines for configuring NB-IoT devices to optimize their energy usage and extend battery life.

As CIoT technology gains greater adoption, understanding the trade-off between latency and energy consumption becomes increasingly crucial, particularly for applications such as smart metering. Energy-saving configurations often involve compromises, such as longer DRX cycles or PSM intervals, which maximize energy savings but introduce additional latency. Conversely, reducing latency for real-time applications often increases power consumption.

Our research emphasizes that energy efficiency is vital for the intended low-throughput applications of NB-IoT and can be significantly enhanced by optimizing energy-saving features. The ML-based optimization models developed in this thesis provide specific guidelines for configuring NB-IoT devices to maximize energy efficiency in real time. By dynamically adapting device configurations to varying network conditions—such as signal quality and traffic patterns—without requiring manual intervention, these models demonstrate the potential for significant energy savings compared to default configurations.

It is also important to acknowledge the limitations of the studies conducted in this thesis. While the parameters studied, such as DRX, RAI, transmission power, EDT, and PUR, are essential for ensuring optimal battery performance, further analysis is needed to explore other critical aspects of NB-IoT operation. For example, congestion control mechanisms, enhanced paging techniques (such as group paging), and the impact of wake-up signals on NB-IoT devices warrant deeper investigation. Exploring these factors could yield additional insights into further reducing energy consumption and improving the performance of NB-IoT devices.

Future research directions should also address the development of advanced application-layer protocols that facilitate efficient data handling and transmission while minimizing energy usage. Additionally, incorporating multi-objective optimization frameworks that account for energy, latency, and throughput trade-offs would be beneficial for tailoring NB-IoT configurations to diverse use cases. These approaches could provide a more holistic understanding of how to optimize energy-saving mechanisms while maintaining the performance requirements of IoT applications.

References

[1] Abhishek Khanna and Sanmeet Kaur. Internet of things (IoT), applications and challenges: a comprehensive review. *Wireless Personal Communications*, 114:1687–1762, 2020.

[2] Ericsson. IoT connections forecast - mobility report - Ericsson, January 2025. Available at: `https://www.ericsson.com/en/reports-and-papers/mobility-report/dataforecasts/iot-connections-outlook#:~:text=Total%20cellular%20IoT%20connections%20are,20%20percent%20up%20to%202029.` [Accessed January 2025].

[3] Daniel Minoli and Benedict Occhiogrosso. Practical aspects for the integration of 5G networks and IoT applications in smart cities environments. *Wireless Communications and Mobile Computing*, 2019(1):5710834, 2019.

[4] Olof Liberg, Marten Sundberg, Eric Wang, Johan Bergman, Joachim Sachs, and Gustav Wikström. *Cellular Internet of Things: from massive deployments to critical 5G applications*. Academic Press, 2019.

[5] Teshager Hailemariam Moges, Demeke Shumeye Lakew, Ngoc Phi Nguyen, Nhu-Ngoc Dao, and Sungrae Cho. Cellular internet of things: Use cases, technologies, and future work. *Internet of Things*, page 100910, 2023.

[6] Abdullah Ahmed Bahashwan, Mohammed Anbar, Nibras Abdullah, Tawfik Al-Hadhrami, and Sabri M Hanshi. Review on common IoT communication technologies for both long-range network (LPWAN) and short-range network. In *Advances on Smart and Soft Computing: Proceedings of ICACIn 2020*, pages 341–353. Springer, 2021.

[7] Olof Liberg, Marten Sundberg, Eric Wang, Johan Bergman, and Joachim Sachs. *Cellular Internet of Things: technologies, standards, and performance*. Academic Press, 2017.

[8] Bassel Al Homssi, Akram Al-Hourani, Sathyanarayanan Chandrasekharan, Karina Mabell Gomez, and Sithamparanathan Kandeepan. On the bound of energy consumption in cellular IoT networks. *IEEE Transactions on Green Communications and Networking*, 4(2):355–364, 2019.

[9] Ahmed Iyanda Sulyman, Sharief MA Oteafy, and Hossam S Hassanein. Expanding the cellular-IoT umbrella: An architectural approach. *IEEE Wireless Communications*, 24(3):66–71, 2017.

[10] Bharat S Chaudhari, Marco Zennaro, and Suresh Borkar. LPWAN technologies: Emerging application characteristics, requirements, and design considerations. *Future Internet*, 12(3):46, 2020.

[11] Suresh R Borkar. Long-term evolution for machines (LTE-M). In *LPWAN technologies for IoT and M2M applications*, pages 145–166. Elsevier, 2020.

[12] Rapeepat Ratasuk, Benny Vejlgaard, Nitin Mangalvedhe, and Amitava Ghosh. NB-IoT system for M2M communication. In *2016 IEEE wireless communications and networking conference*, pages 1–5. IEEE, 2016.

[13] 3rd Generation Partnership Project (3GPP). 3GPP Release 12. Technical report, 3rd Generation Partnership Project (3GPP), March 2015. Available at: `https://www.3gpp.org/specifications-technologies/releases/release-12` [Accessed January 2025].

[14] 3rd Generation Partnership Project (3GPP). 3GPP Release 13. Technical report, 3rd Generation Partnership Project (3GPP), March 2016. Available at: `https://www.3gpp.org/specifications-technologies/releases/release-13` [Accessed January 2025].

[15] Jetmir Haxhibeqiri, Eli De Poorter, Ingrid Moerman, and Jeroen Hoebeke. A survey of LoRaWAN for IoT: From technology to application. *Sensors*, 18(11):3995, 2018.

[16] Alexandru Lavric, Adrian I Petrariu, and Valentin Popa. Sigfox communication protocol: The new era of IoT? In *2019 international conference on sensing and instrumentation in IoT Era (ISSI)*, pages 1–4. IEEE, 2019.

[17] Almudena Diaz Zayas and Pedro Merino. The 3GPP NB-IoT system architecture for the Internet of Things. In *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*, pages 277–282. IEEE, 2017.

[18] Hui-Ling Chang, Chung-Ying Hsieh, and Meng-Hsun Tsai. Flag-assisted early release of RRC scheme for power saving in NB-IoT system. In *International Conference on Smart Grid and Internet of Things*, pages 3–15. Springer, 2019.

[19] Andreas Hoglund, Dung Pham Van, Tuomas Tirronen, Olof Liberg, Yutao Sui, and Emre A Yavuz. 3GPP release 15 early data transmission. *IEEE Communications Standards Magazine*, 2(2):90–96, 2018.

[20] Andreas Hoglund, Gerardo Agni Medina-Acosta, Sandeep Narayanan Kadan Veedu, Olof Liberg, Tuomas Tirronen, Emre A Yavuz, and Johan Bergman. 3GPP release-16 preconfigured uplink resources for LTE-M and NB-IoT. *IEEE Communications Standards Magazine*, 4(2):50–56, 2020.

[21] Esad Kadusic, Christoph Ruland, Narcisa Hadzajlic, and Natasa Zivic. The factors for choosing among NB-IoT, LoRaWAN, and Sigfox radio communication technologies for IoT networking. In *2022 International Conference on Connected Systems & Intelligence (CSI)*, pages 1–5. IEEE, 2022.

[22] Global mobile Suppliers Association (GSA). NB-IoT and LTE-M Deployment Summary - September 2023, September 2023. Available at: `https://gsacom.com/paper/nb-iot-lte-m-september-2023-summary/` (Accessed: January 2025).

[23] Asia-Pacific Telecommunity. APT report on Licensed-Assisted Access (LAA) and 5G New Radio in Unlicensed spectrum (5G NR-U) as national solutions for accessing shared spectrum. Technical report, Asia-Pacific Telecommunity, Sep 2020.

[24] Kai Liu, Gaofeng Cui, Qinjie Li, Shanghong Zhang, Weidong Wang, and Xiuhua Li. An optimal PSM duration calculation algorithm for NB-IoT. In *2019 IEEE 5th International Conference on Computer and Communications (ICCC)*, pages 447–452. IEEE, 2019.

[25] Shaoyi Xu, Yang Liu, and Weiliang Zhang. Grouping-based discontinuous reception for massive narrowband Internet of Things systems. *IEEE Internet of Things Journal*, 5(3):1561–1571, 2018.

[26] Prashanth Lingala, Saidhiraj Amuru, Kiran Kuchi, et al. Energy and delay efficient intelligent release assistant indication scheme for NB-IoT. In *2022 14th International Conference on COMmunication Systems & NETworkS (COMSNETS)*, pages 246–250. IEEE, 2022.

[27] Candice Bentéjac, Anna Csörgő, and Gonzalo Martínez-Muñoz. A comparative analysis of gradient boosting algorithms. *Artificial Intelligence Review*, 54:1937–1967, 2021.

[28] Yanli Liu, Yourong Wang, and Jian Zhang. New machine learning algorithm: Random forest. In *Information Computing and Applications: Third International Conference, ICICA 2012, Chengde, China, September 14-16, 2012. Proceedings 3*, pages 246–252. Springer, 2012.

[29] Yu-chen Wu and Jun-wen Feng. Development and application of artificial neural network. *Wireless Personal Communications*, 102:1645–1656, 2018.

[30] Dongshu Wang, Dapei Tan, and Lei Liu. Particle swarm optimization algorithm: an overview. *Soft computing*, 22(2):387–408, 2018.

[31] Jinseong Lee and Jaiyong Lee. Prediction-based energy saving mechanism in 3GPP NB-IoT networks. *Sensors*, 17(9):2008, 2017.

[32] Ashish Kumar Sultania, Pouria Zand, Chris Blondia, and Jeroen Famaey. Energy modeling and evaluation of NB-IoT with PSM and eDRX. In *2018 IEEE Globecom Workshops (GC Wkshps)*, pages 1–7. IEEE, 2018.

[33] Ashish Kumar Sultania, Chris Blondia, and Jeroen Famaey. Optimizing the energy-latency tradeoff in NB-IoT with PSM and eDRX. *IEEE Internet of Things Journal*, 8(15):12436–12454, 2021.

[34] Muhammad Dangana, Shuja Ansari, Qammer H Abbasi, Sajjad Hussain, and Muhammad Ali Imran. Suitability of NB-IoT for indoor industrial environment: A survey and insights. *Sensors*, 21(16):5284, 2021.

[35] Ahmed Elhaddad, Heiko Bruckmeyer, Markus Hertlein, and Georg Fischer. Energy consumption evaluation of cellular narrowband Internet of Things (NB-IoT) modules. In *2020 IEEE 6th World Forum on Internet of Things (WF-IoT)*, pages 1–5. IEEE, 2020.

[36] Kun-Lin Tsai, Fang-Yie Leu, Tz-Yuan Huang, and Hao-En Yang. IoT device power management based on PSM and eDRX mechanisms. In *Advances on Broad-Band Wireless Computing, Communication and Applications: Proceedings of the 15th International Conference on Broad-Band and Wireless Computing, Communication and Applications (BWCCA-2020)*, pages 244–253. Springer, 2021.

[37] Mads Lauridsen, Rasmus Krigslund, Marek Rohr, and Germán Madueno. An empirical NB-IoT power consumption model for battery lifetime estimation. In *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, pages 1–5. IEEE, 2018.

[38] Eshita Rastogi, Mukesh Kumar Maheshwari, Abhishek Roy, Navrati Saxena, and Dong Ryeol Shin. Energy efficiency analysis of narrowband Internet of Things with auxiliary active cycles for small data transmission. *Transactions on Emerging Telecommunications Technologies*, 33(1):e4376, 2022.

[39] Amin Azari, Guowang Miao, Cedomir Stefanovic, and Petar Popovski. Latency-energy tradeoff based on channel scheduling and repetitions in NB-IoT systems. In *2018 IEEE Global Communications Conference (GLOBECOM)*, pages 1–7. IEEE, 2018.

[40] Ruki Harwahyu, Ray-Guang Cheng, Wan-Jung Tsai, Jeng-Kuang Hwang, and Giuseppe Bianchi. Repetitions versus retransmissions: Tradeoff in configuring NB-IoT random access channels. *IEEE Internet of Things Journal*, 6(2):3796–3805, 2019.

[41] Hilal Bello, Xin Jian, Yixiao Wei, and Min Chen. Energy-delay evaluation and optimization for NB-IoT PSM with periodic uplink reporting. *IEEE Access*, 7:3074–3081, 2018.

[42] Sergio Martiradonna, Giuseppe Piro, and Gennaro Boggia. On the evaluation of the NB-IoT random access procedure in monitoring infrastructures. *Sensors*, 19(14):3237, 2019.

[43] Cheng-Yu Chen, Arvin C-S Huang, Song-Yi Huang, and Jen-Yeu Chen. Energy-saving scheduling in the 3GPP narrow-band Internet of Things (NB-IoT) using energy-aware machine-to-machine relays. In *2018 27th Wireless and Optical Communication Conference (WOCC)*, pages 1–3. IEEE, 2018.

[44] Lishan Bao, Lei Wei, Chengling Jiang, Weiwei Miao, Bo Guo, Wei Li, Xiangdong Cheng, Rui Liu, and Jun Zou. Coverage analysis on NB-IoT and LoRa in power wireless private network. *Procedia computer science*, 131:1032–1038, 2018.

[45] Amin Azari, Čedomir Stefanović, Petar Popovski, and Cicek Cavdar. On the latency-energy performance of NB-IoT systems in providing wide-area IoT connectivity. *IEEE Transactions on Green Communications and Networking*, 4(1):57–68, 2019.

Improving the Energy Efficiency of Cellular IoT Devices

The rapid rise of Cellular Internet of Things (CIoT) is connecting billions of devices worldwide, many of which must run on limited battery power for up to 10 years. Ensuring low energy consumption is vital to avoid frequent recharges or replacements. This thesis focuses on enhancing the energy efficiency of Narrow-Band IoT (NB-IoT) devices by optimizing 3GPP's energy-saving mechanisms. We investigate Discontinuous Reception (DRX), Release Assistance Indicator (RAI), Power Saving Mode (PSM), Early Data Transmission (EDT), and Preconfigured Uplink Resources (PUR) to evaluate how each feature affects battery life and latency. Striking a balance between energy savings and performance is key. Our machine learning-based optimization approach dynamically adjusts configurations based on network conditions, offering valuable guidelines for extending battery life to 10+ years in diverse CIoT scenarios.

ISBN 978-91-7867-562-3 (print)

ISBN 978-91-7867-563-0 (pdf)

ISSN 1403-8099

DOCTORAL THESIS | Karlstad University Studies | 2025:15

Improving the Energy Efficiency of Cellular IoT Devices

The rapid rise of Cellular Internet of Things (CIoT) is connecting billions of devices worldwide, many of which must run on limited battery power for up to 10 years. Ensuring low energy consumption is vital to avoid frequent recharges or replacements. This thesis focuses on enhancing the energy efficiency of Narrow-Band IoT (NB-IoT) devices by optimizing 3GPP's energy-saving mechanisms. We investigate Discontinuous Reception (DRX), Release Assistance Indicator (RAI), Power Saving Mode (PSM), Early Data Transmission (EDT), and Preconfigured Uplink Resources (PUR) to evaluate how each feature affects battery life and latency. Striking a balance between energy savings and performance is key. Our machine learning-based optimization approach dynamically adjusts configurations based on network conditions, offering valuable guidelines for extending battery life to 10+ years in diverse CIoT scenarios.

DOCTORAL THESIS | Karlstad University Studies | 2025:15
ISBN 978-91-7867-562-3 (print) | ISBN 978-91-7867-563-0 (pdf)