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EDT+: Energy Consumption Optimization of NB-IoT

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ABSTRACT

Narrowband Internet of Things (NB-IoT) is a popular communication standard used to construct IoT applications. To optimise energy consumption of NB-IoT, Early Data Transmission (EDT) is included within the standard. In this work we propose and describe Improved Early Data Transmission (EDT+) which further reduces energy consumption. EDT+ takes advantage of the fact that most sensor nodes are static and do not move when deployed. Thus, the work required during an NB-IoT wake-up cycle can be significantly reduced. Our NS3 simulations show that EDT+ reduces communication related energy consumption of a node by at least 20%. Thus, EDT+ will be useful to facilitate energy harvesting and battery free deployments.

CCS CONCEPTS

• **Networks** → **Network protocol design**; **Transport protocols**; **Network simulations**.

KEYWORDS

NB-IoT, EDT+, EDT Energy Harvesting, LPWAN, Energy Optimization

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1 INTRODUCTION

To achieve sustainable IoT deployments, it is desirable to have battery free nodes that can fulfil a set task indefinitely. Energy harvesting is considered to provide the required energy for node operation. Solar, temperature, vibration, pressure and other sources have been used for energy harvesting to power sensor nodes. Usually only a small amount of energy can be generated by a harvesting device and it is therefore essential to optimize energy consumption of all sensor node components [1].

For many sensor nodes the communication transceiver is the dominant energy consumer [2]. Thus, it is vital to reduce energy consumption of this component. This usually requires a multilevel approach, including the optimisation of sensing patterns, reduction of network complexity, and optimisation of transceiver use and technology [3].

Sensing applications increasingly employ Low Power Wide Area Network (LPWAN) technologies like LoRaWAN and NB-IoT for long-range communication with a base station (BS). These solutions bypass complex network procedures, enabling direct data transmission from node to gateway. [4] Although limited in network structure and hardware optimization, improvements can still be made in transceiver usage through communication protocol enhancement between node and BS [5].

In this paper we propose optimisation of the popular NB-IoT protocol in order to reduce energy consumption of a device and, thus, aiding the use of battery free node designs. We refer to our design as EDT+, a significant improvement of the energy saving scheme EDT currently defined within the NB-IoT standard.

EDT+ exploits the static nature of sensor nodes in many application scenarios. If a node is static it will at every reporting interval connect to the same BS.Consequently, it is unnecessary to determine BS and communication parameters at each wake-up. Using EDT+ a node can notify the BS of its static nature and the BS can then allocate resources for future wake-up events. Thus, significant communication overhead and consequently energy is saved for each wake-up. EDT+ can coexist with the normal NB-IoT communication procedure; EDT+ nodes that miss a scheduled wake-up will use normal NB-IoT procedures to reconnect to the network.

We believe that the assumption of static nodes is not too restrictive. In most IoT deployments nodes would not be mobile. For example, for applications such as smart meters, structural monitoring or weather monitoring nodes are predominantly static.

The contributions of this work are:

- *Improved Early Data Transmission (EDT+)*: A specification of EDT+, an enhancement of EDT for NB-IoT considering static node deployments.
- *EDT+ Evaluation*: We provide an NS3 simulation comparison of EDT and EDT+. The results show that EDT+ reduces communication related energy consumption of a node by at least 20%.

The remainder of the paper is structured as follows. Next we describe related work followed by a description of background, including a brief overview of NB-IoT and the existing energy optimisation methods, specifically Cellular Internet of Things Optimization (C-IoT-Opt) and EDT. We then describe our new EDT+ followed by an NS3 simulation comparing EDT with EDT+.

2 RELATED WORK

Zobras et al.[6] tackle the issue of packet collisions in LoRa-based transmissions arising from the ALOHA-style transmission policy. They propose a novel scheduling method where node transmissions are organized in different slots according to their Spreading

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Factor (SF) to minimize collisions and allow parallel transmissions for different SFs. They present two algorithms that facilitate this, working offline to allocate SFs to nodes, significantly reducing data collection time while abiding by radio duty cycle restrictions. The approach demonstrates up to 101% improvement in data collection time and up to 250% in energy efficiency, maintaining nearly a 100% packet delivery ratio.

Haroun et al. [7] delve into the creation of a batteryless, ultra-low-power Wireless Sensor Transmission Unit (WSTx) reliant on solar-energy harvesting and LoRa technology. Their research explores the potential of using polycrystalline photovoltaic cells to harness ambient indoor light, with a focus on power management design and the associated challenges. Findings indicate that the system, which has a maximum power output of 1.4 mW, showcases substantial efficiency, with the ability to power the WSTx for up to six hours through energy harvested at a rate of 1.2 mW per second, reaching peak power efficiency of 85.7%.

Dong et al.[8] developed an ultra-low-power SDR tailored for the energy-efficient demands of contemporary IoT networks. Central to this advancement is the integration of μW-level backscatter in the SDR, which avoids the energy-intensive active radio frequency chains. A distinctive circuit design is introduced, optimizing energy harvesting and power control, while addressing the harmonic and mirror frequencies produced by backscatter hardware. The SDR's performance, assessed across varied modulation techniques, showcases a 100 kb/s data rate with a remarkably low power consumption—under 200 μW in active mode and merely 10 μW in sleep mode. Real-world applications, including a railway inspection scenario achieving a 1 kb/s battery-free data transmission to a UAV 50 meters away, and studies on smart factories and logistics, validate the platform's versatility.

3 BACKGROUND AND THEORY

3.1 Narrowband Internet of Things (NB-IoT)

To cope with increasing demands on Internet of Things (IoT) deployments, 3rd Generation Partnership Project (3GPP) [9] introduced the Narrowband Internet of Things (NB-IoT) standard as a communication technology enabler [10]. The key features of NB-IoT are:

- **Low Power Consumption:** One of the primary advantages of NB-IoT is its low power consumption, allowing devices to operate for years on a single battery charge or potentially make use of power harvesting.
- **Wide Coverage:** NB-IoT provides improved indoor and deep penetration coverage, making it suitable for devices located in basements, underground, or deep within buildings.
- **Low Cost:** The technology is designed for simplicity, which translates to lower device costs. This makes it feasible for large-scale deployments.
- **High Connection Density:** NB-IoT can support a large number of devices in a small area, making it ideal for applications like smart cities where thousands of devices might be deployed in close proximity.

NB-IoT operates on a licensed spectrum, making the most of the existing Global System for Mobile Communication (GSM), Long-Term Evolution (LTE), and 5G network infrastructures. NB-IoT devices, known as User Equipment (UE), have three operational modes: In-band, Guard-band, and Standalone. Our study focuses on the Standalone mode, but the insights we've gathered apply to the other modes as well.

3.2 NB-IoT Energy Consumption

For many NB-IoT applications, devices are expected to operate for extended periods, often more than 10 years, on a single battery charge. While there has been research focused on energy harvesting techniques for NB-IoT [11], the applicability of these methods is predominantly constrained to outdoor environments [12]. Consequently, energy efficiency, particularly in the context of net-zero and energy harvesting strategies, emerges as an indispensable consideration. NB-IoT devices, although engineered for minimal power consumption, encounter energy-related challenges [13] that are influenced by a range of factors:

- **Control and Signaling Overheads**: Every communication protocol has associated control and signaling data that need to be exchanged to establish and maintain a connection. In the case of NB-IoT, these overheads, which are essential for the device's operation, can sometimes be significant compared to the actual data being transmitted. These overheads can lead to higher energy consumption, reducing the effective operational life of the device [14].
- **Repeated Signal Transmission**: To ensure data integrity and to combat poor reception in challenging environments, NB-IoT employs Coverage Enhancement (CE). This involves transmitting the same data multiple times to increase the likelihood of successful reception. However, each transmission consumes energy. In areas with high device density or poor network conditions, where repeated transmissions become the norm rather than the exception, this can challenge the device's power-saving mechanisms [15].
- **Parameter Configuration**: The operational parameters of an NB-IoT device, many of which are configurable, play a pivotal role in its energy consumption profile. For instance, the paging interval, which determines how frequently a device checks for incoming messages, can significantly influence energy consumption. While longer intervals can save energy, they might lead to increased latency. Striking the right balance through careful parameter configuration can optimize both energy consumption and device responsiveness. Empirical studies have shown that even minor tweaks to default configurations can lead to substantial energy savings [16].

3.3 NB-IoT Transmission Procedure

In a standard NB-IoT setup, the UE is programmed to send data reports at regular intervals, for instance, every *t* hours. The detailed process of communication is illustrated in Figure 1. The procedure unfolds as follows:

1. **Waking Up and Synchronization**: Initially, upon waking up, the UE initiates a synchronization with the BS in both time and frequency domains. This synchronization is achieved through the acquisition of the Narrowband Primary Synchronization Signal (NPSS).

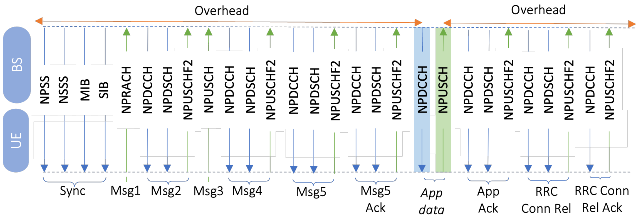


Figure 1: Standard transmission procedure of an NB-IoT node (called UE) and BS.

(2) **Cell ID Acquisition**: Following the NPSS, the UE receives the Narrowband Secondary Synchronization Signal (NSSS). This signal correlates with the NPSS to derive the cell ID, facilitating the decoding of downlink channel data and encoding of uplink channel data.

(3) **Master Information Block (MIB) and System Information Block (SIB) Procurement**:
- MIB Retrieval: After synchronization, the UE retrieves the MIB transmitted via the Narrowband Physical Broadcast Channel (NPBCH). This block is essential in acquiring the scheduling data required for the subsequent steps.
- Narrowband System Information Block 1 (SIB1-NB) and Narrowband System Information Block 2 (SIB2-NB) Acquisition: The UE obtains the SIB1-NB using the data from the MIB, and thereafter procures the SIB2-NB, which contains the necessary settings for initiating the Random Access Procedure (RAP).

(4) **Random Access Procedure (RAP)**: During the RAP, the UE establishes a secure link to the BS through a series of message exchanges:
- **MSG1**: The UE initiates the process by sending a preamble through the Narrowband Physical Random Access Channel (NPRACH).
- **MSG2**: The BS shares vital information directing the UE to proceed with the setup.
- **MSG3**: The UE responds by sending security credentials.
- **MSG4**: Involves the BS sending a HARQ ACK, confirming the successful reception of MSG3.
- **MSG5**: Takes place if MSG4 is not received, prompting the UE to resend MSG3.

(5) **Data Transmission**: Following the successful completion of the RAP, the UE is prepared to send data reports.

(6) **Connection Release and Sleep Mode**: Once the data report is acknowledged by the BS, the BS issues a connection release message, directing the UE to enter sleep mode until the next scheduled data report.

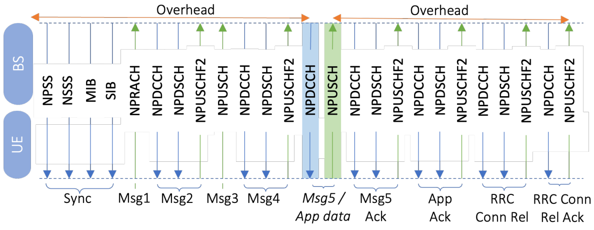
This series of coordinated steps effectively outlines the standard communication procedure in an NB-IoT scenario, emphasizing secure and reliable data transmission.

3.4 C-IoT-Opt and EDT Mechanism

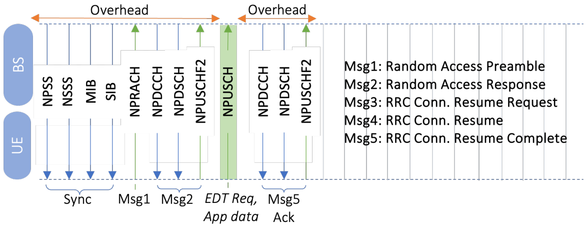
The Cellular Internet of Things Optimization (C-IoT-Opt) and Early Data Transmission (EDT) mechanisms, developed to improve NB-IoT device performance, address latency, energy usage, and spectral efficiency issues, especially in high device density settings.

C-IoT-Opt: This feature facilitates small data transmissions in NB-IoT, enabling data exchange at the Radio Resource Control (RRC) level between the UE and the BS. As shown in Figure 2 (a) it allows the piggybacking of application data in the Downlink and Uplink directions within Msg4 and Msg5 respectively, through a "dedicatedInfoNAS" Information Element (IE) [17].

EDT: Deployed in 3GPP Release 15, EDT empowers idle UEs to transfer data via Msg3, as shown in Figure 2 (b). After successful Uplink (UL) data transmission, the RAP concludes with a RRCEarlyDataComplete message that can also convey downlink data. By reducing the small data transmissions overhead, it significantly enhances spectral and energy efficiency. Demonstrably, it achieves up to 2.9 times lower latency and 3.7 times reduced spectral usage, making it favorable for both application and network operators [17].



(a) NB-IoT C-IoT Optimization



(b) NB-IoT EDT

Figure 2: C-IoT-Opt and EDT transmission procedure reducing communication effort.

Both, C-IoT-Opt and EDT play a pivotal role in optimizing the performance of NB-IoT devices. While C-IoT-Opt focuses on optimizing small data transmissions at the RRC level, EDT emphasizes reducing latency and enhancing spectral efficiency, especially in large-scale scenarios.

4 Improved Early Data Transmission (EDT+)

EDT+ exploits the fact that most nodes are static and can therefore reuse communication parameters throughout periodic wake ups. Thus, overhead is reduced as shown in Fig. 3. The goal is to send data as quickly as possible after wake up, taking full advantage of the stationary nature of the UE.

4.1 Overview

A device first checks if it has the necessary information to utilize EDT+ when it wakes up. If it is connecting for the first time or lacks essential details, it will establish a standard connection and

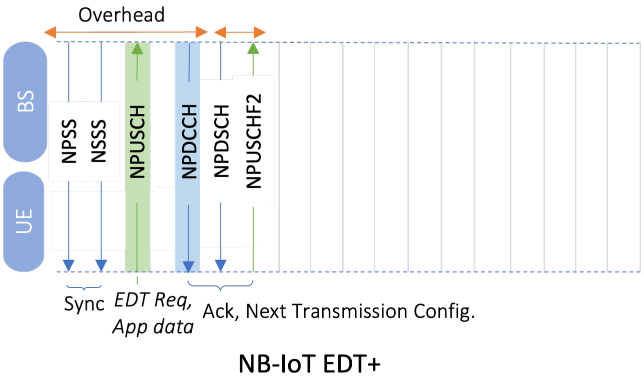


Figure 3: EDT+ transmission procedure.

request the EDT+ details for future transmissions. After receiving this information, the device goes into sleep mode for a duration specified in the new configuration.

When the device already possesses the EDT+ configuration, its next step is to acquire the NPSS and NSSS. The device's subsequent actions are dictated by its clock accuracy; a well-synced clock allows for immediate data transmission. If there's uncertainty about the synchronization, the device fetches the MIB and SIB1-NB to determine the exact degree of its sync discrepancy by analyzing the frame and hyperframe number from the SIB1-NB.

If synchronization within the current time slot is verified, data transmission proceeds. Otherwise, the device reverts to the standard connection procedure. After any transmission, it receives the setup for the next transmission and adjusts its clock to preempt potential drift before the following transmission.

4.2 Initial Connection and Message Transmission

As in standard NB-IoT protocol, the initial connection begins with the device sending a Random Access Request (RAR) to the BS, also known as the BS in the LTE framework. This is followed by the BS's Random Access Response. In our implementation, we have extended the Connection Request message (part of the RRC Connection Setup procedure) to include additional information about the static nature of the device.

This is achieved by appending a "EDT+" flag to the Connection Request message. If the "EDT+" Boolean is set to true, it signifies that the device is static, hence invoking the new static device handling mode. This additional information allows the BS to identify the device as a static device right at the start of the connection setup process.

Along with the "EDT+" flag, we include Payload Size and Transmission Periodicity. The Payload Size indicates the maximum size of the payload that the device will transmit in each cycle. It allows the BS to efficiently allocate resources for the incoming data. The Transmission Periodicity is crucial for the BS to determine the appropriate time-slot for the device to wake up and transmit its payload.

4.3 Time Slot Allocation

After receiving the Connection Request with the "EDT+" flag set to true, the BS processes it as a regular NB-IoT request. Additionally it calculates the next available time-slot for the device to wake up based on the network load and the device's Transmission Periodicity.

In a normal transmission the UE receives the RRCConnectionSetup message, which contains all the radio configurations dedicated for this UE and includes configuration parameters for its sub-layers: PDCP, RLC, MAC, or PHY. In EDT+ similar to RRCConnectionSetup, after every transmission, the UE will receive PDCP, RLC, MAC, or PHY along with the WakeUpTime, the Transport Block Size (TBS), the number of repetitions, and the allocated time slots.

The TBS for EDT+ will be the same as EDT and will supports a TBS of 328, 408, 504, 584, 680, 808, 936, or 1000 bits. In the beginning the TBS should have a lower size if possible thus allowing the number of repetitions to be increased.

The number of repetitions will be decide by three factors, the TBS, the coverage class and the clock accuracy. The value should be selected depending on which factor will have the higher number of repetitions. If the defining factor is the clock accuracy, the number of repetitions will change after each transmission in case the UE is able to adjust to the clock drift [18]. This behavior will be observed by the BS and will transmit the number of repetition during the next transmission scheduling.

4.4 Data Transmission

In order to facilitate the possibility for a device to successfully transmit a package in EDT+ the BS should allocate at least one 3.75 kHz subcarrier for this type of connection and a maximum of 6 subcarrier for a 15 kHz spacing and a six tone transmission, thus leaving a minimum of half of the bandwidth to normal NB-IoT connections and still respecting the Narrowband Physical Uplink Shared Channel (NPUSCH) configurations. This configurations can be adjusted, depending on the number of EDT+ devices.

Furthermore the allocated time slot for transmission should be dynamic on the BS side, thus compensating for possible time drifts on the UE side. It is worth mentioning that a UE should not transmit greater than 410 ms for a single transmission to avoid enhancing the time drift due to overheating. Similar to the NPRACH and NPUSCH, there should be a 40 ms gap between transmissions, where the device should switch back to listening mode and wait for the acknowledgment. Going by the half-duplex nature of the UE, there should be at least a 3-ms gap to allow the device to switch from transmission mode to reception mode and be ready for monitoring the next Narrowband Physical Downlink Control Channel (NPDCCH) search space candidate for the Acknowledgement (ACK) as shown in Fig. 4

When transmitting the data, the device should also include the index of the repetition. This information is important because the BS could then adjust the resources dedicated to that specific device. Some of the adjustment could be:

- Increase/decrease the listening time-slot
- Increase/decrease the number of uplink repetitions
- Adjust the Time-of-Arrival Offset (TAO)

It is important to point out that the EDT+ transmissions will have all the security features that the NB-IoT protocol has, and will transmit encrypted data, since the BS already has the cryptographic credentials stored.

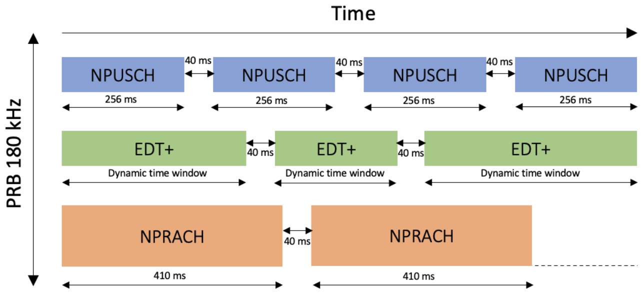


Figure 4: Possible allocation of EDT+ within the Uplink Schedule

4.4.1 *Increase decrease listening time-slot.* As illustrated in Fig. 4, the BS dynamically adjusts the listening period for individual devices considering factors such as clock accuracy, payload size, and available resources. For instance, with 20% EDT+ resource utilization, the BS might extend the allocated time for a device anticipating significant or unknown clock drift, based on historical data. This adjustment facilitates the capture of repetitions and their indices, which in turn aids in calculating the TAO to be conveyed to the UE. Consequently, the UE modifies its clock drift as per the received TAO, optimizing it for subsequent transmissions. This continuous adjustment by the BS, responding even to minor drifts by altering the time-slot accordingly, ensures a dynamic and efficient transmission environment.

4.4.2 *Increase/decrease the number of uplink repetitions.* During data transmission, the UE must include the repetition index to aid the BS in assessing and adjusting for clock drift, detailed in section 4.4.1. Apart from modifying the listening time slot, the BS might instruct the device to alter the repetition count to optimize resource use, generally favoring a reduction in repetitions.

For example, in a context with sufficient EDT+ transmission resources, where the listening period can be maximized and a message is decodable at a repetition index less than 10, a device running with 16 repetitions should decrease the count to 10, saving battery life.

However, in areas with weak signals and synchronization issues, if the BS can't decode the message despite utilizing the fullest allocated listening span, it should send a failure acknowledgment, accompanied by the TAO and a directive to increase repetition numbers, thereby fostering adaptive responses to varying conditions and enhancing system efficiency and reliability.

4.4.3 *Adjust the TAO and Timing Offset Propagation (TOP).* The inherent challenges associated with the frequency references in NB-IoT devices, particularly in the context of temperature variations, can lead to issues like Clock Frequency Offset (CFO) [19] and time drift [20], [18].

The Time-of-Arrival Offset (TAO) is the parameter which will allow the UE to keep the synchronization with the BS on the uplink channel. This parameter plays an essential role for the protocol as it will tell the device, the necessary offset to adjust the clock for further transmission. If we consider an ideal UE without clock drift, this parameter will be adjusted once, and a near perfect transmission will be achieved, where the device wakes up, transmits the data and the BS receives it in the shortest time-slot possible. On the other hand because no such devices exist, the TAO will be calculated and transmitted every time for small adjustments. If the device has a predictable drift, the Timing Offset Propagation (TOP) will be calculated by the UE based on multiple reception of the TAO

4.5 Contingency Plan and Reconnection

EDT+ includes a fail-safe for scenarios where the device sends the first packet but does not receive the acknowledgment within the specified window. If no communication is received for a predefined duration, the device initiates a standard connection process. This ensures that the device is not left in limbo. To be as efficient as possible while monitoring the NPDSCH, the device should also acquire the MIB and the SIB1-NB which will also provide the frame number and the hyperframe number. With these two pieces of information the device will know for sure if it is out of sync. The BS, upon receiving this request, removes the device's previous entry from its device list. This ensures that the BS's records are kept up-to-date and that no redundant entries are maintained.

5 EDT+ EVALUATION

5.1 The LENA-NB-IoT Module in NS3

We based our evaluation on the existing LENA LTE Module [17] for NS3. The LENA-NB-IoT module incorporates enhancements outlined in the 3GPP Release 15, such as EDT, C-IoT-Opt, and a comprehensive energy state machine. These additions enable the module to accurately simulate the functions and behaviours of NB-IoT networks. We extended the LENA-NB-IoT module to include EDT+.

5.2 Evaluation Scenarios and Parameters

In the conducted simulations, five distinct evaluation scenarios were used as shown in Table 1. These scenarios were chosen to facilitate a comprehensive analysis of real-world use cases, leveraging different parameters such as device density and payload size.

Application	No. of Devices in a Single Cell	Reporting Interval Uplink	No. of Uplink Bytes
High Density	172800	1/day	49
Water metering	37500	1/day	200
Gas metering	37500	4/day	100
Parking management	8000	1/hour	100
Watering	200	2/day	100

Table 1: Summary of Evaluation Scenarios Detailing Application Type, Device Density, Reporting Interval, and Data Volume for Uplink Communications

- **High Density Scenario:** Referenced from the work by Pascal et al. [17], this scenario serves as a benchmark for our study, allowing us to draw parallels with the established EDT transmission data. It replicates the conditions stipulated in the study by Pascal, deploying 172,800 devices in a single cell, each transmitting a 49-byte payload daily.

- **Other Scenarios:** Inspired by practical field deployments described by Fattah et al. [21], the scenarios presented in Table 1 are grounded in reality, each representing a different utility management system with varying device densities and reporting intervals.

To mirror real-world conditions, a non-ideal physical channel simulation was employed, characterized by three distinct UE coverage levels: very good, medium, and bad. The UEs were randomly allocated in each simulation to foster a diverse data set.

6 PERFORMANCE ANALYSIS AND COMPARISON

The primary purpose of EDT+ is to take advantage of the static nature of the NB-IoT devices. By simplifying the data transmission process, we expect improvements in network capacity, battery lifetime and latency.

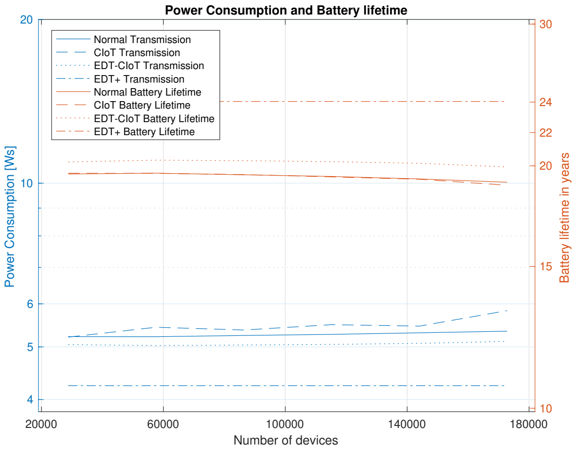


Figure 5: Power consumption and battery lifetime for High Density scenario. Assuming the device has a minimum CFO drift for EDT+

In Fig. 5 we can see that for the High Density scenario the Standard and Cellular IoT (CIoT) transmission have very similar power profiles which are also reflected in the battery lifetime. Similar to the results described by Pascal et al. [17], the EDT has better energy efficiency then Standard and CIoT transmission, which pushes the battery lifetime to just over 20 years, using. When we consider the EDT+ transmission we can observe a significant power reduction as low as 4.2 W/s compared to 5 W/s in the case of EDT. This reduction is due to the low number of messages that need to be sent when using EDT+. When relating the energy consumption to the battery lifetime, we can see a significant increase of around 20% compared to EDT, using the same NS3 battery configurations as [17].

To represent more realistic scenarios we simulate a water meter, gas meter, parking and watering scenario as previously outlined. Fig. 6 depicts the daily energy utilization depending on the scenarios presented in Section 5.2. While the hourly transmission seems aggressive, there are energy harvesting technologies, such as solar and wind [22] that would enable such settings. Contrary if the context does not require intense transmission intervals and high payload size, novel approaches, such as piezoelectric or thermoelectric, presented by [23] could enable UEs to become energy independent.

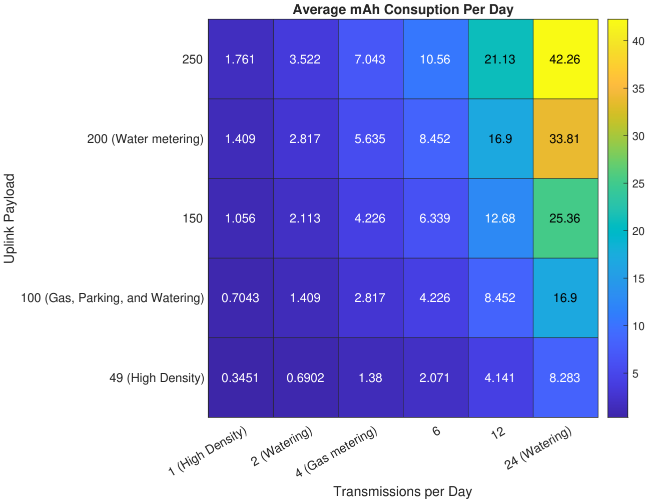


Figure 6: Average energy used per day, factoring in the size of the uplink payload and the number of transmissions occurring daily.

7 CONCLUSIONS AND FUTURE DIRECTIONS

In this study, we introduced EDT+, a novel protocol devised to enhance the energy efficiency of transmissions in the NB-IoT domain. Through NS3 simulations, we demonstrated that the implementation of EDT+ can significantly reduce the energy expenditure per transmission. Notably, this facilitates the integration of various energy harvesting techniques within the NB-IoT framework. Our results indicate a minimum improvement of 20% in battery lifespan compared to existing transmission strategies.

Looking forward, we intend to further refine the EDT+ protocol, with a focus on investigating the impact of clock accuracy on network capacity. Additionally, we aim to identify the most effective approach for the BS to allocate EDT+ resources. This includes an analysis of the protocol's resilience against vulnerabilities identified in prior research [24].

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