Energy Modeling and Evaluation of NB-IoT with PSM and eDRX

Ashish Kumar Sultania*, Pouria Zand†, Chris Blondia* and Jeroen Famaey*
*IDLab, University of Antwerp – imec, Belgium
†Holst Centre/imec, Eindhoven, The Netherlands
Email: {ashishkumar.sultania, chris.blondia, jeroen.famaey}@uantwerpen.be, pouria.zand@imec-nl.nl

***Abstract*—Large-scale deployment and management of Internet of Things (IoT) devices will become a critical issue in the near future. The 3rd Generation Partnership Project (3GPP) has proposed NarrowBand - Internet of Things (NB-IoT) as a new radio technology standard to enable Internet connectivity for a massive number of low-throughput devices. It supports better coverage and lower energy consumption than traditional Long-Term Evolution (LTE). The NB-IoT specification adopts the Power Saving Mode (PSM) and Extended Discontinuous Reception (eDRX) mechanisms to achieve a long battery life. In this paper, we present an energy consumption model for NB-IoT devices using PSM and eDRX, with a Poisson arrival process for uplink and downlink data transmissions. The model is compared to NS-3 simulation results. We analyze NB-IoT energy consumption for different PSM timers, eDRX timers and packet Inter-Arrival Times (IATs) based on the proposed model. Additionally, we have simulated the battery life for an NB-IoT use case on tracking shared bicycles. Comparison of the analytical model and simulation results shows consistency in the results with an average error of 11.82%. Our results also showed that with a 5 Wh battery, a device lifetime of more than 12 years can be achieved when transmitting at most one packet per day, and when properly configuring the PSM and eDRX timers.**

***Index Terms*—NB-IoT, Power Saving Mode, eDRX, Energy Model, NS-3 simulator, Cellular LPWA, battery consumption**

I. Introduction

Many popular Low Power Wide Area (LPWA) technologies like SigFox, Weightless and LoRa exist, but their deployment requires to build a new infrastructure. However, cellular LPWA solutions can benefit from existing LTE systems to be deployed rapidly. Many operators like Orange, Vodafone and TIM are already offering commercial NB-IoT services in many countries based on LTE technology for low data rate devices. There are many use cases that can be supported by NB-IoT networks such as smart metering, smart parking, smart street lighting, asset tracking, air quality monitoring and smart waste management. The characteristics of NB-IoT that attract users include low power consumption enabling long battery life, improved coverage, low cost, secure connectivity and strong authentication [1]. NB-IoT devices are expected to be battery-powered and should be able to operate for several years without battery replacement. NB-IoT has different requirements than LTE and so the existing schemes used for power saving in LTE are inadequate.

There are two new power saving schemes proposed for cellular IoT devices named power saving mode (PSM) and extended discontinuous reception (eDRX) [2]. PSM allows devices to enter into a deep sleep mode by switching off most of its circuitry while staying registered to the network. In this mode, the device is not reachable from the network. However, it can wake up at any time to transmit data. In eDRX, devices enter into an idle mode where they do not listen to the radio channel for a defined period and become active periodically to receive a paging message from the network for possible incoming data before switching to deep sleep mode. Section III explains these schemes in detail.

In this paper, we concentrate on the analysis of the two NB-IoT power saving schemes. We model the energy consumption behavior of a device with a Poisson arrival rate for uplink (UL) and downlink (DL) data packets. We have also implemented these NB-IoT features in the NS-3 network simulator. The simulation and analytical model are compared for different PSM timers, eDRX cycles and Inter-Arrival Times (IATs). The analysis of energy consumption of an NB-IoT device using PSM and eDRX is done using the results of the model. We also present the battery life for a practical use-case of tracking shared bicycles.

The paper is organized as follows. Section II summarizes related work. Section III gives an overview of the NB-IoT power saving features and Section IV explains the analytical model of eDRX and PSM. Subsequently, Section V presents all the evaluation results. Finally, Section VI draws the main conclusions.

II. Related Work

Maldonado et al. [3] evaluate energy consumption of an NB-IoT device considering different coverage levels and different uplink packet IATs for two new mechanisms used to optimize the data transmission. These mechanisms are Control Plane Cellular IoT (CP) optimization and User Plane Cellular IoT (UP) optimization. They also propose an analytical model to calculate the energy consumption for each procedure based on a Markov chain. The authors found that the battery lifetime decreases by shortening IATs or by keeping the device in DRX state. With short IATs, DRX dominates to save energy and for longer IATs, energy consumption saving is done by PSM. The authors also compare the coverage level, concluding that the device uses more energy under extreme conditions compared to normal conditions. In a technical report 3GPP [4] also estimated the battery life for uplink transmissions comparing different cellular IoT deployments.

Hertlein et al. [5] focus on comparing energy consumption of NB-IoT with LTE by taking the measurements over the air with a normal network operator. The authors compare the transmission of different sized data packets and found that NB-IoT consumes less power with respect to normal LTE mode.

Oh et al. [6] analyze and model the energy consumption rate for different device inactivity times and data arrival rates focusing on downlink data reception. Their work mainly focuses on analyzing the efficiency of the RRC connected state for DL data. They conclude that the average battery consumption rate increases by reducing the duration of RRC connected state for an exponential distributed DL data arrival rate. Many existing works [7–11] have focused on performance analysis of DRX, optimization of DRX parameters lowering the energy consumption and modeling it with bursty packet data traffic using a semi-Markov process. Tseng et al. [12] provide an analysis of the average delay and power consumption of the DRX mechanism.

However, to the best of our knowledge, there are neither analytical nor simulation models for analysing average energy consumption of NB-IoT devices using both PSM and eDRX. Our proposed model considers a Poisson arrival rate of data packets. The NB-IoT NS-3 simulation code is enhanced with an energy model, power saving features and RRC states. This paper focuses on both UL and DL data and analyzes a use-case of tracking shared bicycles.

III. NB-IoT POWER SAVING FEATURES

This section discusses the power saving mechanisms of NB-IoT and different states of a device based on power consumption. The device and eNodeB communication require a Radio Resource Control (RRC) connection to be established and this state of the device is called RRC Connected state. When the device releases its active RRC connection, it moves to the RRC Idle state. The device in RRC Connected state consumes more energy as the device gets dedicated bearers established to begin the data transmission and needs to monitor the DL channel in all the subframes except the subframes for UL transmission. The control channel it monitors is called the Narrowband Physical Downlink Control Channel (NPDCCH) which is required to receive the DL data notification or UL data grant from the eNodeB. According to the energy consumption of the device, there can be six possible states *Downlink, Uplink, Connected, Idle, PSM* and *Paging* Figure 1 shows a state transition diagram of these states.

There are two energy saving mechanisms of NB-IoT that target a 5Wh battery lifetime of more than 10 years [4]. These mechanisms modify the pattern of device communication with the network by modifying the RRC state's transition timers. They are briefly described in the remainder of this section.

A. Extended Discontinuous Reception

eDRX mechanism can be used while the device is in either of the RRC states. It is similar to Discontinuous Reception used in LTE systems but with longer timer value to achieve further improvement in energy consumption. eDRX specifies

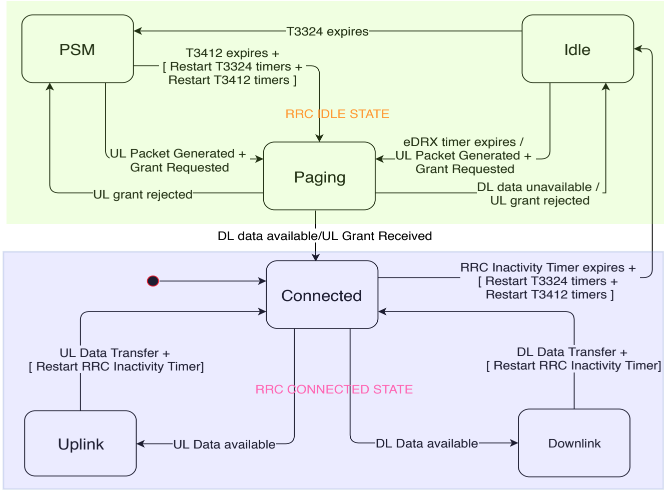


Fig. 1: State diagram of NB-IoT energy components

the timers to deactivate monitoring of the DL control channel. eDRX works in cycles where each cycle consists of an *On Duration* during which device monitors the DL control channel and *eDRX period* during which the device saves its battery and stops monitoring the control channel. The monitoring of the control channel for DL data indication or UL grant is known as $Paging$. The device during these periodic eDRX cycles is said to be in $Idle\ state$. The device remains in Idle state until the expiration of timer T_{3324} without any activity on the control channel and then switches to the $PSM\ state$. As monitoring of the control channel consumes more energy than remaining in Idle Figure 1 shows Paging and Idle as two different states. If the monitored control messages contain a DL data indication or UL grant, the device will switch its state to $Connected$. It is necessary to optimize the eDRX timers to manage the tradeoff between energy consumption and DL communication latency. In RRC Connected state, the maximum eDRX cycle is 10.24 seconds and in the RRC Idle state, it is 10485.76 seconds (2.91 hours). In IoT use cases, the RRC Connected period should be short, and therefore eDRX during RRC Idle makes a bigger contribution to the battery-saving than eDRX during RRC Connected. As such, we have considered eDRX during RRC Idle state as shown in Figure 1.

B. Power Saving Mode

PSM works in RRC Idle state enabling the device to enter into deep sleep. In the deep sleep state, the device is unreachable by the network but stays registered to it. The PSM cycle includes periodic reception of paging messages and deep sleep. For most IoT scenarios, the downlink latency is not important and it is enough to monitor paging infrequently which enables a device to be in deep sleep for a long time. For NB-IoT, one PSM cycle time, named $T_{3412}\ extended$, supports a maximum value up to 310 hours $(12.91 days)$. If a device in PSM state generates an UL packet, it switches to the *Paging* state to monitor the control channel for the UL grant. The device will switch to Connected state if it receives

TABLE I: Symbols used in the analytical model

Parameter name	Symbol
UL packet Poisson arrival rate	λ_{UL}
DL packet Poisson arrival rate	λ_{DL}
Energy needed to transmit a DL packet	E_{DL}
Energy needed to transmit an UL packet	E_{UL}
Energy needed to perform a paging action	E_P
Energy per unit time during Connected state	E_C
Energy per unit time during PSM state	E_{PSM}
Energy per unit time during Idle state	E_{Idle}
RRC inactivity Timer	τ_{RRC}
Idle state Timer	$\tau_{Idle} = T_{3324}$
eDRX cycle Timer	τ_{eDRX}
PSM Timer interval	$\tau_{PSM} = T_{3412}\ ext.$
Number of paging cycles	$\eta = \tau_{Idle}/\tau_{eDRX}$
Total Packet generation rate	$\lambda_{tot} = \lambda_{UL} + \lambda_{DL}$

the grant and if the grant is rejected, the device switches back to the *PSM* state. If there is a DL data packet for the device during the deep sleep state, the network buffers the packet and sends it when the device exits the PSM cycle. The device exits PSM on the expiration of timer T_{3412} extended for initiating the periodic Tracking Area Update (TAU) procedure, to notify the network about its availability.

In comparison to PSM, eDRX saves less energy but provides better downlink communication latency. Therefore, both PSM and eDRX mechanisms can be used to adapt to different IoT scenarios. The state change depends on network traffic, device behavior and use case. Therefore, it becomes crucial to select a feasible eDRX configuration and paging period for various traffic types in order to balance power-saving ratio and downlink communication latency.

The state diagram represents two more states in RRC Connected state named as *Downlink* and *Uplink*. In the Downlink state, the device is awake and the eNodeB transmits DL packets to the device. This state ends as soon as the eNodeB has no DL packets for this device and so the ending time of this state is dynamic depending on the packet size and number of packets. Similarly, during the *Uplink* state, the device transmits UL packets to the eNodeB. When the device receives an RRC Release message, it switches to *Idle* state and restarts the timers T_{3324} & $T_{3412}\ extended$.

IV. Analytical model of eDRX and PSM

In this section, we model the energy consumption of a device with Poisson arrival rate for UL and DL packets. We consider a fixed RRC inactivity timer as τ_{RRC}. The description of the parameters used in the equations is shown in Table I.

Using the state diagram as shown in Figure 1, the system between two consecutive Idle states is considered. The three possible cycles are as follows:

- Cycle 1: Idle $\rightarrow$ Connected $\rightarrow$ Idle
- Cycle 2: Idle $\rightarrow$ PSM $\rightarrow$ Connected $\rightarrow$ Idle
- Cycle 3: Idle $\rightarrow$ PSM $\rightarrow$ Idle

We compute the probability for each cycle, time needed to execute each cycle and energy consumed during each cycle, combining this allows us to compute the average energy consumption per unit time.

A. Cycle 1: Idle $\rightarrow$ Connected $\rightarrow$ Idle

This cycle occurs when an UL or DL data arrival occurs before τ_{Idle} expires. Therefore the probability that the device follows Cycle 1 is given by:

$$P_{C1} = 1 - e^{-\lambda_{tot}\cdot\tau_{Idle}}$$

Cycle 1 consists of two parts: the Idle state and the Connected state.

1) Idle state: We compute the probability that a DL or an UL arrival occurs. The probability that a DL arrival occurs before an UL arrival, knowing that a DL or an UL packet arrives in the interval $[0, \tau_{Idle}]$ is given by the following equation

$$\begin{aligned} P_{DL} &= \frac{1}{P_{C1}} \int_0^{\tau_{Idle}} \lambda_{DL} \cdot e^{-\lambda_{DL}\cdot t} \cdot e^{-\lambda_{UL}\cdot t} dt \\ &= \lambda_{DL}/\lambda_{tot} \end{aligned}$$

Similarly, the probability that an UL arrival occurs before a DL arrival, knowing that a DL or an UL packet arrives in the interval $[0, \tau_{Idle}]$ is given by $P_{UL} = \lambda_{UL}/\lambda_{tot}$. Since Idle mode consists of η paging intervals each lasting τ_{eDRX}, we can discretized the probability that a DL or an UL arrives in an interval of length τ_{eDRX}. The probability that a DL packet arrives in the interval $[\alpha \cdot \tau_{eDRX}, (\alpha+1) \cdot \tau_{eDRX}]$ is given by $e^{-\lambda_{DL}\cdot\alpha\cdot\tau_{eDRX}} - e^{-\lambda_{DL}\cdot(\alpha+1)\cdot\tau_{eDRX}}$. Hence, the probability that a DL packet arrives first and in the interval $[\alpha \cdot \tau_{eDRX}, (\alpha+1) \cdot \tau_{eDRX}]$ is given by Equation 1

$$P_{DL}^{C1} = P_{DL} \cdot \frac{e^{-\lambda_{DL}\cdot\alpha\cdot\tau_{eDRX}} - e^{-\lambda_{DL}\cdot(\alpha+1)\cdot\tau_{eDRX}}}{1 - e^{-\lambda_{DL}\cdot\tau_{Idle}}} \tag{1}$$

Similarly, the probability for an UL packet arriving first and in the interval $[\alpha\cdot\tau_{eDRX}, (\alpha+1)\cdot\tau_{eDRX}]$ is given by Equation 2

$$P_{UL}^{C1} = P_{UL} \cdot \frac{e^{-\lambda_{UL}\cdot\alpha\cdot\tau_{eDRX}} - e^{-\lambda_{UL}\cdot(\alpha+1)\cdot\tau_{eDRX}}}{1 - e^{-\lambda_{UL}\cdot\tau_{Idle}}} \tag{2}$$

Hence, the average duration of the Idle state in Cycle 1 is given by:

$$T_{Idle}^{C1} = \sum_{\alpha=0}^{\eta-1} (\alpha+1) \cdot \tau_{eDRX} \cdot \left(P_{DL}^{C1} + P_{UL}^{C1}\right)$$

And the energy consumption during the Idle state is given by:

$$E_{Idle}^{C1} = \sum_{\alpha=0}^{\eta-1} (\alpha+1) \cdot (E_p + (\tau_{eDRX} \cdot E_{Idle})) \cdot \left(P_{DL}^{C1} + P_{UL}^{C1}\right)$$

2) Connected state: The Connected state consists of two types of rounds with packet arrivals. First, there are κ rounds ($\kappa \geq 0$) that start with the arrival of a DL or an UL packet and that end when the next UL or DL packet arrives and these arrivals occur before the time τ_{RRC} has expired. Second, one round of length τ_{RRC} that starts with an UL packet or a DL packet arrival and that is the last round of the Connected state. The density of any (DL or UL) packet arrival process at any time t knowing that an arrival happened in $[0, \tau_{RRC}]$ is given by Equation 3.

$$a_{RRC}(t) = \frac{\lambda_{tot} e^{-\lambda_{tot}\cdot t}}{1 - e^{-\lambda_{tot}\cdot\tau_{RRC}}} \tag{3}$$

Hence the average duration of RRC connected state is given by:

$$T_C^{C1} = \sum_{\kappa=0}^{\infty} \kappa \cdot \left(\int_0^{\tau_{RRC}} t \cdot a_{RRC}(t) \cdot dt \right) \cdot \left(1 - e^{-\lambda_{tot} \cdot \tau_{RRC}}\right)^{\kappa} \cdot e^{-\lambda_{tot} \cdot \tau_{RRC}} + (\tau_{RRC}) = \frac{1 - e^{-\lambda_{tot} \cdot \tau_{RRC}}}{\lambda_{tot} \cdot e^{-\lambda_{tot} \cdot \tau_{RRC}}}$$

In order to compute the energy consumption, we need to know whether those κ rounds start with a DL or an UL packet arrival. The energy consumption during the RRC connected state round having the length of τ_{RRC} that starts with an UL packet or a DL packet arrival is $(P_{DL} \cdot E_{DL} + P_{UL} \cdot E_{UL})$ with probability $e^{-\lambda_{tot} \cdot \tau_{RRC}}$. Also, there exists at least one round which ends before the τ_{RRC} expires. This happens with the probability of $1 - e^{-\lambda_{tot} \cdot \tau_{RRC}}$ and energy consumption of these κ rounds is given by Equation 4.

$$E_C^{\kappa} = (P_{DL} \cdot E_{DL} + P_{UL} \cdot E_{UL}) + \sum_{\kappa=1}^{\infty} \kappa \cdot (P_{DL} \cdot E_{DL} + P_{UL} \cdot E_{UL}) \cdot \left(1 - e^{-\lambda_{tot} \tau_{RRC}}\right)^{\kappa-1} \cdot e^{-\lambda_{tot} \tau_{RRC}} \quad (4)$$

Hence, the total average energy consumption in Connected state is given by Equation 5.

$$E_C^{C1} = (P_{DL} \cdot E_{DL} + P_{UL} \cdot E_{UL}) \cdot e^{-\lambda_{tot} \cdot \tau_{RRC}} + \left(1 - e^{-\lambda_{tot} \cdot \tau_{RRC}}\right) \cdot E_C^{\kappa} + T_C^{C1} \cdot E_C \quad (5)$$

The average duration of Cycle 1 is derived as Equation 6

$$T_{C1} = T_{Idle}^{C1} + T_C^{C1} \quad (6)$$

The average energy consumption of Cycle 1 is derived as Equation 7.

$$E_{C1} = E_{Idle}^{C1} + E_C^{C1} \quad (7)$$

B. Cycle 2: Idle → PSM → Connected → Idle

This cycle occurs when no data arrival occurs before τ_{Idle} expires and an UL or a DL packet is ready to transmit during the PSM state, i.e before τ_{PSM} - τ_{Idle} expires. Therefore the probability that the device follows Cycle 2 is given by:

$$P_{C2} = e^{-\lambda_{UL} \cdot \tau_{Idle}} \cdot e^{-\lambda_{DL} \cdot \tau_{Idle}} \cdot \left(1 - e^{-\lambda_{tot} \cdot (\tau_{PSM} - \tau_{Idle})}\right)$$

There are no arrivals during the Idle state, hence the duration is τ_{Idle} and the energy consumption during Idle state of Cycle 2 is:

$$E_{Idle}^{C2} = \eta \cdot E_p + \tau_{Idle} \cdot E_{Idle}$$

The device in the PSM state can have multiple UL packet ready for transmission before $\tau_{PSM} - \tau_{Idle}$ expires. Hence, the density of an UL packet arrival process at any time t knowing that this happened in $[\tau_{Idle}, \tau_{PSM}]$ is given by:

$$a_{PSM}(t) = \frac{\lambda_{UL} e^{-\lambda_{UL} \cdot t}}{1 - e^{-\lambda_{UL} \cdot (\tau_{PSM} - \tau_{Idle})}}$$

The average duration of Cycle 2 is given by Equation 8.

$$T_{C2} = \tau_{Idle} + \int_0^{\tau_{PSM} - \tau_{Idle}} t \cdot a_{PSM}(t) \cdot dt + T_C^{C1} \quad (8)$$

The energy consumption in Connected state of Cycle 2 is given by:

$$E_C^{C2} = T_C^{C1} \cdot E_C + E_{UL} + (P_{DL} \cdot E_{DL} + P_{UL} \cdot E_{UL}) \cdot \left(e^{\lambda_{tot} \cdot T_C} - 1\right) + \int_0^{\tau_{PSM} - \tau_{Idle}} t \cdot a_{PSM}(t)\, dt \cdot \lambda_{DL} \cdot E_{DL}$$

The average energy consumption of Cycle 2 is derived as Equation 9

$$E_{C2} = E_{Idle}^{C2} + \int_0^{\tau_{PSM} - \tau_{Idle}} t \cdot a_{PSM}(t)\, dt \cdot E_{PSM} + E_C^{C2} \quad (9)$$

C. Cycle 3: Idle → PSM → Idle

This cycle occurs when no data arrival occurs in Idle state i.e. before τ_{Idle} and no UL or DL packet arrives during PSM state. Therefore, the probability that the device follows Cycle 3 is given by:

$$P_{C3} = e^{-\lambda_{UL} \cdot \tau_{Idle}} \cdot e^{-\lambda_{DL} \cdot \tau_{Idle}} \cdot e^{-\lambda_{tot} \cdot (\tau_{PSM} - \tau_{Idle})} = e^{\lambda_{tot} \cdot \tau_{PSM}}$$

The average time of Cycle 3 is derived as Equation 10.

$$T_{C3} = \tau_{Idle} + (\tau_{PSM} - \tau_{Idle}) = \tau_{PSM} \quad (10)$$

The average energy consumption of Cycle 3 is derived as Equation 11.

$$E_{C3} = \eta \cdot E_p + \tau_{Idle} \cdot E_{Idle} + (\tau_{PSM} - \tau_{Idle}) \cdot E_{PSM} + E_p \quad (11)$$

D. Total energy consumption

The total average duration of a cycle is given by:

$$T_{tot} = P_{C1} \cdot T_{C1} + P_{C2} \cdot T_{C2} + P_{C3} \cdot T_{C3} \quad (12)$$

The average total energy consumption per cycle is derived as Equation 13.

$$E_{tot} = P_{C1} \cdot E_{C1} + P_{C2} \cdot E_{C2} + P_{C3} \cdot E_{C3} \quad (13)$$

The average total energy consumption of the system per unit time is derived as Equation 14.

$$E_{avg} = E_{tot} / T_{tot} \quad (14)$$

E. Special Case: τ_{Idle} = 0

In the case where there is no Idle state $(i.e., \tau_{Idle} = 0)$, the above mentioned cycles are reduced to a single cycle having n PSM state rounds and one Connected state round in the case when an UL arrival occurs. The corresponding probability is given by Equation 15.

$$P_{CS} = \left(e^{-\lambda_{UL} \cdot \tau_{PSM}}\right)^{n-1} \cdot \left(1 - e^{-\lambda_{UL} \cdot \tau_{PSM}}\right), \quad \text{where } 1 \leq n < \infty \quad (15)$$

And the corresponding duration is given by

$$T_{CS} = \sum_{n=1}^{\infty} (n-1) \cdot \tau_{PSM} \cdot P_{CS} + \int_{0}^{\tau_{PSM}} t \cdot \frac{\lambda_{UL} e^{-\lambda_{UL} \cdot t}}{(1 - e^{-\lambda_{UL} \cdot \tau_{PSM}})} dt + T_C^{C1}$$

The energy consumption is given by

$$E_{CS} = \sum_{n=1}^{\infty} (n-1) \cdot \tau_{PSM} \cdot P_{CS} \cdot E_{PSM} + \int_{0}^{\tau_{PSM}} t \cdot \frac{\lambda_{UL} e^{-\lambda_{UL} \cdot t}}{(1 - e^{-\lambda_{UL} \cdot \tau_{PSM}})} dt \cdot E_{PSM} + T_C^{C1} \cdot E_C + E_{UL} + (P_{DL} \cdot E_{DL} + P_{UL} \cdot E_{UL}) \cdot e^{\lambda_{tot} \cdot \tau_{RRC} - 1}$$

The average total energy consumption per unit time in this special case is derived as Equation 16.

$$E_{avg}^{cs} = E_{CS}/T_{CS} \tag{16}$$

V. Evaluation

In this section, we provide a comparison of the proposed model and a simulator implementation. Some numerical examples to evaluate the impact of various parameters on battery life and energy consumption of the device are presented. Finally, a use-case of tracking shared bicycles is discussed.

A. NS-3 Implementation

In order to evaluate the energy consumption of the NB-IoT system and validate the proposed model, we implemented an NB-IoT model in the NS-3 network simulator. Mainly, the PSM and eDRX in RRC idle mode features have been implemented in NS-3 on top of the NB-IoT implementation of Soussi et al. [13]. Their implementation adapted the LTE physical layer to be in line with NB-IoT. Specifically, they limited the allocated resource blocks to one, use QPSK as DL and UL modulation scheme, and introduced cross-subframe delays and RF switching delays.

B. Simulation setup

The analytical model is solved using MATLAB. The default simulation parameters are shown in Table II. The reference power values are taken from the u-blox SARA-N2 specification. For simplicity, the experiments are performed using one device and one eNodeB. However, it should be noted that the NS-3 simulation model supports an arbitrary number of devices. The energy per unit time of the Connected state is calculated considering that the device is periodically listening to messages such as Master Information Block (640 ms), System Information Block 1 (2560 ms), PSS (10 ms), SSS (20 ms) and Downlink Control Information (based on data arrivals). In total, 72 parameter combinations were simulated in NS-3, with T_{3324} equal to $[0, 30, 60]$ seconds, T_{3412} equal to $[300, 600, 1800, 3600]$ seconds, and the UL Poisson inter-arrival time $1/\lambda_{UL}$ equal to $[30, 60, 120, 600, 3600, 21600]$ seconds. Each transmitted packet was 56 bytes, and all simulation results are averaged over at least 25 UL transmissions.

TABLE II: Simulation and model parameters

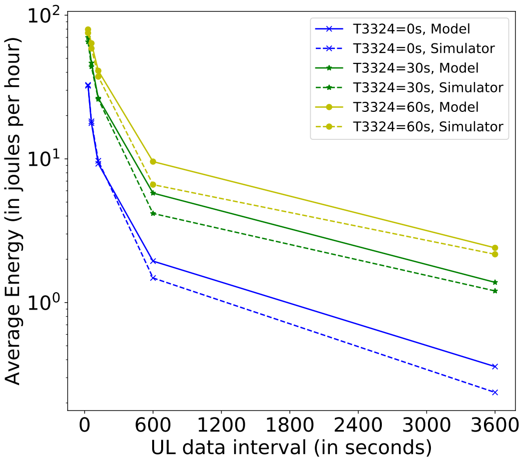
Parameters	Symbol	Value
PSM state power consumption	E_{PSM}	0.0108 μW
Idle state power consumption	E_{Idle}	0.0216 W
Rx power consumption	E_{DL}	$0.1656 J \cdot \tau_{dch}$ (per RB)
Tx power consumption	E_{UL}	$0.792 J \cdot \tau_{dch}$ (per RB)
Tx time on data channel	τ_{dch}	0.92857 ms (per RB)
Tx time on control channel	τ_{cch}	0.214285 ms (per RB)
Connected power consumption	E_C	$0.0320\ J + \tau_{cch} \times (\lambda_{UL} + \lambda_{DL} + \lambda_{tot})$
Paging state power consumption	E_P	0.1656J $\cdot \tau_{cch}$
RRC inactivity timer	τ_{RRC}	10s
Number of paging cycles	η	1
Modulation Scheme	MCS	9

C. Model Validation

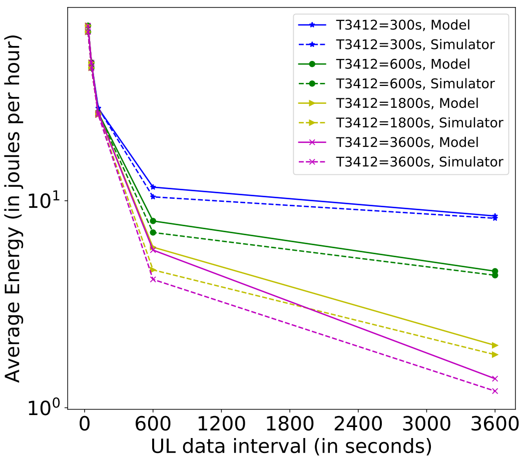
Figure 2 compares the results of the analytical model and NS-3 simulation, for UL transmissions. The effect of UL data arrival rate on average energy for different Idle state timers (i.e., τ_{Idle} or T_{3324}) and for different PSM state timers (i.e., τ_{PSM} or T_{3412}) is investigated. The average difference in calculated energy consumption between the model and simulation results for all 72 considered test cases is around 11.82%. In 4 out of 72 cases (the ones with inter-arrival time 21600 s), a difference of up to 57% was observed. These are cases where the absolute energy consumption is very small. As such, even if the relative difference is large, the absolute difference in the estimation is negligible. In general, the model is very accurate, with a relative error of less than 10% in 70% of the test cases and less than 15% in 78% of the test cases. It can be seen that the analytical model is capable of estimating the energy consumption closely matching the simulation results.

D. Evaluation of power saving mechanisms

We can see from Figure 2 that as the UL data interval increases, the average energy consumption decreases accordingly. If the PSM timer T_{3412} is larger than the average UL data interval, then this decrease is nearly linear (cf., Figure 2a). However, if the PSM timer is much shorter than the average UL transmission interval, then the decrease in energy consumption due to less frequent transmissions becomes negligible (cf., Figure 2b). For example, for $T_{3412} = 300$ s, reducing the UL transmission interval fourfold from 600 to 3600 s, only results in a 21% reduction in energy consumption. In contrast, the same fourfold UL transmission interval reduction for $T_{3412} = 3600$ s reduces the energy consumption by 71%. This is a consequence of the device waking up out of PSM more often due to timeouts and shows the importance of properly configuring the PSM timer based on the application characteristics. Moreover, Figure 2b shows that for a very small UL transmission interval (i.e., less than 600 s), the PSM timer has very little influence on energy consumption. However, even for an average 600 s interval, increasing T_{3412} from 600 to 3600 s gives a 38% energy reduction. For UL-only scenarios, it therefore makes sense to select a very high value for T_{3412}. However, the downside is an associated linear increase in DL latency, as DL data cannot be received while



(a) Energy Consumption for different Idle state timers T_{3324} timers with PSM state timers T_{3412} fixed to 3600 s



(b) Energy Consumption for different PSM state timers T_{3412} with Idle state timer T_{3324} equal to 30 s

Fig. 2: Comparison of energy consumption for Analytical Model and Simulator implementation

the device is in the PSM state. As such, latency-sensitive applications with DL traffic require a more intelligent selection of the PSM timer value, leveraging the trade-off between DL latency and energy consumption.

Figure 2a also shows the effect of the Idle state timer T_{3324}. Increasing this timer gives the network more opportunity to transmit DL data. However, it also increases energy consumption. Increasing the timer from 0 s (i.e., DL is only possible during the RRC connected state immediately after UL) to 30 s increases energy consumption threefold and sevenfold for an UL transmission interval of 600 and 3600 s respectively. As such, the Idle state timer T_{3324} has an immense effect on energy consumption and should only be used for IoT applications with large amounts of latency-sensitive DL data.

NB-IoT is advertised to achieve a 12.8 year battery lifetime using a 5 Wh (equal to 1388 mAh at 3.6 V) battery [14]. To validate this claim, we evaluate the battery lifetime of an NB-IoT device using both PSM and eDRX, with a Poisson

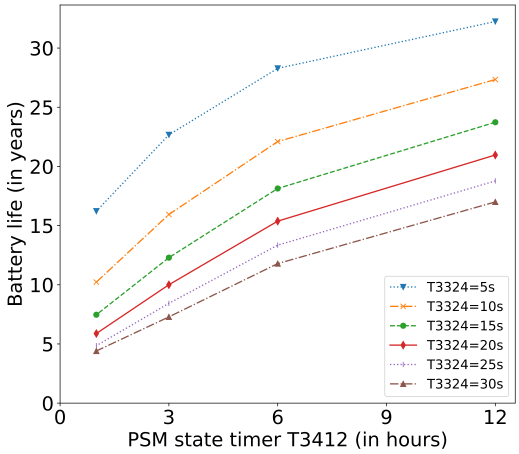


Fig. 3: Estimated life of a 1388 mAh battery for different values of T_{3412} and T_{3324} and an UL data interval of 24 hours

distributed UL data rate of 24 hours. The results, obtained from the analytical model, are shown in Figure 3. The results show that for such an infrequently communicating device, this lifetime can be achieved for most combinations of PSM and Idle timer. Only for an Idle timer T_{3324} above 25 s or a PSM timer T_{3412} below 6 hours, a battery life of 12.8 years may not be reachable.

E. Use-case: Tracking Shared Bicycles

Nowadays, shared bicycle services are very popular in many countries. NB-IoT can be used to provide communication between the bicycle and the application server. The aim is to keep track of a connected bicycle for at least two years without any external power supply. However, the application is also characterized by coverage needs, latency or data rate. The bicycle periodically transmits an update to the network consisting of 17 bytes, which includes lock status, GPS position, and ID of the current user. In addition, the network sends back a response with a data size of at most 17 bytes, consisting of an acknowledgment, and optionally some instructions (e.g., to change the status of the bicycle lock). The power consumption to calculate the GPS position is taken from the u-blox ZOE-M8B specification, equaling 66 mW with an acquisition time of 30 s. Figure 4 shows the expected battery life as a function of various battery capacities for different data periodicities when T_{3324} equals 5 s and T_{3412} equals 24 hours. Results are shown with and without (i.e., NB-IoT only) the energy consumed by the GPS. We can conclude that a battery of 2250 mAh used with a data periodicity of 120 minutes or more can achieve a battery lifetime of 2 years. The battery life decreases linearly by decreasing the data periodicity. However, the calculation of the GPS position consumes nearly 85 % of the total energy. If the energy to calculate GPS position is not taken in account, a 750 mAh battery can also achieve a lifetime of 2 years for a data periodicity of 45 minutes or higher.

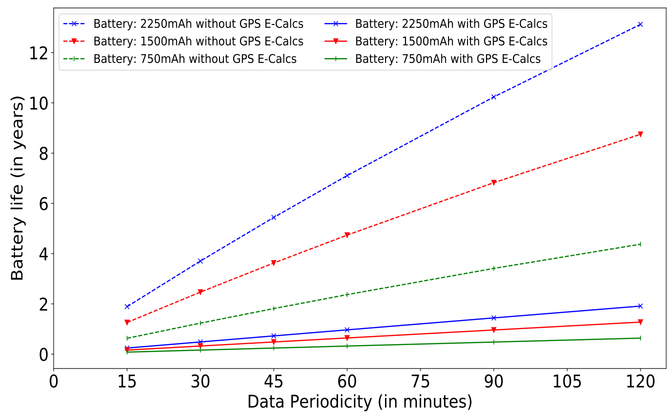


Fig. 4: Battery life for shared bicycle tracking use case as a function of data periodicity and battery capacity

VI. Conclusion

In this paper, we analyzed and compared the average energy consumption of an NB-IoT device with power saving features when it sends and receives data packets with Poisson arrival rate. Particularly, we have presented an analytical model to estimate the average energy consumption of the device. Comparing the model to accurate NS-3 simulation results showed an average deviation in estimated energy consumption of 11.8%, with 78% of the tested cases having an error below 15%. Moreover, results showed that for typical IoT scenarios, with long transmission intervals, properly configuring the PSM timer can easily result in a 40% or more gain in battery lifetime. The results also showed that even a very small Idle timer, which allows devices to stay awake briefly after each UL transmission to receive DL transmissions, can easily increase total energy consumption 3 to 7 times. Finally, evaluation of the potential battery life of NB-IoT devices showed that with very sporadic transmissions (e.g., once per day), a battery lifetime of more than 12 years is feasible. In combination with GPS, a 2 year battery life is achievable with a large battery and a 2 hour transmission interval.

Acknowledgment

Part of this research was funded by the Flemish FWO SBO S004017N IDEAL-IoT (Intelligent DEnse And Longe range IoT networks) project and FWO, GOB7915N, "Modeling and control of energy harvesting wireless sensor networks", and by the ICON project MAGICIAN. MAGICIAN is a project realized in collaboration with imec, with project support from VLAIO (Flanders Innovation and Entrepreneurship). Project partners are imec, Orange, Televic, Citymesh and REstore.

References

[1] 3GPP Low Power Wide Area Technologies, GSMA, 2016.
[2] Y. E. Wang, X. Lin, A. Adhikary, A. Grovlen, Y. Sui, Y. Blankenship, J. Bergman and H. S. Razaghi, "A Primer on 3GPP Narrowband Internet of Things", IEEE Communications Magazine, vol. 55, no. 3, pp. 117–123, 2017.
[3] P. A. Maldonado, P. Ameigeiras, J. P. Garzon, J. N. Ortiz and J. M. L. Soler, "NarrowBand IoT Data Transmission Procedures for Massive Machine Type Communications", IEEE Networks Magazine, vol. 31, pp. 8-15, 2017.
[4] 3GPP, "TR45.820 Cellular system support for ultra-low complexity and low throughput Internet of Things (CIoT)", Rel 13 v13.1.0, 2015.
[5] M. Hertlein, S. Breun, G. Cappel, A. Schwarzmeier, F. Lurz, R. Weigel and G. Fischer, "Evaluation of cellular standards for low data rate applications regarding power consumption and timing parameters",IEEE Radio and Wireless Symposium, pp. 217-219, 2018.
[6] S. M. Oh, K. R. Jung, M. Bae and J. Shin, "Performance Analysis for the Battery Consumption of the 3GPP NB-IoT Device", International Conference on Information and Communication Technology Convergence, pp. 981-983, 2017.
[7] L. Zhou, H. Xu, H. Tian, Y. Gao, L. Du and L. Chen, "Performance Analysis of Power Saving Mechanism with Adjustable DRX Cycles in 3GPP LTE", IEEE Vehicular Technology Conference, pp. 1–5, 2008.
[8] A. T. Koc, S. Jha, R. Vannithamby and M. Torlak, "Optimizing DRX Configuration to Improve Battery Power Saving and Latency of Active Mobile Applications over LTE-A Network", Wireless Communications and Networking Conference (WCNC) IEEE, Shanghai, China, pp. 568–573, 2013.
[9] S. C. Jha, A. T. Koc, R. Vannithamby and M. Torlak, "Adaptive DRX configuration to optimize device power saving and latency of mobile applications over LTE advanced network", in IEEE International Conference on Communications (ICC), pp. 6210–6214, 2013.
[10] S. Xu, Y. Liu, and W. Zhang, "Grouping Based Discontinuous Reception for Massive Narrowband Internet of Things Systems", IEEE Internet of Things Journal, pp. 1561-1571, 2018.
[11] X. Wang, M. J. Sheng, Y. Y. Lou, Y. Y. Shih, and M. Chiang, "Internet of Things Session Management Over LTE Balancing Signal Load, Power, and Delay", IEEE Internet of Things Journal, vol. 3, no. 3, pp. 339–353, June 2016.
[12] C. C. Tseng, H. C. Wang, F. C. Kuo, K. C. Ting, H. H. Chen and G. Y. Chen, "Delay and Power Consumption in LTE/LTE-A DRX Mechanism with Mixed Short and Long Cycles", IEEE Transactions on Vehicular Technology, vol. 65, no. 3, pp. 1721-1734, 2016.
[13] M. El Soussi, P. Zand, F. Pasveer and G. Dolmans, "Evaluating the Performance of eMTC and NB-IoT for Smart City Applications", IEEE International Conference on Communications (ICC), 2018.
[14] M. Chen, Y. Miao, Y. Hao, and K. Hwang, "Narrow band Internet of Things", IEEE Access, vol. 5, pp. 20557–20577, 2017.
[15] J. Lee and J. Lee, "Prediction-based energy saving mechanism in 3GPP NB-IoT networks", Sensors, vol. 17, no. 9, 2017.