Modeling of IoT Devices Energy Consumption in 5G Networks

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***Abstract*—The rising number of connected Internet of Things (IoT) devices in 5G networks and the standardization of the 3GPP reduced capability (RedCap) devices, turn the IoT energy efficiency into a topic of paramount importance for 5G. The design goals and use cases of RedCap devices highlight the need for long device battery life due to the infeasibility of replacing batteries. With the focus emerging on sustainable networks, battery lifetime prediction becomes essential. Therefore, in this paper, we propose and evaluate a Markov Chain based energy consumption model suitable for IoT devices in 5G networks, especially RedCap devices. We design a realistic model consistent with the procedures described in 3GPP standardization, mainly focused on the uplink transmission procedures. The proposed model is validated through extensive analysis with varying inter-arrival times (IAT) of the uplink traffic. For short IAT, the analytical results show a decrease of 33% in energy consumption and 89% in transmission latency. This demonstrates that our model can be applied to evaluate battery life for a broad range of IoT devices.**

***Index Terms*—IoT, RedCap, energy consumption model, battery lifetime estimation, 5G networks.**

I. INTRODUCTION

The number of IoT devices connected to cellular access technologies, especially 5G networks, is increasing exponentially [1]. This growth is triggered by various applications and uses cases supported by IoT devices, ranging from smart metering to automation in industry, from healthcare to smart city. The range of applications can not be supported solely by the LTE industrial IoT (IIoT), LTE-M, and Narrowband IoT (NB-IoT) devices due to diverse quality of service (QoS) requirements [1]. In more detail, IIoT devices are part of the ultra-reliable, low latency communication (URLLC) use case, while LTE-M and NB-IoT fall under the massive machine type communication (mMTC). Even though these devices fulfill the requirements of URLLC and mMTC, they fail to support use cases such as video surveillance and wearable devices. An example is the data rate requirement in Mbps, which exceeds those of URLLC and mMTC, as shown in Table I.

To this end, 3GPP [2], [3] addresses these applications by introducing RedCap devices, defined as mid-range IoTs with requirements between URLLC and mMTC. Industrial wireless sensors, video surveillance, and wearable devices are depicted as their use cases. While RedCap devices have a low device complexity and cost, are small in size, and often run applications relying solely on batteries, their battery lifetime requirements reach up to 10 years. Battery replacement is usually not feasible due to high costs and device deployment in a hard-to-reach environment. Hence, the objective is to extend the battery life of these devices by increasing the energy efficiency, which is a key performance indicator in 5G.

TABLE I: Comparison of IoT devices requirements in 5G [2].

QoS	URLLC	mMTC	RedCap
Battery life	N/A	10 years	wearables: 1-2 weeks sensors: several years
Latency (ms)	1	10000	safety reports: 5-10 others: 100
Peak data rate (Mbps)	N/A	LTE-M DL: 2.4 UL: 2.6 NB-IoT DL: 0.127 UL: 0.159	DL: 150 UL: 50

A. *Contribution: Energy consumption model in 5G networks*

The development of different energy-saving methods [4] aiming to extend the battery lifetime of IoT devices arises the need to evaluate if they contribute to achieving the target lifetime. Consequently, accurate and detailed energy consumption models are required for the validation and extension of service duration. In LTE networks, the energy consumption models are studied extensively for NB-IoT and LTE-M devices. However, these models are simplified targeting only mMTC device requirements and LTE protocols. With the introduction of new devices, applications, and signaling protocols in 5G networks, the energy consumption models need to evolve and depict the realistic behavior of 5G IoT devices. Besides including broader QoS requirements than LTE networks, the applications run in distinctive traffic patterns, where packets can arrive with a short IAT, especially in wearable devices' use cases. Related to signaling protocols, new energy-saving radio resource control (RRC) state, named RRC Inactive, is introduced in 5G to enhance the energy savings gained from power-saving mode (PSM) and discontinuous reception (DRX) mechanisms. The RRC Inactive state aims to reduce the energy consumption, latency, and signaling overhead during connection resumption. Even though previous research accounts for DRX, for short packets IAT, there is inconsistency compared to the procedure described by the 3GPP. These aspects, not considered in state-of-the-art research, create space for further contribution to the accurate modeling of the 5G devices' energy consumption.

For this purpose, we develop a Markov Chain based realistic model. We include the new RRC Inactive state in the model,

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detail the DRX cycles for every RRC state, and enable the protocol procedures followed for short IAT. To verify the results, we perform extensive simulations varying packets IAT and model parameters, while analysing energy consumption, transmission delay, and number of transmitted packets. Our model performance is compared with a representative state-of-the-art model developed for NB-IoT devices [5], concluding the generality of the proposed model for all use cases and increased accuracy in the prediction of battery lifetime.

The paper is structured as follows. Section II provides a thorough state-of-the-art review of existing device energy consumption models. We describe the system and elaborate on the analytical model of energy consumption in Section III. Section IV computes the energy consumption of each state of our model. The performance of the proposed model is evaluated in Section V. Section VI concludes the paper.

II. RELATED WORK

The research on device battery lifetime evaluation has evolved with the communication network generations, aiming to increase prediction accuracy. Early works analytically model the device energy consumption in a simplified manner only for the transmission procedure [6] or for a part of device states [7]. Although these works set the basis for the energy consumption evaluation, the used simplifications reduce the evaluation accuracy. Papers [8], [9] build more complex models defined for NB-IoT devices. The authors in [8] design a semi-Markov chain energy consumption model with four states: PSM, idle, random access, and transmission state. While [8] studies the impact of PSM duration on energy efficiency, it does not account for the extended DRX (eDRX). On the contrary, authors in [9] claim to be the first regarding both power-saving mechanisms of PSM and eDRX. Their efficiency is evaluated for two NB-IoT devices in the uplink (UL) and downlink (DL) scenarios with various IAT, PSM, and eDRX timers. Even though models in [8], [9] have high accuracy in LTE, considering the periodic transmission of UL packets with long IAT, they do not account for new traffic patterns and procedures introduced in 5G networks.

Papers [10], [5], and [1] create the transition models towards 5G, but investigating still mMTC devices. [10] evaluates the energy efficiency improvements of the control plane and user plane optimizations. The authors show battery life extension when applying the control user plane optimization compared to the standard service request procedure, during different coverage levels and IAT. [5] improves the previous work [10] by using a Markov Chain analytical model and validating the simulation results in an experimental framework, for an IAT of $6\,\mathrm{min}$. The designed model describes only the control plane optimization procedure. Another Markov Chain model targeting both NB-IoT and LTE-M is designed in [1]. It defines the crucial role of traffic and network parameters in energy consumption and emphasizes the need for proper traffic and network configuration parameters to reach a battery life of 10 years. It is noted that the existing work is suitable for MTC devices, but not for RedCap applications and devices defined in 5G networks. The main issues observed in current state-of-the-art works, in terms of modeling the energy consumption and evaluating the battery lifetime of 5G IoT devices are the lack of accuracy and flexibility in updating system parameters.

Although extensive work is done to achieve an accurate estimation of the battery lifetime, the evolution of the communication networks towards 5G introduces new challenges, with new protocol procedures, applications, and devices. Therefore, there is demand for more realistic models supporting a wide range of IAT and evaluating the battery lifetime of various devices. This work aims to propose an accurate model to calculate the energy consumption of 5G IoT devices, including all three RRC states and detailed protocol procedures. The model is flexible in the IAT of the packets, depicting different types of applications that the IoT devices support.

III. ANALYTICAL ENERGY CONSUMPTION MODEL

This section presents the proposed discrete-time Markov Chain used to evaluate energy consumption and delay of transmitted packets. Departing from standard procedures used in 3GPP [11] and previous research [1], [5], we provide a realistic model representing the behavior of IoT devices in 5G networks. Fig. 1 illustrates the proposed Markov Chain, defined as irreducible, non-absorbing, and stable. The irreducibility is fulfilled because each state can be reached by any other state. The Markov Chain does not have any absorbing states, from which other transitions are not possible. We consider RedCap scenarios, with devices transmitting periodic UL packets. Even though UL traffic is the focus of our study, we also consider DL traffic due to the control and synchronization messages. The packet's average UL traffic IAT is modeled through a Poisson arrival process, with a rate $\lambda = \frac{1}{IAT}$, as independence and randomness are needed for smart city and wearable scenarios. The periodic traffic patterns would cover only the industrial sensors and present limitations. We incorporate the energy-saving states, *RRC Inactive* and *Resume*, extending the battery lifetime and reducing transmission latency for short packets IAT. Additionally, the device conduct during DRX in *Connected*, *Inactive* and *Idle* states is designed in detail through *connected DRX (cDRX)* and *idle DRX (iDRX)* cycles. They enable the immediate transition to the *Connected* state upon receiving a UL packet, shown in Fig. 1.

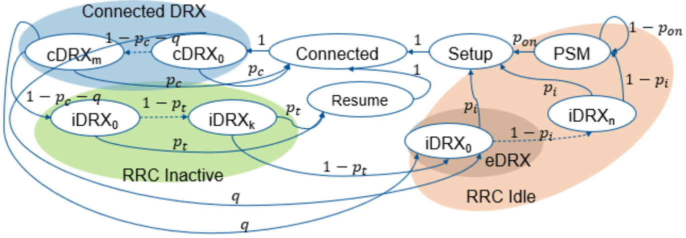


Fig. 1: Proposed Markov Chain modeling in details IoT devices behaviour in 5G networks.

The average packet energy consumption is estimated as a function of Markov chain steady-state probabilities, energy consumption, and delay of each state. The calculation of the steady-state probability π using transition probabilities P is deducted by the balance equation $\pi = P \cdot \pi$, where the $\sum_{state} \pi_{state} = 1$ [12]. These probabilities are calculated as

$$\pi_{iDRX_n} = \frac{p_{on}\,(1-p_i^n)}{(1-p_i)^N}\,\pi_{PSM} = b_{iDRX_n}\,\pi_{PSM}, \tag{1}$$

$$\pi_{setup} = p_{on}\,\pi_{PSM} + p_i \sum_{n=0}^{N} \pi_{iDRX_n}, \tag{2}$$

where $p_{on} = 1 - e^{-\lambda\,T_{on}}$ denotes transition probability from *PSM* to *Setup*, when receiving UL packet during *PSM* period T_{on}. Similarly, $p_i = 1 - e^{-\lambda\,T_{iDRX}^{cycle}}$ is the transition probability from *Idle* to *Setup* when receiving UL packet during T_{iDRX}^{cycle} of *iDRX* cycle $n \in \{0, 1 ... N\}$. The *Connected* steady-state

$$\pi_{conn} = \frac{(p_{on} + p_i \sum\limits_{n=0}^{N} b_{iDRX_n})\,\pi_{PSM}}{1 - (p_t \sum\limits_{k=0}^{K} b_{inDRX_k}) - (p_c \sum\limits_{m=0}^{M} b_{cDRX_m})}, \tag{3}$$

includes transition $p_t = 1 - e^{-\lambda\,T_{inDRX}^{cycle}}$ from *Inactive iDRX* cycle $k \in \{0, 1 ... K\}$ to *Connected*, when receiving UL packet during T_{inDRX}^{cycle}. Variable $p_c = 1 - e^{-\lambda\,T_{cDRX}^{cycle}}$ expresses the transition probability from *cDRX* cycle $m \in \{0, 1 ... M\}$ to *Connected* if UL data is received during cycle duration T_{cDRX}^{cycle}. The steady-state probability of each *cDRX* cycle is

$$\pi_{cDRX_m} = (1 - p_c - q)^m\,\pi_{conn} = b_{cDRX_m}\pi_{conn}, \tag{4}$$

where q distinguishes the transition probability from *Connected* to *Idle* state due to radio link failure, handover failure, or not meeting the cell reselection criteria. Moreover, the steady-state probability for *Inactive iDRX* and *Resume* are

$$\pi_{inDRX_k} = (1 - p_t)^k\,\pi_{cDRX_M} = b_{inDRX_k}\,\pi_{conn}, \tag{5}$$

$$\pi_{resume} = (p_t \sum_{k=0} b_{inDRX_k})\pi_{conn}. \tag{6}$$

Since the steady-state probability calculation of the PSM state is quite complex, we separate the formula in three components b_{PSM_1}, b_{PSM_2}, and b_{PSM_3}, to simplify the representation. The π_{PSM} is obtained as $\frac{1}{\pi_{PSM_1} + \pi_{PSM_2}\pi_{PSM_3}}$, where

$$\pi_{PSM_1} = 1 + (2p_{on}) + (1 + 2p_i) \sum_{n=0}^{N} b_{iDRX_n}, \tag{7}$$

$$\pi_{PSM_2} = \frac{p_{on} + p_i \sum\limits_{n=0}^{N} b_{iDRX_n}}{1 - (p_t \sum\limits_{k=0}^{K} b_{inDRX_k}) - (p_c \sum\limits_{m=0}^{M} b_{cDRX_m})}, \tag{8}$$

$$\pi_{PSM_3} = 1 + (1 + 2p_t) \sum_{k=0}^{K} b_{inDRX_k} + \sum_{m=0}^{M} b_{cDRX_m}. \tag{9}$$

A. Calculation of model's performance values

The steady-state probabilities in equations (1) - (9), are utilized to calculate the performance values of our Markov Chain [12]. The average energy consumption, transmission delay, and number of transmitted packets present a particular interest for our study. A packet is transmitted only in the *Connected* state. Therefore the number of transmitted packets depends on the π_{conn}, the IAT, and packet's average transmission delay. The latter assures that the transmission of the current packet is completed before serving the next packet. The number of transmitted packets (TP) in a day D_{day}, depicting the change of the system behavior for different IATs, can be expressed as

$$\mathit{TP} : P_{day} = \frac{D_{day}}{\sum\limits_{state} \pi_{state} \cdot \Delta_{state}} \cdot \pi_{conn}, \tag{10}$$

where Δ_{state} is the Markov Chain state delay. The average energy consumption per packet ($\overline{E}$) is calculated using the performance value as $\overline{E} : E_{packet} = \sum\limits_{state} \pi_{state} \cdot E_{state}$, where the E_{state} is the energy consumption of Markov Chain states. The average transmission delay per packet ($\overline{\Delta}$) is calculates as $\overline{\Delta} : \Delta_{packet} = \sum\limits_{state} \pi_{state} \cdot \Delta_{state}$.

IV. STATES ENERGY CONSUMPTION AND DELAY

A. Packet energy consumption

The energy consumed during the data exchange between user equipment (UE) and network is classified depending on the message type, in UL, DL, and downlink control information (DCI). DCI messages are required for UL grants, DL scheduling, and paging messages, with energy consumption modeled as in [5]. In the following subsection, we write the equations only for UL, as the same applies to DL when replacing the respective values. Continuous transmission of data is interrupted periodically T_{gap}^{period} by measurement gaps with duration $T_{gap}^{duration}$ to perform synchronization and measurements on the DL signals. During these gaps, the consumed power P_{gap} is lower than the transmission P_{TX} or reception P_{RX} power. Therefore, the total energy consumed for the data transmission with size k $bytes$ is composed of two parts

$$E_{TX}(k) = P_{TX}\,t_{TX}(k) + P_{gap}\,t_{TX}^{gaps}. \tag{11}$$

The time needed for the data exchange $t_{TX}(k)$ depends on number of repetitions n_{rep}, subframe length t_{SF}, number of allocated subframes n_{SF} and number of segments $s(k)$, expressed as $t_{TX}(k) = t_{SF}\,n_{SF}\,n_{rep}\,s(k)$. The segment number is defined by operations between MAC and physical layer, depending on transport block size (TBS), and header size h appended from protocol layers. TBS changes with the changing channel conditions, represented by modulation and coding scheme (MCS). A higher MCS means more data is transmitted in a resource block [13]. Whereas a higher number of subframes means more resources are used for the data exchange and at the same time longer transmission time. We calculate the number of segments as below

$$s(k) = \left\lceil \frac{k}{TBS(MCS, n_{SF}) - h} \right\rceil \tag{12}$$

, where $\lceil\rceil$ is ceil function. The time spent in the measurement gaps is calculated from the time needed for data exchange, maximum continuous transmission time, and gap duration

$$t_{TX}^{gaps}(t_{TX}) = \left\lfloor \frac{t_{TX}}{T_{gap}^{period} - T_{gap}^{duration}} \right\rfloor t_{TX}^{gaps}. \tag{13}$$

In contrast to packet transmission, measurement gaps do not follow a regular pattern during the reception. They depend on the available resources for reception, estimated roughly in 14 subframes out of 20 available subframes for the control and data reception [4]. The DL measurement gap time is

$$t_{RX}^{gaps}(t_{RX}) = \left\lceil t_{RX}\left(\frac{20}{14}-1\right)\right\rceil. \tag{14}$$

B. Radio Resource Control Idle

DRX is applied to devices in the *Idle* state without UL data to transmit. Timer T_{3324} defines the period during which UE runs DRX and is reachable from the network through core network (CN) paging. During T_{3324}, UE can run periodically two DRX types, iDRX or eDRX. The iDRX is composed of iDRX cycles, as depicted in Fig. 1, consisting of active and sleeping periods. During the active period, UE synchronizes shortly with the network for T_{iDRX}^{sync} and afterward monitors the paging occasions for T_{iDRX}^{onD}. If messages were not received, UE goes into the sleeping period T_{iDRX}^{sleep}. The iDRX cycle duration T_{iDRX}^{cycle} varies and is defined by the network. The following variables denote power consumption for synchronization P_{iDRX}^{sync}, for paging monitoring P_{iDRX}^{onD} and for sleeping P_{iDRX}^{sleep}. The iDRX cycle energy consumption is

$$\begin{aligned}
&E_{iDRX}^{cycle} = P_{iDRX}^{sync} T_{iDRX}^{sync} + P_{iDRX}^{onD}\, T_{iDRX}^{onD} + P_{iDRX}^{sleep}\, T_{iDRX}^{sleep},\\
&T_{iDRX}^{sleep} = T_{iDRX}^{cycle} - \left(T_{iDRX}^{sync} + T_{iDRX}^{onD}\right).
\end{aligned} \tag{15}$$

To further decrease energy consumption, UEs with energy efficiency requirements apply the eDRX mechanism. eDRX elongates the sleeping period compared to iDRX, increasing energy savings. The eDRX cycle includes two components, the Paging Time Window (PTW) period T_{eDRX}^{PTW} and the sleeping period $T_{eDRX}^{sleep} = T_{eDRX}^{cycle} - T_{eDRX}^{PTW}$. The PTW contains multiple iDRX cycles, during which the device monitors paging messages. The number of iDRX cycles depends on the length of PTW and the length of iDRX cycle, $N_{iDRX}^{cycles} = \left\lceil T_{PTW}/T_{iDRX}^{cycle}\right\rceil$. Meanwhile, the number of eDRX cycles depends on timer T_{3324} and the cycle duration T_{eDRX}^{cycles}, $N_{eDRX}^{cycles} = \left\lceil T_{3324}/T_{eDRX}^{cycle}\right\rceil$. The energy consumption of eDRX cycle is calculated as

$$E_{eDRX}^{cycle} = E_{iDRX}^{cycle}\, N_{iDRX}^{cycle} + P_{eDRX}^{sleep}\, T_{eDRX}^{sleep}. \tag{16}$$

We calculate the total energy consumption during T_{3324} as $E_{Idle} = N_{eDRX}^{cycle}\, E_{eDRX}^{cycle}$.The reception of UL data before the T_{3324} expiration yields the UE connection via *Setup* procedure. Otherwise, UE enters the *PSM*, where UE is in deep sleep, connected to the network but unreachable. In *PSM*, UE wakes up to transmit UL data or execute the tracking area update (TAU), triggered by the change in tracking due to users' mobility or by a periodic timer T_{3412}, starting upon entering RRC Idle state [4]. Due to our use case, we opt for a long periodic T_{3412} to reduce the impact of TAU on energy consumption. As a result, the UE always exits the *PSM* state upon receiving a UL packet, since the longest IAT we consider is 24 h. The *PSM* energy consumption is expressed as $E_{PSM} = P_{PSM}\,(T_{3412} - T_{3324})$.

C. Radio Resource Control Inactive

The RRC Inactive state, introduced in [11], is an energy-efficient state constructed by multiple iDRX and eDRX cycles, as described in the *Idle* state. The UE is still reachable through radio access network (RAN) network paging or core network paging. RAN stores the context of the device, maintaining the connection to the core network established and reducing the amount of signaling required for transitioning to the *Connected* state. The transition from *Connected* to *Inactive* state, using RRC release (rel) is triggered by data inactivity timer expiration T_{Dinac}, request by UE, or by a command from gNB [4]. In our implementation we account for the timer expiration. While RAN paging messages or UL data trigger transition to the *Connected* state, expiration of timer T_{Didle} or CN paging, transition UE state to *Idle*. Equations (15) and (16) are valid for this state, using *Inactive* state parameters. The energy consumption is $E_{inactive} = N_{eDRX}^{cycle}\, E_{eDRX}^{cycle} + E_{RX}^{rel}$.

D. Radio Resource Control Connected

UE transmits and receives data in the *Connected* state, defined as the most energy-consuming state due to the consumed power for transmitting packets and continuous monitoring of the Physical Downlink Control Channel (PDDCH) to receive paging or UL scheduling grants. The monitoring of the channel continues until the expiration of the inactivity timer T_{inac}, after which UE enters *connected DRX* state. Transmitting uplink data resets the T_{inac} and elongates the time UE spends in the *Connected* state. The consumed energy is calculated as $E_{Connect} = E_{RX}^{dci} + E_{TX}(data) + P_{RX}\, T_{inac}$.

E. Connected DRX

cDRX enables connected devices to shut down their transceivers periodically and reduce energy consumption upon expiration of the inactivity timer T_{inac}. During cDRX cycles T_{cDRX}^{cycle}, UE monitors PDCCH for scheduling grants at active period T_{cDRX}^{onDur} and sleeps at $T_{cDRX}^{sleep} = T_{cDRX}^{cycle} - T_{cDRX}^{onDur}$. UE performs cDRX until a UL data or DL message transition the device back to *Connected* state or expiration of T_{Dinac} sends UE to *Inactive* state. The number of cDRX cycles is defined by $N_{cDRX}^{cycle} = \lceil (T_{Dinac} - T_{inac})/T_{cDRX}^{cycle}\rceil$. We calculate the energy consumption in *cDRX* state as below

$$E_{cDRX} = N_{cDRX}^{cycle}\Big[P_{cDRX}^{onDur}\, T_{cDRX}^{onDur} + P_{cDRX}^{sleep}\, T_{cDRX}^{onDur}\Big] \tag{17}$$

F. Connection request and resume

Device transitions from *Idle* to *Connected* state through the RC Setup procedure, which consists in exchanging the random access procedure messages, as described in [4]. In more detail, these messages include initial synchronization, random access preamble, random access response (rar), RRC connection setup request (req), RRC connection setup response (set), RRC connection setup complete (setCmp). Since device transitions from *Idle* state it requires establishment of UE context data, which include security keys, UE capabilities and PDU session context, introducing additional energy consumption. Therefore, service accept (acc), security command (sec) and security complete (secCmp), RRC reconfiguration (rec) and RRC reconfiguration complete (recCmp) are executed in addition. The energy consumption of this state is calculated as

$$\begin{aligned}E_{setup} = {} & P_i\,(T^{w}_{MIB} + T_{RAP}/2) + P_{RX}\,(T^{RX}_{MIB} + T_{SSS}) \\ & + 6\,E^{dci}_{RX} + P_{TX}\,T_{PRE} + E^{rar}_{RX}(32) + E^{req}_{TX}(9) \\ & + E^{set}_{RX}(10) + E^{setCmp}_{TX}(108) + E^{acc}_{RX}(15) + E^{sec}_{TX}(41) \\ & + E^{secCmp}_{RX}(30) + E^{rec}_{TX}(9) + E^{recCmp}_{RX}(2). \qquad (18)\end{aligned}$$

Whereas device transitions from *Inactive* to *Connected* state using the *Resume* state, as described in [4]. gNB stores context information of the device, maintaining the core network connection. Applying RRC Resume instead of RRC Setup procedure substantially decreases energy consumption and latency, especially for short IAT, as presented by

$$\begin{aligned}E_{resume} = {} & P_i\,(T^{w}_{MIB} + T_{RAP}/2) + P_{RX}\,(T^{RX}_{MIB} + T_{SSS}) \\ & + 3\,E^{dci}_{RX} + P_{TX}\,T_{PRE} + E^{rar}_{RX}(32) + E^{req}_{TX}(9) \\ & + E^{res}_{RX}(10) + E^{resCmp}_{TX}(108). \qquad (19)\end{aligned}$$

We do not consider device contention for random access preambles as it is not the focus of this work.

V. NUMERICAL EVALUATIONS

In this section, we demonstrate that our proposed Markov Chain models realistically the behavior of IoT devices in 5G, especially RedCap devices. From the design perspective, accuracy is increased by making the model compliant with the 3GPP standard procedures [11]. To validate our analytical calculations, we use the Symbulate package [14], which performs simulations with probability models. Our model is verified by the thorough analysis of Markov Chain performance values. In particular, we study energy consumption, transmission delay, and the number of transmitted packets as crucial metrics in determining the fulfillment of QoS requirements.

To show the improvements introduced in this work, we compare the computed performance metrics with those accomplished by a representative state-of-the-art Markov Chain model, defined in [5]. In that regard, previous research only models the energy consumption of NB-IoT devices as part of the mMTC. Consequently, short IATs in the packet's arrival are excluded from the study. However, the use cases of RedCap devices raise the need for a broader range of IAT, roughly from hundreds of milliseconds to multiple hours. So, the result generation is conducted with IAT from $100\,\mathrm{ms}$ to $24\,\mathrm{h}$ [2]. We differentiate between two categories of IAT based on the state of UE when receiving the UL packet. Therefore, we define short IAT with a range of $100\,\mathrm{ms} - 25\,\mathrm{s}$ and long IAT with a range of $25\,\mathrm{s} - 24\,\mathrm{h}$ and generate results as box-plots, to demonstrate the effectiveness of the proposed model for every value of the categories. Our results evaluate the energy consumption model by using parameter values reported from 3GPP [11], displayed in Table II. However, the analysis is affected by the lack of power measurements for RedCap devices because they are not yet commercially available. Therefore, IAT classification, utilized power levels and message sizes [1], [5] may be prone to change upon obtaining RedCap devices. However, this does not affect the general results of our analysis. We assure the usage of the same parameters for the state-of-the-art and proposed model while generating the results for a single device. In the remainder of the paper, we refer to the proposed model as the 5G model and to the state-of-the-art model as the NB-IoT model.

TABLE II: Simulation parameters [1], [4], [5].

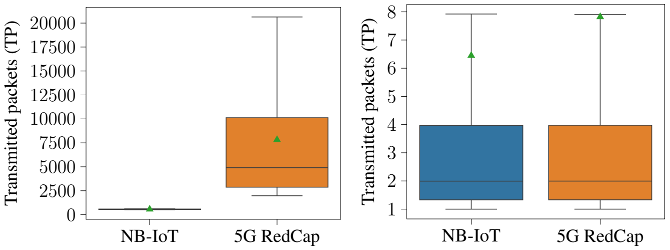
Parameter	Description	Value
P_{TX}	Transmission power consumption	731 mW
P_{RX}	Reception power consumption	215 mW
P_{gap}	Measurement gaps power consumption	128.4 mW
P_i	Waiting power consumption	17.8 mW
P_s	Sleeping power consumption	14.14 µW
P^{sync}_{iDRX}	Short synchronization power consumption	34.5 µW
T_{SSS}	Initial synchronization time	547.5 ms
T^{RX}_{MIB}	Master information block reception time	8 ms
T^{w}_{MIB}	Master information block waiting time	103 ms
T^{sync}_{iDRX}	Short synchronization duration	250 ms
T_{RAP}	Random access preamble periodicity	640 ms
T_{PRE}	Random access preamble duration	5.6 ms
T^{onDur}_{cDRX}	cDRX cycle on duration length	2 ms
T^{cycle}_{cDRX}	cDRX cycle length	2.048 s
T^{onDur}_{iDRX}	iDRX cycle on duration length	2 ms
T^{cycle}_{iDRX}	iDRX cycle length	2.56 s
T^{onDur}_{inDRX}	Inactive iDRX cycle on duration length	2 ms
T^{cycle}_{inDRX}	Inactive iDRX cycle length	2.56 s
T^{PTW}_{eDRX}	eDRX PTW length	20.48 s
T^{cycle}_{eDRX}	eDRX cycle length	81.92 s
T_{inac}	Inactivity timer	2 ms
T_{Dinac}	Data inactivity timer	20 s
T_{Didle}	Data inactivity timer in Inactive state	10.24 s
T_{3324}	Active timer	120 s

A. *Number of transmitted packets per day (*TP*)*

We start the evaluation with the *TP*, illustrated in Fig. 2 because it affects the calculated packet's energy consumption and transmission delay. For short packet IAT, the 5G model evaluates on average 6000 transmitted packets more than NB-IoT model, as displayed in Fig. 2a. The increase in the *TP* is caused by short IAT and higher steady-state probability of being in the *Connected* state. Due to the detailed design of the model, arriving UL packets trigger a direct and faster transition from *cDRX*, *Inactive*, or *Idle* state to *Connected* state, as illustrated in Fig. 1. On the contrary, for long IAT, the device mostly receives UL data when being in *PSM* mode. Consequently, it set ups the connection to transmit the data and transitions to all Markov Chain states before receiving another UL data. The above is depicted in Fig. 2b, where transmitted packets from both models are approximately the same, implying that the 5G models' behavior is the same with NB-IoT for long IAT. We emphasize that the first contribution of the model is supporting the transmission of a higher number of packets, which actually happens for RedCap devices.

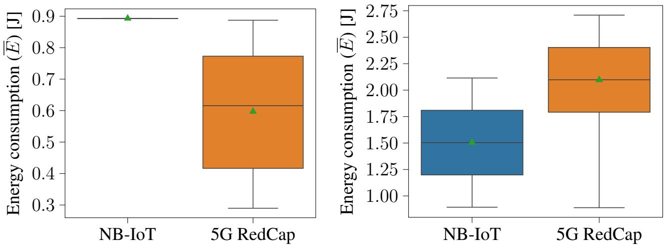
B. *Energy consumption and delay per transmitted packet*

The $\overline{E}$ is presented in Fig. 3, where the results differentiate based on IAT. To better analyze the model, we study the



(a) Short IAT (b) Long IAT

Fig. 2: Number of transmitted packets for state-of-the-art and proposed 5G RedCap model for short and long IATs.



(a) Short IAT (b) Long IAT

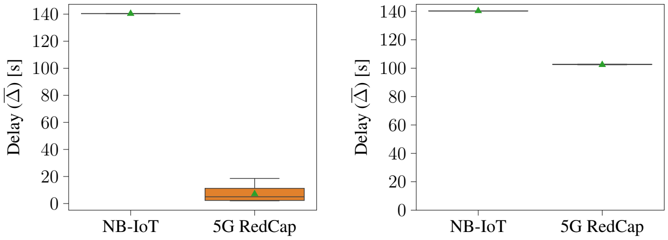
Fig. 3: Average energy consumption per packet for state-of-the-art and proposed 5G RedCap model.

$\overline{\Delta}$ needed to transmit a packet in Fig. 4. For short IAT, the benefit of evaluation with the 5G model is obvious in Fig. 3a, where we calculate an average energy consumption decrease of 33% and a transmission delay decrease of 89% per packet transmission. This output is as expected considering the transitions from *cDRX*, *Inactive* and *Idle* to *Connected* state upon receiving a UL packet, also modeled in our Markov Chain. The resuming of connection requires less energy and time than setting it up. While the former only connects to RAN, the latter also sets up the CN connection, accompanied by additional messages and processing time. The transition from any DRX cycle in the *Idle* state to the *Connected* further reduces the $\overline{E}$ and $\overline{\Delta}$ as devices set up the connection upon receiving the UL packet. While we enable the above features aligned with 3GPP, the NB-IoT model, driven by specific scenarios, designs only the transition from the *PSM* state.

For long IAT, $\overline{E}$ for a transmitted packet is increased while the $\overline{\Delta}$ values are close. The increase in $\overline{E}$ is caused by the detailed modeling of the energy consumption in our Markov Chain, including the *RRC Inactive*, *Setup*, and *Resume* state, which is missing in the NB-IoT model. In the *Setup* state, we account for all messages exchanged to establish the core connection. Moreover, a part of the increase comes from performing more DRX cycles. A solution is to update the duration of the RRC Inactive time, depending on the IAT. This means that for short IAT, we have a long duration of the RRC Inactive, while for long IAT the duration can decrease.

VI. CONCLUSIONS

This work proposes an accurate model for the energy consumption of IoT devices in 5G networks, focusing on RedCap devices. We design a Markov Chain model based on 5G network procedures described in 3GPP standardization, particularly implementing the RRC Inactive, RRC Resume, and eDRX energy-saving techniques, and modeling state transitions, energy consumption, and delay. Besides mMTC traffic profiles, which have long IATs reaching multiple hours, a thorough analysis is performed for short IAT, which is the type of traffic we are interested in. Our results show that the proposed model accurately depicts the RedCap's realistic behavior, where the energy consumption and the transmission delay decrease for short IAT, while the number of transmitted packets increases. The evaluations for long IAT prove that our model can be used to calculate the energy consumption of multiple types of IoTs, from RedCap to NB-IoT devices. We plan to utilize our model for predicting IoT devices' lifetime and update the network parameters based on the context information to reach the target battery life.



(a) Short IAT (b) Long IAT

Fig. 4: Average transmission delay per packet for state-of-the-art and proposed 5G RedCap model for short and long IATs.

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