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 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].

<table>
<thead>
<tr>
<th>QoS</th>
<th>URLLC</th>
<th>mMTC</th>
<th>RedCap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery life</td>
<td>N/A</td>
<td>10 years</td>
<td>wearable: 1-2 weeks</td>
</tr>
<tr>
<td>Latency (ms)</td>
<td>1</td>
<td>10000</td>
<td>safety reports: 5-10 others: 100</td>
</tr>
<tr>
<td>Peak data rate (Mbps)</td>
<td>N/A</td>
<td>LTE-M UL: 2.4</td>
<td>NB-IoT DL: 0.127 UL: 0.159</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DL: 150</td>
<td>UL: 50</td>
</tr>
</tbody>
</table>

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,
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 analyzing 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 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.

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 $\pi$ 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
\[ \pi_{iDRX} = \frac{p_{on} (1 - p_i^n)}{(1 - p_i)^N} \pi_{PSM} = b_{iDRX_n} \pi_{PSM} \quad (1) \]
\[ \pi_{setup} = p_{on} \pi_{PSM} + p_i \sum_{n=0}^{N} \pi_{iDRX_n} \quad (2) \]
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, $p_i = 1 - e^{-\lambda T_{cDRX}}$ is the transition probability
from $Idle$ to $Setup$ when receiving UL packet during $T_{cDRX}$ of
$iDRX$ cycle $n \in \{0, 1...N\}$. The $Connected$ steady-state
\[ \pi_{conn} = \left( \frac{(p_{on} + p_i \sum_{n=0}^{N} b_{iDRX_n}) \pi_{PSM}}{1 - (p_t \sum_{k=0}^{K} b_{iDRX_n} - (p_c \sum_{m=0}^{M} b_{cDRX_m})} \right), \]
includes transition $p_t = 1 - e^{-\lambda T_{cycle}}$ from $Inactive$ $iDRX$
cycle $k \in \{0, 1...K\}$ to $Connected$, when receiving UL packet
during $T_{cycle}$. Variable $p_c = 1 - e^{-\lambda T_{cDRX}}$ expresses the transition probability from $cDRX$ cycle $m \in \{0, 1...M\}$ to
$Connected$ if UL data is received during cycle duration
$T_{cycle}$. The steady-state probability of each $cDRX$ cycle is
\[ \pi_{cDRX_m} = (1 - p_q)^m \pi_{conn} = b_{cDRX_m} \pi_{conn} \quad (4) \]
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
\[ \pi_{inDRX_k} = (1 - p_i)^k \pi_{cDRX_M} = b_{inDRX_k} \pi_{conn} \quad (5) \]
\[ \pi_{resume} = (p_i \sum_{k=0}^{K} b_{inDRX_k}) \pi_{conn} \quad (6) \]
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
$\pi_{PSM}$ is obtained as
\[ \pi_{PSM_1} = 1 + (2p_{on}) + (1 + 2p_t) \sum_{n=0}^{N} b_{iDRX_n} \quad (7) \]
\[ \pi_{PSM_2} = \frac{p_{on} + p_i \sum_{n=0}^{N} b_{iDRX_n}}{1 - (p_t \sum_{k=0}^{K} b_{iDRX_k} - (p_c \sum_{m=0}^{M} b_{cDRX_m})} \quad (8) \]
\[ \pi_{PSM_3} = 1 + (1 + 2p_t) \sum_{k=0}^{K} b_{inDRX_k} + \sum_{m=0}^{M} b_{cDRX_m} \quad (9) \]
A. Calculation of model’s performance values
The steady-state probabilities in equations (1) - (9), are uti-
lized 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
$\pi_{conn}$, 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
\[ TP : P_{day} = \sum_{state} \pi_{state} \cdot \Delta \cdot \pi_{conn} \quad (10) \]
where $\Delta$ is the Markov Chain state delay. The average
energy consumption per packet $(\overline{E})$ is calculated using the performance value as
$\overline{E} : E_{packet} = \sum_{state} \pi_{state} \cdot E_{state}$, where the
$E_{state}$ is the energy consumption of Markov Chain states.
The average transmission delay per packet $(\overline{\Delta})$ is calculates as
$\overline{\Delta} : \Delta_{packet} = \sum_{state} \pi_{state} \cdot \Delta_{state}$.

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 $T_{gap}$ by measurement gaps with duration $T_{gap}$ 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
\[ E_{TX}(k) = P_{TX} t_{TX}(k) + P_{gap} t_{T_{gap}} \quad (11) \]
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
\[ s(k) = \left\lceil \frac{k}{TBS(MCS, n_{SF}) - h} \right\rceil \quad (12) \]
where $\lceil \cdot \rceil$ 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
\[ t_{T_{gap}}(t_{TX}) = \left\lceil \frac{t_{TX}}{t_{T_{period}} - t_{T_{duration}} T_{gap}} \right\rceil \quad (13) \]
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

\[ t_{\text{gap}}^\text{RX}(t_{\text{RX}}) = \left[ t_{\text{RX}} \left( \frac{20}{14} - 1 \right) \right]. \quad (14) \]

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 with the network for \( T_{\text{iDRX}}^\text{sync} \) and afterward monitors the paging occasions for \( T_{\text{iDRX}}^\text{onD} \). If messages were not received, UE goes into the sleeping period \( T_{\text{iDRX}}^\text{sleep} \). The iDRX cycle duration \( T_{\text{iDRX}}^\text{cycle} \) varies and is defined by the network. The following variables denote power consumption for synchronization \( P_{\text{sync}}^\text{iDRX} \), for paging monitoring \( P_{\text{onD}}^\text{iDRX} \), and for sleeping \( P_{\text{sleep}}^\text{iDRX} \). The iDRX cycle energy consumption is

\[ E_{\text{iDRX}} = P_{\text{sync}}^\text{iDRX} T_{\text{iDRX}}^\text{cycle} + P_{\text{onD}}^\text{iDRX} T_{\text{iDRX}}^\text{onD} + P_{\text{sleep}}^\text{iDRX} T_{\text{iDRX}}^\text{sleep} \]

\[ T_{\text{iDRX}}^\text{sleep} = T_{\text{iDRX}}^\text{cycle} - (T_{\text{iDRX}}^\text{sync} + T_{\text{iDRX}}^\text{onD}) \]. \quad (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 Pacing Time Window (PTW) period \( T_{\text{PTW}}^\text{cycle} \) and the sleeping period \( T_{\text{eDRX}}^\text{cycle} = T_{\text{eDRX}}^\text{onD} - T_{\text{eDRX}}^\text{sleep} \). 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, \( N_{\text{iDRX}}^\text{cycles} = \left[ T_{\text{PTW}} / T_{\text{iDRX}}^\text{cycle} \right] \). Meanwhile, the number of eDRX cycles depends on timer \( T_{3324} \) and the cycle duration

\[ T_{\text{eDRX}}^\text{cycles} = N_{\text{iDRX}}^\text{cycles} / T_{3324} / T_{\text{iDRX}}^\text{cycle} \]. \quad (16)

The energy consumption of eDRX cycle is calculated as

\[ E_{\text{eDRX}} = E_{\text{iDRX}} N_{\text{iDRX}} + P_{\text{sleep}} T_{\text{eDRX}}^\text{sleep} \]

We calculate the total energy consumption during \( T_{3324} \) as

\[ E_{\text{idle}} = E_{\text{iDRX}} N_{\text{iDRX}} + E_{\text{eDRX}} \]. \quad (17)

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 \( T_{\text{Diac}} \) 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 \( T_{\text{Diac}} \) 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 \( E_{\text{inactive}} = N_{\text{cDRX}}^\text{cycle} E_{\text{cDRX}}^\text{cycle} + E_{\text{RX}}^\text{rel} \).

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 (PDCCH) to receive paging or UL scheduling grants. The monitoring of the channel continues until the expiration of the inactivity timer \( T_{\text{inac}} \), after which UE enters connected DRX state. Transmitting uplink data resets the \( T_{\text{inac}} \) and elongates the time UE spends in the Connected state. The consumed energy is calculated as

\[ E_{\text{Connect}} = E_{\text{TX}} + E_{\text{RX}}(\text{data}) + P_{\text{RX}} T_{\text{inac}} \].

E. Connected DRX

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

\[ N_{\text{cDRX}}^\text{cycles} = (T_{\text{Diac}} - T_{\text{inac}}) / T_{\text{cDRX}}^\text{cycle} \]. \quad (16)

We calculate the energy consumption in cDRX state as below

\[ E_{\text{cDRX}} = N_{\text{cDRX}}^\text{cycles} \left( P_{\text{onDur}}^\text{cDRX} T_{\text{onDur}}^\text{cDRX} + P_{\text{sleep}}^\text{cDRX} T_{\text{sleep}}^\text{cDRX} \right) \]. \quad (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 (setComp). 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)
TABLE II: Simulation parameters [1], [4], [5].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{tx})</td>
<td>Transmission power consumption</td>
<td>731 mW</td>
</tr>
<tr>
<td>(P_{rx})</td>
<td>Reception power consumption</td>
<td>215 mW</td>
</tr>
<tr>
<td>(P_{gap})</td>
<td>Measurement gap power consumption</td>
<td>128.4 mW</td>
</tr>
<tr>
<td>(P_i)</td>
<td>Waiting power consumption</td>
<td>17.8 mW</td>
</tr>
<tr>
<td>(P_s)</td>
<td>Sleeping power consumption</td>
<td>14.14 µW</td>
</tr>
<tr>
<td>(P_{tx,DRX})</td>
<td>Short synchronization power consumption</td>
<td>34.5 µW</td>
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<td>(T_{iDRX,req})</td>
<td>Initial synchronization time</td>
<td>547.5 ms</td>
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<tr>
<td>(T_{iDRX,setup})</td>
<td>Master information block reception time</td>
<td>8 ms</td>
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<tr>
<td>(T_{RX,MIB})</td>
<td>Master information block waiting time</td>
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<td>(T_{iDRX,short})</td>
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<td>250 ms</td>
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<td>(T_{RAP})</td>
<td>Random access preamble periodicity</td>
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<td>(E_{tx,DRX})</td>
<td>cDRX PWT length</td>
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<td>(E_{tx,DRX})</td>
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<td>(T_{inac})</td>
<td>Inactivity timer</td>
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<tr>
<td>(T_{inac})</td>
<td>Data inactivity timer</td>
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<tr>
<td>(T_{islic})</td>
<td>Data inactivity timer in Inactive state</td>
<td>10.24 s</td>
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<tr>
<td>(T_{3324})</td>
<td>Active timer</td>
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</table>
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.

**REFERENCES**


