Modelling and Experimental Validation for Battery Lifetime Estimation in NB-IoT and LTE-M

André Sørensen*, Hua Wang†‡, Maxime Jérôme Remy*, Nicolaj Kjettrup*, René Brandborg Sørensen†, Jimmy Jessen Nielsen†, Petar Popovski‡, Germán Corrales Madueño∗†

*Keysight Technologies Denmark Aps, Aalborg, Denmark
†Department of Electronic Systems, Aalborg University, Aalborg, Denmark
‡{andre.soerensen,maxime.remy,nicolaj.kjettrup,german.madueno}@keysight.com

Abstract—Internet of Things (IoT) is one of the main features in 5G. Low-power wide-area networking (LPWAN) has attracted enormous research interests to enable large scale deployment of IoT, with the design objectives of low cost, wide coverage area, as well as low power consumption. In particular, long battery lifetime is essential since many of the IoT devices will be deployed in hard-to-access locations. Prediction of the battery lifetime depends on the accurate modelling of energy consumption. This paper presents a comprehensive power consumption model for battery lifetime estimation, which is based on User Equipment (UE) states and procedures, for two cellular IoT technologies: Narrowband Internet of Things (NB-IoT) and Long Term Evolution for Machines (LTE-M). A measurement testbed has been setup and the proposed model has been tested and validated via extensive measurements under various traffic patterns and network scenarios, achieving the modelling inaccuracy within 5%. The measurement results show that the battery lifetime of an IoT device can reach up to 10 years as required by 3GPP, with proper configuration of the traffic profile, the coverage scenario, as well as the network configuration parameters.

Index Terms—IoT, NB-IoT, LTE-M, Power consumption models, Battery lifetime estimation

I. INTRODUCTION

The number of IoT connections has increased exponentially worldwide since 2015, reaching over 1 billion in 2020, and is predicted to keep growing to roughly 5 billion by 2025 [1]. Early IoT deployments have been used for smart metering, asset monitoring and smart logistics, industrial automation, traffic monitoring, fleet tracking, smart home appliances, etc. The IoT applications are designed to support massive deployment, e.g., more than 100,000 per cell. Replacing the batteries for such a large number of devices would not only be costly and cumbersome, but also sometimes impractical, since devices may be deployed in locations where it is hard for human to access, for example in basement where the water meters are placed. It often ends up that the battery lifetime determines the lifetime of the IoT device. Therefore, massive connectivity, low cost, wide coverage, and low power consumption are the key requirements for the IoT devices.

To address the requirements imposed by IoT applications, 3rd Generation Partnership Project (3GPP) has introduced two standards for Cellular Internet of Things (CIoT): LTE-M and NB-IoT, both of which are developed based on 4G Long Term Evolution (LTE), but are targeted for LPWAN solutions. The main advantages of 3GPP standardized technologies as compared to other proprietary solutions are the reuse of existing infrastructure and the use of a licensed spectrum, allowing for more stable and predictable performance.

Energy efficiency is certainly a major concern for typical IoT deployment, especially for battery-powered IoT devices, which are normally affected by a vast number of network configurations as well as implementation parameters. 3GPP requires a battery lifetime of more than 10 years with a battery capacity of 5 Wh for an IoT device operating with a predefined traffic profile in certain deployment scenarios [2]. Therefore, accurate modelling of the energy consumption for an IoT device is of great importance, as the application developers as well as the network operators need to predict and plan which IoT technology or device should be chosen and how the network parameters should be configured based on the performance requirements and the expected battery lifetime for a given use case. The model should be general enough so that it can be applied to different devices running on same or different IoT technologies. The model should also be flexible enough with different configurations of network and application parameters, for example various traffic profile and network scenarios, and should be able to analyze the impact of different configurations on the device performance.

Early studies on the modelling of power consumption and the empirical performance characterization with respect to NB-IoT are discussed in details in Section II. A preliminary study on the power consumption model specifically for NB-IoT was presented in our earlier work [3]. Comparatively, this paper improves the power consumption model proposed in [3] and adapts the analysis to also include LTE-M. Additionally, the proposed model has been validated via empirical power consumption measurements and the impact of network and application configuration parameters on the device’s battery lifetime has been analyzed. Specifically, the main contributions of this paper are summarized below:

1) We extend the power consumption model to include LTE-M. The proposed model can be generalized to estimate the energy consumption and the battery life-
time of any devices running either NB-IoT or LTE-M, with flexible configurations of traffic profile, coverage scenario, as well as network parameters.

2) The accuracy of the model has been improved based on PHY-level measurements and detailed modelling of each UE state and procedure. By composing different components of UE states and procedures, the power consumption of any UE behaviour can be modelled. Extensive measurements have been performed using two commercial IoT devices with the latest NB-IoT/LTE-M features to validate the proposed model under various traffic profile and network configurations. The empirical results show that the proposed power consumption model can achieve an estimation error within 5%, which is the lowest to the best of the author’s knowledge.

3) We defined three coverage scenarios for NB-IoT and LTE-M based on the coupling loss with the aim to compare the two technologies fairly. We also analyzed the impact of traffic profile, coverage scenario, and network configuration parameters on the device’s battery lifetime based on the proposed model, shedding some light on how the IoT application developers as well as the network operators should carefully configure the parameters to best tradeoff between the performance and device lifetime of their use case.

The rest of the paper is structured as follows. A review of the latest literature on the power consumption of IoT devices is presented in Section II. Section III introduces the UE states and procedures, followed by the energy consumption of those states and procedures in Section IV and V, respectively. The considered coverage scenario, traffic profile, and the battery lifetime estimation model are presented in Section VI. The tested setup and the measurement results are presented and discussed in Section VII. Conclusions are drawn in Section VIII. The main acronyms used in this paper are listed in Table I.

II. RELATED WORK

The power consumption model for regular broadband LTE network has been addressed widely in the literature, as discussed in [4] and the references therein. In recent years, various works have been published focusing on the power consumption analysis of IoT devices via simulations, analytical modelling, or experimental measurements.

El Soussi et al. [5] evaluated the performance of NB-IoT and LTE-M in the context of smart city use case, by using NS-3 simulation in an urban cell. It was found that an 8-year battery lifetime is achievable for both both technologies in a poor coverage scenario with a reporting interval of one day. The network coverage and capacity of various IoT technologies, including NB-IoT and LTE-M, have been evaluated in [6], [7] through both simulation and empirical measurements.

It was found that NB-IoT provides better coverage, especially for indoor cases, at the cost of lower capacity in terms of the total number of supported devices. The authors also showed the results of the average power consumption for the two technologies in various propagation scenarios. In addition to their previous work, the power consumption and a battery lifetime estimation model of two NB-IoT devices were proposed in [8] using experimental measurements. However, the abstraction level of the power consumption model is relatively high, which reduces the complexity of the model, but also introduces inaccuracies and obfuscates energy trade-offs at lower-level mechanisms. An energy consumption model for NB-IoT devices considering Power Saving Mode (PSM) and Extended Discontinuous Reception (eDRX) with different timer parameters was proposed in [9]. The analysis is compared to the NS-3 simulation results, showing an average inaccuracy of around 11.8%. A tractable theoretical model of energy consumption in NB-IoT was presented in [10], providing some insights in the tradeoff between energy efficiency, latency and coverage. Andres-Maldonado et al. [11], [12] proposed a Markov chain based analytical model to estimate the energy consumption and delay of a NB-IoT device sending periodic uplink reports using the control plane procedure. The model has been validated

| Acronym | Description |
|---------|-------------|
| eDRX   | Connected mode Discontinuous Reception |
| CE     | Coverage Enhancement |
| CIoT   | Cellular Internet of Things |
| CP     | Control Plane optimization |
| DCI    | Downlink Control Information |
| DL     | Downlink |
| DRX    | Discontinuous Reception |
| DUT    | Device Under Test |
| ECM    | EPS Connection Management |
| eDRX   | Extended Discontinuous Reception |
| EMM    | EPS Mobility Management |
| EPS    | Evolved Packet System |
| iDRX   | Idle mode Discontinuous Reception |
| IoT    | Internet of Things |
| LPWAN  | Low Power Wide Area Network |
| LTE    | Long Term Evolution |
| LTE-M  | Long Term Evolution for Machines |
| MCL    | Maximum Coupling Loss |
| MCS    | Modulation and Coding Scheme |
| NAS    | Non-Access Stratum |
| NB-IoT | Narrowband Internet of Things |
| NPDCCH | Narrowband Physical Downlink Control Channel |
| NPRACH | Narrowband Physical Random Access Channel |
| NPUCCH | Narrowband Physical Uplink Control Channel |
| NPUSCH | Narrowband Physical Uplink Shared Channel |
| OFDM   | Orthogonal Frequency-Division Multiplexing |
| OFDMA  | Orthogonal Frequency-Division Multiple Access |
| PDCCH  | Physical Downlink Control Channel |
| PRACH  | Physical Random Access Channel |
| PRB    | Physical Resource Block |
| PSN    | Power Saving Mode |
| PTW    | Paging Time Window |
| PUCCH  | Physical Uplink Control Channel |
| PUSCH  | Physical Uplink Shared Channel |
| RA     | Random Access |
| RAP    | Random Access Preamble |
|RAR     | Random Access Response |
|RRC     | Radio Resource Control |
| RU     | Resource Unit |
| SC-FDMA| Single-Carrier Frequency-Division Multiple Access |
| SF     | Subframe |
| SR     | Scheduling Request |
| TAP    | Test Automation Platform |
| TAU    | Tracking Area Update |
| TBS    | Transport Block Size |
| UE     | User Equipment |
| UL     | Uplink |
| USS    | UE specific Search Space |

TABLE I: List of Acronyms
using two commercial NB-IoT device and three test cases, obtaining a maximum relative error of the battery lifetime estimation of 21%. It is noted that the periodic Tracking Area Update (TAU) procedure is not considered [11].

Hertlein et al. [13] compared the power consumption of several cellular standards via measurements. It is confirmed that NB-IoT can reduce the power consumption as compared to other cellular standards. Experimental assessment of the expected lifetime of an NB-IoT device is presented in [14], based on measurements from both a commercial and a private network in the context of aviation use case. It is found that the battery lifetime can be extended significantly by using PSM in the idle state. Although the results obtained in [14] have high credibility in terms of realism, it is not straightforward to extrapolate those results to different network scenarios, traffic patterns, and transmission parameter configurations. An End-to-End (E2E) integration study of an experimental NB-IoT trial network was performed in [15] by Telekom Malaysia. The assessment results showed that a careful setup of the NB-IoT device’s firmware is critical to prolong the battery lifetime, e.g., avoiding unnecessary network attach and detach procedures, and proper configuration of the T3324 timer and T3412 timer to best match the tradeoff between delay and energy efficiency, etc. Martinez et al. [16] empirically investigated the performance boundaries of NB-IoT in terms of energy consumption, reliability, and delays. The measurements were performed over a commercial NB-IoT network in Spain with two commercial NB-IoT devices, using different device and network configurations. It is found that some of the timers associated with the power saving mechanisms have an obvious effect on the device energy consumption. Abbas et al. [17] proposed guidelines on how to configure both tunable and non-tunable parameters with the target to conserve the energy consumption by means of simulations. A more comprehensive measurement study of the energy consumption is conducted in [18] with two popular NB-IoT devices in two major western European operators under different parameter configurations, with the aim to identify the key parameters for enhancing the battery lifetime. Its findings indicate that careful configurations are required to improve the energy efficiency. For higher level IoT applications, Lin et al. [19] developed a service platform for fast development of NB-IoT applications, which is used in a smart parking application as an example.

The main issue we observed in the current state of the art work on analytical energy consumption modelling of IoT devices is the lack of accuracy and flexibility. Besides, although quite much work has been done trying to fine tune the parameters to lower the energy consumption, those results are mainly obtained from extensive experimental measurements. The main objective of this work is to first propose a highly accurate framework for modelling the power consumption of NB-IoT and LTE-M, consisting of detailed modelling of UE states and procedures. The model is flexible for different configurations of traffic profile, transmission and network parameters. Based on the proposed model, we also attempt to identify the parameters that mostly impact the battery lifetime. Our findings are in line with the observations obtained from the measurements as mentioned in the previous literature.

III. UE STATES AND PROCEDURES

Our framework for the power consumption modelling is based on the states of the UE and the transition among the states which is triggered by the procedures. The main differences between NB-IoT and LTE-M will be described first, followed by a general description of the UE states and procedures.

A. Differences between NB-IoT and LTE-M

Both LTE-M and NB-IoT are developed based on LTE with the aim to offer better coverage and lower energy consumption. Although these two technologies share a lot of similarities, they are targeted for different use cases and therefore have some differences. Comparatively, LTE-M supports higher data rate, lower latency, and higher mobility, while NB-IoT is focused on enhanced coverage, longer battery life, and lower device complexity [20].

LTE-M has defined two Coverage Enhancement (CE) Modes: Mode A and Mode B, targeting for different coverage levels [21]. This paper only considers CE Mode A, as this is a mandatory feature for LTE-M while Mode B is optional. Some of the main differences between the two technologies are summarized in Table II. Specifically, the transmission bandwidth of NB-IoT is reduced from 1.08 MHz to 180 kHz, resulting in a lower data rate as compared to LTE-M. In downlink, both LTE-M and NB-IoT support multi-tone transmissions based on Orthogonal Frequency-Division Multiple Access (OFDMA) with 12 subcarriers and 15 kHz subcarrier spacing. In uplink, LTE-M only supports multi-tone transmissions based on Single-Carrier Frequency-Division Multiple Access (SC-FDMA) while NB-IoT supports both single-tone and multi-tone transmissions. The minimum resource allocation unit in both uplink and downlink for LTE-M is a Physical Resource Block (PRB), consisting of 12 subcarriers and 1 slot (7 OFDM symbols). The minimum resource allocation unit in downlink for NB-IoT is also a PRB, while in uplink the minimum unit is a Resource Unit (RU), of which the number of subcarriers and slots within a RU depend on the transmission option (i.e., single-tone or multi-tone) [22]. The number of repetitions in NB-IoT has increased up to 128 in uplink and 2048 in downlink to further extend the coverage level. By trading off data rate and latency, i.e., reducing the transmission bandwidth and/or increasing the number of retransmissions, the coverage in terms of Maximum Coupling Loss (MCL) is extended to 164 dB in NB-IoT (20 dB deeper than LTE).

As previously stated, the physical layer channels and signals of both LTE-M and NB-IoT are mostly inherited from LTE, but are optimized to meet the constraints and requirements of IoT modules. There is not much difference for the downlink channels between LTE-M and NB-IoT. However in the uplink, NB-IoT transmits the data and control information both in Narrowband Physical Uplink Shared Channel (NPUSCH) with different formats [22], while LTE-M transmits data in Physical Uplink Shared Channel (PUSCH) and control information in Physical Uplink Control Channel (PUCCH).
TABLE II: Differences between NB-IoT and LTE-M.

| Attribute       | LTE-M               | NB-IoT              |
|-----------------|---------------------|---------------------|
| Deployment      | In-band, Guard-band, Stand-alone | In-band, Guard-band, Stand-alone |
| Coverage        | 155.7 dB MCL        | 156 dB MCL          |
| Bandwidth       | 1.08 MHz            | 180 kHz             |
| Downlink        | OFDMA, multi-tone with 12 subcarriers, 15 kHz tone spacing | OFDMA, multi-tone with 12 subcarriers, 15 kHz tone spacing |
| Transmission    | SC-FDMA, multi-tone with 12 subcarriers, 15 kHz tone spacing | Multi-tone with 3, 6 or 12 subcarriers (SC-FDMA), 15 kHz tone spacing Single-tone, 3.75 kHz & 15 kHz tone spacing |
| Uplink          | PRB in DL, PRB in UL | PRB in DL, RU in UL |
| Resource Allocation | Max number of repetitions | Peak rate |
| Resource Allocation | 32 in UL (CE mode A) | 1 Mbps for DL, 32 in UL (CE mode A) |
| Resource Allocation | 20 kHz in UL | 12 Mbps for DL, 20 kHz in UL |
| Resource Allocation | 5 MHz for DL and UL | Single-tone, 15 kHz tone spacing |
| Resource Allocation | DL: 250 Kbps | Single-tone, 15 kHz tone spacing |
| Resource Allocation | UL: 20 Kbps, (multi-tone) | | |
| Resource Allocation | Single-tone, 3.75 kHz & 15 kHz tone spacing | |
| Resource Allocation | DL: 250 Kbps, (multi-tone) | DL: 250 Kbps, (multi-tone) |
| Resource Allocation | UL: 20 Kbps (single-tone) | UL: 20 Kbps (single-tone) |
| Uplink Channel  | PUCCH: Transmission of control information | NPUSCH format 2: Transmission of control information |
| PRACH: Transmission of preamble | PUSCH: Transmission of data | NPUSCH format 1: Transmission of data |
| PRACH: Transmission of preamble | NPRACH: Transmission of preamble with a new waveform | |

**TABLE II: Differences between NB-IoT and LTE-M.**

**B. UE Procedures**

To be able to establish a connection to the network and start data transmission, the UE has to perform a series of actions with specific purposes and functions, such as frequency and time synchronization, performing Random Access (RA), sending service request, etc. These actions can be referred to as procedures. Some of the main procedures performed in NB-IoT and LTE-M are listed below:

- **Synchronization:** When the UE is switched on or wakes up, it has to synchronize with the network both in time and frequency domains by decoding synchronization signals, namely Primary Synchronization Signal and Secondary Synchronization Signal. After the completion of synchronization and cell search, the UE can perform the RA procedure.

- **Attach:** If the UE has the intention to communicate with the network but has not been registered in the network yet, i.e., in EMM_DEREGISTERED state, it performs the attach procedure after being synchronized to the network. The attach procedure is used to create the Evolved Packet System (EPS) bear between the UE and the Packet data network Gateway in order to be able to send and receive data.

- **Service Request:** The service request procedure is similar to the attach procedure, but with fewer steps. It is used to activate a user plane connection for data transmission when the UE has already been registered in the network, i.e., in EMM_REGISTERED state. It will bring the UE from ECM_IDLE state into ECM_CONNECTED state.

- **Connection Resume:** The Radio Resource Control (RRC) connection resume procedure is initiated by the UE when upper layers requests the resume of a suspended RRC connection. It is used as a replacement of the service request procedure if the connection has been suspended instead of released. The UE should have valid and up to date essential system information before initiating the connection resume procedure.

- **Connection Release:** The release procedure is used to release an RRC connection. If the UE does not have any activity in the network but still would like to be registered in the network, the network initiates the RRC connection release procedure to the UE. The UE can still be contacted via paging after the release procedure. If the UE has data to transmit, it has to perform a service request procedure.

- **TAU:** A UE in ECM_IDLE state sends a TAU message to the Mobility Management Entity periodically to notify the network that it is still alive and is able to receive data. Otherwise, the network would assume the UE is not reachable and will not perform paging even when there is data traffic for it.

The power consumption modelling of the aforementioned procedures will be described in Section V.

**C. UE States**

The UE states can be defined in several aspects: from a device perspective and from a network perspective.

From a network perspective, the network status of the UE indicates how reachable the UE is and what are the available resources for the UE. It is the EPS Mobility Management (EMM) and EPS Connection Management (ECM) protocols that determine the network status of the UE. An example of UE procedures and the corresponding network status is illustrated in Fig. 1.

![Fig. 1: Example of UE procedures and the corresponding EMM/ECM network status.](image)

The EMM protocol indicates whether the UE is registered in the network or not. After the UE is switched on, it performs the synchronization and cell search procedure before entering the Synchronized state. At this moment, the UE is in EMM_DEREGISTERED state. The EMM state of the UE is changed to EMM_REGISTERED after the UE has performed a network attach procedure, i.e., RRC Connection setup including the RA procedure, Non-Access Stratum (NAS) authentication and NAS security. The EMM state of the UE is changed back to EMM_DEREGISTERED when either the TAU timer has expired or a detach procedure is performed.

The ECM protocol indicates whether the UE has established signalling to the Evolved Packet Core or not. In the ECM_CONNECTED state, the UE has an active RRC connection with the network and is semi-actively monitoring the network in order to preserve energy. In the ECM_IDLE state, there is no active RRC connection and the UE will only be reachable in certain time intervals according to the selected power saving technique, which can be for example Discontinuous Reception (DRX) and PSM.
types of DRX. When the UE is in ECM_CONNECTED state it is named as Connected Mode Discontinuous Reception (cDRX) and when the UE is in ECM_IDLE state it is named as Idle Mode Discontinuous Reception (iDRX). The UE changes from ECM_IDLE to ECM_CONNECTED state by performing either a service request, an attach, or a connection resume procedure. To change from ECM_CONNECTED to ECM_IDLE, the UE performs either a detach, a connection suspend, or a release procedure. From a device perspective, the UE can be in different states such as Reception (RX), Transmission (TX), idle, etc. The state diagram for the UE is depicted in Fig. 2 together with the procedures required to move from one state to another. The grey area indicates the UE is in EMM_DEREGISTERED while the white area indicates the UE is in EMM_REGISTERED.

There is a power cost associated with UE state transitions in addition to the power cost of staying in a specific UE state. By characterising the power consumption of each UE state and the associated procedure(s), the power consumption of any UE behaviour can be modelled by composing different components of the states and procedures illustrated in Fig. 2. The modelling of power consumption for different UE states and procedures will be presented in the following sections.

IV. ENERGY CONSUMPTION OF UE STATES

In this section, the energy consumption models for different UE states are presented. For brevity, the details of the performed power measurements in each UE state are not included in this paper, but are available in [3].

A. TX State

In TX state, the UE is transmitting data in the uplink. The energy consumption in the TX state is determined by the UE’s power level as well as the length of the transmission. The UE’s required transmission power is controlled by the uplink power control specified in [23]. From measurements, it is observed that the UE’s uplink transmission power is independent of the selection of Modulation and Coding Scheme (MCS).

1) Uplink Packet: The uplink data packets are transmitted in PUSCH and NPUSCH with format 1 for LTE-M and NB-IoT, respectively. During uplink transmission, a mandatory gap of 40 milliseconds after 256 milliseconds of continuous transmission is introduced to allow the low-quality oscillators to resynchronize with the network [24], [25]. The power consumption is much lower during these transmission gaps as compared to the power consumption during data transmission.

The estimated energy consumption for the TX state with an uplink packet of payload size $k$ can be calculated as:

$$E_{\text{TX}}(k) = t_{\text{TX}}(k) \cdot P_{\text{TX}} + t_{\text{exp}}^{\text{TX}}(t_{\text{TX}}) \cdot P_{\text{exp}}^{\text{TX}}$$

where $t_{\text{TX}}(k)$ is the time spent in data transmission with $k$ bits, $P_{\text{TX}}$ is the power consumption during data transmission, $t_{\text{exp}}^{\text{TX}}(t_{\text{TX}})$ is the time spent in transmission gaps, and $P_{\text{exp}}^{\text{TX}}$ is the power consumption during transmission gaps.

The transmission time $t_{\text{TX}}(k)$ for a packet with payload size $k$ in bits depends on the selection of MCS, the number of allocated RUs or Subframe (SF)s, and the number of repetitions. For NB-IoT and LTE-M, the transmission time can be calculated as:

$$t_{\text{NB-IoT}}^{\text{TX}}(k) = t_{\text{RU}} \cdot \rho_{\text{RU}} \cdot N_{\text{pkt}}^{\text{NB-IoT}} \cdot t_{\text{NB-IoT}}(k)$$  \hspace{1cm} (2)

$$t_{\text{LTE-M}}^{\text{TX}}(k) = t_{\text{SF}} \cdot \rho_{\text{SF}} \cdot N_{\text{pkt}}^{\text{LTE-M}} \cdot t_{\text{LTE-M}}(k)$$  \hspace{1cm} (4)

$$t_{\text{SF}} = \left\lceil \frac{k}{TBS(MCS, \rho_{\text{SF}}) - h_{\text{NB-IoT}}} \right\rceil$$  \hspace{1cm} (3)

where $t_{\text{RU}}$ is the duration of a RU, $\rho_{\text{RU}}$ is the number of allocated RUs, $t_{\text{SF}}$ is the duration of a SF, $\rho_{\text{SF}}$ is the number of allocated SFs, $t_{\text{NB-IoT}}(k)$ and $t_{\text{LTE-M}}(k)$ are the number of segments, $N_{\text{pkt}}^{\text{NB-IoT}}$ and $N_{\text{pkt}}^{\text{LTE-M}}$ are the number of repetitions, TBS is the transport block size determined by the selected MCS and the number of allocated resources in terms of RU(s) for NB-IoT and SF(s) for LTE-M, $h_{\text{NB-IoT}}$ and $h_{\text{LTE-M}}$ are the header size, and $\lceil \cdot \rceil$ is the ceil function. The length of a SF $(t_{\text{SF}})$ is always 1 ms, while the length of a RU $(t_{\text{RU}})$ can range from 1 ms to 32 ms, depending on the configured uplink transmission option, e.g., subcarrier spacing, the number of configured subcarriers and slots. The available transmission options of one RU can be referred to [22]. It should be noted that Eq. (4) does not hold if frequency hopping is enabled for LTE-M. In that case, PRBs are scheduled over multiple SFs.

The time spent in transmission gaps depends on $t_{\text{TX}}$, and can be calculated as:

$$t_{\text{exp}}^{\text{TX}}(t_{\text{TX}}) = \left\lceil \frac{t_{\text{TX}}}{t_{\text{TXmax}}} \right\rceil \cdot t_{\text{exp}}$$  \hspace{1cm} (6)

where $t_{\text{TXmax}}$ is the maximum continuous transmission time allowed, $t_{\text{exp}}^{\text{TX}}$ is the duration of a gap, and $\lceil \cdot \rceil$ is the floor function. According to [24], $t_{\text{TXmax}}$ and $t_{\text{exp}}^{\text{TX}}$ for NB-IoT are 256 ms and 40 ms, respectively.
2) Uplink Control: Uplink control information (e.g., ACK/NACK) is transmitted in PUCCH for LTE-M and in NPUSCH with format 2 for NB-IoT, respectively. It should be noted that using NPUSCH format 2, the RU is always configured with one subcarrier and 4 slots. The energy consumption for transmitting uplink control information can be calculated similarly as for uplink data packet:

\[
E_{\text{TX}(\text{ack})} = t_{\text{TX}(\text{ack})} \cdot P_{\text{TX}} + t_{\text{gaps}}^{\text{TX}(\text{ack})} \cdot P_{\text{gaps}}^{\text{TX}} \tag{7}
\]

\[
t_{\text{RX}(\text{ack})} = t_{\text{RX(ack)}} \cdot N_{\text{ack}}^{\text{NB-IoT}} \tag{8}
\]

\[
t_{\text{LTE-M(ack)}} = t_{\text{SF}} \cdot N_{\text{ack}}^{\text{LTE-M}} \tag{9}
\]

\[
t_{\text{gaps}}^{\text{TX}(\text{ack})} = \left[ \frac{t_{\text{TX}(\text{ack})}}{t_{\text{RX}}^{\text{RX}}} \right] \cdot \frac{t_{\text{exp}}}{t_{\text{TX}}} \tag{10}
\]

3) Random Access: The transmission of preamble is performed in PRACH for LTE-M and in NPRACH for NB-IoT, respectively. There is no transmission gap during the transmission in Random Access Preamble (RAP). So the energy consumption for transmitting the preamble can be calculated as:

\[
E_{\text{RAP}} = t_{\text{RAP}} \cdot P_{\text{TX}} \tag{11}
\]

where \(t_{\text{RAP}}\) is the duration of the RAP, and can be calculated as:

\[
t_{\text{RAP}}^{\text{NB-IoT}} = \left( t_{\text{format}}^{\text{CP}} + 5 \cdot t_{\text{RASym}} \right) \cdot 4 \cdot N_{\text{RAP}}
\]

\[
t_{\text{RAP}}^{\text{LTE-M}} = t_{\text{format}}^{\text{RAP}} \cdot N_{\text{RAP}} \tag{12}
\]

where \(t_{\text{format}}^{\text{CP}}\) is the duration of the cyclic prefix, \(t_{\text{RASym}}\) is the symbol duration in NB-IoT NPRACH, \(t_{\text{format}}^{\text{RAP}}\) is the duration of the RAP for LTE-M, and \(N_{\text{RAP}}\) is the number of repetitions for RAP. For NPRACH in NB-IoT, \(t_{\text{RASym}}\) is equal to 266.7 µs (3.75 kHz subcarrier spacing), \(t_{\text{format}}^{\text{RAP}}\) is equal to 66.7 µs for format 0 and 266.7 µs for format 1. The specific value of \(t_{\text{format}}^{\text{RAP}}\) can be referred to Table 5.7.1-1 in [24], e.g., 0.903 ms for format 1.

B. RX State

In RX state, the UE is receiving data in the downlink. From the measurement, it is observed that the RX state is characterized by periods of reception interleaved by reception gaps. LTE-M and NB-IoT have a similar downlink channel, and can be modelled in a similar way. The estimated energy consumption of the RX state with a downlink packet of size \(k\) in bits can be calculated as:

\[
E_{\text{RX}}(k) = P_{\text{RX}} \cdot t_{\text{RX}}(k) + P_{\text{gaps}}^{\text{RX}} \cdot t_{\text{gaps}}^{\text{RX}}(t_{\text{RX}}) \tag{13}
\]

\[
t_{\text{RX}}(k) = t_{\text{SF}} \cdot \rho_{\text{SF}} \cdot N_{\text{SF}} \cdot l(k) \tag{14}
\]

\[
l(k) = \left[ \frac{k}{TBS(MCS, \rho_{\text{SF}})} - h \right] \tag{15}
\]

where \(t_{\text{RX}}\) and \(P_{\text{RX}}\) indicate the time spent and the power consumption in data reception respectively, \(t_{\text{gaps}}^{\text{RX}}\) and \(P_{\text{gaps}}^{\text{RX}}\) indicate the time spent and the power consumption in reception gaps respectively, \(t_{\text{SF}}\) is the length of a subframe which is 1 ms in both NB-IoT and LTE-M, \(\rho_{\text{SF}}\) is the number of allocated SFs, \(N_{\text{SF}}\) is the number of repetitions, \(l\) is the number of segments, and \(h\) is the header size.

Reception gaps are introduced in the downlink channel because of the reception of System Information Block (SIB) and other control signalling [23], [24]. Similar to the TX state, the power consumption is much lower during the reception gaps as compared to the power consumption during data reception. Also the power consumption in RX state is MCS independent. Different from the TX model where the transmission gaps follow a clear pattern, it is not straightforward to accurately model the reception gaps in RX state because they are dependent on the length of the reception as well as its starting position. Instead, the number of reception gaps during a data reception is estimated. The time spent in reception gaps is dependent on \(t_{\text{RX}}\) and can be calculated as:

\[
t_{\text{gaps}}^{\text{RX}}(t_{\text{RX}}) = \left[ t_{\text{RX}} \cdot \left( \frac{1}{M_{\text{SF}}^{\text{RX}}} - 1 \right) \right] \tag{16}
\]

where \(M_{\text{SF}}^{\text{RX}}\) is the fraction of subframes available for data reception. To simplify the model, only the most recurring gaps such as Narrowband Primary Synchronization Signal, Narrowband Secondary Synchronization Signal, Master Information Block, and SIB1 are taken into account when modelling the RX state, resulting in roughly 14 subframes out of 20 subframes are available for downlink data reception (\(M_{\text{SF}}^{\text{RX}} = 14/20\)) [24], [25].

C. ECM Connected State

A UE that is not transmitting or receiving data in the ECM_CONNECTED state must monitor the network for paging or uplink scheduling grants in the form of Downlink Control Information (DCI). This can happen in default or cDRX mode, as described in the following.

1) Default mode: By default the UE monitors the UE specific Search Space (USS) in Physical Downlink Control Channel (PDCCH) for LTE-M or in Narrowband Physical Downlink Control Channel (NPDCCH) for NB-IoT continuously for relevant DCI, i.e., paging and uplink grants. The USS must be monitored periodically and the UE will go into sleep for the rest of the time. The time duration for the USS monitoring in each cycle is given by:

\[
t_{\text{monitoring}}^{\text{USS}} = M_{\text{USS}} \cdot t_{\text{SF}} \cdot N_{\text{USS}} \tag{17}
\]

where \(M_{\text{USS}}\) is the number of subframes that the UE has to monitor in PDCCH or NPDCCH, and \(N_{\text{USS}}\) is the number of repetitions for USS.

The estimated energy spent in each cycle using default USS monitoring in the ECM_CONNECTED state can be calculated as:

\[
E_{\text{cycle}}^{\text{ECMC}} = E_{\text{monitoring}}^{\text{USS}} + P_{\text{sleep}}^{\text{USS}} \cdot t_{\text{sleep}}^{\text{USS}} \tag{18}
\]

where \(E_{\text{monitoring}}^{\text{USS}}\) is the energy consumption for USS monitoring which can be obtained using Eqs. (13) and (16) with \(t_{\text{monitoring}}^{\text{USS}}\) as input.

2) cDRX: DRX allows the UE to monitor the relevant USS discontinuously to improve the energy efficiency. While iDRX operates in the ECM_IDLE state, cDRX operates in the ECM_CONNECTED state. In connected state the UE does not perform paging, but rather monitors the PDCCH or NPDCCH.
cDRX essentially provides a way for the network and the UE to synchronize the timing of potential downlink data. It narrows down the USS window, which enables the UE to sleep for much longer periods. The UE notifies the network of its non-mandatory DRX capabilities through RRC messaging and the network transmits the DRX configuration as part of the RRC configuration.

The synchronization between the network and UE in DRX mode is controlled by the LongDRX-cycle and the OnDuration timer [25]. The OnDuration timer sets the number of consecutive PDCCH subframes that the UE has to monitor for DCI. The value of the OnDuration timer can be set up to 200 ms. The time that the UE has to monitor for DCI in the OnDuration is given by:

$$t_{\text{onDur}} = M_{\text{onDur}} \cdot t_{\text{SF}}$$

(19)

Assuming that the OnDuration timer stays constant during the UE’s lifetime, the energy consumption of the cDRX can be calculated as:

$$E_{\text{cDRX}} = E_{\text{onDur}} + P_{\text{sleep}}^{\text{cDRX}} \cdot t_{\text{sleep}}^{\text{cDRX}}$$

(20)

$$t_{\text{sleep}}^{\text{cDRX}} = (M_{\text{LongDRX}} - M_{\text{onDur}}) \cdot t_{\text{SF}}$$

(21)

where $M_{\text{LongDRX}}$ and $M_{\text{onDur}}$ are the number of subframes of a cDRX LongDRX-cycle and the number of subframes the UE has to monitor for DCI in the OnDuration respectively. $P_{\text{sleep}}^{\text{cDRX}}$ is the power consumption when the UE is in cDRX sleep mode, and $E_{\text{onDur}}$ is the energy consumption in the OnDuration which can be calculated using Eqs. (13) and (16) with $t_{\text{onDur}}^{\text{cDRX}}$ as input. It is worth mentioning that the inactivity timer which triggers the UE to enter into the cDRX state is neglected here, because in most cases the UE is not expected to frequently alternate between RX and cDRX as it is taxing for the battery.

**D. ECM Idle State**

A UE in the ECM_IDLE state must monitor the network for paging for relevant DCI. Several energy saving modes are available.

1) Default mode: By default the UE monitors the USS in PDCCH or NPDCCCH continuously for paging. The energy consumption in the ECM_IDLE state operating in default mode is similar to the approach described in Section IV-C1.

2) iDRX: DRX was introduced in release 8 to save the energy consumption of a device by introducing the DRX cycle, during which the UE alternates between active monitoring of the paging and sleep [26]. During the active period, the UE first gets synchronized with the network, then it monitors the paging. The number of paging occurrences the UE has to monitor is indicated by the paging repetitions [25]. When the UE has finished listening to the paging, it goes into sleep. The duration of a DRX cycle is given by the network parameter defaultPagingCycle in number of radio frames.

The energy consumption of the iDRX can be calculated as:

$$E_{\text{iDRX}} = E_{\text{sync}} + E_{\text{sleep}} + N_{\text{paging}} \cdot E_{\text{Sleep}}^{\text{iDRX}} + t_{\text{sleep}}^{\text{iDRX}}$$

(22)

$$t_{\text{sleep}}^{\text{iDRX}} = \left( t_{\text{cycle}}^{\text{iDRX}} - t_{\text{onDur}}^{\text{iDRX}} + t_{\text{sync}}^{\text{iDRX}} \right)$$

(23)

where $E_{\text{sync}}$, $E_{\text{sleep}}$, $t_{\text{cycle}}^{\text{iDRX}}$, $t_{\text{onDur}}^{\text{iDRX}}$, and $t_{\text{sync}}^{\text{iDRX}}$ are the time and power consumption for synchronizing in an iDRX cycle, $t_{\text{sleep}}^{\text{iDRX}}$ is the time spent on monitoring the paging in an iDRX cycle, and $t_{\text{cycle}}^{\text{iDRX}}$ is the length of an iDRX cycle.

3) eDRX: eDRX is an extension of the DRX with the objective to further reduce the energy consumption. It is mainly used in IoT applications operating with energy saving mode. The basic principle of eDRX is to extend DRX cycle length to allow a device to remain in sleep mode for longer period of time, thus reducing the energy consumption. Furthermore, the length of an eDRX cycle can be set by the device rather than the network, which provides the application developers with more flexibility to better balance the device’s reachability and its energy consumption. An eDRX cycle can be decomposed into two parts: the Paging Time Window (PTW) period and the sleep period. During the PTW period, the UE behaves similarly as being in iDRX state with several iDRX cycles. The number of iDRX cycles is determined by the PTW length and the iDRX cycle length. The UE remains dormant during the sleep period, the duration of which can be calculated based on the PTW length and the eDRX cycle length.

The energy consumption of the eDRX can be calculated as:

$$E_{\text{eDRX}} = \left[ \frac{T_{\text{PTW}}}{t_{\text{cycle}}^{\text{eDRX}}} \right] \cdot E_{\text{cycle}}^{\text{eDRX}} + t_{\text{sleep}}^{\text{eDRX}} \cdot P_{\text{sleep}}^{\text{eDRX}}$$

(24)

$$t_{\text{sleep}}^{\text{eDRX}} = t_{\text{cycle}}^{\text{eDRX}} - T_{\text{PTW}}$$

(25)

where $t_{\text{sleep}}^{\text{eDRX}}$ and $P_{\text{sleep}}^{\text{eDRX}}$ are the time and power consumption during the eDRX sleep period respectively, $T_{\text{PTW}}$ is the PTW length, $t_{\text{cycle}}^{\text{eDRX}}$ is the length of a eDRX cycle, and $E_{\text{cycle}}^{\text{eDRX}}$ is the energy spent in an iDRX cycle.

4) PSM: PSM is another power saving feature for NB-IoT and LTE-M. In PSM the UE alternates between a deep sleep state and a period when the UE is reachable by the network. There are two main timers associated with PSM: $T_{3324}$ and $T_{3412}$. The $T_{3324}$ timer determines the period when the UE is reachable, during which the UE can be operating either with iDRX or eDRX. The energy consumption model of iDRX and eDRX derived above can be reused within the period of $T_{3324}$. The UE will shut down all Access Stratum functions and go into deep sleep upon the expiration of the $T_{3324}$ timer. The UE remains in deep sleep until the $T_{3412}$ timer expires, after which the UE will perform a TAU procedure. It is observed from measurements that the TAU procedure can be energy expensive. From an energy consumption point of view, it is better to configure the TAU periodicity (i.e., $T_{3412}$) long enough to reduce the number of TAU occurrences, while still meeting the service requirements of its use case.

The energy consumption of PSM with iDRX can be calculated as:

$$E_{\text{PSM}} = \left[ \frac{T_{3324}}{t_{\text{cycle}}^{\text{iDRX}}} \right] \cdot E_{\text{cycle}}^{\text{iDRX}} + t_{\text{sleep}}^{\text{PSM}} \cdot P_{\text{sleep}}^{\text{PSM}}$$

(26)

$$t_{\text{sleep}}^{\text{PSM}} = T_{3412} - T_{3324}$$

(27)

where $P_{\text{sleep}}^{\text{PSM}}$ is the power consumption during sleep period. When using eDRX the terms $E_{\text{cycle}}^{\text{eDRX}}$ and $t_{\text{cycle}}^{\text{eDRX}}$ should be
replaced with the eDRX equivalent. The TAU procedure is not included here, but will be modelled separately in Section V.

It is observed from the measurements that the power consumption during sleep period in PSM is lower than DRX or eDRX, as the device turns off the radio. The disadvantage is that the device has to reconnect to the network when wakes up, which is energy expensive. Therefore for IoT applications not requiring frequent transmit, PSM is more energy efficient.

E. Key Parameters of States

From the previous subsections, it is noticed that the calculation of the energy consumption in each UE state for LTE-M and NB-IoT is similar to each other, as both technologies are developed based on LTE and share a lot of similarities. The main differences in the calculation of energy consumption are in the TX and RX states. Specifically, for TX state the uplink resources in LTE-M are allocated in terms of PRBs with 1 ms time resolution (subframe length). While in NB-IoT the uplink resources are allocated in terms of RU’s with different lengths depending on the transmission option. For RX state, the downlink resources are allocated in terms of PRBs with 1 ms time resolution for both LTE-M and NB-IoT. But NB-IoT only supports 1 PRB resource allocation in downlink, while the default resource allocation for LTE-M is 6 PRBs in downlink. Besides, different number of repetitions are supported in LTE-M and NB-IoT. These differences in the resource allocation and the number of repetitions effectively affect the required TX and RX time, resulting in different data rates and energy consumption between the two technologies. The key parameters for the calculation of the energy consumption in each UE state are summarized in Table III, including physical layer transmission parameters and network configuration parameters.

| UEs State | Key Parameters |
|-----------|---------------|
| TX        | Payload size, TX power, MCS, Repetitions, allocated RUs (NB-IoT), allocated PRBs (LTE-M), RU length (NB-IoT), Subframe length (LTE-M) |
| RX        | Payload size, MCS, allocated PRBs, Repetitions, Subframe length |
| iDRX      | iDRX Cycle, OnDurationTimer, Paging Repetitions |
| eDRX      | eDRX Cycle, OnDurationTimer |
| PSM       | $T_{3234}$, $T_{4412}$ |

TABLE III: Key parameters for the calculation of energy consumption in each UE state

It is of great importance to properly configure these parameters not only to ensure a good link performance such as radio coverage and throughput, but also to save UE energy consumption while satisfying the service requirements. The general guideline on how to configure the physical transmission parameters in the TX state, which is the most energy consuming state, is detailed in Section VI-A. The analysis of some of the important network configuration parameters which impact the UE’s battery lifetime effectively, such as TAU periodicity ($T_{4412}$ timer), is discussed in Section VII.

V. ENERGY CONSUMPTION OF UE PROCEDURES

The transition among the UE states is dictated by higher layer protocol procedures. The main procedures in NB-IoT and LTE-M are similar to each other and have been introduced in Section III-B. Each procedure can be decomposed into a sequence of uplink and downlink message exchanges. By combining the associated TX (uplink transmission) and RX (downlink reception) state model together with the corresponding message size, the energy consumption in each procedure can be calculated.

A. Message Exchange in Different Procedures

The synchronization procedure is not explicitly modeled in this paper because it varies from device to device and is heavily dependent on the implementation. Instead, the energy and time consumption for the synchronization of a specific device is obtained from measurement. The measurement starts from the beginning of synchronization and ends before the occurrence of the first PRACH.

The measured message exchanges and the corresponding message size for the Attach, Service Request, RRC Release/Resume, and TAU procedures are listed in Tables IV to VII, recorded from a specific NB-IoT device N211 and an LTE-M device R410M. These two devices are the ones considered for measurements and the validation. A general description of these two devices are given in Section VII.

The measured message sequence is in accordance with the protocol specifications defined in [25]. From the measurements it is observed that the size of the message might be device and network dependent, as the implementation of the protocol is device specific and some messages are dependent on the configuration of the network. It is also worth mentioning that the user data can be transmitted within the services request by using the CIoT EPS Optimization, thereby reducing the signalling overhead by skipping the EPS bearers establishment [12].

There are delays during the communication between the eNB and the UE for postprocessing of the received information and preparation for the next transmission. These delays should also be taken into consideration in the calculation of the energy
TABLE V: Message exchange in the **Service Request** procedure, measured from N211 (NB-IoT) and R410M (LTE-M).

| Messages                      | NB-IoT | LTE-M | Direction |
|-------------------------------|--------|-------|-----------|
| Random Access Preamble        | RAP    | RAP   | uplink    |
| Random Access Response        | 104 bit| 66 bit| downlink  |
| RRC Connection Request        | 88 bit | 72 bit| uplink    |
| RRC Connection Setup          | 144 bit| 336 bit| downlink |
| RRC Connection Complete       | 424 bit| 650 bit| uplink   |
| Service Accept + UL data      | 56 bit | N/A   | uplink    |
| Service Accept                | 176 bit| N/A   | downlink  |
| Service Accept ACK            | 32 bit | N/A   | uplink    |
| RRC Reconfig                  | 72 bit | N/A   | downlink  |
| RRC Reconfig Complete         | 18 bit | N/A   | uplink    |
| Total Uplink                  | 616 bit| 728 bit|          |
| Total Downlink                | 496 bit| 392 bit|          |

TABLE VI: Message exchange in the **RRC Release/Resume** procedure, measured from N211 (NB-IoT) and R410M (LTE-M).

| Messages | NB-IoT | LTE-M | Direction |
|----------|--------|-------|-----------|
| RRC Release | 72 bit | 86 bit| downlink  |
| RRC Resume  | 72 bit | 90 bit| downlink  |
| ACK       | 32 bit | 32 bit| uplink    |

B. Energy Consumption in the Procedure

For each procedure, the number of exchanged messages and the corresponding message size are required to calculate the energy consumption. That information can be obtained for example from measurements as listed in Tables IV to VII. The energy consumption in each procedure can be calculated as the sum of the energy cost of the exchanged messages and the energy cost of the delays between the message exchange, given as:

\[ E_{\text{Proced}} = \sum_{i=1}^{I} \left( E_{\text{Msg}}(d_i) + E_{\text{DCI}}(t_{\text{delay}}) \right) + P_{\text{delay}} \cdot \sum_{i=1}^{I-1} t_{\text{delay}}^i \]  

where \( I \) is the total number of exchanged messages in the procedure excluding DCIs, \( E_{\text{Msg}}(d_i) \) is the energy cost of transmitting (uplink) or receiving (downlink) message \( i \) with payload size \( d_i \) in bits, \( E_{\text{DCI}}(t_{\text{delay}}) \) the energy cost of receiving the \( i \)th DCI, \( P_{\text{delay}} \) is the power consumption during the delay, and \( t_{\text{delay}}^i \) is the delay between message \( i \) and \( i+1 \).

\( E_{\text{Msg}}(d_i) \) can be calculated based on the message type (e.g., uplink or downlink) by using the corresponding TX and RX state model described in Section IV. \( t_{\text{delay}} \) can be obtained from Table VIII. From the measurements it is observed that \( P_{\text{delay}} \) is device and technology dependent. Specifically, it is equivalent to the RX state in R410M (LTE-M), while it is equivalent to the cDRX idle state in N211 (NB-IoT).

In NB-IoT the energy consumption of signalling overhead is negligible as it is much smaller compared to data transmissions. In LTE-M, the energy consumption in the waiting time between the signalling messages can be costly, for example the delay between the two Scheduling Request (SR) in LTE-M is observed with 40 ms interval.

TABLE VII: Message exchange in the **TAU** procedure, measured from N211 (NB-IoT) and R410M (LTE-M).

| Delay Type                      | N211 | R410M |
|---------------------------------|------|-------|
| RAP (TX) → DCI (RX)             | 3 ms | 1 ms  |
| DCI (RX) → RAR (RX)             | 4 ms | 1 ms  |
| RAR (RX) → RRC Request (TX)     | 8 ms | 1 ms  |
| RRC Request (TX) → DCI (RX)     | 3 ms | 1 ms  |
| DCI (RX) → RRC Setup (RX)       | 4 ms | 1 ms  |
| RRC Setup (RX) → DCI (RX)       | 12 ms| 1 ms  |
| DCI (RX) → RRC Setup Complete (TX)| 8 ms| 1 ms  |
| RRC Setup Complete (TX) → DCI (RX)| 3 ms| 1 ms  |
| DCI (RX) → Service Accept (TX)  | 4 ms | 1 ms  |
| Service Accept (TX) → DCI (RX)  | 12 ms| 1 ms  |
| DCI (RX) → Data (RX)            | 4 ms | 3 ms  |
| DCI (RX) → Data (TX)            | 8 ms | 3 ms  |
| Data (RX) → DCI (RX)            | 12 ms| 3 ms  |
| Data (TX) → DCI (RX)            | 3 ms | 1 ms  |
| DCI (RX) → SI-Release           | 4 ms | 1 ms  |
| SR → SR                        | N/A  | 40 ms |
| SR → DCI (RX)                   | N/A  | 3 ms  |

TABLE VIII: The delays between different message exchanges, measured from N211 (NB-IoT) and R410M (LTE-M).

VI. BATTERY LIFETIME ESTIMATION

The calculation of the energy consumption of each UE state and procedure is derived in Section IV and V, respectively. By combining different components of UE states and procedures, the energy consumption of any UE behaviour can be calculated. The other two prerequisites required to estimate the battery lifetime of an IoT device are the coverage scenario which determines the physical transmission parameters, and the traffic profile which defines the traffic characteristics of an IoT application.

A. Coverage Scenario

The actual calculation of the proposed power consumption model is tightly associated with the configuration of physical layer transmission parameters such as MCS, the number of allocated RUs/PRBs, and the number of repetitions, which further depends on the coverage level of the UE.

To allow the UE to be served in different coverage conditions characterized by different path loss, 3GPP Release 13 has defined three CE levels: CE level 0 (normal coverage with MCL≈144 dB), CE level 1 (robust coverage with MCL≈154 dB), and CE level 2 (extreme coverage with MCL≈164 dB). The CE level is selected based on the channel conditions, and determines the physical layer transmission parameters.
In our measurement, three coverage scenarios, namely "Good", "Bad", and "Extreme", have been defined corresponding to a coupling loss of 140 dB, 150 dB, and 160 dB, respectively. Those values are derived based on the link budget calculations with configured uplink transmission parameters. Specifically, the allocated bandwidth in uplink is restricted to a single PRB for LTE-M and a single subcarrier of 15 kHz for NB-IoT. The receiver noise figure is assumed to be 5 dB and the thermal noise density is 174 dBA/Hz. The UE’s maximum transmission power is 23 dBm. Based on these assumptions, the estimated Signal to Noise Ratio (SNR) without using repetitions for the good, bad, and extreme coverage scenarios are 10.24 dB, 0.24 dB and -9.76 dB for NB-IoT, and -0.55 dB, -10.55 dB and -20.55 dB for LTE-M [21]. When blind repetition with chase combining is used in Hybrid Automatic Repeat Request, the effective received SNR in linear scale after combining assuming infinite Transport Block Size can be calculated as [27]:

$$SNR_{combined} = N \cdot SNR_{RX}$$  \hspace{1cm} (29)

where $N$ is the number of repetitions. The number of repetitions in uplink can reach up to 128 for NB-IoT. In our analysis, the maximum number of repetitions is limited to 32 for realistic scenarios.

Once the received SNR is calculated for each coverage scenario, the physical layer transmission parameters such as MCS is selected for a target Block Error Rate (BLER). For LTE systems, the target BLER is set to 10% for data channels. The mapping between SNR and MCS for a target BLER can be found either from link level performance curves or from analytical approximations.

Based on the link budget analysis mentioned above, the considered uplink physical layer transmission configurations for the three coverage scenarios for NB-IoT and LTE-M are listed in Table IX. In order to make a fair comparison between NB-IoT and LTE-M, the physical layer transmission parameters are configured for each technology targeted for a similar coupling loss. The configuration for LTE-M in the extreme scenario is left blank as it can not reach the area with 160 dB coupling loss.

| Parameters | NB-IoT Good | Bad | Extreme | LTE-M Good | Bad | Extreme |
|------------|-------------|-----|---------|------------|-----|---------|
| MCL [dB]   | 140         | 150 | 160     | 140        | 150 | 160     |
| MCS        | 10          | 2   | 32      | 5          | 0   | -       |
| Repetitions| 1           | 8   | 32      | 2          | 16  | -       |

TABLE IX: Considered uplink transmission configurations for NB-IoT and LTE-M in different coverage scenarios.

B. Traffic Profile

The traffic profile defines how often the UE transmits/receives data and how big the transmitted/received data is. It has a big impact on the battery lifetime of a device. The IoT use cases and traffic patterns associated with some of the verticals have been defined in [28], which indicates that most of the IoT traffic is uplink dominated with periodic traffic pattern. Therefore in this study, a deterministic uplink traffic model is used, assuming that the UE transmits $B$ Bytes of uplink payload towards the eNB periodically at an average rate of $\lambda$ transmissions per hour.

A transmit cycle is defined as the time interval between the start of a data transmission to the time instance right before the start of the next data transmission. The UE will go through certain procedures in a transmit cycle to establish and release a connection. An example of uplink UE transmit cycle that starts and ends in a power saving state is illustrated in Fig. 3. Upon waking up from PSM, the UE first synchronizes to the network, then performs a service request together with uplink data transmission. After that the UE stays in the cDRX state for certain time until the release procedure is initiated by the network. Then the UE enters the power saving mode until the next uplink transmission is initiated or paging indicates a downlink transmission. In Fig. 3 it is assumed that the UE is in EMM_REGISTERED state. If the UE is in EMM_DEREGISTERED state, e.g., the UE is powered up for the first time, the attach procedure is initiated instead of the service request procedure.

C. Battery Lifetime Modelling

Once the energy consumption for each UE state and procedure has been determined, the physical layer transmission parameters have been set according to certain coverage scenario, and the traffic profile has been defined, the energy consumption of an IoT device can be calculated and the corresponding battery lifetime can be estimated.

The energy consumption of the modem during a transmit cycle depicted in Fig. 3 with a payload size of $B$ Bytes can be calculated as:

$$E_{cycle}(B) = E_{Sync} + E_{SR} + E_{cDRX} + E_{Release} + E_{PSM/eDRX}$$  \hspace{1cm} (30)

where $E_{Sync}$, $E_{SR}$, and $E_{Release}$ are the energy consumption in the synchronization, service request, and RRC release procedures respectively, which can be obtained using Eq. (28). $E_{cDRX}$ and $E_{PSM/eDRX}$ are the energy consumption when the UE is in cDRX state and iDRX state using either PSM or eDRX respectively, which can be obtained following the energy consumption approach described in Section IV-C and Section IV-D.

Let $\lambda$ denote the average transmission rate per hour. The average energy consumption of the modem during one hour can be calculated as:

$$E_{hour}(\lambda, B) = E_{cycle}(B) \cdot \lambda$$  \hspace{1cm} (31)
The estimated battery lifetime (in hours) of an IoT device can be calculated as:

\[ L(\lambda, B) = \frac{C_{\text{bat}} \cdot SF_{\text{bat}}}{E_{\text{hour}}(\lambda, B) + E_{\text{device}}} \]  

(32)

where \(C_{\text{bat}}\) is the battery capacity in [Wh], \(SF_{\text{bat}}\) is the battery safety factor accounting for self-discharge effect, and \(E_{\text{device}}\) is the sensor circuitry average energy consumption per hour, i.e. the energy consumption besides the modem.

VII. MEASUREMENTS AND VALIDATION

A testbed has been developed to validate the proposed power consumption model as well as to estimate the battery lifetime of an IoT device.

A. Measurement Setup

The power consumption of two commercial device-under-test (DUT)s have been measured, namely U-Blox EVK-N211 and U-Blox EVK-R410M. The N211 is an NB-IoT device, while R410M can be connected to both NB-IoT and LTE-M networks.

The measurement setup is depicted in Fig. 4. The DUT’s antenna port is connected via cables to a Keysight E7515A UXM Wireless Test Set, which is a standard-compliant base station emulator supporting both Release 14 NB-IoT and LTE-M features with debugging capabilities. The DUT is also connected to a Keysight N6705B DC Power Analyzer which acts as both a power supply and a sensor for battery drain measurements. The measurement setup is controlled by Keysight’s Test Automation Platform (TAP), which provides interfaces to both the measurement equipments and the DUT, and orchestrates the behaviour of different components by using TAP test plans. The measurement setup is capable of synchronizing the network logs and power consumption measurements with \(\leq 1\) ms accuracy. This allows for in-depth analysis of measurements to quantify the power consumption.

Table X: The measured power consumption of N211 and R410M in different states.

B. Characterization of the Modem

The analytical energy consumption model for each UE state described in Section IV depends on the inputs of the modem characterization information such as the UE power level in different states, e.g., \(P_{\text{TX}}, P_{\text{RX}}, P_{\text{sleep}}, P_{\text{eDRX}}, P_{\text{cDRX}}, P_{\text{PSM}}\), etc. Therefore it is important to accurately characterize the power consumption of the modem so that the derived energy consumption model can work correctly. A test case has been executed for each UE state. From each measurement, only the power or energy consumption related to the target UE state is extracted and averaged over certain period. The measured power or energy consumption of N211 and R410M in different states are summarized in Table X, which serves as inputs to the equations in Section IV. Typically this modem characterization information is available from the vendors.

It is observed from the measurements that the power or energy consumption of R410M is higher than N211 in most of the states, regardless of whether it is operating in NB-IoT or LTE-M mode, which is not surprising as the power consumption of a device is implementation specific. In particular, the measured power consumption of the two devices in the TX state as a function of uplink transmission power is plotted in Fig. 5. It can be seen that the power consumption curve can be split into two parts. The first part is when the power amplifier is not required, resulting in almost linear increase of the power consumption. The second part is when the power amplifier is used. In this case, the power consumption increases exponentially, which is due to the fact that the efficiency of the power amplifier decreases with the increase of the output power. Similar trend is observed for both devices, but the power consumption of R410M is higher than N211 when the uplink transmission power is larger than \(-8\) dBm. This difference is much more visible when the uplink transmission power becomes higher.

C. Model Validation

To validate the accuracy of the proposed power consumption model, extensive measurement campaigns have been executed on both NB-IoT device N211 and LTE-M device R410M with different configurations. Both short (with periodic transmit cycle of 1 hour) and long (with periodic transmit cycle of
24 hours) measurements have been performed with a fixed payload size of 100 Bytes. The $T_{3324}$ and $T_{3412}$ timers are used in PSM, which is applied due to its relatively low power consumption during the sleep period as compared to eDRX. The setting of the $T_{3324}$ timer has a tradeoff between low energy consumption and low response time to the application server. It is recommended by GSM Association (GSMA) that the $T_{3324}$ timer should best fit the IoT use case, and the ratio between $T_{3324}$ Active Timer and $T_{3412}$ Extended Timer, calculated as $(T_{3412} - T_{3324})/T_{3412}$, should be > 90% in order to achieve optimum battery savings [29]. In our measurement, the $T_{3324}$ timer is set to be 60 seconds, and the $T_{3412}$ timer for the TAU periodicity is configured to be 2 hours which indicates that the TAU procedure is not included in the short measurement, but is included in the long measurement. The battery capacity is set to be 5 Wh, assuming an ideal case without the self-discharge effect. Since the focus of this work is on the power consumption modelling of the modem, the power consumption of the sensor circuitry is not taken into account, which means that all of the available battery capacity is allocated to the modem. The available MCS index ranges from 0 to 10, and the number of repetitions for data channels ranges from 1 to 16, with different combinations between the two parameters. An example of the configured MCS index and repetition number for different scenarios are listed in Table IX.

All measurements are performed in LTE band 20 (∼ 806 MHz). For NB-IoT, a single tone with 15 kHz spacing is allocated in uplink and a single PRB is allocated in downlink. For LTE-M, a single PRB is allocated in uplink and 6 PRBs are allocated in downlink. The number of allocated RU/SF is set to be 5 for both NB-IoT and LTE-M. The measurement settings used for model validation and battery lifetime estimation are summarized in Table XI.

Fig. 5 shows the measured and estimated energy consumption per transmit cycle (i.e. 1 hour and 24 hours) for both NB-IoT device N211 and LTE-M device R410M with different configurations. If we compare the energy consumption between the two devices, it is shown clearly that the R410M consumes more energy as compared to N211, due to the reason that the energy consumption in each state is higher in R410M than in N211 as shown in Table X. If we compare the energy consumption of the same device but with different configurations, it can be seen that the energy consumption decreases as the MCS index increases. Though not shown in the paper, it is found from the measurements that the average power consumption is independent of MCS for both uplink and downlink. However, for a fixed payload size and TX bandwidth, the selection of MCS affects the number of allocated RU/SFs/subframes (i.e., transmission time), which means that for lower MCS the UE has to stay in the TX state for longer time, resulting in higher energy consumption. Also it is shown clearly that increasing the number of repetitions would increase the total energy consumption as expected.

Fig. 6 clearly demonstrates that the proposed power consumption model matches very well with the measurement results for the selected two devices, regardless of different configurations of transit cycles and transmission parameters. The measured estimation error is within 5% in all cases.
D. Battery Lifetime Estimation

Next we apply Eqn. (32) to estimate the battery lifetime with different configurations of traffic profiles, coverage scenarios (i.e., good, bad, and extreme defined in Table IX), and network parameters. The same parameter settings listed in Table XI are used for the battery lifetime estimation.

Fig. 7 and Fig. 8 show the estimated battery lifetime for NB-IoT device N211 versus different payload size and transmit cycles with different coverage scenarios and $T_{3412}$ timer settings, respectively. Reduce the payload size and/or increase the transmit cycle length would result in a longer battery lifetime in all scenarios as expected. Also it is clearly shown that the coverage scenario, which determines the PHY transmission parameters, has a great impact on the battery lifetime. Note that in Fig. 8, there is a turning point where the transmit cycle equals the $T_{3412}$ timer. This is because when the transmit cycle is longer than the $T_{3412}$ timer (i.e. TAU periodicity), the TAU procedure will occur which consumes additional energy. When the transmit cycle is much longer than the TAU periodicity, the performing of the TAU procedure can be energy expensive and will dominate the total energy consumption. That explains why in the extreme scenario in Fig. 8, the battery lifetime does not increase very much with the increase of the transmit cycle. Increasing the TAU periodicity will decrease the total energy consumption within one transmit cycle, as the occurrence of TAU decreases, resulting in an increase of the battery lifetime as shown in Fig. 7 and Fig. 8.

The estimated battery lifetime for LTE-M device R410M versus different payloads and transmit cycles with different coverage scenarios and $T_{3412}$ timers is plotted in Fig. 9. Similar behaviour has been observed in R410M as compared to N211.

Fig. 10 shows the energy consumption in different procedures and states during one transmit cycle (12 hours) for NB-IoT device N211 under different scenarios and $T_{3412}$ timer settings, assuming the payload size to be 100 Bytes. Using lower MCS index and higher number of repetitions (e.g., the bad scenario) will cause higher energy consumption as compared to the good scenario, because of the increase in the uplink transmission time. It is shown in the figure that the $T_{3412}$ timer has no effect on the energy consumption on the service request, uplink data transmission, RRC inactivity and release procedures, but has big impact on the TAU and PSM. Increasing the $T_{3412}$ timer would not only decrease the energy consumption in the TAU procedure, but also in the PSM procedure, because the $T_{3412}$ timer determines the period when the device is in sleep mode.

A comparison between the proposed energy consumption model and the model proposed in [11] is depicted in Fig. 11 with different transmit cycles and $T_{3412}$ timer, assuming in scenario good and a payload size of 100 Bytes. There are similarities between the two models in modelling the energy consumption of the UE states and behaviors, e.g., transmitting/receiving packets or signaling. The difference is that the calculation of the total energy consumption in our proposed model is based on the composition of the associated UE procedures according to the desired UE behavior, while the calculation in [11] relies on the Markov chain analysis. The other main difference between the two models is that the TAU procedure is included in our model while it is not considered in [11]. It can be seen from Fig. 11 that the two models matches quite well when there is no TAU. However, the difference is much obvious when the TAU procedure occurred. From the measurement it is observed that the occurrence of the TAU procedure can be energy expensive and therefore should be carefully configured (i.e., $T_{3412}$ timer) by the network operator.

Fig. 12 shows the estimated battery lifetime for both the NB-IoT device N211 and the LTE-M device R410M under different transmit cycles and coverage scenarios, assuming the payload size to be 100 Bytes and $T_{3412}$ timer to be 4 hours. The curve for the LTE-M device R410M in the extreme scenario is missing as LTE-M can not reach the area with 160 dB coupling loss. The estimated battery lifetime of N211 is longer than
R410M, due to the lower energy or power cost of N211 in each state as compared to R410M. When the transmit cycle is \( \geq 24 \) hours, the battery lifetime for NB-IoT device N211 can reach up to 10 years, satisfying the 10-year battery lifetime requirement specified by 3GPP.

### E. Discussions and Future Work

It should be noted that the battery lifetime comparison shown in Fig. 12 is only based on the two specific NB-IoT and LTE-M devices. The comparison between those two devices can not be generalized to a conclusion that the NB-IoT device can last for longer time than the LTE-M device, as the energy footprint of a device is implementation specific. However, the proposed energy consumption model and the battery lifetime estimation method can be generalized to all devices operating with either NB-IoT or LTE-M. In order to apply the proposed model for a new NB-IoT or LTE-M device, one has to measure and characterize the power consumption in each state of that specific device, as listed in Table X. Typically this modem characterization information is provided by the vendors.

From Fig. 7 and Fig. 8, it is shown that the battery lifetime of a device not only depends on the power consumption of the device in each state, but also depends on the traffic profile, the coverage scenario, as well as the network configuration parameters. While an IoT application developer can adjust the frequency and size of the payload data to be sent towards the server, the coverage and network configuration parameters including power saving parameters are normally set by the network operators. It is found during the study that some of the network configuration parameters, such as the \( T_{3412} \) timer which determines the TAU periodicity, have a great
impact on the energy efficiency. Increasing the $T_{3412}$ timer can decrease the energy consumption due to fewer occurrence of the TAU procedure and the increased sleep time, at the expense of longer response time. A minimum setting of 240 minutes for the $T_{3412}$ timer is recommended by GSMA [29]. As a general guideline, it is of crucial importance not only for the IoT application developer to carefully select the traffic parameters that best tradeoff between energy efficiency and performance metric, but also for the network operators to fine tune the coverage and the network parameters to ensure a long battery lifetime. With proper configuration of these parameters, the battery lifetime of an IoT device can last for 10 years as required by 3GPP.

This paper only considers the energy consumption model for NB-IoT and LTE-M. Other LPWAN technologies such as Sigfox and LoRa could also be interesting to model and compare with NB-IoT and LTE-M. In addition, only the power consumption model for the modem is considered in this paper. Other hardware such as the sensors, the actuators and the processor also need to be taken into account when estimating the battery lifetime. For the traffic model, only deterministic traffic with periodic transmission is assumed. Other traffic models such as non-deterministic traffic are also of interest. Furthermore, for accurate estimation of the battery lifetime, the capacity leakage of the battery should also be taken into account instead of assuming an ideal battery without capacity leakage. Those could be the future work for modelling the energy consumption of LPWAN IoT devices.

VIII. Conclusion

This paper presented a comprehensive energy consumption model for IoT device battery lifetime estimation, focusing on 3GPP standardized LPWAN technologies NB-IoT and LTE-M. We start with the introduction of the UE states and procedures, followed by the detailed energy consumption modelling for each UE state and the main procedures. By composing the associated UE states and procedures, the energy consumption of any UE behaviour can be calculated. Besides, a traffic profile which resembles the uplink traffic of most IoT applications and three coverage scenarios which determine the physical layer transmission parameters with respect to different coverage levels have also been presented. Once the modem energy consumption model, the traffic profile, and the coverage scenario have been determined, the energy consumption of an IoT device within a transmit cycle can be calculated and the corresponding battery lifetime can be estimated. A measurement testbed has been set up to validate the proposed energy consumption model with two commercial NB-IoT and LTE-M devices, namely U-Blox EVK-N211 and U-Blox EVK-R410M. The results show that the proposed energy consumption model matches very well with the measurement results in different configurations, with the estimation error within 5%. The impact of the traffic profile, the coverage scenario, as well as the network configuration parameters on the device’s battery lifetime has also been analyzed, showing that both the application specific and the network specific parameters are of crucial importance to ensure a long battery lifetime.

REFERENCES

[1] Ericsson, “Ericsson Mobility Report,” https://www.ericsson.com/ 4adc87/assets/local/mobility-report/documents/2020/november-2020- ericsson-mobility-report.pdf, 2020.
[2] 3GPP, “Cellular System Support for Ultra Low Complexity and Low Throughput Internet of Things; (Release 13),” 3rd Generation Partnership Project (3GPP), Technical Report (TR) 45.820, Version 2.0.0.
[3] H. Wang, A. Sorensen, M. Remy, N. Kjettrup, J. J. Nielsen, and G. M. Madueno, Wireless Networks and Industrial IoT, Springer, 2021, ch. Power Measurement Framework for LPWAN IoT, pp. 105–129.
[4] M. Lauridsen, “Studies on Mobile Terminal Energy Consumption for LTE and Future 5G,” Ph.D. thesis, Aalborg University, Jan. 2015.
[5] M. El Soussi, P. Zand, F. Pasveer, and G. Dolmans, “Evaluating the performance of emtc and nb-iot for smart city applications,” in IEEE International Conference on Communications (ICC), May 2018, pp. 1–7.
[6] M. Lauridsen, I. Z. Kovacs, P. Mogensen, M. Sorensen, and S. Holst, “Coverage and capacity analysis of lte-m and nb-iot in a rural area,” in 2016 IEEE 84th Vehicular Technology Conference (VTC-Fall), Sep. 2016, pp. 1–5.
[7] B. Vejlgaard, M. Lauridsen, H. Nguyen, I. Z. Kovacs, P. Mogensen, and M. Sorensen, “Coverage and capacity analysis of sigfox, lora, gprs, and nb-iot,” in IEEE 85th Vehicular Technology Conference (VTC Spring), June 2017, pp. 1–5.
[8] M. Lauridsen, R. Krigslund, M. Rohr, and G. Madueno, “An empirical nb-iot power consumption model for battery lifetime estimation,” in 2018 IEEE 87th Vehicular Technology Conference (VTC-Spring), June 2018, pp. 1–5.
[9] A. K. Sultanina, P. Zand, C. Blondia, and J. Famaey, “Energy modeling and evaluation of nb-iot with psm and edxr,” in 2018 IEEE Globecom Workshops (GC Wkshps), Dec. 2018, pp. 1–7.
[10] A. Azari, C. Stefanovic, P. Popovski, and C. Cavdar, “On the latency-energy performance of nb-iot systems in providing wide-area iot connectivity,” IEEE Transactions on Green Communications and Networking, vol. 4, no. 1, pp. 57–68, Oct. 2020.
[11] P. Andres-Maldonado, M. Lauridsen, P. Amelieira, and J. M. Lopez-Soler, “Analytical modeling and experimental validation of nb-iot device energy consumption,” IEEE Internet of Things Journal, vol. 6, no. 3, pp. 5691–5701, June 2019.
[12] P. Andres-Maldonado, P. Amelieira, J. Prados-Garzon, J. Navarro-Ortiz, and J. M. Lopez-Soler, “Narrowband iot data transmission procedures for massive machine-type communications,” IEEE Network, vol. 31, no. 6, pp. 8–15, November 2017.
[13] 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,” in IEEE Radio and Wireless Symposium (RWS), Jan. 2018, pp. 1–3.
[14] S. Duhovnikov, A. Baltaci, D. Gera, and D. A. Schupke, “Power consumption analysis of nb-iot technology for low-power aircraft applications,” in IEEE 5th World Forum Internet Things (WF-IoT), April 2019, pp. 719–723.
[15] G. Vos, J. Bergman, Y. Bitran, M. Beale, M. Cannon, R. Holden, Y.S. Chan, R. Toledano, R. Bras, T. Wakayama, R. Ratnasuk, N. Okubo, K.
Park, Y., Akimoto, T.H., Siregar and S. Lee, “Coverage Analysis for LTE-M CAT-M1 Devices,” Sierra Wireless White Paper, 2017, (Accessed on 03/18/2019).

[22] M. Kanj, V. Savaux, and M. L. Guen, “A tutorial on nb-iot physical layer design,” IEEE Communications Surveys & Tutorials, vol. 22, no. 4, pp. 2408–2446, Sep. 2020.

[23] 3GPP, “LTE: Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 36.213, Version 13.8.0.

[24] 3GPP, “LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 36.211, Version 13.9.0.

[25] 3GPP, “LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 36.331, Version 13.8.1.

[26] H. Holma and A. Toskala, LTE for UMTS: Evolution to LTE-Advanced. Wiley, 2012, no. ISBN: 978-0-470-66000-3.

[27] A.S. Pagès, “Link Level Performance Evaluation and Link Abstraction for LTE/LTE-Advanced Downlink,” 2015.

[28] J. Mocnej, A. Pekar, W. K. Seah, and I. Zolotova, “Network Traffic Characteristics of the IoT Application Use Cases,” Technical Report Series, 2018.

[29] GSMA, “LTE-M Deployment Guide to Basic Feature Set Requirements,” https://www.gsma.com/iot/wp-content/uploads/2019/08/201906-GSMA-LTE-M-Deployment-Guide-v3.pdf, 2019.