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Energy-Saving Solutions for Cellular Internet of Things—A Survey

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ABSTRACT The Cellular Internet of Things (CIoT), a new paradigm, paves the way for a large-scale deployment of IoT devices. CIoT promises enhanced coverage and massive deployment of low-cost IoT devices with an expected battery life of up to 10 years. However, such a long battery life can only be achieved provided the CIoT device is configured with energy efficiency in mind. This paper conducts a comprehensive survey on energy-saving solutions in 3GPP-based CIoT networks. In comparison to current studies, the contribution of this paper is the classification and an extensive analysis of existing energy-saving solutions for CIoT, e.g., configuration of particular parameter values and software modifications of transport- or radio-layer protocols, while also stressing key parameters impacting the energy consumption such as the frequency of data reporting, discontinuous reception cycles (DRX), and Radio Resource Control (RRC) timers. In addition, we discuss shortcomings, limitations, and possible opportunities which can be investigated in the future to reduce the energy consumption of CIoT devices.

INDEX TERMS CIoT, 3GPP, energy-saving, mMTC, NB-IoT, LTE-M, EC-GSM-IoT.

I. INTRODUCTION

In the past few years, the Third Generation Partnership Project (3GPP) has proposed new cellular technologies [1] intending to cover a wide variety of IoT applications. In order to address the future market of IoT applications in the fifth-generation cellular system (5G) [2], the following requirement categories are defined [3]: massive Machine-Type Communication (mMTC) and critical MTC, also known as Ultra-Reliable Low Latency Communications (URLLC), where the mMTC is defined to target massive deployment of simple devices to handle small and infrequent traffic volumes. The vast deployment of such devices requires scalability, which further motivates a move to have less complex hardware powered by non-rechargeable batteries. Examples of use cases targeted by mMTC are smart metering, smart wearables, tracking logistics, fleet management, and industry management [4].

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To support mMTC, 3GPP has defined three Cellular Internet of Things (CIoT) technologies in release 13, as shown in Fig. 1: Narrowband Internet of Things (NB-IoT) [5], LTE Machine-Type Communications (LTE-M) [1] and Extended Coverage Global System for Mobile Communications Internet of Things (EC-GSM-IoT) [6]. The CIoT paradigm is envisioned to gain a substantial yearly growth with massive deployments of Low-Power Wide-Area Network (LPWAN) devices [7] from big cities to hard-to-access remote locations. These technologies are attributed as licensed spectrum-based CIoT, which can be deployed in 5G New Radio (NR), Long-Term Evolution (LTE), or even the Global System for Mobile Communications (GSM).¹ Along with wide-area coverage, CIoT promises reliable connectivity, latency, and quality of service. CIoT also has the characteristics of low cost [8], low complexity, and, most importantly, low power consumption [7], [9]–[11]. 3GPP standards aim to have a battery life of

¹A complete list of abbreviations used in this survey paper is provided at the end of this paper

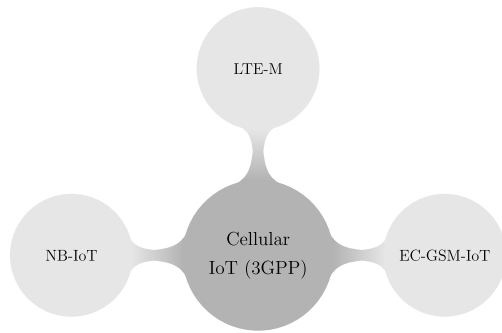


FIGURE 1. Classification of CIoT technologies proposed by 3GPP.

approximately ten years for CIoT technologies for worst-case scenarios. However, energy efficiency is the primary concern for such deployment scenarios. Also, since the CIoT devices are often not designed to have replaceable or rechargeable batteries, their battery life restricts the life of the device itself. Therefore, it is crucial to access energy-efficient mechanisms without impacting the desired device performance. Thus, this paper aims to study all the energy-saving mechanisms and parameter configurations, standardized and those proposed in the literature, for CIoT technologies to conserve energy.

In the 3GPP standards, various mechanisms to reduce energy consumption and thus enable for extended life of these devices are included, e.g., Power Saving Mode (PSM), extended Discontinuous Reception (eDRX), and energy-efficient Tracking Area Updates (TAU) are included in the standards for all the three technologies, and Release Assistance Indicator (RAI) is standardized for NB-IoT. However, later releases also employ other mechanisms proposed by 3GPP, such as user plane and control plane optimizations, energy-efficient paging receptions, wake-up signal calls, and less frequent cell monitoring. In addition to implied mechanisms, 3GPP also defines various standard parameter values with the ambition to cover deployment scenarios with devices located in basements of buildings or at remote places and are equipped with applications having specific requirements for reliability, latency, traffic patterns, and radio connectivity. However, finding optimized parameter values without considering their impact on energy consumption is challenging. Therefore, along with studying energy-efficient mechanisms, this paper also investigates the literature to find particular parameter settings for specific deployment scenarios.

Fig. 2 illustrates the relation between the major CIoT technologies' energy-saving mechanisms in a state transition diagram. During the connected state, a device transmits the data and waits for the release of the connection. The device actively listens to the radio channel for any downlink information during this time. Most of the time, this continuous listening is inefficient and consumes additional energy. 3GPP defines two mechanisms during this state to save battery: 1) Discontinuous Reception (DRX): forcing the radio to alternate between listening and sleep cycles to save battery, which is called cDRX since it is employed during the CONNECTED

state, 2) Release Assistance Indicator (RAI): radio connection is released promptly without any listening period. In addition, 3GPP employs the following main energy-saving mechanisms during the IDLE state: 1) extended Discontinuous Reception (eDRX): similar to cDRX, but the device sleeps more and listens to the radio channel for paging, 2) the PSM state, when a device turns off its radio entirely and goes into a deep sleep mode, where it is not connected with the network. Employing only these techniques does not fully ensure long battery life and requires careful parameter settings, e.g., the duration of device connection and the DRX mechanism. In an attempt to gain longer battery life, some energy-saving configurations for NB-IoT and LTE-M have been proposed [12]–[15]. Furthermore, several novel energy-efficient techniques that go beyond 3GPP standardized mechanisms have been suggested, e.g., software modifications to enhance transport layer protocols [16], hardware integration to add low-power receivers [13], [14]. However, what configurations, software modifications, and hardware integration are suitable in different situations remains unclear.

To provide an overview of proposed energy-saving solutions in 3GPP-based CIoT networks, this review paper provides a comprehensive analysis of research articles presented in the past few years. The paper focuses on and discusses the major and minor factors affecting the device energy consumption with the proposed solutions. Moreover, our contribution to this paper is also to recognize shortcomings in the existing energy-saving solutions and to provide guidance for the development of future solutions.

A. RESEARCH MOTIVATION AND CONTRIBUTION

This paper primarily focuses on providing a comprehensive survey of energy-saving solutions proposed by 3GPP for CIoT technologies. It also provides an in-depth discussion of the relevant parameters crucial for the energy consumption of CIoT devices. In addition, our analysis provides a significant exposure to open issues for future investigation. We are the first to survey energy-saving solutions for 3GPP CIoT technologies to the best of our knowledge. Furthermore, our paper covers the aspects of simulations and real-world experiments performed to analyze device battery life under different conditions and environments to highlight the key performance indicators. The contribution of this paper can be summarized as follows:

- Classification of energy-efficient solutions for CIoT technologies based on parameter configurations, software modifications and hardware integrations:
 - Parameter configurations are studied because parameters are easy to adjust according to certain situations and play a vital role. However, tuning those parameters is not straightforward. Therefore, this paper has analyzed different parameter settings for particular situations to save device battery.
 - Energy efficiency in CIoT technologies mainly relies on the application, MAC, and transport layer

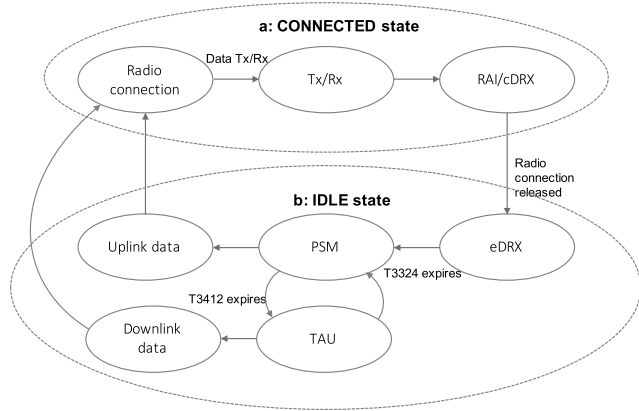


FIGURE 2. A state diagram illustrating the relation between the major CIoT energy-saving mechanisms: (a) is the CONNECTED state when the radio is turned on, (b) is the IDLE state when the radio is turned off.

protocols. Therefore, this paper focuses on studying the impact of all the standard protocols with their enhanced versions in terms of energy efficiency.

- This paper also considers studying the additional energy-efficient hardware designs for CIoT technologies.
- The impact of parameter configurations and software modifications are surveyed for simulated as we as the real-world scenarios to achieve energy efficiency.
- A detailed analysis of research gaps, a discussion of trends, open issues, and potential future research directions are provided.

Section II surveys the three CIoT technologies standardized by 3GPP: NB-IoT, LTE-M, and EC-GSM-IoT. In this section, we also discuss standardized mechanisms to achieve objectives set by 3GPP for each technology, particularly the objective of having longer battery life. A detailed discussion on energy-saving solutions proposed for CIoT is presented in Section III. Section III is classified into three major categories based on the nature of the provided solutions: configurations, software modifications, and hardware integration. Moreover, Section IV addresses the energy-efficient solutions in terms of implication and discussion, and Section V explores the open issues regarding energy efficiency and avenues for future work. Finally, Section VI concludes the paper.

II. CELLULAR INTERNET OF THINGS

In this section, we provide a brief overview of the three CIoT technologies put forth by 3GPP: NB-IoT, LTE-M, and EC-GSM-IoT, as shown in Table 1. Since the focus of this paper is energy-saving solutions, we mainly look into the energy-saving mechanisms described by 3GPP, and a brief overview of each technology will be discussed. Starting with the operations of CIoT devices (User Equipment or UE), two primary states are defined by 3GPP for the Radio Resource Control (RRC) protocol: RRC CONNECTED and RRC IDLE. A device alternates between these two states throughout its operational period. During the CONNECTED

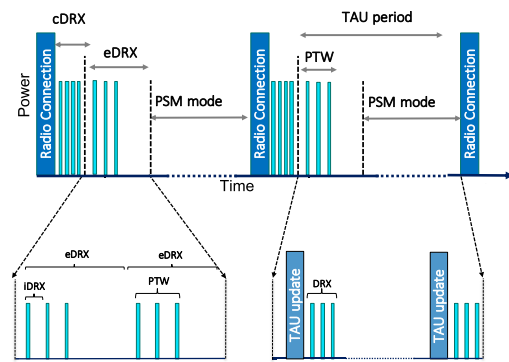


FIGURE 3. PSM, eDRX and TAU timers. A TAU update can happen more than once if PSM is set to a value larger than the TAU timer.

mode, a UE has an established link to the network for uplink/downlink traffic. After the connection is released, the UE switches to IDLE mode. Instead of constantly checking for any downlink traffic in both states, the Discontinuous Reception (DRX) mechanism is introduced to lower the UE energy consumption. DRX defines a mechanism of alternately listening and sleep periods for radio to conserve energy. However, during the IDLE state, sleep cycles are extended to a longer period and is called extended Discontinuous Reception (eDRX). Power Saving Mode (PSM) is another energy-saving technique used during the IDLE state. PSM is the most effective way of saving energy for all the three technologies where a device turns off its radio and moves into deep sleep mode. It is worth mentioning that the UE in the IDLE state still keeps network registration, and it only needs to perform a connection resume operation to send/receive any data. Below follows a description of all primary energy-saving techniques proposed by 3GPP.

1) DISCONTINUOUS RECEPTION

The DRX mechanism in CIoT closely resembles the mechanism employed by LTE. During one DRX cycle, a device monitors the physical channel for a while and sleeps most of the time. However, this listening is very relaxed in CIoT compared to LTE. The maximum DRX cycle in LTE can be set to 2.56 seconds, whereas the same parameter can be set to 10.24 seconds or more in CIoT. Longer DRX cycles have implications on downlink data delivery and device energy consumption. Since CIoT is designed for applications to tolerate latency, longer DRX cycles are reasonable as an important key to save energy.

As shown in Fig. 3, DRX cycles can be implemented in both CONNECTED and IDLE mode. DRX cycles during the CONNECTED mode (CONNECTED-mode DRX or cDRX) enable the device to alternate between active and sleep periods while also keeping the radio connection. DRX cycles during the IDLE state, a state where the network has released the connection and the device stays idle, make it possible for a device to listen to the paging channel for downlink control signaling to receive downlink traffic by re-establishing the

TABLE 1. A comparison of CIoT technologies [17]–[22].

Specification	NB-IoT	LTE-M	EC-GSM-IoT
Standardization	3GPP	3GPP	3GPP
Peak data rates	~200 kbit/s	~1 Mbit/s	~10 kbit/s
Max. bandwidth	200 kHz	1.4 MHz	2.4 MHz
Battery capacity	~10 years	~10 years	~10 years
Transmission Power	23 dBm	20 - 23 dBm	23 - 33 dBm
Range	<15 km	~11 km	<25 km
Maximum Coupling Loss	164 dBm	157 dBm	164 dBm
Mobility	limited	handover	handover
Latency	1.6 – 10 sec	10 – 15 ms	700 ms – 2 sec

radio connection. During the CONNECTED mode, the UE sends an uplink transmission followed by an acknowledgment in some scenarios where confirmation is needed. While waiting for an acknowledgment, a device intentionally consumes energy by listening to the downlink channel. Therefore, the DRX mechanism is employed in this mode which incorporates active listening and sleep cycles while allowing the device to turn off the radio during sleep periods, as shown in Fig. 3. Since, the device listens to the physical channel for a few milliseconds and sleeps most of the time, this significantly contributes to energy efficiency. cDRX reduces the energy consumption by approximately 90% during maximum sleep periods [12] and allows the device to receive any downlink information without interruption.

DRX cycles also play an essential role during the IDLE state. A UE alternates between listening and sleep cycles during the IDLE state, a mode called extended DRX (eDRX). However, these cycles are more sporadic and correspond to a sequence of iDRX cycles known as Paging Time Window (PTW), as shown in Fig. 3, followed by an extended sleep period. The combination of PTW and the sleep period constitutes eDRX. The period when a UE completes one DRX cycle in the CONNECTED and IDLE modes is defined by the cDRX and iDRX parameter values. In the same way, a period in which the UE executes a group of iDRX cycles is controlled by the PTW parameter. The maximum value for cDRX and iDRX, defined by 3GPP, is 2.56 seconds, where the UE listens to the physical channel for the first half and sleeps during the next half. However, PTW and eDRX are defined with a maximum value of 40.96 seconds and 10485.76 seconds, respectively. The values of cDRX, iDRX, PTW, and eDRX are tunable and can be adjusted according to application requirements. More detailed values for each tunable parameter are presented in Tables 5 and 6 in Section III-A.

Once a UE finishes the eDRX cycles, and if it does not receive any paging for downlink data, it turns off its radio and moves into the PSM mode, a mode where the device is not reachable by the network. A detailed study is provided regarding the operations of PSM in the section below and in Section II-A2.

2) POWER SAVING MODE

PSM is the most efficient approach to achieve a longer battery life. As shown in Fig. 3, a device turns off its radio completely

to save energy during PSM. During this state, a device is not accessible by the network and needs to re-establish the connection to perform any transmission. In fact, in this state, the device can only be woken up by a message from the UE application layer or through the regularly occurring Tracking Area Update (TAU) procedure [19]–[21]. The TAU Timer (T_{3412}) determines the time between two TAU procedures and their duration is decided during the attachment procedure. The time between two TAU updates can be set to a maximum of 9912 hours. Once the TAU Timer expires, a UE completes the TAU procedure to update its location on the network. The UE initiates the TAU procedure by sending a TAU request message. The TAU request message enables the UE to omit the attach procedure with the network. However, the TAU procedure is followed by an interval during which the UE listens for the paging messages. The duration of this interval is governed by the Active Timer. The UE triggers a new radio connection if the network has any downlink data for the UE.

If the network receives any data for the device in PSM mode, data is buffered by the network. For each CIoT technology, the network has support to store ten latest messages simultaneously, which are then delivered to that particular device upon connection re-establishment.

Regular TAU updates let the network know that the particular device is still registered. Since the network holds the device information, re-establishing the connection requires only a few resources and thus consumes less energy compared to a new connection establishment procedure. The PSM state is one of the significant energy-saving mechanisms in CIoT technologies, and a key to saving energy is to stay in PSM mode as long as possible.

3) COVERAGE EXTENSION, CELL MONITORING, AND POWER CLASS

One of the objectives of CIoT is to provide reliable communication for hard-to-access areas. Consequently, Extended Coverage Level (ECL) is introduced in release 13 to support CIoT with the tuning of robust communication. In order to target the applications with devices deployed at remote locations, several coverage extensions have been made, such as ECL0, ECL1, ECL2 [10]. The repetition of the same message achieves the coverage depth to enhance the receiver's ability to perfectly grab the sent message. These repetitions depend on the channel quality and the coverage class in which the device is located. Moreover, the number of

repetitions is defined by 3GPP for each technology with different coverage classes. However, these repetitions negatively impact the device battery with increased delays and low data rates. To encounter such cases, different power classes are defined for each technology. Apart from the standard power class, as shown in Table 1, low-power classes are introduced for each technology to save energy. Coverage extensions and power classes are explained for these technologies in their respective sections below. Moreover, devices are also instructed to have relaxed/no cell monitoring in case of showing no mobility or if the topology has not changed. A relaxed cell monitoring also corresponds to an extended battery life.

4) RELEASE ASSISTANCE INDICATOR

In CIoT devices, the radio connection period is determined by the network and is governed by a timer called the Inactivity Timer, as shown in Fig. 4. A device consumes a large amount of energy while staying in the CONNECTED state if it does not have any further traffic to transmit or receive. A device waits for the timer to expire, and the network releases the connection. The Release Assistance Indicator (RAI) procedure is introduced by 3GPP in releases 13 and 14 for NB-IoT and LTE-M to tell the network to tear down the connection right after a device has sent its last packet or after receiving the acknowledgment for the same packet. This informs the network that it does not have any uplink or downlink data transmission while allowing the network to release a connection faster. In the absence of RAI indication, the network will keep the connection until the Inactivity Timer expires. However, if the RAI is enabled, a device can quickly move into the IDLE mode while saving significant device energy, as shown in Fig. 4.

Along with the above discussed energy-saving features, we have compiled some of the other methods proposed by 3GPP in different releases in Table 2.

A. NB-IoT

To provide cellular support for ultra-low-power and low throughput IoT, attributed as CIoT, 3GPP proposed a new narrow-band IoT technology in release 13 [1] where the core specifications were completed in 2016 [5]. This technology aims to better serve IoT verticals while providing extended coverage, long battery life, ultra-low-cost and low device complexity, and improved capacity in terms of the maximum number of concurrent device connections. The NB-IoT system has a channel bandwidth of 200 kHz but occupies only 180 kHz. The limited bandwidth of NB-IoT results in a low peak data rate for this technology; however, it also makes it possible to keep the device complexity down. NB-IoT primarily targets non-mobile wireless IoT applications, and it reuses the frequency spectrum from LTE or GSM. These applications vary from smart cities, building, agriculture to basement car parking with deep indoor coverage [23]. Deep coverage is generally realized by extending the power class and repeating the same message, which we will cover in the following subsection.

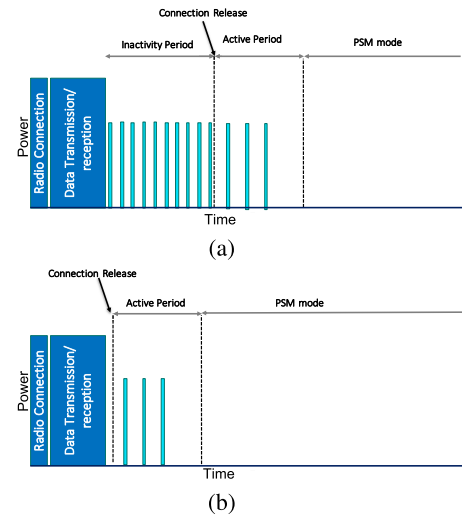


FIGURE 4. The graph illustrates how the energy consumption depends on how the radio connection is released. Fig. 4a illustrates the energy consumption when the connection is released after the Inactivity Timer expires, and Fig. 4b shows the energy consumption when the connection is released due to a request from the UE (RAI).

In this section, apart from discussing NB-IoT features, we will also highlight the objectives for the same technology, e.g., longer battery life and improved coverage.

1) EXTENDED COVERAGE

NB-IoT defines a maximum coupling loss (MCL) of 20 dB which reaches up to 164 dB to provide coverage for devices installed in the basement of the buildings. MCL is characterized as the maximum loss at a particular power level where the UE can still perform its operations. 3GPP has defined three coverage levels or enhanced coverage levels (ECL): ECL0, ECL1, and ECL2 [10] to achieve extensive coverage in NB-IoT. Each coverage level is served with a particular MCL value:

- ECL 0 represents an approximate MCL value of 144 dB
- ECL 1 represents an approximate MCL value of 154 dB
- ECL 2 represents an approximate MCL value of 164 dB

Where ECL0 targets the normal network conditions, and ECL2 targets deep indoor coverage or worst-case scenarios. In the worst-case scenarios, while having single transmission, there are more risks that a packet might get lost. Therefore, in order to have at least one successful transmission, several repetitions are triggered for the same packet back-to-back. However, only a certain number of repetitions are allowed for each coverage class to avoid network congestion. The network operator dictates the selection of these coverage levels and the selection depends on the network conditions. Each ECL defines the number of repetitions (more than one sub-frame) in the uplink/downlink channel. The number of repetitions varies from 2 to 128 in the uplink channel, and up to 2048 repetitions are employed in the downlink channel. The reason that the number of repetitions varies is that the end device adopts less power, and hence fewer repetitions

are sent in comparison to the downlink channel where the base station holds ideally unlimited resources. Due to the high number of repetitions, and higher coding schemes [24] for data transmissions in ECL2, NB-IoT devices consume extra energy. NB-IoT defines a few energy-saving techniques to minimize this energy consumption, which are surveyed in the following sections.

2) LONG BATTERY LIFE

NB-IoT is designed to target use cases with devices deployed at remote areas where changing a device battery is cumbersome, as shown in Fig. 5. NB-IoT aims to have a device battery lifetime of more than 10 years with a battery of 5 Wh. However, achieving such an energy efficiency depends on how the device operates in situations when it has no active data sessions. When a device is turned on for the first time, it performs a connection establishment procedure and shifts state to the RRC CONNECTED, as shown in Fig. 6. In this state, a device can send/receive uplink/downlink traffic to/from the network. As described above, the time in this state is governed by the Inactivity Timer, whose value is controlled by eNodeB. The value of the Inactivity Timer is restarted every time a new transmission/reception event occurs. The Inactivity Timer can be set to a high or low value depending on network conditions. It can be set to a concise value (1 – 5 seconds) in situations with very low network delays. However, in scenarios where a device has to wait slightly longer for the downlink traffic, a long Inactivity Timer of 20 seconds can also be used.

In those cases the Inactivity Timer expires, a device transitions to the RRC IDLE state. This state is controlled by TAU timer (T_{3412}) and Active Timer (T_{3324}), as shown in Fig. 6. During the Active Timer, eDRX enables a device to save energy since during eDRX a device only periodically listens to the physical channel for any downlink traffic. During eDRX, the device is not connected to the network, and no physical resources are allocated. A device transitions to the PSM state when the Active Timer expires.

Since NB-IoT focuses on applications with infrequent short transmissions, the device stays mainly in the IDLE state. Generally, a device in the IDLE state needs to monitor the physical channel for pagings and to perform mobility procedures. Although a device consumes less energy in the IDLE state than the CONNECTED state, a significant amount of energy can be saved by simply increasing the time between paging occasions or not listening to them at all. In order to achieve an extended battery life for NB-IoT devices, two primary energy-saving mechanisms: eDRX and PSM are used. During PSM state, the device is not reachable by the network except when it has to perform tracking area updates. However, both the network and the device keep the device context to avoid the extra signaling when a device returns to the CONNECTED state again. Furthermore, NB-IoT also has support for cDRX and RAI to save energy.

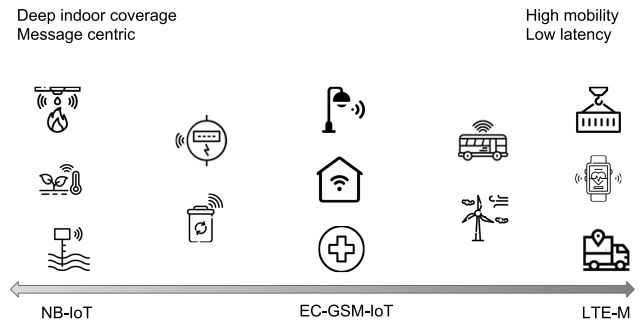


FIGURE 5. The use case for the three major CIoT technologies².

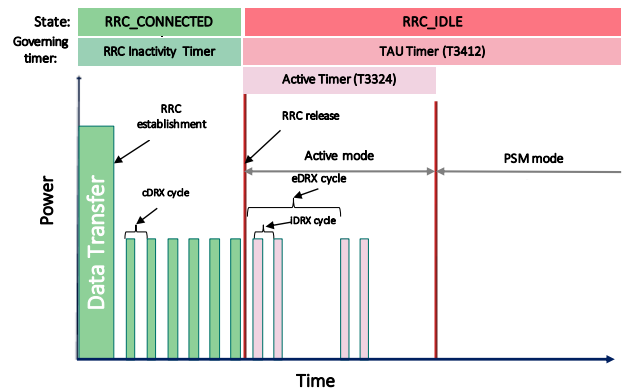


FIGURE 6. NB-IoT RRC states with energy-saving features, such as: cDRX, eDRX, PSM, etc.

3) CELL CAPACITY

Since the NB-IoT technology focuses on applications with small, infrequent data transmissions, it has support for more than 60,000 connections per cell in release 13 and 100,000 connections in release 14. NB-IoT achieves this high capacity by introducing efficient transmission and reception schemes with low-bandwidth device requirements.

4) NETWORK DEPLOYMENT

Unlike other LPWAN devices, NB-IoT brings more flexibility to its deployment using licensed spectrum. NB-IoT supports three different deployments: in-band deployment, stand-alone deployment, and guard-band deployment. NB-IoT is designed with the flexibility to be deployed within the unused spectrum of LTE; e.g., NB-IoT can use one physical resource block of LTE for in-band deployment. In addition, it can be deployed in a stand-alone fashion to any available GSM or LTE spectrum, which has a bandwidth of more than 180 kHz. It is also possible for NB-IoT to be deployed using the existing LTE guard-band due to the fact that LTE uses 90% of the channel bandwidth, and the NB-IoT carrier occupy the rest.

B. LTE-M

LTE-M is another CIoT technology proposed by 3GPP in releases 13, 14, and the standardization is completed in release 15. The design principle for LTE-M is to achieve

²The icons used in this figure are downloaded from flaticon [25]

TABLE 2. 3GPP release wise comparison of energy-saving techniques.

	Release 13	Release 14	Release 15
NB-IoT	<ul style="list-style-type: none"> • Power Saving Mode (PSM) • extended Discontinuous Reception (eDRX) • connected mode DRX (cDRX) • Paging Mechanism • Power Class • User Plane CIoT optimizations • Tracking Area Update (fixed and periodic timer) 	<ul style="list-style-type: none"> • Release Assistance Indicator (RAI) • New Category NB2 (optional 2 HARQ processes) • New Power Class 6 • Control Plane CIoT optimizations • Less frequent cell monitoring 	<ul style="list-style-type: none"> • Improved battery efficient security mechanism • Small cell support • Early Data Transmission (EDT) • Wake-up Signal calls
LTE-M	<ul style="list-style-type: none"> • Power Saving Mode (PSM) • extended Discontinuous Reception (eDRX) • connected mode DRX (cDRX) • Power Class • Control Plane CIoT optimizations • User Plane CIoT optimizations • extended periodic TAU • Sim card deactivation during eDRX 	<ul style="list-style-type: none"> • Release Assistance Indicator (RAI) • 10 down-link HARQ processes • Less frequent cell monitoring 	<ul style="list-style-type: none"> • Improved battery efficient security mechanism • Power Class 6 • Early Data Transmission (EDT) • Wake-up Signal calls
EC-GSM-IoT	<ul style="list-style-type: none"> • Power Saving Mode (PSM) • extended Discontinuous Reception (eDRX) • extended periodic TAU • Power class • Power control procedure 	<ul style="list-style-type: none"> • Less frequent cell monitoring 	<ul style="list-style-type: none"> • Energy-efficient Paging reception

Summary of energy-saving mechanisms proposed by 3GPP for each CIoT technology in different releases are shown in the above Table. Dominant aspects of energy-saving solutions were reported in release 13 and 14 and have been discussed by a number of papers. However, release 15 features have not been studied rigorously, neither implemented by the network operators.

massive deployments with low cost and low device complexity, longer battery lifetime, and extended coverage. LTE-M technology also addresses the more demanding applications with peak data rates [26] and higher mobility while ensuring flexible deployment within the LTE network, as shown in Fig. 5. To ensure a longer battery lifetime, release 13 provided LTE-M with many energy-saving features to extend the battery life, such as coverage enhancement modes, PSM, eDRX [27]. Later in releases 14 and 15, various other mechanisms are introduced to assure longer battery life, as shown in Table 2 in Section II-A. As far as other architectural components are concerned, LTE-M extends a bit generic features from LTE but with additional features to have support for Machine-Type Communications (MTC) and low- to mid-range IoT applications [1]. LTE-M applications are not limited to smart buildings, but it also focuses on applications which require high bandwidth, such as smart logistics, smart wearables, tracking sensors, etc. [28]. The motivation for reusing the design of LTE in the design of the LTE-M system is to take advantage of already deployed networks while sharing the same spectrum. Similar to NB-IoT, LTE-M targets long device battery life, deep coverage, low device cost, and extensive deployment of devices per cell [29]. In addition, LTE-M provides better data rates than NB-IoT. The rationales behind LTE-M are discussed in the following subsections.

1) EXTENDED COVERAGE

Unlike LTE, LTE-M provides additional coverage of 20 dB to support devices in limited coverage areas. The fact that LTE-M focuses on IoT applications with low latency, the coverage enhancement can be achieved by the repetition techniques both for the control and data channels for the applications which usually doesn't require low latency. The repetition technique defines a number of repetitions for the same packet until its successful delivery. Taking this technique into account, 3GPP has defined two coverage enhancement (CE) modes for LTE-M: CE A mode and CE B mode [22]. In the CE A mode, LTE-M supports up to 32 repetitions, and in the CE B mode, it supports up to 2048 repetitions. The CE A mode is also the default mode of operation for LTE-M with average coverage enhancements. This mode of operation ensures the data rates with CONNECTED mode mobility promised by LTE-M. On the other hand, to achieve deep coverage in CE B mode, LTE-M performs up to 2048 repetitions of the same data packet while compromising the data rates. This mode of operation targets stationary/low mobility applications with minimal data rate requirements.

2) MOBILITY

Another feature of LTE-M technology is to have support for applications with mobility while assuring the connectivity and required data rates. 3GPP release 13 defines two primary mobility modes: Connected Mode Mobility (CMM) and Idle Mode Mobility (IMM). In the CMM, the network has the authority for cell re-selection, where it triggers the handover

procedure according to the device mobility. CMM is considered an essential feature for applications with Voice over LTE (VoLTE) support. However, the end device initiates a cell re-selection procedure based on decent signal quality above the defined threshold value in the IMM.

Release 13 defines only intra-frequency RSRP measurement support for both modes, which is, however, further extended to have full mobility support while providing intra- and inter-frequency RSRQ/RSRP measurements.

3) LONG BATTERY LIFE

Long battery life in LTE-M is realized by lowering the transmit and receive power during the CONNECTED mode. However, LTE-M also extends the power saving features such as PSM and eDRX, introduced by 3GPP in releases 12 and 13, respectively. These two techniques potentially reduce the power consumption by mostly turning off the radio during the device's idle period. In addition, LTE-M employs similar CONNECTED and IDLE mode energy-saving mechanisms like NB-IoT technology does.

C. EC-GSM-IoT

EC-GSM-IoT is another low-power wide-area network technology standardized by 3GPP in release 13 that is based on the enhanced General Packet Radio Service (eGPRS) [6]. In the same way as the technologies mentioned above, EC-GSM-IoT is designed particularly for extended coverage and long battery life. In addition, it has a less complex cellular system to cover a wide variety of IoT applications. EC-GSM-IoT targets the IoT applications for such areas where GSM is still a popular standard. It can be deployed alone or within the guard band of 3G and 4G infrastructure with software modifications only. EC-GSM-IoT also promises to provide a maximum data rate of 10 Kbit/second and a service latency of 10 seconds with ultra-low device complexity.

1) EXTENDED COVERAGE

EC-GSM-IoT employs a similar mechanism of repetitions as GSM to achieve extended coverage. In particular, EC-GSM-IoT inherits a mechanism of blind repetitions or transmissions from GPRS to attain such extended coverage. Blind repetition is a common technique for enhancing the coverage for 2G technologies [30]. A device using this mechanism transmits the same packet without having any feedback/acknowledgement from the sender side for each repetition. Four different coverage classes (CC) are defined for any given channel: CC1, CC2, CC3, and CC4. These coverage classes ensure 1, 8, 16, and 32 blind repetitions in the downlink channel and 1, 4, 16, and 48 in the uplink channel. However, for the initial synchronization process, only one blind repetition is defined by 3GPP. A similar approach is adopted by other CIoT technologies but is termed repetitions.

2) LONG BATTERY LIFE

In order to support an extensive deployment of EC-GSM-IoT devices with nominal or no maintenance requirements,

TABLE 3. A comparison of CIoT technologies in terms of advantages and disadvantages.

	Advantages	Disadvantages
NB-IoT	<ul style="list-style-type: none"> •Long battery life •Deep penetration •Very simple and cheap hardware •5G ready technology •Extended coverage •Better efficiency at low data rates •Can cope with an exponential increase in device deployments 	<ul style="list-style-type: none"> •Limited mobility support (designed for fixed sensors in agriculture fields) •No SMS or voice support
LTE-M	<ul style="list-style-type: none"> •Ultra low latency •Support for end-to-end secure connection •Support for high mobility •Better transmission rates •Support for voice and SMS services 	<ul style="list-style-type: none"> •Complex hardware architecture •High power consumption in harsh conditions
EC-GSM-IoT	<ul style="list-style-type: none"> •Support variable transmission rates •Deployable in existing GSM network covering 90% of world •Improved security •Improved coverage range 	<ul style="list-style-type: none"> •Does not support voice calls •Commercial deployments are limited by network operators

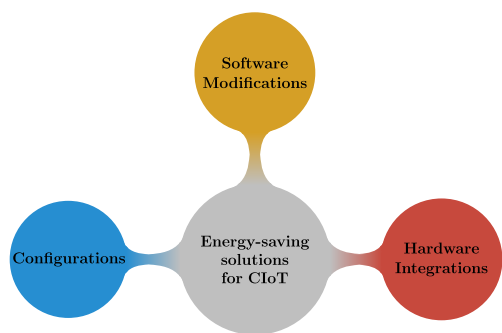


FIGURE 7. Relationship between different categories of energy-saving solutions for Cellular IoT.

a battery life of up to 10 years is expected for EC-GSM-IoT devices. In addition to extending some features inherited from GSM, EC-GSM-IoT exploits eDRX, PSM, and a paging mechanism, which we have discussed in Section II-A, in order to gain a longer battery life. As far as cell capacity is concerned, in addition to longer battery life, EC-GSM-IoT also provides 60, 000 connections per cell with deep indoor coverage.

Apart from covering all the details for each CIoT technology, we have compiled the advantages and disadvantages of using them for different applications, as shown in Table 3. These advantages or disadvantages also refer to how each technology has been designed to serve different use cases which we have discussed earlier in Fig. 5, in Section 5.

III. PROPOSED ENERGY-SAVING SOLUTIONS FOR CIoT

Energy-saving solutions, proposed by 3GPP and also in the literature, vary a lot from just tweaking some of the parameters to completely reworked software and hardware designs. However, to develop a better understanding of each method for the energy-saving techniques, we have designed our own taxonomy for the sake of simplicity and comparison. As shown in Fig. 7, the proposed energy-saving CIoT solutions for 3GPP-based cellular networks can be put into three categories: 1) configurations, 2) software modification, and 3) hardware integration. The configuration cate-

gory includes all solutions which reduce the energy consumption by tuning certain parameters in a CIoT stack, as shown in Fig. 8. The blue-colored boxes represent the protocols with tunable parameters, which we will discuss one by one in detail. The configurations category is partitioned into two subgroups depending on which side is configured, i.e., the user-equipment side or the network-operator side. This division implies the fact that it is easy to manage the parameters on the user-equipment side. However, there are a number of parameters that need to be controlled from the network-provider side based on varying environments, which is, however, not in the control of an ordinary user.

The second group includes proposed energy-saving solutions that entail some kind of software modification, e.g., an improved transport-layer or MAC-layer protocol for the end-user devices or the network operator side. However, such modifications require specific skills with appropriate equipment and cannot be done without prior knowledge. The third category mirrors the second category but for hardware modifications. Providing such solutions also requires specialized skills for the development and its proper integration with the vendor’s hardware, which is again not possible from a layman’s perspective. To this end, a well detailed classification of the surveyed papers is shown in Table 4.

A. CONFIGURATIONS

In this section, we will discuss the CIoT stack configuration approaches made by different authors to reduce energy consumption. Changing different parameters of a protocol stack is an easy task. Still, it is difficult to find efficient parameter settings to achieve energy efficiency. This is because of various interdependent parameters, both at user-end devices and at eNodeB, e.g., traffic models, connectivity period, DRX cycles, etc. This section will provide an overview of the currently proposed energy-saving configurations. Starting with the application layer, we will continue our discussion with transport-layer protocols and possible solutions, and finally, we will consider the radio layer, whose configuration has a

TABLE 4. Energy-saving solutions for cellular internet of things.

Characterization	Description	Aim of paper	Technology	Reference
Tunable parameters	UE radio stack	Study the energy consumption of NB-IoT devices with different tunable parameters, e.g., eDRX, cDRX, etc., and in different coverage levels.	NB-IoT	[12], [31]
Tunable parameters	UE and eNodeB radio stack	Study the different energy-saving mechanisms, e.g., eDRX, cDRX and Inactivity Timer, a tunable parameter at eNodeB.	NB-IoT	[32], [33]
Tunable parameters	UE transport layer	Study the impact of CoAP and MQTT protocols.	NB-IoT	[16]
Tunable parameters	UE application layer and radio stack	Study the impact of the power-saving mode and different traffic models in real-world experiments.	NB-IoT, Cellular IoT	[15], [34], [35]
Tunable parameters	UE application layer and radio stack	Evaluate the power consumption of NB-IoT technology for aviation applications, focusing on PSM and the number of messages transmitted per day.	NB-IoT	[36]
Tunable parameters	UE application layer and radio stack	Evaluate the energy consumption of a NB-IoT device for different values for PSM, eDRX and number of transmitted messages.	NB-IoT	[37]–[39]
Tunable parameters	UE application layer	Emphasises the importance of the data traffic over energy consumption.	Cellular IoT	[40]–[43]
Tunable parameters	UE application and radio layer	Suggests power saving mechanisms for cellular IoT and emphasize the importance of Active Timers, cDRX and eDRX cycles.	Cellular IoT	[44]
Software-based solutions	EnodeB and Core network	Propose a prediction-based energy-saving mechanism (PBESM) that entails implementing two software based entities at MME (PIE) and eNodeB (PPE).	NB-IoT	[45]
Software-based solutions	UE radio stack	Study the impact of data transmission procedures over the energy consumption such as conventional Service Request (SR), Control Plane (CP), and User Plane (UP) optimizations.	Cellular IoT	[46]
Software-based solutions	UE radio stack	Propose an uplink link adaptation method that guarantees transmission reliability with reduced energy consumption.	NB-IoT	[47]
Software-based solutions	UE radio stack	Propose a new cross-layer based uplink scheduling scheme to gain energy efficiency.	LTE-M	[48]
Software-based solutions	UE radio stack	Paper investigates the adoption of cooperative relaying technique in NB-IoT to reduce device energy consumption.	NB-IoT	[49]
Software-based solutions	UE radio stack	Investigate the adoption of group-based paging in cellular IoT with improved device energy efficiency.	Cellular IoT	[50]–[52]
Software-based solutions	UE radio stack	Investigate the traffic congestion problem and provides a solution using an Access Class Barring (ACB) mechanism in which the collision probability is reduced by decreasing the number of transmitting devices on the same channel.	Cellular IoT	[53]
Software-based solutions	UE radio stack	Explore different MAC layer protocols, i.e., B-MAC, X-MAC etc., for all cellular IoT technologies.	Cellular IoT	[54]
Software-based solutions	EnodeB radio stack	Demonstrate that the current DRX mechanism is inadequate and to propose a novel group-based DRX mechanism.	NB-IoT, EC-GSM-IoT	[55], [56]
Hardware-based solutions	UE radio layer	Propose a wake-up signal to be received by the main receiver in the existing receiver circuitry to save power during the IDLE mode.	Cellular IoT	[13]
Hardware-based solutions	UE radio layer	A simple wake-up receiver is added at the front-end of the device to achieve better efficiency. It also proposes a framework for statistical analysis of the RF wake-up solution in cellular IoT networks.	Cellular IoT	[14]

significant impact on device energy consumption. In the last part of this section, we discuss the impact on the end-user device consumption of eNodeB and its protocol stack configuration, see Fig. 9.

1) USER EQUIPMENT STACK

The architecture of CIoT technologies is explained in [1], [57]–[62]. Our focus will be on the mechanisms regarding low-power consumption. In CIoT, tunable parameters are, most of the time, governed by two RRC states: CONNECTED and IDLE. Sections III-A1.a and III-A1.b discuss these parameter settings from the literature, in order to maximize the battery lifetime.

a: APPLICATION AND TRANSPORT LAYER

It is expected that the IoT devices will be deployed at various places with support to multiple applications, e.g., smart

metering, smart health devices, and intelligent environment. Based on different application requirements, IoT devices will follow different traffic models, e.g., 3GPP has used the following uplink reporting traffic model for NB-IoT device capacity analysis [1]: 1 message after every 24 hours (40% of total messages), 2 hours (40% of total messages), 1 hour (15% of total messages) and 30 minutes (5% of total messages). Further, based on device capacity analysis, 3GPP in document [1] claims to have a battery lifetime of 1.5 years with reporting interval of 2 hours and with a Maximum Coupling Loss (MCL) of 164 dB, a total radio channel loss between a device and eNodeB. A battery lifetime of 12.8 years is achievable with the same MCL, provided the reporting interval is set to 1 message per 24 hours. However, in a best-case scenario with an MCL of 144 dB, a battery life of 18.2 and 34.9 years is achievable with reporting interval of 2 and 24 hours, respectively. With reference to traffic models

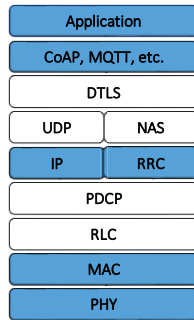


FIGURE 8. The Clot protocol stack in an end-user device.

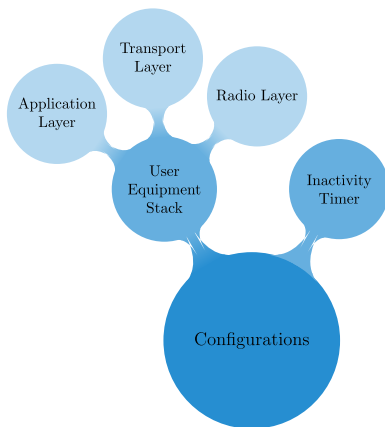


FIGURE 9. Categorization of configurations.

proposed by 3GPP [17], [18], [40] for LTE-M and EC-GSM-IoT technology, battery life of 11.9 and 11 years is achievable with an MCL of 164 dB if reporting interval is set to 24 hours.

In order to further validate these results, the authors of [15] employed an NB-IoT network, built with commercial off-the-shelf NB-IoT modules, to study the NB-IoT device energy consumption. After performing device energy measurements with a message interval of 2 hours in an environment with good coverage (MCL of 59 dB), the authors claim to have a battery life of 11.8 and 12.6 years, provided the PSM is enabled. After the PSM state, a device does not need to complete the network registration again. However, on the other hand, if the device needs to perform a new network registration and an Evolved Packet System (EPS) bearer activation each time it has data to send, the battery life would drastically decrease from 11.8 and 12.6 years to 409 and 310 days, respectively.

Lauridsen *et al.* [38] performed energy measurements on NB-IoT with commercially available devices. The results from these experiments also strengthen the statement provided by 3GPP that adjusting the reporting interval to 1 message per day significantly increases the battery life to 12.8 years provided PSM is enabled. During these experiments, T_{3324} was set to 6 seconds, and T_{3412} was assigned a value of 20 hours. However, the energy consumption can be enhanced further if these timers are configured care-

fully [33]. Sultania *et al.* [37] modeled the energy consumption of NB-IoT devices when traffic was transmitted according to different models. The results showed that a battery life of 12 years is achievable provided only one message is transmitted per day. In addition, results also showed that increasing the packet size does have a negligible impact on the device battery life.

In [36], the authors performed an experimental energy consumption analysis of NB-IoT devices. In order to test the critical parameters, an experimental setup was made with a public as well as a private network using the Sara N211 NB-IoT chip module. Based on these experiments, battery lifetime was evaluated, and the results suggested a lifetime of only eight days with a message interval of 30 seconds. Further, experiments suggest that a battery lifetime of 10 years is achievable only with a low-intensity traffic model, e.g., by using a transmission rate of 1 message per day. Last but not least, authors in [12] achieved a battery lifetime of 8.5 years with a reporting interval of 4 hours under certain network configurations, e.g., enabling DRX during the CONNECTED state, and studies showed that the battery life could be further extended to almost 30 years if RAI is enabled. The authors of [46] achieved a battery lifetime of 19 years with a reporting interval of 6 messages per day by using both the control plane optimization and RAI.

In cellular IoT, application-level protocols depend on transport-layer protocols. For example, the Constrained Application Protocol (CoAP) is based on UDP, and the Message Queue Telemetry Transport (MQTT) is based on TCP. The selection of these transport protocols is crucial since they have a considerable impact on energy consumption, latency, coverage, security, and system capacity.

CoAP is a lightweight, RESTful protocol for IP-based, HTTP-like interactions and is designed by IETF to accommodate resource-constrained devices [63]. Being a subset of HTTP, CoAP follows the exact client-server mechanism. However, unlike HTTP, it runs over UDP instead of TCP. As a result, CoAP has no TCP overhead, something which makes it more suitable for IoT applications. However, since CoAP relies on a non-reliable transport protocol, it uses its own mechanisms to achieve reliability. In particular, CoAP defines two different modes of operations: confirmed mode and non-confirmed mode. In the confirmed mode, CoAP achieves its reliability by retransmitting lost messages. CoAP outlines this simple technique of retransmissions after fixed intervals to avoid network congestion. Unfortunately, this simple congestion-control mechanism is sometimes too aggressive (if a number of retransmissions are not well-defined) or too conservative since it does not have information about the network status, something which eventually results in extra energy consumption. A new congestion-control mechanism is proposed in [64], the CoAP Congestion Control Advanced (CoCoA), which offers a network-adaptive congestion control while at the same time providing a dynamic Retransmission Timeout (RTO). CoCoA showed better performance than CoAP in terms of throughput and packet

TABLE 5. Different NB-IoT timer values during the CONNECTED and IDLE mode.

Mode	Timers	Possible values (sec)	Benefits
CONNECTED	Inactivity	0 – 65.536	Inactivity Timer is controlled by the network operator which determines the device active connection period.
	cDRX	1.28, 2.56, 5.12, 10.24	DRX defines a mechanism of active listening and sleep periods during the connected mode to save device battery life.
IDLE	eDRX	20.48, 40.96, ..., 10485.76	A mechanism used by the device and the network to save energy by extending the sleep period and shortening the listening period.
	PTW	2.56, 5.12, ..., 40.96	A paging transmission window (PTW) provides a device with paging opportunities to increase its reach-ability by the network.
	iDRX	1.28, 2.56, 5.12, 10.24	Similar to cDRX, iDRX defines a mechanism of active listening and sleep periods to save device battery life.
	Active	16 – 11160	Active state defines number of eDRX cycles containing PTW to extend device battery lifetime.
	TAU	1 – 9912 hours	A device in this state is considered to be in deep sleep mode to save energy, however, it still keeps the registration with this network.

TABLE 6. Different LTE-M timer values during the CONNECTED and IDLE mode.

Mode	Timers	Possible values (sec)
CONNECTED	Inactivity	0 – 65.536
	cDRX	0.64, 1.28, 2.56
	c-eDRX	1.28, 2.56, 5.12, 10.24
IDLE	i-eDRX	5.12, 10.24, ..., 2621.4
	PTW	1.28, 2.56, 5.12, 10.24
	iDRX	0.64, 1.28, 2.56
	Active	16 – 11160
	TAU	1 – 9912 hours

processing time, which also gained energy efficiency. However, this newly proposed protocol has not been appropriately tested with CIoT.

MQTT is another application-layer transfer protocol that runs over TCP, follows asynchronous publish/subscribe communication patterns, and is specified by OASIS [65]. In this mechanism, a broker, a publisher, and a subscriber is involved. The broker acts as a middle man and controls the packets being exchanged between a publisher and a subscriber. MQTT operates in three different modes; in the first mode, the sender does not receive an acknowledgment back from the receiver; in the second mode, the sender retransmits the same packet until it receives its confirmation back and, finally, in the third mode, a message is assured to be received the first time it is transmitted.

The authors of [16] [66] studied CoAP and MQTT for NB-IoT and wireless-sensor environments with less frequent and short messages being exchanged between a low-power device and a cloud server. CoAP offered a higher throughput than MQTT due to an additional three-way handshake of MQTT. Since the device with the MQTT protocol offers a lower throughput and spends more time in the CONNECTED state, huge energy consumption was observed. CoAP also performed better when the traffic load was high, but the traffic comprised small-sized packets; however, MQTT performed well when the system was less loaded. Overall, studies confirmed the negative impact of MQTT in terms of energy consumption, throughput, system load, availability, and coverage. Authors in [67] studied the impact of CoAP and MQTT_SN. MQTT_SN is a new version of MQTT

designed for low-power sensor networks by adding a new entity, a gateway, that buffers messages for the devices which are in deep-sleep mode. Messages are delivered once the receiving device leaves its deep-sleep mode and enters the CONNECTED state. Unlike default MQTT, MQTT_SN runs over UDP, which performs better in terms of energy consumption. Their paper claims to have more or less the same energy efficiency for both the protocols; however, MQTT_SN adds less complexity to the end-device when compared to CoAP. Since all the complexity of MQTT_SN lies at the broker side, it outperforms regular MQTT for applications that do not have any security concerns and only aim to save energy.

TAKE AWAY

In conclusion, we can say that the message reporting interval plays a crucial role in achieving the required battery life. Most of the device’s energy consumption happens when the device establishes the radio connection with the network [36]. Therefore, keeping fewer radio connections, e.g., low frequency of message reporting, can help save the device battery. Also, it is evident from several studies that sending one message per day is a good option in most cases [1], [17], [18], [40]. 3GPP [1] and other studies suggest that having at least 80% of data traffic with one message/day and 20% with more frequent reporting is acceptable. However, this only applies to scenarios with devices close to the base station that do not need to perform extra repetitions for extended coverage.

This section also emphasizes the importance of application-layer transfer protocols. Several papers studied CoAP, MQTT, and enhanced versions of their variants. Since CoCoA has shown better performance over CoAP and MQTT_SN over MQTT for low power technologies, we can say that configuring the end devices with these protocols could be helpful. However, since CoCoA has not been explicitly tested for CIoT, we keep this part for further testing by mobile network operators.³

³This section of the paper identifies a basic set of key guidelines for mobile operators and researchers based on the studied literature. The recommendations/suggestions are solely developed by the authors of this paper based on the surveyed papers. The provided guidelines are not very conclusive and cannot be used as is due to a number of inter-dependent parameters, which we have discussed throughout this paper.

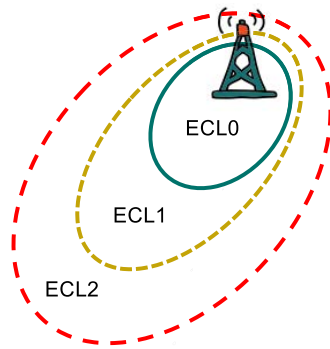


FIGURE 10. NB-IoT Extended Coverage Levels defined by 3GPP to gain deep indoor coverage.

b: RADIO LAYER

In NB-IoT, the configuration of the radio layer often plays a vital role in device energy consumption. In Section III-A1, we have discussed different parameters controlling the radio connectivity over the physical channel. These parameter settings, under various radio network conditions, significantly impacts the device energy consumption [12], [15], [31], [32], [34]. Although 3GPP has defined different parameters values, Table 5 and 6 highlight some of the parameter values for NB-IoT and LTE-M, choosing the best configurations for a specific situation is crucial.⁴ To this end, we will discuss these parameters in this section.

The authors of [15], [35]–[37], [46] studied the impact of PSM state on the device energy consumption. Studies showed that one could extend the battery lifetimes of devices to 6 – 10 years by just enabling PSM, where it takes only a few days for a battery to drain out completely when PSM is disabled. Sultania *et al.* [37] claim to achieve a battery life of 12 years if the Active Timer with eDRX cycles is set to less than 25 seconds and the PSM timer is set to more than 6 hours. The impact of PSM and eDRX cycles are studied in paper [31]. The authors of this paper argue for longer eDRX cycles in situations where downlink data is expected and demonstrate that in these cases, the battery life can be extended by 40%.

Michelinakis *et al.* [12] have discussed multiple aspects of NB-IoT device energy consumption using two different NB-IoT modules: Quectel BG95 and u-blox SARA-N211. Energy measurements were performed for three Extended Coverage Levels (ECL), ECL0, ECL1, and ECL2, as shown in Fig. 10, and for all possible settings of the RAI flag: default time out, i.e., a device releases its connection after an inactivity timeout; connection release, i.e., a device makes a transition into the IDLE state immediately after having sent uplink data; acknowledged connection release; i.e., the device waits for the acknowledgment back from the receiver side before it initiates a connection-release procedure. When the coverage is good, i.e., ECL is 0, the authors found that the energy

⁴The provided values in the table are not exact values and sometimes are estimated from the 3GPP documents.

consumption of the u-blox, mainly due to its hardware design, was twice as high as for BG96. Furthermore, running the same device for two different operators resulted in different levels of energy consumption since one of the operators did not implement cDRX properly. Another case, where the first operator consumed 2.39 joules during a single-data operation with no RAI, while the second operator consumed 0.82 joules with the RAI flag enabled, shows the importance of RAI for low energy consumption. Michelinakis *et al.* also found roughly the same level of energy consumption for the two coverage levels, 0 and 1. However, a huge difference was observed in those cases a device moved from coverage level 1 to coverage level 2.

In the second setting, where the device was tested with the RAI flag enabled, the NB-IoT device reduced its energy consumption by more than 80%. However, the energy consumption was slightly higher when a device waited for the acknowledgment from the server. The authors claimed to have a battery lifetime of 6.1, 25.5, and 45.5 years with reporting intervals of 1, 4, and 24 hours. However, it is necessary to have RAI, PSM, cDRX, and eDRX enabled for these figures to hold. Last but not least, the authors did not find any impact of packet size on the energy consumption except in those cases the RAI flag was enabled. Yeoh *et al.* [15] performed experiments with a similar kind of device and found that keeping a device longer in PSM state is beneficial since it avoids EPS bearer activation.

A more detailed evaluation is performed by Martinez *et al.* [32] in order to analyze the deciding factors for energy consumption in NB-IoT devices. For this purpose, two NB-IoT modules from different vendors are used in a cellular network operated by Vodaphone in Barcelona, Spain. In their work, they study three different device configuration modes: 1) a device sends a packet and keeps the connection until the Inactivity Timer expires and moves directly into PSM state; 2) a device immediately moves into the IDLE state. A state that it stays in for some period after sending data and listens to paging occasion for any downlink traffic and after that, it moves into PSM state; 3) a device releases its connection immediately after an uplink transmission and moves into PSM state directly.

The first configuration mode resulted in more significant energy consumption as compared to other modes due to a longer Inactivity Timer of 20 seconds which is set by the network operator. In addition, experiments also showed different energy levels for two different NB-IoT devices despite the fact that the network provider was the same. This behavior emphasizes the importance of selecting suitable hardware for NB-IoT devices. Results showed minimal impact with the increase in packet size starting from 64 bytes to 512 bytes in scenarios with good coverage. However, a noticeable impact was observed in scenarios with poor coverage since several packets were retransmitted several times.

In the second and third modes of configurations, i.e., configurations in which a device releases its connection immediately, Inactivity Timer of 0, both of the modes exhibited

a similar energy consumption. Thus, we can infer that the listening during the IDLE period has very little impact; even the second configuration mode enables a device to stay in the same state for eight more seconds before going into the PSM state. Thus, a long eDRX value is beneficial for delay-tolerant applications, i.e., a device is expecting some downlink traffic with longer delays. Furthermore, both the NB-IoT devices performed very well in scenarios with good and average coverage levels. In fact, its energy consumption did not rise until it was run in environments with lousy coverage. Under these circumstances, the device energy consumption correlated with packet size and significantly increased with increasing packet size. Based on these findings, Martinez *et al.* claim to have a battery lifetime of 3.1 years when a reporting interval of 1 hour was used.

TAKE AWAY

It follows from this section that PSM is an essential part of all CIoT devices to save energy. Configuring it with the highest possible value is recommended, provided the requirements for the application are fulfilled. Along with that, keeping the eDRX cycles and Active Timer (T_{3324}) short are recommended in cases where we do not expect any downlink information. However, slightly extending the eDRX cycles in scenarios with expected downlink traffic does not have a major impact on energy consumption. However, it is important that both the mobile network operators and CIoT devices have support for all the energy-saving techniques provided by 3GPP. Perhaps, having strict/inflexible parameter values set by the network operator would also result in a significant decrease in the device battery life. It is clear from a number of studies that keeping the TAU Timer (T_{3412}) very long and a short Active Timer (T_{3324}) helps in the optimizations of device energy consumption [23], [28].

2) INACTIVITY TIMER AND WAKE-UP CALL

As shown in Section III-A1.a, a substantial traffic load results in an additional radio activity, which has a significant impact on the device's battery lifetime. Another critical factor for the device energy consumption is how long the device stays in state RRC CONNECTED, i.e., the length of the Inactivity Timer. During Inactivity Timer, a radio is not transmitting anything; instead, it listens to the physical channel actively or partially active depending on the configurations by the network operator. In a partial configuration, a device alternates between active listening and sleep cycles, also called cDRX cycles, to save energy. However, in the active listening mode with no cDRX support, a device continuously listens to the physical channel for any downlink traffic. In such cases, a connection is released by the network after receiving a RAI message from the device.

Michelinakis *et al.* [12] studied the impact of the Inactivity Timer with and without cDRX cycles in two networks operated by different companies and with the Inactivity Timer being varied between 0 and 65 seconds. Experiments suggested that the energy consumption raised three times

when cDRX was disabled. The experiments also suggested that when RAI was used, the energy consumption could be reduced by as much as 15 times. Although cDRX and RAI are crucial parameters and enabling them can save more energy, one of the studied network operators completely ignored these parameters. Michelinakis *et al.* claim to have an extended battery lifetime of 30 years with a reporting interval of 4 hours and with the RAI enabled.

Martinez *et al.* [32] also demonstrate the importance of cDRX by testing NB-IoT devices from two different vendors. The evaluation comprised three different use cases: 1) A device keeps a connection for 20 seconds after sending a packet, 2) a device makes the transition into IDLE state immediately after having sent a packet, 3) a device keeps the connection up until the first acknowledgment arrives. The results suggested that letting a device directly go into the IDLE state gave a significant reduction in energy consumption. However, the authors also observed twice the energy consumption in one of the devices because it did not seem to go into a deep sleep between cDRX cycles in CONNECTED mode. Martinez *et al.* claim that the problem occurred either due to some hardware or firmware limitation, which again points toward using the latest and most up-to-date firmware. Their experiments also indicated that shortening the Inactivity Timer could lead to significant reductions in energy consumption.

Pilar *et al.* [46] investigated the impact of the Inactivity Timer on the device's energy consumption. They carried out their investigation for different traffic interval arrival times (IAT) and communication optimizations, e.g., control plane and user plane optimizations. Authors found a massive impact of IAT over energy consumption and suggest having a short Inactivity Timer of 10 seconds or so for longer and medium IAT, e.g., IAT of 20 seconds or more. However, Pilar *et al.* emphasize that enabling RAI in order to keep the connection short and to activate the control plane optimization are the key to saving energy.

Liu *et al.* [68] proposed an energy-efficient technique of activation and transmissions of uplink traffic for cellular IoT. The core of this paper is twofold: First, the paper addresses the problem of a true/false activation of the end devices by the base station with probability functions. Second, the paper considers the energy-efficient uplink transmission by the end device. This paper targets a scenario of a false wake-up call from the base station for the devices outside of its vicinity. As a result, a redundant uplink transmission from that device may end up in the device consuming unnecessary energy. Liu *et al.* suggested proper coordination between the base stations to avoid such scenarios.

TAKE AWAY

This section recommends configuring the Inactivity Timer to a small value. However, this parameter is entirely controlled by the mobile network operator and cannot be configured by the user. It is also noticeable from a number of studies that enabling cDRX and RAI is very effective in keeping energy

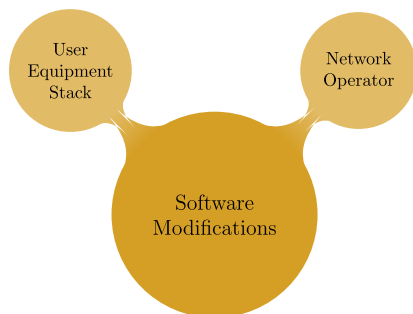


FIGURE 11. Categorization of software modifications.

consumption to a minimum. However, studies stressed the proper implementation of these energy-saving techniques by mobile operators to ensure a longer battery life.

B. SOFTWARE MODIFICATIONS

This part of the paper discusses the energy efficiency achieved by software modifications done either at the UE or on the network operator side, as shown in Fig. 11. We will analyze software modifications such as improved radio layer protocols for cellular IoT technologies, modifications in scheduling request procedures to access radio channel resources, the addition of new software entities at the core network to enhance uplink and downlink communication, etc.

Saahithyan *et al.* [56] proposed a new energy-saving mechanism for EC-GSM-IoT based on DRX cycles with values between 0.5 s - 4.5 s. During each paging cycle, a device receives paging bursts, and for each paging reception, a message block is decoded for any necessary information. In EC-GSM-IoT, a device can only start decoding after having received a certain amount of bursts. The decoding of a paging block that is not intended for a particular device, consumes an extra amount of energy. They proposed to use two “stealing bits” to indicate that a paging block has some useful information. No extra decoding is required since the device will get to know whether the paging block contains valuable information or not by decoding the first two bursts. Stealing bits are primarily used to indicate whether the information in a certain frame belongs to either the Traffic Channel (TCH) or the Fast Associated Control Channel (FACC) during a voice call. However, these bits are used as a dummy over the Paging Channel (PCH) and are discarded by the receiver. Saahithyan *et al.* claim to have a 40% reduction in energy consumption during paging-block decoding as compared to standard decoding.

CIoT technologies target a wide variety of applications in our daily lives, the traffic volume in the cellular network infrastructure is expected to be increased by 1000 times [69]–[71]. Data traffic generated by the massive deployment of end devices would not only impact the current cellular infrastructure by introducing congestion and system overload but also the end devices in terms of energy consumption. This system overload will cause packet loss and unexpected delays but

also affect the channel access ratio by the end devices. This results in many retransmission attempts and hence increasing the energy consumption as well. In order to counter the congestion problem, 3GPP proposed a Group Paging (GP) mechanism [72]. In this mechanism, end devices are grouped based on different parameters such as quality of service, delay-tolerant, time-controlled, etc., and are assigned with a specific group identification number, also named as Group ID (GID). The network accesses each group with the respective GID whenever it needs some information by sending out the paging messages. After receiving a paging message, devices in that respective group start the random access procedure to complete the connection. However, the performance of the proposed mechanism degrades with the increase in the number of group devices [73], [74]. Therefore, an improved/new method is required to address this issue.

Osama *et al.* [50] proposed an improved version of the GP mechanism, Traffic Scattering For Group Pagig (TSFGP) [50] and Further Improved-TSFGP (FI-TSFGP) in [51] for CIoT technologies. In the proposed method, devices in a certain group responded to the paging messages by accessing the physical channel and sending the preamble. After transmitting the preambles, there is a number of devices with successful connections. However, there are still a number of devices that failed to establish the connection. A number of reasons can define such connection failures: either the preambles collided, or was not detected by the base station correctly, or even was not indicated in the random access messages. A backoff timer is defined for such devices, during which a device waits and retransmits the preamble. This simple mechanism not only reduces the network overhead, but also lowers the device’s energy consumption. A number of experiments also show that FI-TSFGP outperforms the standard GP method by saving up to 80% of overall device energy.

Pradhan *et al.* [52] proposed an energy-efficient GP mechanism for CIoT technologies. A genetic algorithm is suggested in order to have a certain number of groups with the number of devices closely related to their functionalities and duty cycle period. Initially, four major groups are assembled based on the device mobility, delay tolerance, traffic patterns, and DRX configurations. However, to counter network congestion due to large number of end devices in a single group, groups are further divided into subgroups based on the priority of data. Based on these parameters setting, a threshold value is calculated for each subgroup and also for each individual device in terms of energy consumption. Experiments showed that one could save up to 44% of device energy using this method when compared to a random grouping of the devices.

Lee, Jinseong, and Jaiyong Lee [45] proposed a Prediction Based Energy-Saving Mechanism (PBESM) for NB-IoT to address the problem of repeated scheduling request procedures. In NB-IoT, repeating transmissions of NPRACH and NPUSCH can cause extra energy consumption, which may result in a reduced battery life. The proposed mechanism

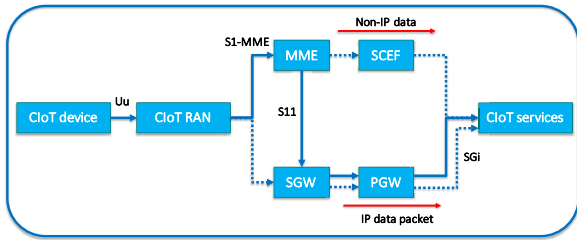


FIGURE 12. User Plane Clot EPS optimization (dotted line path) and Control Plane Clot EPS optimization (solid line path).

consists of two entities: a Packet Inspection Entity (PIE) and a Packet Prediction Entity (PPE) at eNodeB and MME, respectively. The PIE module measures and predicts the session delays for different response messages, e.g., transport-layer protocol messages including TCP, CoAP, DTLS, and NAS messages. The predicted session delays are transmitted to the PPE, which calculates the processing delay between a downlink and an uplink data transmission. In this way, the eNodeB pre-assigns radio resources to an NB-IoT device. The authors show that PBESM can save 34% of the consumed energy.

To be able to set up a communication link between a UE and an eNodeB in LTE, a service request procedure needs to complete the RRC connection and physical resources need to be acquired. Since cellular IoT focuses on less complex and low-power devices, less complex mechanisms are proposed by 3GPP for a radio connection with reduced signaling: User Plane optimization (UP) and Control Plane optimization (CP), as shown in Fig. 12. In the figure, the dotted line depicts the path explored for UP optimization, and the solid line path represents the CP optimization. In CP, messages are piggybacked on NAS messages towards MME, and no other signaling is required, such as access stratum security context and RRC reconfiguration. However, in the UP optimization, two new control procedures are explored: connection resume and connection suspend, and the data is transmitted over the data plane while still preserving the RRC context. Andres-Maldonado *et al.* [46] studied the impact of a conventional service request procedure, a control-plane and a user-plane optimization for cellular IoT. They studied these three different modes of operations under varying traffic IATs ranging between 320 ms to 48 hours. For smaller and larger IATs, all three consumed roughly the same amount of energy. However, CP optimization saved 87% of total energy consumption when compared to other modes during medium IAT, and the reason was the RAI procedure which shortened the connection period. A longer IAT impacted the CP negatively due to a premature RRC connection release and since a new connection needed to be established.

Dawaliby *et al.* [48] proposed a new energy-efficient resource allocation scheme for LTE-M technology. The proposed cross-layer scheme enables LTE-M to schedule the network traffic in frequency and time domain using a memetic-based algorithm. To gain additional energy effi-

ciency, DRX cycles are tuned according to application priority levels, e.g., applications with high and low latency requirements. An application with high priority cannot accept longer delays, and hence shorter DRX values are assigned. On the other hand, applications with low priority are assigned with longer DRX cycles to save energy, but at the cost of more delays. Results showed better performance of the proposed algorithm with extended DRX cycles compared to state-of-the-art Round Robin and PF-Riding peaks algorithm.

In order to enhance coverage in Clot, repeating control signals or data transmission is considered one of the most promising solutions, irrespective of coverage conditions. However, depending on the coverage levels, the number of repetitions varies from zero to hundred times, and a device also upgrades/downgrades its Modulation and Coding Scheme (MCS) level to enhance communication. Doing this also impacts the device battery life directly and is crucial for low-power devices. Keeping in mind the importance of repetitions and the MCS level for low-power devices, Changsheng *et al.* [47] proposed an adaptive uplink scheduling mechanism that determines the number of repetitions on the fly by using a feedback mechanism. In order to provide reliability and better throughput for an NB-IoT device, the proposed mechanism provides inner-loop and outer-loop link adaptation techniques. The outer-loop link adaptation mechanism determines the level of MCS by successfully decoding a number of ACKs and NACKs. It also determines the number of repetitions based on channel status, MCS level, and most importantly, the ACK/NACK response. If the eNodeB supports target block error ratio (BLER), the number of repetitions is decreased provided the ACK is successful. However, if BLER is not supported, the number of repetitions is increased and the MCS level adjusted. The inner-loop link adaptation technique also determines the BLER variation based on ACKs/NACKs. If the BLER is less than 7% for the current transmission, the number of repetitions is decreased, and it will not increase until the current BLER is greater than 14%. Changsheng *et al.* claim to save 14 – 46% in the number of active radio periods compared to standard uplink scheduling methods.

Di Lecce *et al.* [49] proposed an energy-saving solution for NB-IoT devices located in places with a lousy coverage: cooperative relaying. Devices in poor coverage need to perform a number of repetitions in order to deliver a packet to the eNodeB successfully. In the solution proposed by Di Lecce *et al.*, a device tries to limit the number of energy-costly repetitions by finding neighboring or relaying nodes to deliver the same packet to eNodeB. A greedy algorithm is proposed to select relaying nodes with the shortest distance to the eNodeB that are also in the IDLE state. Although this technique is not very common and requires extra computation by the devices, the authors argue that it reduces the energy consumption by 12 – 30%.

Another way of achieving the energy efficiency in cellular networks is the selection of relevant MAC layer protocols. Duty cycling is one of the primary mechanisms

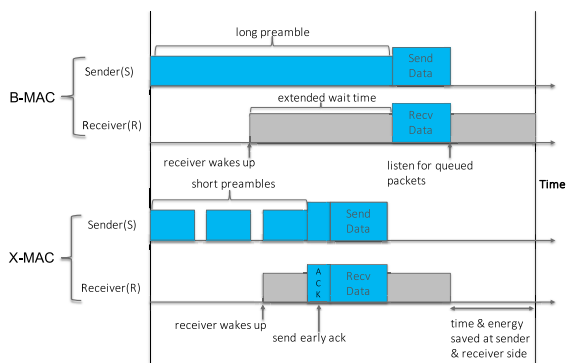


FIGURE 13. A timeline comparison of energy-efficient X-MAC with B-MAC [75] (long and short preamble comparison, respectively).

at the MAC layer to achieve required energy efficiency. A device listens to the channel during each duty cycle, also known as the wake cycle, and sleeps for the next half-cycle. The major problem arises to gain energy efficiency, low latency, and high throughput when the end devices wake and sleep in the network without sending/receiving and data. A number of MAC protocols have been proposed to reduce the idle listening period of the devices, e.g., Sensor-MAC (S-MAC) [76], Timeout-MAC (T-MAC) [77], Berkeley-MAC (B-MAC) [78], X-MAC [75]. Josifović *et al.* [54] studied MAC layer protocols such as B-MAC and X-MAC for all three cellular technologies: EC-GSM-IoT, NB-IoT, and LTE-M. B-MAC protocol provides an adaptive preamble sampling scheme that samples the medium with fixed intervals. In order to send a data packet, a device listens to the medium for its availability. Next, a long wake-up preamble is sent, followed by the data packet. However, the X-MAC approach is the opposite, where a sending device sends short preamble packets, and waits for acknowledgment. When the acknowledgment has been received, the data packet is immediately forwarded. The mechanism of keeping short cycles reduces not only the device energy consumption but also the latency, as shown in Fig. 13. Simulated results also showed that B-MAC consumes more energy as it keeps the radio alive due to frequent data transmissions. On the other hand, X-MAC consumed less energy due to infrequent transmissions and the use of fewer physical resources. Their study found the X-MAC protocol to be a suitable option for low-power devices.

TAKE AWAY

Apart from standardization provided by 3GPP, we have observed a number of studies where a team of researchers came up with new/ revised techniques to improve the device energy consumption. Although some of the techniques have been tested at a smaller scale, they have the potential to carry out further experimentation by the mobile network operators. For example, Group-based paging is a technique directed by 3GPP standardization to address a group of devices altogether. If the devices are grouped intelligently, either based

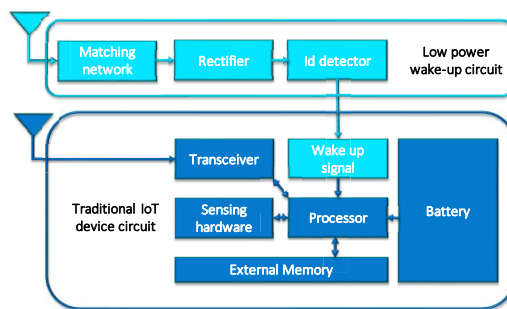


FIGURE 14. Low power wake-up circuitry for Cellular IoT devices.

on different parameters or by calculating a threshold value based on multiples parameters, it would reduce the problem of false wake-up calls and hence save the device energy. In conclusion, it is necessary to accommodate such software modifications to achieve at least the required battery life.

C. HARDWARE INTEGRATION

A device saves much energy by spending as much time as possible in the deep-sleep or PSM state. In this state, a device only wakes up periodically to perform a TAU procedure or when it has some data to send to the application server. A TAU timer typically controls TAU procedures, which decides how many times a device needs to send its location update. In some use cases, where this information is unnecessary, these connections add an extra burden to a device with limited energy capacity. Evading periodic connection mechanism, Kouzayha *et al.* [14] proposed a new energy-saving mechanism for CIoT where a serving base station sends a wake-up signal to the device in order to complete the connection when it is required. A low-power wake-up receiver is added in front of an IoT device, as shown in Fig. 14, and when the device receives a wake-up signal from the base station, it activates the primary circuit of the IoT device in order to perform uplink transmission. The proposed PSM mechanism is similar to the one standardized by 3GPP [1] apart from the TAU procedure, which is replaced by an on-demand radio connection using a wake-up signal call from the base station. Simulation results confirm that adding a low-power receiver can save up to 50% of the energy consumed compared with a traditional TAU procedure. However, in the proposed mechanism, a device may wake up by receiving a wake-up call not intended for that device, a.k.a. a false wake-up call, resulting in extra energy consumption. Therefore, an error-proof mechanism is required to avoid such false calls.

In [13], a similar architecture is discussed where a low-power receiver is embedded with the device receiver in order to detect any downlink traffic for that device. The proposed mechanism enables a device to save more energy by deactivating the main receiver and activating the low-power receiver during DRX and eDRX cycles. Integrating a low-power receiver could add an extra delay for time-critical applications, but it has shown outstanding results for

delay-tolerant applications while gaining 10 times of energy efficiency. To further validate the performance of a low-power receiver, the authors of [13] performed experiments in an LTE-M environment with and without a low-power receiver during cDRX and eDRX cycles. The results gave a 10 times less energy consumption during eDRX cycles and a 4 times reduction during cDRX cycles when a low-power receiver was enabled in a normal coverage scenario. Although the proposed solution is very fascinating, the same energy efficiency cannot be achieved with less sensitive, low-power receivers in extended coverage scenarios.

TAKE AWAY

In the above sections, the authors have studied an essential aspect of energy consumption and provided the hardware-based solution by adding low power receivers. However, these solutions do not seem to be very practical and they could not be implemented on a larger scale in comparison with configuration settings and software updates. In addition, it can be a challenging scenario for the industry and telecom operators to make changes to the hardware. Although, few studies showed a reasonable reduction of energy consumption, the solutions are not very feasible for common network operators to deploy and test on a large scale.

IV. IMPLICATION AND DISCUSSION

CIoT is a newly proposed technology standardized by 3GPP to facilitate a wide variety of IoT and machine-to-machine applications, as specified in Fig. 5 in Section II-A. Proposed technologies primarily operate in licensed spectrum and thus provide very stable and reliable radio connections to IoT devices. Moreover, the use of licensed spectrum allows IoT applications to work in harsh conditions while providing long-distance coverage in crowded environments. Of course, the long battery life for such devices is a serious concern, and replacing batteries in thousands of devices is costly in terms of time and maintenance. Therefore, this paper explored the literature and comprehensively studied the energy-saving mechanisms and tunable parameters to achieve extended battery life. Along with standardized mechanisms proposed by 3GPP, we also have investigated other studies with energy-efficient techniques.

To better understand a variety of proposed mechanisms, we have characterized them into three main categories:

- Configurations that are required to find efficient settings according to specific situations.
- Software modifications where we have discussed software-based changes to achieve energy efficiency.
- Hardware integrations that require additional low energy transceivers.

This section will discuss all the categories individually and provide a brief summary.

We mainly discuss the parameter settings for application, transport, and radio-layer protocols starting with configurations. CIoT technologies aim at providing support for appli-

cations with different traffic patterns and message reporting. Therefore, it is crucial to understand how frequent and how much data an application needs to send. NB-IoT is designed mainly for less frequent and small data transmissions; however, LTE-M can support more frequent transmission due to the nature of the design. Overall, we have found a single transmission per day more appropriate for most applications. In addition, devices with non-critical data can hold the transmissions for a few days to save battery. Similarly, the base station supports buffering of ten downlink messages for a particular device. However, the same is not the case for critical applications where data needs to be transmitted promptly. Therefore, it is essential to configure reporting intervals accordingly.

We also have studied application layer protocols in detail for CIoT, such as CoAP, CoCoA, MQTT, and MQTT_SN. Because each protocol is designed and works differently, studied protocols are advised to operate in different situations. However, since this paper focuses on energy efficiency, MQTT_SN was found to be a better choice as it runs over the UDP protocol and adds less complexity to the device.

Typical CIoT devices incorporate a micro controller, radio transceiver, additional hardware, and a battery. Among all the components, the transceiver consumes a significant amount of energy. Therefore, it is essential to recognize the radio parameters to estimate the device's battery life. This paper has studied the impact of the Inactivity Timer, cDRX, RAI, eDRX, iDRX, Active Timer, PSM, and periodic and fixed TAU updates. A long Inactivity Timer and radio connected state have the highest magnitude of energy consumption. However, the magnitude can be reduced by enabling cDRX and RAI. Still, studies suggest having a short Inactivity Timer value when the network operator does not support RAI. Moreover, the Active Timer has little impact on energy consumption due to eDRX with long sleep cycles. Hence, we can configure it to a slightly higher value in situations where we are expecting downlink traffic. In addition, unnecessary fixed interval TAU updates also consume extra energy. Therefore, the periodic TAU procedure should be adapted.

Another category we have defined for energy-efficient solutions is software modifications. These modifications are adapted to acquire additional battery life. Software modifications are not limited to end devices but can also be done on the network operator side. This paper has covered both sides. For example, several researchers have proposed efficient paging procedures by adding additional bits at the paging block's start, allowing the device to know if that paging block is relevant by decoding only some part of the paging block and saving more energy.

On the other hand, many other studies proposed efficient group paging to invoke a group of devices to report sensor data. However, this solution also invokes devices outside that group, called false wake-up calls, and more research is needed to avoid such scenarios. Some other studies also proposed a prediction-based energy-efficient module that can be deployed at MME. This module helps predict regular sessions

TABLE 7. Research work that has partially studied/discussed open issues.

Research work		Open Issues							
Study	Year	Tunable Parameters	Radio Coverage	Enhanced Paging	Efficient hardware and firmware designs	Random access and congestion control	Group Paging	Wake-up call	Real-world measurements
Michelinakis <i>et al.</i> [12]	2020	✓	✓	-	-	-	-	-	✓
Yeoh <i>et al.</i> [15]	2018	✓	-	-	-	-	-	-	-
Anna <i>et al.</i> [16]	2019	✓	-	-	-	-	-	-	-
Martinez <i>et al.</i> [32]	2019	-	✓	-	-	-	-	-	✓
Saahithyan <i>et al.</i> [56]	2016	-	-	✓	-	-	-	-	-
Kouzayha <i>et al.</i> [14]	2017	-	-	-	✓	-	-	✓	-
Lee, Jinseong, and Jaiyong Lee [45]	2017	-	-	-	-	✓	-	-	-
Dawaliby <i>et al.</i> in [48]	2018	-	-	-	-	✓	-	-	-
Pradhan <i>et al.</i> [52]	2021	-	-	-	-	-	✓	-	-

with possible delays and allocate the resources accordingly to save device energy. Indeed, all these software-based solutions are very efficient for CIoT technologies and can also be adapted for other LPWAN technologies. However, we still need these solutions to be standardized for these solutions to be deployed all over the world.

The third and last category discussed in this paper is hardware integrations. Although only a few research studies have made contributions to achieving long battery life in this way, and general deployment of hardware integrations appear impractical, it may still make a huge difference in select scenarios. Apart from discussing the energy-saving mechanisms, we still have many unanswered research questions and open issues, which we will investigate in the next section. However, as shown in Table 7, only a few studies have tried to examine them, and more detailed studies are required to address the issues left unanswered.

V. OPEN ISSUES

We have observed various ways to achieve battery efficiency for CIoT technologies from the above literature. Still, many open issues and research questions are left unanswered. In the following sections, we discuss what we believe are the major open issues.

A. TUNABLE PARAMETERS

The tuning of CIoT stack parameters is a simple way to reduce energy consumption. Still, it is everything but straightforward to find an appropriate tuning. For example, eDRX cycles are energy economical but keeping them longer may result in an extra delay for downlink traffic reception. Selecting a certain set of parameters may provide energy efficiency in a particular environment; however, this may result in extra energy consumption in environments with longer delays.

B. RADIO COVERAGE

The deployment of cellular infrastructure varies from one location to another, e.g., a more dense network is required within the city than some remote areas. Keeping similar parameter values at the radio layer for different coverage con-

ditions is not sufficient and requires a dynamic allocation of the resources. A comprehensive study is required for different scenarios with varying radio conditions, and hence it is an open challenge for researchers.

C. ENHANCE PAGING MECHANISM

A few enhanced paging mechanisms have been proposed by authors with improved energy efficiency. In these paging mechanisms, the energy efficiency is achieved by not decoding all the packets in order and in that way know whether the downlink information is intended for that particular device or not; however, these mechanisms still need to be tested to demonstrate their reliability.

D. EFFICIENT HARDWARE AND FIRMWARE DESIGNS

Designing and developing firmware for IoT devices that strictly follows the 3GPP standards is crucial. Even a little flaw in implementing DRX cycles or not properly managing power during PSM could result in unnecessary energy consumption. It follows from a number of research papers that having such issues in the first and second-generation devices are very common [15], [33].

E. RANDOM ACCESS AND CONGESTION CONTROL MECHANISMS

Due to massive deployments of CIoT devices, energy-saving radio channel access is crucial. Since the end devices are allotted a limited amount of radio resources, the probability of network congestion increases with an increase in the number of devices per cell, e.g., 60,000 devices per cell in EC-GSM-IoT, 100,000 and 1000,000 devices per cell in NB-IoT and LTE-M, respectively. Many solutions are available for other wireless technologies such as Extended Access Barring (EAB) [79], prioritized random access schemes [80], enhanced random access procedure [81]; however, testing them for CIoT could be more beneficial. Some of the authors have found data aggregation and node clustering [82]–[84] as beneficial ways of making more efficient use of CIoT radio resources. Still, proper testing of these techniques for CIoT is missing from the literature.

Among other schemes, a comprehensive comparison of different application-layer protocols, such as CoAP [64], [85], CoCoA+ [86], MQTT [16], and MQTT_SN [67], also require more exploration in terms of congestion control from the researchers.

F. GROUP PAGING

Group Paging (GP) is considered one of the solutions to be adopted to reduce the energy consumption of CIoT devices. A number of papers have suggested an improved version of standard GP techniques. These are, however, suitable for a specific set of scenarios, such as the Push and Pull approach. During the Push approach, the connection is initiated by the base station, and the end device initiates the connection in the pull approach. Moreover, the congestion caused by massive deployment of devices, which results in more delays, and retransmissions, remains an open issue.

G. WAKE-UP SIGNAL CALLS

Nafiseh *et al.* [13] used low-power radio receivers to wake up a device by sending a wake-up call from the base station to the CIoT device. The solution is proposed for scenarios where a device wakes up due to the expiration of a timer, something which could result in extra energy consumption if the device does not have any uplink traffic. The proposed solution is also envisioned to reduce energy consumption in scenarios with infrequent data transmissions. Still, a device is more likely to wake up due to a false wake-up call [87], something which causes an unnecessary radio-connection establishment. Further research is required to make this technique more energy-efficient.

H. REAL-WORLD MEASUREMENTS

Most of the existing work focuses on CIoT device measurements during ideal conditions, while measurements during more realistic conditions are missing. Most importantly, testing the devices in all the available coverage levels could be more exciting while also considering the effects of device mobility on the energy consumption of LTE-M devices. In addition, more empirical tests are needed to evaluate the effect of limited coverage over the device battery consumption.

I. NB-IoT: CENTER OF ATTENTION

It is evident from contemporary research that NB-IoT is the 3GPP-based CIoT technology that has thus far received the most attention. As a consequence, there is a vast knowledge gap between this and the other two technologies: LTE-M and EC-GSM-IoT, as shown in Fig. 15. Also, the number of surveyed papers in this research article actively demonstrates the importance of research studies for LTE-M and EC-GSM-IoT.

VI. CONCLUSION

This survey paper discusses the 3GPP-based CIoT technologies and comprehensively studies energy-saving solutions.

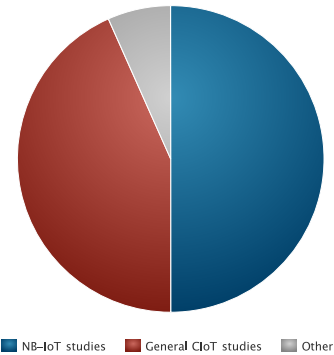


FIGURE 15. An approx. visualisation of published papers for energy efficiency of CIoT technologies in the past few years.

CIoT technologies provide a suitable alternative for short-to-long range IoT applications with a longer battery lifetime and a large number of small messages, e.g., health monitoring, home safety, agriculture, transportation, etc. Since these technologies target applications with low throughput and an extended battery life, energy efficiency is crucial. In order to achieve such low energy consumption, CIoT usually operates in narrow communication bandwidth, and thus, it can be deployed within the current cellular infrastructure, e.g., LTE guard-band or in-band. Furthermore, as an extension to earlier cellular technologies, CIoT also inherits some of its energy-saving mechanisms to satisfy low battery consumption needs, such as discontinuous reception cycles or DRX. The technical details, along with 3GPP-based energy-saving methods, are discussed in this paper.

As illustrated by the survey, there are multiple parameters affecting the device energy consumption differently in particular situations; the surveyed papers for instance showed that an improper implementation of DRX or no DRX at all could cause an extensive energy consumption in most cases. 3GPP also indicates fewer data transmissions a day, e.g., one message per day, to achieve a longer battery life. It is very clear from several studies that an application with too frequent data transmission is costly in terms of energy consumption, e.g., data transmission every 1 – 2 hours. However, a device with less frequent data transmissions, e.g., one message per day, is shown to achieve an expected battery life.

This survey paper not only studies the energy-saving mechanisms standardized by 3GPP, solutions provided by other researchers are also surveyed. Software modifications and hardware integrations consider such kinds of energy-efficient techniques. Papers suggesting improved radio stack protocols at UE and eNodeB are surveyed in software modification scenarios. Lastly, the hardware integration section investigates the papers where energy efficiency is achieved by adding some hardware modules. One of the significant contributions of this paper is to study the open challenges and knowledge gaps and provide further research directions. These open challenges can further lead to better solutions and hence provide CIoT devices with a longer battery life.

TABLE 8. The following table illustrates the significance of various acronyms and abbreviations used throughout this survey paper.

Abbreviation	Meaning
ACB	Access Class Barring
B-MAC	Berkeley-MAC
BLER	Block Error Ratio
CloT	Cellular Internet of Things
CoCoA	CoAP Congestion Control Advanced
cDRX	connected mode DRX
CMM	Connected Mode Mobility
CoAP	Constrained Application Protocol
CP	Control Plane
CC	Coverage Classes
CE	Coverage Enhancement
DTLS	Datagram Transport Layer Security
DRX	Discontinuous Reception
EDT	Early Data Transmission
eGPRS	enhanced General Packet Radio Service
EPS	Evolved Packet System
EAB	Extended Access Barring
EC-GSM-IoT	Extended Coverage Global System for Mobile Communications Internet of Things
ECL	Extended Coverage Levels
eDRX	extended Discontinuous Reception
FACC	Fast Associated Control Channel
5G	fifth-generation cellular system
FI-TSFGP	Further Improved-TSFGP
GSM	Global System for Mobile Communications
GID	Group ID
GP	Group Paging
iDRX	idle mode DRX
IMM	Idle Mode Mobility
IoT	Internet of Things
IAT	Interval Arrival Times
LTE	Long-Term Evolution
LPWAN	Low-Power Wide-Area Network
LTE-M	LTE Machine-Type Communications
MTC	Machine-Type Communications
mMTC	massive Machine-Type Communications
MCL	Maximum Coupling Loss
MAC	Medium access control
MQTT	Message Queue Telemetry Transport
MME	Mobility Management Entity
MCS	Modulation and Coding Scheme
MQTT_SN	MQTT for Sensor Networks
NB-IoT	Narrowband Internet of Things
NR	New Radio
NAS	Non-access stratum
PIE	Packet Inspection Entity
PPE	Packet Prediction Entity
PCH	Paging Channel
PTW	Paging Transmission Window
PSM	Power Saving Mode
RRC	Radio Resource Control
RAI	Release Assistance Indicator
RTO	Retransmission TimeOut
S-MAC	Sensor-MAC
SR	Service Request
SMS	Short Message Service
3GPP	Third Generation Partnership Project
T-MAC	TimeOut-MAC
TAU	Tracking Area Update
TCH	Traffic Channel
TSFGP	Traffic Scattering For Group Pagig
TCP	Transmission Control Protocol
ULLC	Ultra-Reliable Low Latency Communications
UDP	User Datagram Protocol
UE	User Equipment
UP	User Plane
VoLTE	Voice over LTE

In our future work, we intend to further our work on NB-IoT energy efficiency with parameter configurations [88] including simulated as well as real-world measurements. A simulated environment comes very handy because we cannot change specific parameters in real-world measurements. In addition, we also plan to consider how mobile edge computing could contribute to more energy-efficient IoT solutions.

APPENDIX

See Table 8.

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