Cellular Internet of Things: Use Cases, Technologies, and Future Work

Teshager Hailemariam Moges[a], Demeke Shumeye Lakew[b], Ngoc Phi Nguyen[c], Nhu-Ngoc Dao[a], Sungrae Cho[b]

[a]*Department of Computer Science and Engineering, Sejong University, Seoul 05006, South Korea*
[b]*School of Computer Science and Engineering, Chung-Ang University, Seoul 06974, South Korea*
[c]*Department of Aerospace Engineering, Sejong University, Seoul 05006, South Korea*

Abstract

The Internet of Things (IoT) has revolutionized how we live and work by connecting everyday devices to the Internet. As the demand for IoT devices grows, a reliable and efficient communication infrastructure to support these devices has become crucial. Cellular IoT (CIoT) has emerged as a promising solution to this challenge, offering a low-cost, low-power, and scalable communication network for IoT devices. This paper presents a comprehensive overview of CIoT technology in response to the growing demand for IoT applications with low latency, high coverage, low power consumption, high device connection, and low cost. The four major CIoT technologies standardized by the Third Generation Partnership Project (3GPP) organization are investigated, including extended coverage global system for mobile communications IoT (EC-GSM-IoT), long-term evolution for machine-type communications (LTE-M), narrowband IoT (NB-IoT), and recently, new radio reduced capability (NR-RedCap). These technologies are analyzed regarding their fundamental focuses, features, use cases, requirements, and future work. In addition, we provide a comparative study of these types of IoT technology to assist researchers in understanding the available options and their potential limitations. Finally, open challenges are discussed to direct future research in the field.

Keywords: Internet of things, cellular Internet of things, machine-type communications, mobile networks

1. Introduction

The cellular Internet of Things (CIoT) refers to using cellular networks, such as fourth and fifth-generation (4G and 5G) networks, to connect IoT devices to the Internet. These devices can range from simple to complex, from smart thermostats and surveillance cameras to agricultural monitoring systems. The concept of CIoT is derived from an interest in a wide coverage area, massive connectivity, security, trustworthiness, ultralow latency, throughput, and ultra-reliability. One of the main benefits of using cellular networks for the IoT is their wide coverage area and ability to connect to the Internet, even in remote or hard-to-reach locations. Compared to other types of wireless networks, cellular networks typically offer greater reliability and lower latency, making them ideal for applications that require real-time data transfers or remote control [1].

Moreover, because many IoT applications are mission critical and demand more than 99.99% reliability with less than 1 ms end-to-end latency, cellular connectivity is considered the most appropriate option because it has access to the licensed spectrum, ensuring the security and reliability of the communication service [2]. Due to their global and standardized nature, cellular technology is required for the connection of billions of devices in IoT applications. The cellular network offers a variety of attributes that makes it a good choice for various IoT applications, including good quality of service (QoS) and experience (QoE), the ability to support mobility and service-level agreements, fast data rates, and worldwide coverage [1]. To support massive connectivity, the Third Generation Partnership Project (3GPP) organization has standardized three new types of technology: the extended coverage (EC) global system for mobile communications (GSM) IoT (EC-GSM-IoT), long-term evolution (LTE) for machine-type communications (LTE-M), and narrowband IoT (NB-IoT), known as the CIoT, since Release (Rel.) 13. Additionally, Rel. 17 introduced the fourth category of CIoT technology, called reduced capability (RedCap) new radio (NR), which is specifically designed to offer cellular services to a vast number of IoT devices planned for use in the 5G licensed spectrum [3]. The improvements made by 3GPP from Rel. 13 [4] to 15 [5] are on their baseline deployment; however, since Rel. 16, LTE-M and the NB-IoT can share the 5G NR channels with 5G devices. 3GPP is working on a technology that assures better coverage for a large number of inexpensive, low-throughput devices with low power consumption in applications that can tolerate delays. The CIoT is being applied as a new approach to global connectivity and remote device management. Moreover, given the enhanced data rate and capacity, 5G networks are expected to drive numerous IoT connections. Thus, cellular networks should be optimized to support low-power and low-data-rate use cases to satisfy IoT demands [6, 7, 8, 9, 10].

Machine-type communication (MTC) applications can be delay-tolerant (tolerate low data rates and longer latencies, e.g., utility meters) or delay-sensitive (cannot tolerate low data rates

---

Email addresses: `22110612@sju.ac.kr` (Teshager Hailemariam Moges), `demeke@uclab.re.kr` (Demeke Shumeye Lakew), `npnguyen@sejong.ac.kr` (Ngoc Phi Nguyen), `nndao@sejong.ac.kr` (Nhu-Ngoc Dao), `srcho@cau.ac.kr` (Sungrae Cho)

Table 1: Definitions of Abbreviations

Abbreviations	Definition	Abbreviations	Definition
3GPP	Third Generation Partnership Project	8PSK	Eight-phase shift keying
BS	Base station	CEL	Coverage enhancement level
CE	Coverage enhancement	CIoT	Cellular Internet of Things
DRI	Day reporting interval	DL	Downlink
DRX	Discontinuous reception cycles	EC-GSM-IoT	Extended coverage global system for mobile communications Internet of Things
eDRX	extended discontinuous reception	EDR	Early data transmission
eGPRS	enhanced-general packet radio service	eMBB	enhanced mobile broadband
FD-FDD	Full-duplex frequency division duplexing	GMSK	Gaussian minimum shift keying
GPRS	General packet radio service	HARQ	Hybrid automatic repeat request
HRI	Hour reporting interval	IIoT	Industrial Internet of Things
IoT	Internet of Things	LPWA	Low-power wide-area
LTE-M	Long-term evolution for machine-type communication	MAC	Medium access control
MCL	Maximum coupling loss	mMTC	Massive machine-type communications
MWUS	Machine-type communications wake-up signals	NB-IoT	Narrowband IoT
NR	New Radio	NRSRP	Narrowband reference signal received power
OFDMA	Orthogonal frequency-division multiple access	PDCCH	Physical downlink control channel
PDSCH	Physical downlink shared channel	PRBs	Physical resource blocks
PSM	Power-saving mode	PUSCH	Physical uplink shared channel
QAM	Quadrature amplitude modulation	QoE	Quality of experience
QoS	Quality of service	QPSK	Quadrature phase-shift keying
RedCap	Reduced capacity	RRC	Radio resource control
SC-FDMA	Single-carrier frequency division multiple access	TAU	Tracking area update
TBS	Transport block size	TDMA	Time division multiple access
UE	User equipment	UL	Uplink
URLLC	Ultra-reliable and low-latency communications	VoLTE	Voice over long-term evolution

and longer latencies, e.g., remote robotics surgery), certain applications, such as smart cities, fall in the middle of these two opposite ends. Considering these categories, as per Ericsson's mobility report [11], by 2023, 3.5 billion CIoT connections are expected to be deployed, and by 2026 [12], the NB-IoT and LTE-M are expected to comprise 45% of all CIoT connections. Consequently, research has been conducted to provide a review of the CIoT with various scopes and themes, as detailed in the subsequent section (Section 2). However, the existing studies have covered only a subset of the CIoT technology or were limited to a specific focus area.

To the best of our knowledge, this survey paper holistically details all the existing CIoT use cases, general architecture, requirements, technology, and challenges. We have come up with a broader concept of CIoT networks that covers various aspects, including standards and emerging technology, to offer a complete view of the available development technology and the specific challenges that exist. Moreover, a state-of-the-art review of CIoT technology regarding the focuses, features, and applications is provided. The main contribution of this comprehensive survey consists of the following.

- We deliver an in-depth and updated overview of the current state-of-the-art CIoT technology. The technology is examined regarding advancements and innovations, and the current development state is discussed, making it a valuable resource for those interested in the field. A detailed explanation of the general network design and infrastructure of CIoT systems is reviewed.
- We provide an analysis of the various real-world applications and the importance of the CIoT. In addition, we analyze the use cases for the CIoT in terms of their significance and the potential effect on various industries and societal systems.
- We examine the key features, including wide coverage, massive connectivity, low cost, low power consumption, and focus areas for each type of CIoT technology (i.e., EC-GSM-IoT, LTE-M, NB-IoT, and NR-RedCap). The study offers a deep understanding of the capabilities of each type of technology and the areas where they excel or require improvement.
- We identify the open challenges to be addressed for the future development of the CIoT to provide insight into its future direction and the steps to be taken to overcome these challenges.

The remainder of this article is organized as follows. Section 2 reviews related work, and Section 3 provides a general understanding of the structure and components of the CIoT networks. Next, Section 4 investigates the general application use-case classifications to be supported by the CIoT from the perspective of 3GPP and Ericsson. We present a review of the current CIoT technologies: EC-GSM-IoT, LTE-M, NB-IoT, and NR-RedCap in Section 5 divulging each technology's briefing from Sections 5.1 to 5.4, respectively. Regarding the focuses, features, and applications of CIoT, we discuss from Sections 6 to 8, respectively. Section 9 outlines the potential challenges and limitations of the CIoT, and Section 10 concludes the paper. For ease of reference, we display the paper organization in Fig. 1. Table 1 lists the abbreviations used in this survey.

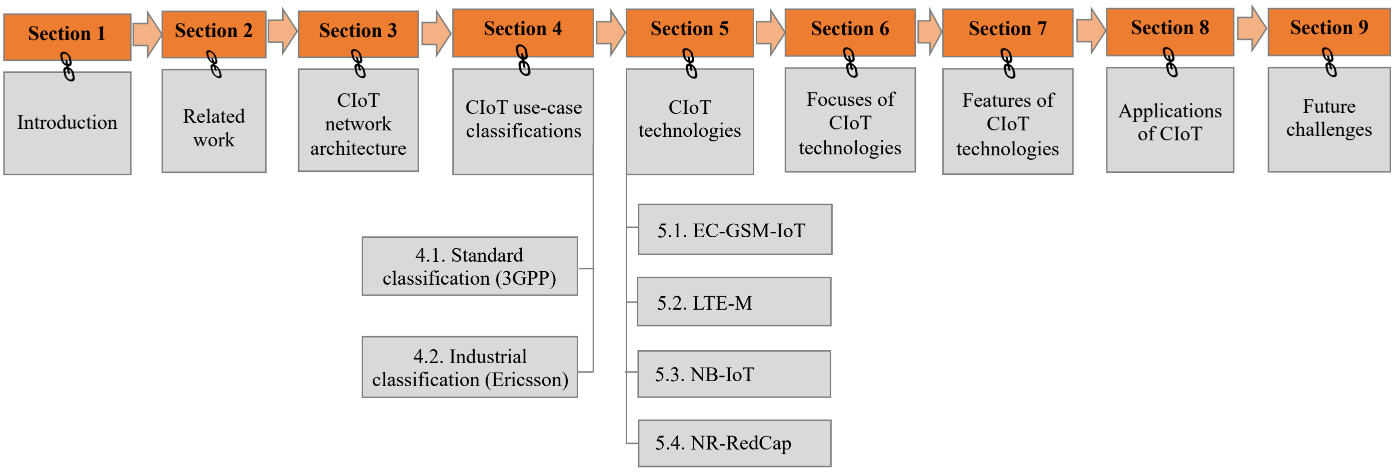

Figure 1: Paper organization.

2. Related Work

Since the introduction of the CIoT, various research has been conducted from different perspectives to provide an overview of the related use cases, key enablers, and challenges. A comparative study [13] evaluated the NB-IoT against other technology regarding latency, QoS, battery lifetime, capacity, and cost, applying some application scenarios. In other studies [14], [15], authors have analyzed the indoor coverage, low power consumption, latency insensitivity, and massive connection support of NB-IoT-targeted technical features, such as resource allocation, energy-efficiency techniques, and latency-energy performance evaluations. In addition, some applications, such as smart agriculture and smart health, have been analyzed with future research directions. In [16], the authors detailed and analyzed possible security attacks on NB-IoT-enabled devices and proposed various approaches and techniques for smart home and smart healthcare applications. Standardization efforts employed on the security aspects of the NB-IoT and security requirements of IoT applications with an extensible combination of the NB-IoT to the 5G are addressed in [17]. In [18], basic factors, such as the modulation scheme selection and channel coding that affect the energy consumption of the NB-IoT from the perspective of resource management, were analyzed and synthesized, and future work suggestions were offered. In [19], the physical layer, specifically the base station (BS) and user equipment (UE) of the NB-IoT system, was presented in detail, exploring the radio resource control (RRC) and medium access control (MAC) layers in the physical design of channels as well. In [20], the power consumption and communication range of self-powered NB-IoT in remote monitoring applications were evaluated. However, these studies [13, 14, 15, 16, 17, 18, 19, 20] considered only the NB-IoT technology in the CIoT. The authors of [21] focused on integrating low-power wide-area network (LPWA) technology to preserve an affordable low-battery device and a wide geographical area while enhancing power consumption and providing future research directions. In [22], channel control procedures and massive MTC (mMTC) standard guidelines with NB-IoT and LTE-M features, including wide coverage, low power consumption, and massive connectivity, were explored along with future challenges and innovative ideas. A comparative study on the performance of CIoT technology was conducted in [30], focusing primarily on the NB-IoT and LTE-M. Coverage (i.e., coverage enhancements (CEs)), power consumption, module cost, connection count (i.e., number of connections per cell), supported features (i.e., voice support), and service modes have been compared. In [23], the authors provided comprehensive guidance on the IoT localization methods of NB-IoT and LTE-M devices, which is vital for ultra-dense devices that result in IoT positioning problems. Power consumption is the primary concern in IoT applications. Hence, improving battery life and message latency is essential, especially in rare data transmission cases, because it has a large signaling overhead in LTE-M and the NB-IoT due to the process of establishing a connection. In [31], the authors clarified early data transmission (EDT) mechanisms introduced by 3GPP to transmit data during the random-access procedure (triggers the connection to a cell) to enhance the power efficiency of the device and minimize message delay, which is vital in a wide coverage scenario. The authors of [24] evaluated mMTC features and QoS provisioning issues with critical enablers for mMTC in cellular networks. A detailed overview is presented on the channel access mechanisms and radio access network (RAN) congestion problems in the NB-IoT and LTE-M with machine learning (Q-learning approach) solutions for congestion relief, including future research directions. However, these surveys [21, 22, 30, 23, 31, 24] reviewed only the NB-IoT and LTE-M.

In [7], the authors investigated EC-GSM-IoT, NB-IoT, and LTE-M as licensed LPWA technologies, focusing on their low power consumption, low data rate, and broad coverage area features. Their study had a limited scope and aimed to facilitate LPWAN-5G integration to support a more extensive range of industrial applications, including process control and high data-rate multimedia applications. The authors of [25] compared the cost of EC-GSM-IoT, LTE-M, and NB-IoT in urban and ru-

Table 2: Summary of recent surveys on the CIoT

Reference	Year	CIoT Technology	Focus	Contributions
[13]	2019	NB-IoT	Latency and QoS	This paper investigated the benefits of the NB-IoT in terms of latency and QoS compared with other types of LPWA technology.
[14]	2019	NB-IoT	Energy-efficiency techniques	This paper investigated the resource allocation and energy-efficiency techniques of the NB-IoT to achieve green IoT objectives.
[15]	2020	NB-IoT	Latency and Battery life	The paper investigated the battery life and latency of NB-IoT devices, as well as future research prospects in the integration and interconnection of AI and IoT.
[16]	2020	NB-IoT	Security	The paper analyzed the security issues of NB-IoT technology, focusing on the aspects of secured network communication in network access and the security requirements of IoT applications, along with future work recommendations.
[18]	2020	NB-IoT	Resource management of NB-IoT	This paper presented some challenges faced by the NB-IoT advancement in energy efficiency, data-rate performance, scalability, and most importantly, resource management, along with identifying potential research opportunities for future work.
[19]	2020	NB-IoT	Physical layer design	This paper offered a tutorial that outlined the features and scheduling of physical channels on the NB-IoT BS and UE.
[20]	2021	NB-IoT	Power consumption and communication range	This paper developed an effective strategy for practical applications of self-powered remote monitoring systems in 5G NB-IoT systems in terms of power consumption, limited communication range, and operation lifespan.
[21]	2019	NB-IoT, LTE-M	Coverage, signal propagation, and energy conservation	The performance of LTE-M and NB-IoT in terms of signal propagation, coverage, and energy conservation with viable future work is analyzed.
[22]	2020	NB-IoT, LTE-M	URLLC and mMTC in CIoT	The paper provided an in-depth review of the enablers, challenges, and techniques involved in the integration of essential mMTC in CIoT networks with upcoming innovative concepts.
[23]	2020	NB-IoT, LTE-M	Localization	The paper supplied a detailed overview of LTE-M and NB-IoT localization techniques for a massive number of IoT devices.
[24]	2020	NB-IoT, LTE-M	Application scenarios of the mMTC and channel access mechanisms	The paper provided a detailed overview of LTE-M and NB-IoT features in a precise manner from the perspective of channel access mechanisms and offered solutions for the RAN congestion problem using machine learning techniques and future research directions.
[7]	2022	EC-GSM-IoT, LTE-M, NB-IoT	5G, EC-GSM-IoT, LTE-M, and NB-IoT integration	The research paper presented a survey and tutorial about the integration of the 5G network and LPWA network (LPWAN).
[25]	2021	EC-GSM-IoT, LTE-M, NB-IoT	Cost structure and scalability	The paper assessed the cost structure of the NB-IoT, LTE-M, and EC-GSM-IoT with other non-CIoT LPWA technology.
[26]	2022	EC-GSM-IoT, LTE-M, NB-IoT	Energy-saving solutions	The survey examined the top solutions to minimize the energy consumption of the CIoT devices, such as the frequency of data transmission, DRX, and RRC timers with future directions for solutions on energy consumption reduction.
[9]	2021	RedCap	Rural, urban, and indoor coverage analysis	This paper demonstrated a thorough assessment of NR-RedCap coverage for various physical channels, specifically on the coverage limitations for RedCap UE in rural, urban, and indoor scenarios.
[27]	2021	RedCap	Device complexity reduction, coverage, capacity, and power analysis	This paper discussed an overview of RedCap and details the important complexity features standardized by 3GPP, including device complexity reduction, coverage compensation, and power saving.
[28]	2022	RedCap	Analysis of battery life, coverage, and cost	In this article, the authors discussed 3GPP Rel. 17 RedCap in terms of performance improvements and cost reductions, including future release enhancement requirements.
[29]	2022	EC-GSM-IoT, LTE-M, NB-IoT, RedCap	AI and IoT integration and future research directions	The paper detailed the short and generic characteristics of various IoT standards, primarily EC-GSM-IoT, LTE-M, NB-IoT, and RedCap focused on AI integration.
Ours	2023	EC-GSM-IoT, LTE-M, NB-IoT, RedCap	Overall feature analysis, general architecture, applications, release enhancement analyses, and focus area explorations.	This paper clarifies the state-of-the-art CIoT features, general network architecture, the release advancements since Rel. 13, focus areas, use cases, technology, and future challenges.

ral deployments and key cost factors from the perspective of profitability in employing the CIoT in firms. A broad survey on energy-saving solutions in EC-GSM-IoT, LTE-M, and NB-IoT was conducted, including analyzing critical factors that affect power usage, such as data reporting frequency, discontinuous reception cycles (DRX), and RRC timers, [26], directing future energy consumption reduction techniques. However, these studies [7, 25, 26] investigated EC-GSM-IoT, NB-IoT, and LTE-M within limited key enablers.

In [27], the authors provided the primary features of the RedCap device standardized by 3GPP to support mid-range IoT applications with complexity reduction, coverage compensation, and power-saving prerequisites. The authors of [9] conducted a detailed assessment of coverage for RedCap UE in various settings, including rural, urban, and indoor scenarios. In [28], a comprehensive overview of 3GPP Rel. 17 RedCap regarding cost reduction, and power-saving results were presented with design guidelines with future expected 3GPP RedCap release specifications. These surveys [27, 9, 28] focused on RedCap with some feature components based on the 3GPP standard specifications.

In [29], the authors analyzed EC-GSM-IoT, LTE-M, NB-IoT, and RedCap and verified that they are proven as 5G IoT standards employed in various real-time applications when integrated with artificial intelligence (AI). However, the research focuses on AI and IoT integration in the CIoT with future research directions. Hence, considering the various surveys conducted, the surveys and studies address various aspects with limited focus. However, this survey provides comprehensive all-in-one information on coverage, power consumption, cost, device complexity, and device connection analysis. Furthermore, this review covers the general architecture, applications, release enhancement, development analysis, focus area explorations, and future challenges based on previous studies and on-hand survey results. Table 2 summarizes related studies to illustrate the difference from this survey.

3. General Network Architecture of the CIoT

This section discusses the general network architecture of the CIoT. The cellular network standards organizations, such as 3GPP and its member companies: Ericsson, Huawei, Qualcomm, and Vodafone endorse the cellular-network-based architecture of CIoT. Cellular-network-based architectures connect IoT devices to the cellular network's IoT infrastructure and allow them to access the Internet through middleware provided by the operators. Various requirements, such as bandwidth, energy efficiency, coverage, mobility, and reliability, are considered when network architecture is developed and deployed. The network architecture of the CIoT is designed to be scalable and flexible to support a wide range of devices and applications. Its ultimate goal is to transition from inflexible network structures, where all devices communicate directly with a network access point, to a more flexible architecture. This new approach allows devices and the network to dynamically form interconnected sub-networks, resembling a mesh, as and when needed [32]. It can support low-power, low-bandwidth, and high-power, high-bandwidth devices and can be easily integrated with existing networks and systems. Integration with existing networks and systems allows organizations to leverage the advantages offered by IoT without having to completely overhaul the existing infrastructure.

Figure 2 presents the general network architecture of CIoT, facilitating communication between IoT devices and the Internet. A CIoT network architecture focuses on increasing network robustness against dynamic resource availability and providing ubiquitous connectivity. For instance, to meet the requirements of CIoT, existing legacy network architectures need to undergo substantial changes, such as enabling non-orthogonal access to increase the number of connected devices, implementing grant-free UL communication for fast and reliable communication, and adopting a multihop mesh network to support low-power devices in challenging locations [33]. As CIoT operates within existing cellular infrastructure, it facilitates interoperability between devices and harvests communication and computing resources across the network [34]. As depicted in the figure, the architecture comprises four main components: the IoT devices, BS, network stack (user plane and control plane), and Internet (CIoT applications). The first layer, the IoT devices include sensors, actuators, and other connected devices that collect and transmit data. Using these nodes, sensor data will be collected and transmitted to the access point, or they will receive data from it, to perform the response associated with the actuators. These devices communicate with the next layer, the BS, using CIoT technology (EC-GSM-IoT, LTE-M, NB-IoT, and RedCap), which connects the IoT devices to the network.

The next layer is the network stack, comprising the user and control planes responsible for the efficient and effective data delivery between IoT devices and applications which are the two optimizations for the CIoT. The user and control planes form two distinct layers of the network stack and serve distinct functions, with the user plane carrying the data and the control plane managing the network resources [35]. Specifically, the user plane manages the data transmission and chooses the best path for control data packets for uplink (UL) and downlink (DL) [36], and the control plane manages the overall network. In addition, the user and control planes work together to ensure an efficient and reliable exchange of information among IoT devices and the Internet. Finally, CIoT applications are at the top layer, which includes the applications and services that use the data collected by IoT devices. These applications can include everything from smart home systems to industrial automation systems [37]. The CIoT network architecture allows for the seamless integration of IoT devices and applications, making it an essential part of the IoT and plays a significant role to enable massive CIoT applications.

Some of the CIoT technology (e.g., LTE-M and the NB-IoT) operates over a shared spectrum of LTE architecture with certain optimization techniques [38]. Some features were removed to reduce the complexity, equipment cost, and battery consumption in the shared LTE architecture, including handover for fast connection, carrier aggregation, and channel quality measurements [39]. In the CIoT network, two dedicated machines are used for communication: the MTC device and the MTC gateway. An MTC device is an endpoint that can communicate directly with a BS or connect via two hops to MTC gateways, as illustrated in Fig. 2. In this way, MTC gateways help increase data transmission efficiency by relaying data to the BS [40]. In fact, gateway utilization is feasible in numerous instances, but certain regions and circumstances lack such infrastructure. Consequently, in such scenarios, it becomes imperative to establish direct communication.

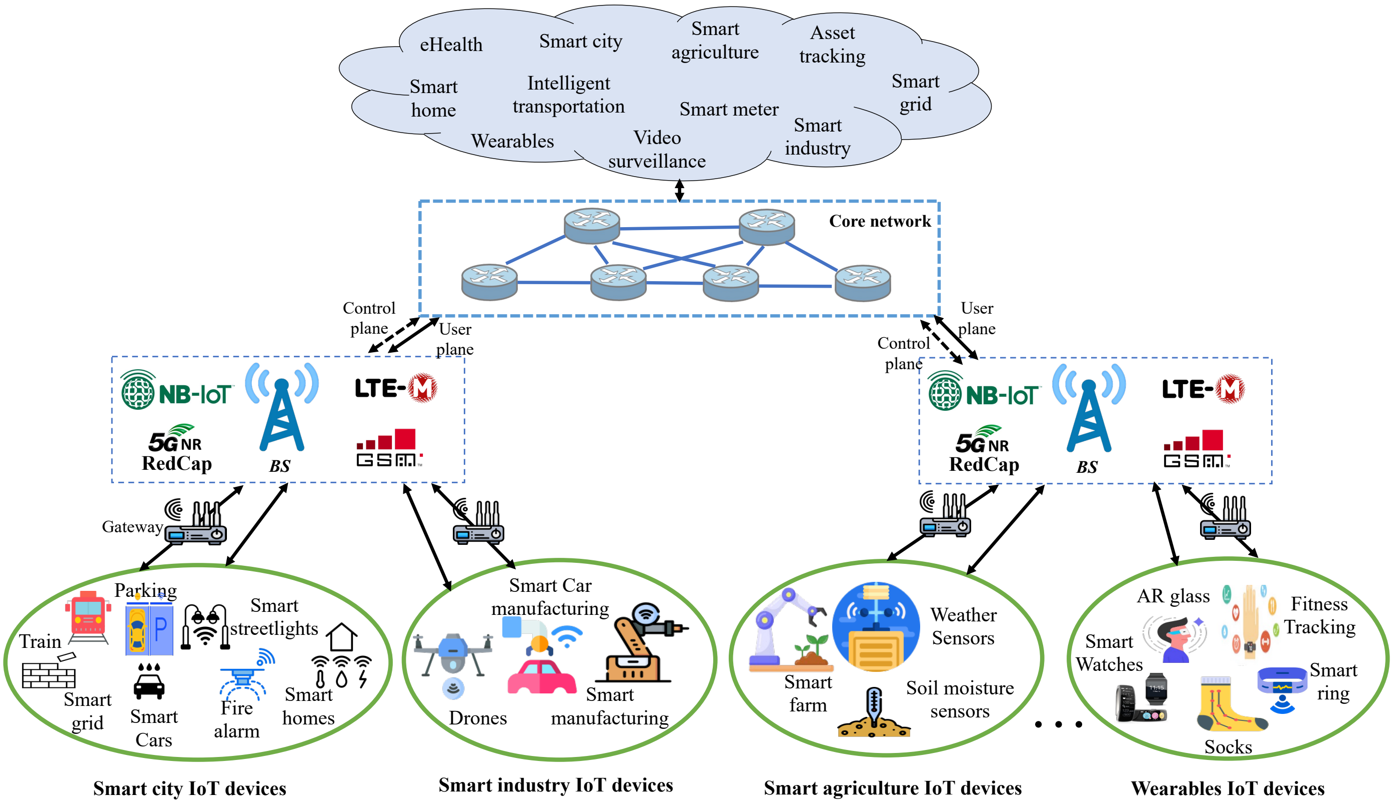

Figure 2: Overall architecture of the CIoT.

4. CIoT Application Use-Case Classifications

The development of CIoT results from collaboration and innovation from multiple companies and researchers [11, 41, 42]. It has emerged as a way to extend the capabilities of cellular networks to establish connectivity for a diverse range of devices to enable a broad range of new use cases and applications, such as smart cities, industrial automation, and remote monitoring, to mention a few, by offering low-cost, low-power, and reliable connectivity. Globally, the standards of the CIoT have been developed by 3GPP and Ericsson, among others, which have different methods of classifying CIoT application use cases, as presented in Fig. 3. Accordingly, this section discusses the application use classification by 3GPP and Ericsson.

4.1. 3GPP Classification

3GPP is a collaboration between telecommunications standard organizations to develop global standards for cellular communication technologies [43]. Specifically, 3GPP is working on the development of 5G technology and standardization of IoT technologies to improve connectivity and communication between devices [44]. They also work on developing new features and functionalities for cellular networks, such as network slicing, improved security, and reduced latency, to support the growing demands of IoT and other emerging technologies. This section focuses on their classifications from the application perspectives that 3GPP defines three usage scenarios of 5G: mMTC, ultra-reliable and low-latency communications (URLLC), and enhanced mobile broadband (eMBB) [45], [46].

4.1.1. mMTC

Specifically, mMTC is designed to enable numerous low-power, low-cost IoT devices to connect to cellular networks where many devices infrequently transmit small volumes of data. It is designed to connect numerous low-cost devices (e.g., about 1,000,0000 devices/km^2) with sporadic, low-throughput data transmissions within a 10-s latency [47]. The focus is on low power consumption with up to 10 years of battery life and high reliability to efficiently use the network resources. It is intended for use cases requiring high device density, such as smart cities, industrial automation, smart homes, smart metering, and asset tracking, where many devices must connect to the network simultaneously. In Rel. 13, 3GPP proposed LPWA cellular technology that specified long-range coverage of 164 dB, inexpensive and extremely energy-efficient devices that necessitate intermittent and periodic connectivity, including EC-GSM-IoT, LTE-M, and NB-IoT [45].

4.1.2. URLLC

Higher reliability and lower latency are the most important design standards in wireless communications. From Rel. 14 to the present, reliability and latency have been the focus requirements, such as new data center interconnect formats, enhanced physical DL control channel (PDCCH) monitoring capability, hybrid automatic repeat request acknowledgment (HARQ ACK) feedback based on sub slots, enhanced inter-UE transmitter (Tx) multiplexing, physical UL shared channel (PUSCH) enhancements, and a variety of active configuration grants [48]. It is intended for IoT applications that are mission-critical, such as emergency services, which demand high availability and coverage with a low response time of fewer than 1 ms. It is intended for use cases, such as factory automation, autonomous driving, and remote surgery [46] for which NR-RedCap is a complement.

4.1.3. eMBB

The eMBB is designed to provide high-bandwidth and low-latency media streaming applications [49], such as virtual and augmented reality, smart offices, and 4k and 8k video streaming with ultra-high speed Internet access. The eMBB is intended for use cases, such as smart cities and entertainment. Although eMBB and CIoT differ, they can work together to offer more comprehensive and reliable connectivity solutions. The purpose of organizations in the CIoT regarding eMBB is to work to integrate them to share the capabilities of the trending wireless development in 5G. These categories are not mutually exclusive and can overlap. For example, an IoT application may require both mMTC and URLLC capabilities (e.g., autonomous vehicles, smart grids, industrial automation), or an IoT device may require mMTC and eMBB capabilities (smart cities, healthcare, and smart agriculture). 3GPP aims to establish a framework that can cater to the varied needs of IoT applications and devices and ensure seamless interoperability among devices and networks.

4.2. Ericsson Classification

Ericsson [50], a leading information communication technology network provider, working on developing solutions for connecting a large number of devices to the network, improving network coverage, and increasing the efficiency and security of IoT applications. Involved in the standardization and development of CIoT technology and refined the IoT applications incorporated into the CIoT into four divisions: massive IoT, broadband IoT, critical IoT, and industrial automation IoT [51, 32].

4.2.1. Massive IoT

Massive IoT is focused on low-cost devices, small data volumes, and extreme coverage. It is intended to enable increased network coverage, longer device lifespan, and high connection density, which is known as mMTC. Ericsson identified the massive IoT as LPWA technology, as classified by 3GPP, employed on licensed spectrum bands. Massive IoT is employed when low-complexity devices, long battery life, extensive coverage, and massive deployments are necessary. Massive IoT applications (i.e., smart building, retail, shopping, and manufacturing; smart home systems; personal IoT devices; etc.) tend to tolerate delays at various levels in operation [52, 53, 54]. Hence, LTE-M, EC-GSM-IoT, and NB-IoT were developed by 3GPP to support the massive IoT [55] in which according to Ericsson's projection massive IoT will make up 51 percent of CIoT connections by 2027 [56].

4.2.2. Broadband IoT

The broadband IoT provides significantly faster data transfer speeds and reduced latency compared to the massive IoT, which was released based on mobile broadband [50]. The broadband IoT is evolving due to the requirements of accessing multimedia information with high throughput, low latency, and large data volumes for communication purposes. The broadband IoT is designed for high-bandwidth applications, such as video surveillance and remote health monitoring. Due to its capability of supporting high-speed data transfer, it enables devices to transmit numerous data quickly and efficiently, which is relevant in healthcare applications (e.g., where high-resolution images and data-intensive information is transmitted in real-time).

4.2.3. Critical IoT

The critical IoT is necessary when the industrial IoT (IIoT) and mission-critical applications that require ultrahigh performance, very high availability (99.999%), ultra-reliability, and ultralow latency are in demand [57]. Unlike the massive IoT, applications of the critical IoT that require a minimal delay, such as smart healthcare (e.g., remote surgery), industrial automation in smart manufacturing [22], autonomous driving, asset tracking, traffic safety and control, and remote control of the sensitive components of a smart grid automation [58], are particularly sensitive to delays. Critical IoT applications are technically known as URLLC, comprising industrial control, robotic machines, and autonomous vehicles [32] that require real-time data transmission. Ultra-reliable, very low latency, and very high availability are the key performance indicators of the critical IoT [54].

4.2.4. Industrial Automation IoT

The IIoT targets improving the operational efficiency, safety, and sustainability of industrial processes and systems that require unique network deployments. The IIoT is designed for applications in manufacturing and industrial process automation [46], achieving increased reliability, reduced latency, higher data transfer rates, greater flexibility, and secure communication. The IIoT is the focus and enabler of Industry 4.0 [59, 60, 32], enhancing the controlling capability with remote monitoring applications, such as smart factories, agricultural monitoring, and industrial assets [61]. The IIoT is primarily applied in IoT applications that demand Ethernet protocol integration, time-sensitive networking, clock synchronization services, and other requirements. Furthermore, in these industrial real time applications proper implementation and effective design of deep learning algorithms are necessary aiming for high performance in terms of reliability, speed, and security. Deep learning provides a dynamic optimization of the warehouse facilities, enhances assembly line performance, improves the generative design, predicts future demands, and reduces errors [62]. Moreover, low cost and complexity are the most important factors in the IIoT [63].

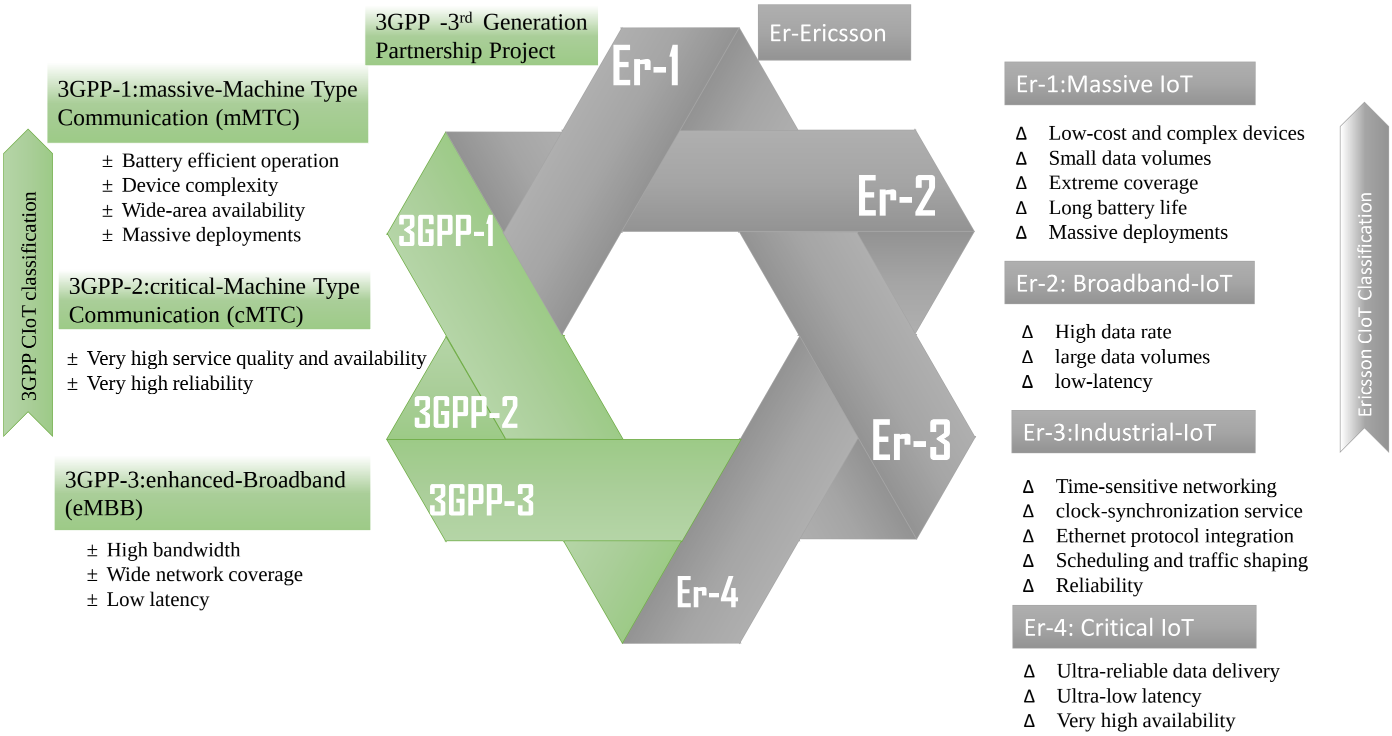

Figure 3: 3GPP and Ericsson's CIoT use-case classifications.

5. CIoT Technologies

This section discusses CIoT technology from various perspectives. Initially, 3GPP collated cellular network technology for the IoT in Rel. 13 included EC-GSM-IoT, LTE-M, NB-IoT, and in Rel. 17 the NR-RedCap. As illustrated in Table 3, we summarize the fundamental parameters of the first Rel. 13 for the three types of CIoT technology and the first NR-RedCap Rel. 17 technology. 3GPP worked on the EC-GSM-IoT (a complete backward-compatible solution for CIoT that builds upon the existing GSM or enhanced-GPRS (eGPRS) deployments) under the 850-900 MHz and 1800-1900 MHz frequency bandwidth with the aim of achieving extended battery life and lower device costs compared to general packet radio service (GPRS) or GSM devices. It also has extended coverage of up to 164 dB maximum coupling loss (MCL) for 33 dBm UE and 154 dB MCL for 23 dBm UE, with variable rates using Gaussian minimum shift keying (GMSK) ranging from approximately 350 bps to 70 kbps, and eight-phase shift keying (8PSK) up to 240 kbps. The technology can handle a large number of devices, with around 50,000 per cell, and provides enhanced security compared to GSM orEDGE. It can be installed through a software update to the GSM infrastructure [66].

Moreover, as shown in the table, the first release of LTE-M, Cat-0, was out on Rel. 12 in March 2015 to be configured as a UE Cat-0 (Cat-0 MTC) IoT version. In Rel. 13 in March 2016, LTE enhanced MTC or Cat-M1 (Cat-1 MTC) IoT, and the NB-IoT was released to afford IoT applications. In the combined Cat-0 and Cat-M1, LTE-M was introduced to contribute a 1 Mbps data-rate capacity, supporting full mobility features with a battery life exceeding a duration of 10 years, which can be configured easily with a software update to the LTE infrastructure. In the multiple access techniques, both Cat-0 and Cat-M1 in the UL transmission scenario support the single-carrier frequency division multiple access (SC-FDMA) methods, and in the downlink scenario, they both employ orthogonal frequency-division multiple access (OFDMA). However, Cat-0 and Cat-M1 have differences in terms of the UL and DL bandwidth coverage. The former has a 20 MHz bandwidth, and the latter has a 1.4 MHz bandwidth derived from the legacy LTE. The coverage or link budget of Cat-0 is around 141 and is 156 dB for Cat-M1 [43].

In contrast, the NB-IoT was developed from an LTE or GSM network with 200 kHz of physical resource blocks (PRBs) and a clean sheet format of 180 kHz that can be compatible with a software update to the existing legacy LTE or GSM systems under the 700, 800 and 900 MHz frequency bandwidth. Because the NB-IoT utilizes many of the same design aspects as LTE, including channel modulation, coding schemes, and higher-layer protocols, it provides deployment flexibility and is primarily designed to address ultralow-end IoT applications [65, 68]. The NB-IoT introduces two modes of operation types, different from the LTE, where the whole PRB is assigned to a single piece of UE in the UL and DL. In the single-tone mode, the NB-IoT utilizes one PRB that has a bandwidth of 180 kHz in both the DL and UL of the LTE spectrum. However, in the multitone mode, the resource units are allocated to multiple pieces of UE to attain the massive device deployment objective of the CIoT, specifically for the NB-IoT. The NB-IoT system assigns each tone a transmission bandwidth of either 3.75 or

Table 3: First release parameter values of the CIoT (LTE-M, NB-IoT, EC-GSM-IoT, and NR-RedCap)

Parameters	**LTE-M**		**NB-IoT**		**EC-GSM-IoT**	**RedCap**
	Cat-0	**Cat-M1**	**Single-tone mode**	**Multitone mode**		
DL Bandwidth	20 MHz	1.08 MHz (1.4 MHz carrier bandwidth)	180 kHz (200 kHz carrier bandwidth) (12 by 15 kHz)	180 kHz (200 kHz carrier bandwidth) (12 by 15 kHz)	200 kHz	20 MHz for FR1, 50, 100 MHz for FR2
UL Bandwidth	20 MHz	1.08 MHz (1.4 MHz carrier bandwidth)	180 kHz (by 3.75 kHz or 15 kHz)	180 kHz (by 15 kHz)	200 kHz	20 MHz for FR1, 50, 100 MHz for FR2
Frequency Bandwidth	Cellular band	Cellular band	700, 800, 900 MHz	700, 800, 900 MHz	850,900 1800, 1900 MHz	100 MHz in FR1, 200 MHz in FR2
DL Multiple Access	OFDMA	OFDMA	OFDMA	OFDMA	TDMA	TDMA, FDMA, OFDMA
UL Multiple Access	SC-FDMA	SC-FDMA	FDMA	SC-FDMA	TDMA	TDMA, FDMA, SC-FDMA
DL Modulation	BPSK, QPSK 16 QAM 64 QAM	BPSK, QPSK 16 QAM, 64 QAM	BPSK, QPSK optional 16 QAM	BPSK, QPSK optional 16 QAM	GMSK	16 QAM 64 QAM 256 QAM
UL Modulation	QPSK, 16 QAM	QPSK, 16 QAM	BPSK, QPSK 8 PSK	BPSK, QPSK optional 16 QAM	GMSK	16 QAM, 64 QAM, 256 QAM
Peak Data Rate	1 Mbps	1 Mbps	DL 128 kbps, UL 48 kbps Transport Block Size	DL 128 kbs, UL 64 kbps Transport Block Size	DL and UL (using 4 time slots): 70 kbps (GMSK), 240 kbps (8 PSK), respectively	2 Mbps for WIS, 25 Mbps for wearables 150 Mbps (DL), 50 Mbps (UL) for surveillance
Max. Coverage (MCL)	~141 dB	~156 dB	~164 dB	~164 dB	~164 dB	same as legacy NR ~144 dB
Range(km)	~11	~11	10–15 (on rural areas)	10–15 (on rural areas)	~15	–
Latency (s)	≤15 s	≤10 s	≤10 s	≤10 s	700 ms–2 s	–
Battery life	≥10 years	≥10 years	up to 15 years	up to 15 years	≥10 years	1–2 weeks for wearables, several years for industrial sensors
Device Capacity/ cell	~10 k	~50 k	~40 k	~52 k	~50 k	–
Mobility	Full	Full	Nomadic	Nomadic	Nomadic	Full/Nomadic
Deployment	Based on LTE	Based on LTE	Clean-slate	Clean-slate	Based on GSM	Based on 5G NR
Standard	3GPP Rel. 12	3GPP-Rel. 13	3GPP-Rel. 13	3GPP-Rel. 13	3GPP-Rel. 13	3GPP-Rel. 17
References	[14] [47][64][42]	[14][47][64][4]	[14][47][64][4]	[14][47][64][4][65]	[14] [47] [52][66]	[67][9][51][28][3]

15 kHz for UL transmission using the SC-FDMA scheme. For DL transmission, 15 kHz transmission bandwidth is used with the OFDMA scheme similar to LTE. Using 15 kHz spacing, NB-IoT can allocate either one or multiple tones (three, six, or twelve) to different UE with durations of 4, 2, and 1 ms, respectively. However, with 3.75 kHz spacing, only a single-tone allocation is supported for various users, with 48 sub-carriers of 32 ms duration [69], which allows the NB-IoT for increased deployment flexibility and higher system capacity. From the Rel. 13 specifications, the data rate in the single-tone allocation is 48 kbps for the UL, 64 kbps for the multitone mode, and 128 kbps in the single- and multitone modes in the DL, with a +20 dB link budget from the legacy LTE of 144 dB supporting more than 10 years of battery life but without mobility support [70].

In addition, 3GPP introduced RedCap on 5G device specifications with reduced features in Rel. 17, designed objectively to simplify the standard NR technology. In the 5G technology, it is insufficient to reuse traditional existing frequency bands for high-end 5G requirements, so another new and varied frequency band is needed. For 5G NR, frequency band 1 (FR1) is below 6 GHz or 4.10 to 7.125 GHz, and frequency band 2 (FR2) is above 6 GHz or 24.250 to 52.600 GHz [71]. Hence, RedCap is supposed to use 20 MHz for FR1 and 50 and 100 MHz for FR2 in the UL and DL bandwidths, respectively [67]. The multiple access method is FDMA or time division multiple access (TDMA), where frequency or time slot is employed. The peak data rate varies based on the use cases (e.g., 2 Mbps is expected for wireless industry sensors, 25 Mbps for wearables, and 150 Mbps (DL and UL) for surveillance applications). Moreover, after Rel. 13, 3GPP added subsequent enhancements to the current releases. The subsequent sections discuss these CIoT technologies in detail, considering their focuses, features, and applications. Following is a detailed explanation of each CIoT technology, including their unique features, applications, focuses, and review state of the art. In this section, we will explore the different CIoT technologies available, including EC-GSM-IoT, LTE-M, NB-IoT, and RedCap, and discuss how they are being used in various industries and sectors.

5.1. EC-GSM-IoT

3GPP standardized it to support IoT applications in Rel. 13 using the Technical Specifications Group GSM RAN using LTE-advanced pro [7, 75, 76]. Its development can be considered a great success because it only requires design reuse and software upgrades to deploy EC-GSM-IoT in the existing 2G GSM or eGPRS network without needing new network infrastructure. It plays a pivotal service in M2M or IoT communications in the form of voice, data, and SMS. Moreover, most sub-Saharan African subscriptions are still GSM or EDGE, which is vital for MTC and global IoT deployment [77]. In particular, the EC-GSM-IoT technology is intended to facilitate the use of IoT devices in areas with difficult radio coverage and can operate in frequency deployments as narrow as 600 kHz. Operators and companies, such as Broadcom Corporation, Cisco Systems, Ericsson, Gemalto NV, Intel Corporation, KDDI Corporation, LG Electronics, MediaTek, Nokia, Oberthur Technologies, Ooredoo, Orange, Samsung Electronics, Saudi Telecom Company, Sierra Wireless, Telit Communications, and VimpelCom, are also trying to use it with 3G and 4G mobile networks [78]. As shown in Table 4, the maximum UL-DL instantaneous peak data rates from the Rel. 14 to Rel. 17, in the 8PSK modulation, is 489.6 kbps both in DL and UL, 153.6 kbps in GMSK modulation in the UL [45, 72]. The channel bandwidth is 200 kHz, and the device capacity (i.e., devices/km^2) is around 60,000. Additionally, the technology uses CE through message repetitions [73, 29].

Indeed, the GSM technology is well-established, and it still plays an important role in the deployment of IoT. With the upgrades implemented by 3GPP in Rel. 13, GSM offers advantages in terms of time, coverage footprint, and cost that are crucial for IoT development. In addition, spectrum availability is an essential controlling factor of the CIoT and its innovation capability, growth rate, and development paths. Backward compatibility has been applied to use the existing devices and network in the EC-GSM-IoT deployment. As illustrated in [79], only new synchronization, the broadcast control channel, and common control channels on time slot 1 of the broadcast control channel carrier are required for EC-GSM-IoT functioning. The extended Discontinuous Reception (eDRX) with radio control level enhancements provides several advantages, including extended battery life, lower device cost in comparison to GPRS or GSM devices, improved coverage, and variable rates. The technology can accommodate a large number of devices while offering improved security features.

As shown in Figure 4, the 3GPP did efforts to enhance the EC-GSM-IoT service levels to cope with the requirements of IoT application requirements. Enhancements on EC-GSM-IoT have been done including achieving reduced complexity, low device power consumption, ensuring support of a massive number of CIoT devices and backward compatibility with GSM, securing low-device cost, improving end-user security, and so on. In the consequent release, Rel.14, fundamentally, they developed three enhancement requirement objectives including improving the positioning of devices, coverage for 23 dBm devices, and new time slots (TSs) mapping in extended coverage for improved resource handling [45]. In EC-GSM-IoT, there are four coverage classes, namely CC1, CC2, CC3, and CC4, that are assigned to different channels. Each coverage class determines the number of blind repetitions in the DL channel, which are 1, 8, 16, and 32 respectively. Similarly, in the UL channel, the coverage classes determine the number of blind repetitions as 1, 4, 16, and 48 respectively that can help to attain the MCL [26]. In Rel.15, feature enhancements such as supporting multicast to operate in extended coverage in both UL and DL, incorporating coverage class CC5 and CC6 to attain 33 dBm, mobility support, and power consumption reduction techniques (e.g., eDRX, paging) were employed. In Rel.16, enhancements in localization, power consumption reduction (eDRX, WUS, paging, Preconfigured UL Resources (PUR)), and improved multicarrier operation. The PUR is employed to allocate radio resources to a UE in advance, enabling the transmission of UL data without requiring a connection setup process. In Rel.17, enhancements have been incorporated into EC-GSM-IoT to better meet the requirements of application scenarios. These enhancements focus on improving the battery lifecycle, device density, and link budget.

However, in developed countries, after Rel.15, since the 2G-GSM and 3G-Universal Mobile Telecommunications System (UMTS) wireless networks are winding down, and some mobile network operators plan to phase out their GSM and UMTS networks soon [83]. They are shifting to 5G and confirmed the LTE-M and NB-IoT are a candidate for CIoT technology in addition to RedCap. Instead of EC-GSM-IoT, they are focused on LTE improvements and 5G NR so that no further EC-GSM-IoT feature enhancement is applied. However, in the Middle East, South-East Asia, and Africa, 2G, 3G, and 4G mobile networks are still applicable, know that it can co-exist with 3G, and 4G mobile networks, EC-GSM-IoT is serving well even though demand for 5G is getting high. In spite of the relatively lesser attention the EC-GSM-IoT network receives than the LTE-M and NB-IoT networks, EC-GSM-IoT still offers some promising applications. In fact, it is a good solution for IoT deployment in developing countries, where cellular networks are primarily used for voice and other locations where GSM coverage exceeds LTE coverage.

5.2. LTE-M

Under the 3GPP feasibility study titled "Study on Provision of Low-Cost MTC UEs Based on LTE," LTE-M started in September 2011, earlier than the EC-GSM-IoT and NB-IoT [84]. The main objective was to enhance the LTE device capabilities in the low-end MTC domain, present an option for the GPRS and EGPRS devices, and roam GSM networks to LTE. At the time, eGPRS was incompatible with supporting more devices and was not cost-effective for MTC devices. They aimed to provide a solution with device complexity and cost to facilitate better requirement satisfaction regarding data rates, spectrum efficiency, and power consumption than the eGPRS. In 2012,

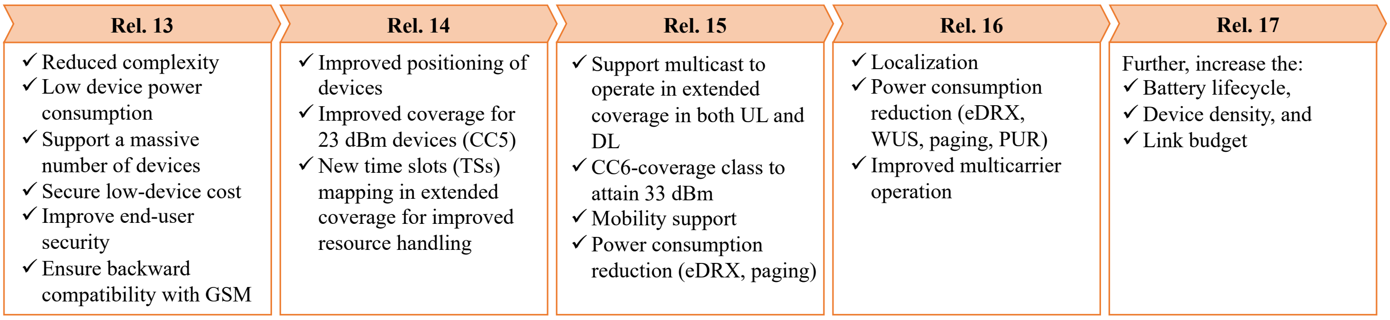

Figure 4: EC-GSM-IoT release enhancement features.

Table 4: EC-GSM-IoT release enhancement metrics.

Parameters	Rel. 14	Rel. 15	Rel. 16	Rel. 17
UL-DL Peak Rates	489.6(8PSK) (UL), 153.6 (GMSK) (UL), 489.6 kbps (DL)	489.6(8PSK) (UL), 153.6 (GMSK) (UL), 489.6 kbps (DL)	489.6(8PSK) (UL), 153.6 (GMSK)(UL), 489.6 kbps (DL)	489.6(8PSK) (UL), 153.6 (GMSK) (UL), 489.6 kbps (DL)
Energy-Efficient Solution	PSM, eDRX	eDRX, WUS, Energy-efficient paging reception	WUS, eDRX, Energy-efficient paging reception	WUS, eDRX, Energy-efficient paging reception
References	[45, 25, 72, 29, 73]	[45, 72, 29, 73]	[45, 72, 29, 73]	[45, 72, 26, 44, 74]

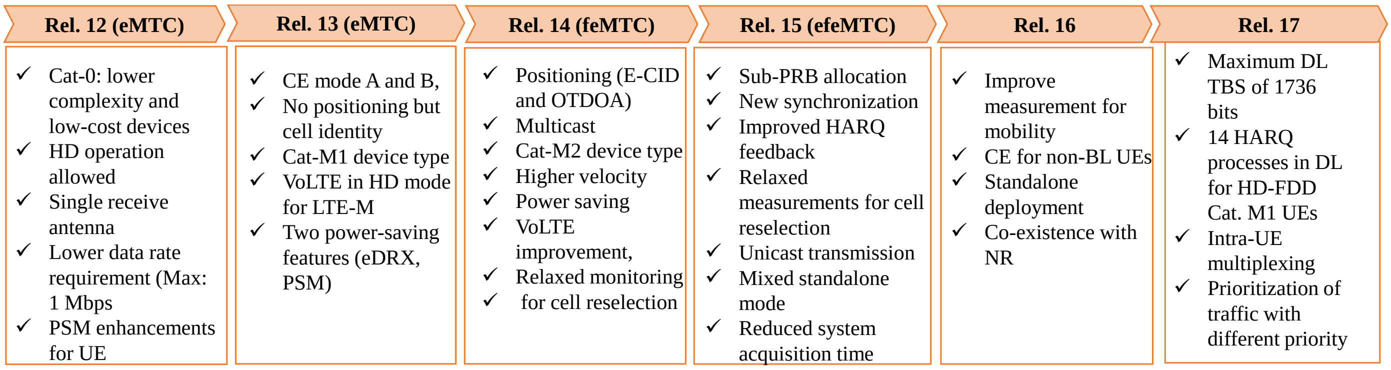

Figure 5: LTE-M release enhancement features.

Table 5: LTE-M release enhancement metrics.

Parameters	Rel. 14	Rel. 15	Rel. 16	Rel. 17
DL/UL Peak Rates	(Cat-M1) 1.119 Mbps, 4 Mbps, (Cat-M2) 2.613 Mbps, and 7 Mbps any duplex mode	1 Mbps	800 kbps, 1 Mbps	1.2 Mbps
UL/DL Bandwidth	1.4/5 MHz (Mode A), 20 MHz (Mode B)	1.4/5 MHz (Mode A), 20 MHz (Mode B)	1.4/5 MHz (Mode A), 20 MHz (Mode B)	1.4/5 MHz (Mode A), 20 MHz (Mode B)
Energy-Efficient Solution	PSM, eDRX, HARQ feedback (UL), RAI	MWUS, EDT, HARQ feedback (DL), cell reselection, RSS	MWUS, EDT, HARQ feedback (UL), cell reselection, RSS	MWUS, EDT, HARQ feedback (UL), cell reselection, RSS
References	[80] [81][33]	[80][82] [81] [33]	[80][81]	[80][81]

in addition to the mentioned requirements, the group extended coverage improvement over the normal LTE coverage capacity by at least 20 dB to support deep indoor coverage, as summarized in as shown in Table 5. Furthermore, LTE devices were more expensive than GSM or eGPRS, so it was worth reducing the device cost to address the low-end mMTC use cases.

The LTE-M release feature enhancements increased the number of supported devices per cell, from 361,000 to 1,000,000 devices/km ^{2} allowing for more IoT devices to connect to a single BS, enabling better use of the available spectrum and improved scalability. New CE techniques (i.e., Mode A, a moderate number of retransmissions with 32 repetitions, and Mode B, a high number of repetitions with 2,048 repetitions, from Rel. 14 forward) are introduced to improve the QoS for IoT devices operating in remote or challenging environments [85]. Through shorter transmission time intervals, the latency is reduced from 50 to 100 ms in Rel. 12 to 10 to 15 ms in recent releases [82]. The LTE-M release enhancements increased the maximum number of HARQ processes from eight to 10 to improve the reliability of data transmissions, reducing the number of retransmissions needed to deliver data to IoT devices, improving overall system efficiency and reliability, and reducing latency. The HARQ allows for more flexibility in determining the type and amount of retransmitted data, as explained by [86]. Compared with other CIoT components, LTE-M has important features.

LTE-M is considered the most suitable LPWA technology for IoT applications that need high data rates, low latency, and full mobility, including voice, under standard coverage conditions. It is also an ideal choice for IoT applications that require deep coverage, where the demands for latency, mobility, and data speed are less rigorous. Indeed, LTE-M is a highly adaptable LPWA technology that can cater to both lower and higher data rates, with its system bandwidth being flexible and capable of accommodating 1.4 MHz or more. It can handle real-time traffic, full mobility, and voice features.

In general, in the form of low-cost devices and coverage improvements, Rel. 14 and Rel. 15 further developed the standard, as shown in Table 5. In addition, MTC was further enhanced for LTE [82], commonly referred to as the "feMTC" work item in Rel. 14, which brought further enhanced improvements for supporting higher data speeds, improved voice over long-term evolution (VoLTE) support, improved positioning, multicast support, and the new LTE device, Cat-M2. In Rel. 14, a new UE Cat-M2, unlike the normal LTE UE for IoT applications that require a higher data rate (e.g., wearables, such as smartwatches) but lower device cost. The UE Cat-M2 has a UE bandwidth of 5 MHz and can achieve peak rates of around 4 Mbps for the DL and 7 Mbps for the UL, assuming it supports FD-FDD operations [87]. For UE that supports HD-FDD, these peak rates are roughly half of the aforementioned figures, and for UE that supports time division duplex, the peak rates depend on the DL/UL subframe configuration, as stated in [82]. The Cat-M2 UE supports larger maximum TBSs for unicast transmission than Cat-M1 UE. Valuable enhancements have been provided in each release, as illustrated in Fig. 4. Rel. 13 enhanced by employing coverage enhancement modes (CE mode A and B), improved device type having lower complexity and cost, enabled VoLTE in HD mode and introduced additional power saving features (eDRX) than Rel. 12 that was featured as lower complexity (a single receive antenna) and low-cost devices (Cat-0), HD operation, supports a lower data rate requirement (Max: 1 Mbps) and PSM enhancements for the UE. Rel. 14 further enhanced LTE-M, offering further developments than Rel. 13 regarding mobility, data rate, HARQ processing, new Cat-2 specifications, supporting positioning features, and additional power consumption management techniques [82]. The other power-saving mechanism developed in Rel. 14, the Release Assistance Indication (RAI) feature is employed to conserve power by permitting the network to terminate a connection that is no longer required. By turning off the device radio and freeing network resources sooner, RAI can help to minimize battery consumption.

A Rel. 15 work item that added use cases, increased spectrum efficiency, and additional benefits even further enhanced MTC (efeMTC) for LTE [88] while reducing latency and power consumption. Particularly, LTE-M is suited for industry operations with mobility features that must be tracked and monitored while moving. In Rel. 15, the central objective was to improve latency, spectral efficiency, and power consumption further. Potential enhancements to enhance latency include reducing the system acquisition time (e.g., improving the BS search or system information acquisition performance) and supporting EDT. To increase system capacity, spectral efficiency was improved in the DL by introducing higher-order modulation (64 QAM), and in the UL by enabling more precise resource allocation using sub-PRB granularity, as stated in [89]. To reduce power consumption, several possible enhancements could help including the implementation of EDT, sub-PRB resource allocation, WUSs, novel synchronization signals, improved HARQ feedback, and less stringent measurements for cell reselection [90] [81][88]. Rel. 15 offered even further enhancements of increased spectral efficiency, latency improvement, and lower power class. In Rel. 16, 5G integration has been realized to share 5G capabilities, CE for non-bandwidth reduced low complexity, standalone development, and mobility improvements. Rel. 17 [91, 92] introduced a maximum DL TBS of 1736 bits, 14 HARQ processes, and traffic management capabilities. In each release, enhancements in data rates, device capacities, and energy-efficient solutions have been integrated.

5.3. *NB-IoT*

The NB-IoT is a promising technology for the massive IoT specifically designed for low data-rate applications [14]. Improving the design of the UL/DL Rx to function effectively in situations where the signal-to-noise ratio is extremely low is pivotal [96]. The latency is enhanced between 1.6 and 10 s [97] with a maximum of one or two HARQ techniques. The maximum TBS in Rel. 14 was enhanced to 2,536 b in the DL and UL by applying the HARQ process [65]. The NB-IoT has three deployment options and can be deployed inside an LTE carrier (in-band in 3, 5, 10, 15, and 20 MHz LTE bandwidths), in its guard-band (in 10 MHz LTE carriers), or its own designated spectrum (standalone, 200 kHz in the GSM band) [65, 98, 99, 100]. When a guardband is applied, NB-IoT devices transmit data with great performance and efficiency while avoiding interfering with regular voice or data traffic on cellular networks. It can be considered a new radio access technology that is different from EC-GSM-IoT and LTE-M with no backward compatibility [101]. In Rel. 14, it was intended to optimize the battery efficiency for up to 35 years with extended coverage of 164 dB [25] with transmission repetitions, power boosting, software modifications enhancing transport layer protocols [102], low complexity, support for a massive number of

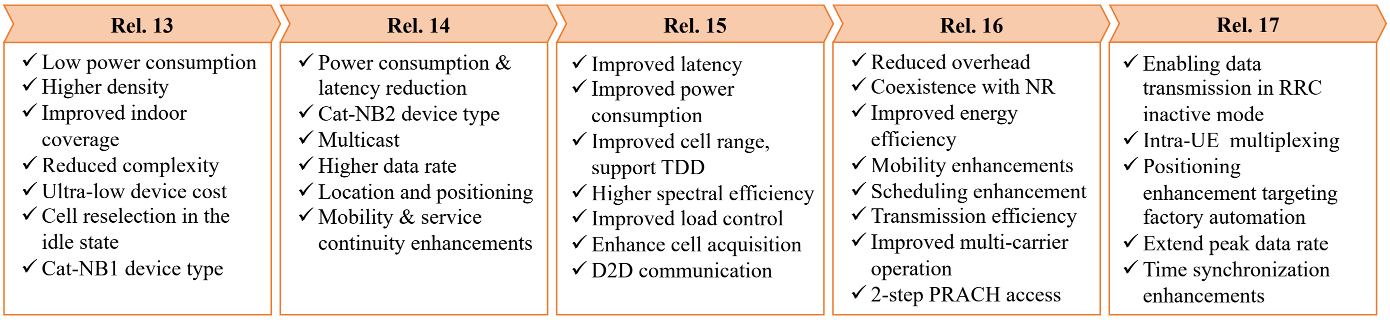

Figure 6: NB-IoT release enhancement features.

Table 6: NB-IoT release enhancement metrics.

Parameters	Rel. 14 (Cat. NB 2)	Rel. 15	Rel. 16	Rel. 17
UL/DL Peak Rates	standalone and guard-band (79.3 kbps), in-band (54.3 kbps) (DL), 105.7 kbps (UL) with 1 HARQ process, standalone and guard-band (127.3 kbps), in-band (87.1 kbps) (DL), 158.5 kbps (UL) with 2 HARQ process	127 kbps (UL) support of 2 HARQ processes	∼127 kbps (DL), 169 kbps (UL)	254 kbps
Device Capacity (devices/km^2)	∼80,000 in an urban environment	∼1,000,000 in an urban environment	∼1,000,000 in an urban environment	∼1,000,000 in an urban environment
Energy-Efficient Solution	PSM, I-eDRX, C-DRX, cell reselection	PSM, CI-eDRX, NWUS, improved scheduling request, EDT, quick release of RRC connection, small cell support	PSM, I-eDRX, NWUS, improved scheduling request, EDT, quick release of RRC connection, small cell support	PSM, CI-eDRX, NWUS, improved scheduling request, EDT, quick release of RRC connection, small cell support
References	[81] [93][94][73] [19][33]	[81][93][94] [95][73][19][33]	[82] [81][93] [73] [94][73]	[26][44]

devices, improved power efficiency, and 10 s or less latency with positioning and multicast features [103].

The ITU and 3GPP's mMTC performance criteria are further met by NB-IoT Rel. 15 (2018), which can fulfill 5G IoT requirements. It provides IoT connectivity with high data rates and reliable communication, boosting the 5G capacity while increasing IoT connectivity [104]. These requirements comprise high-performance and low-complexity features with an improved spectral efficiency and data rate [8]. Recently, 6G IoT has been studied extensively regarding the convergence of the 6G and IoT on five key domains: healthcare IoT, vehicular IoT and autonomous driving, unmanned aerial vehicles (UAVs), satellite IoT, and IIoT [105] in which 3GPP must work on the CIoT to support these stringent requirements. CIoT is also envisioned to support monitoring real-time applications in UAVs under the circumstances of Age of Information (AoI) handling status. As shown in Table 6, the same way as LTE-M, in each release; enhancements in data rates, device capacities, and energy-efficient solutions are recorded. As shown in Figure 6, enhancements made available in each release including low device power consumption, higher density, improved indoor coverage, reduced complexity, ultra-low device cost, optimized network architecture, cell reselection in the idle state, and Cat-NB1; power consumption and latency reduction (DL and UL for 2 HARQ processes and larger maximum TBS), new power class of 14 dBm, Cat-NB2, multicast, higher data rate, location and positioning protocol OTDOA, non-anchor PRB enhancements, mobility, and service continuity enhancements; improved latency, improved power consumption(WUS, EDT), improved cell range, support TDD, higher spectral efficiency, improved load control, enhance cell acquisition, D2D communication; reduced control-signaling overhead, coexistence with NR, better UE energy efficiency, scheduling enhancement, better UL or DL transmission efficiency, improved multi-carrier operation, 2-step PRACH; enabling data transmission in RRC inactive mode, intra-UE multiplexing, positioning enhancement targeting factory automation, extend peak data rate, time synchronization enhancements, 2-HARQ process enhancement, CSI enhancements in the subsequent releases. In Rel. 14, a new UE Cat. NB2 has developed with lower device cost and supports a massive number of IoT devices8̃0,000 in an urban environment. In resolving energy-consumption problems, they employed solutions including PSM, I-eDRX, C-DRX, and cell reselection in addition to the eDRX.

In Rel. 15 [95], 3GPP introduced the RRC-connected inactive state, which can benefit low data transmission optimization for devices operating for a short period. It is because of the substantial battery consumption, high demand for specialized resources, and high measurement reports and handovers, keeping the device in the RRC-connected state without active data transfer is not financially advantageous. The NB-IoT shortens the network monitoring duration for UE in idle mode, reduces the unnecessary startup of receiving cells, and reduces power consumption. Furthermore, Rel. 15 introduced the following energy efficiency solutions, as illustrated in Table 6. Wake-up signaling for IDLE mode (FDD) is served in an energy efficiency solution, reducing energy consumption. In communications, UE must frequently determine whether a paging message is from the core network when in DRX or eDRX. When paging is available, the UE mostly does not receive a message, and power is saved. With this capability, the BS can advise the UE to watch the narrowband physical DL control channel for paging by sending it an NB-IoT WUS (NWUS) introduced in Rel. 15 [106] to enhance the device energy efficiency, but otherwise, the UE is free to ignore the paging operations. NWUS enables the UE to potentially keep some of its hardware off for longer periods while saving the energy required to decode the narrowband physical DL control channel and shared channel for paging. The time the network allows the UE to "wake up" after receiving an NWUS determines whether the UE can maintain only one Rx switched on for WUS detection, leaving most of the UE conventional hardware in a very low-power state. The other viable solution is scheduling requests, included in the Rel. 13 and Rel. 14 NB-IoT as a higher-layer procedure that causes a random-access process to request enough UL resources to send a buffer status report. In addition, Rel. 15 has provided new, more resource and power-effective methods to accomplish this goal that the BS can configure, the EDT. The EDT is an idle mode with a bitrate of 328 to 1,000 bits. For example, UE can send data in msg 3 of the random-access procedure [107]. The random-access operation ends if a BS successfully receives a signal and the UE does not switch to connected mode. If the UE waiting data are less than the maximum permissible size established by the BS, the UE requests a grant for EDT by transmitting its preamble using a preconfigured set of narrowband physical random-access channel resources. To save energy on transmitting padding bits, the BS can authorize the UE to transmit fewer data than the maximum allowed size [106]. Due to minimizing the signaling overhead and message latency, the battery life is prolonged [19].

5.4. RedCap

The RedCap approach was created to address use cases (IIoT, video surveillance, and wearables) in IoT requirements that cannot be met using the EC-GSM-IoT, NB-IoT, or LTE-M [108, 44] operating at a higher data rate and reliability with lower latency than LTE-M and the NB-IoT. It offers a lower cost, lower complexity, and longer battery life than NR eMBB and wider coverage than URLLC. Some requirements often necessitate higher reliability and quicker response time than those offered by LTE-M and the NB-IoT, while still maintaining lower complexity and expenses, as well as longer battery life compared to eMBB and URLLC services. The RedCap interface is designed to bridge the gap between the intricate and expensive 5G-NR interface that caters to eMBB and URLLC services and the lower data rates and increased latency of NB-IoT and LTE-M interfaces that support mMTC services.

Under the study item "Low complexity NR devices" [67], in June 2019, 3GPP introduced RedCap NR devices in Rel. 17 with lower cost, lower complexity, and longer battery life compared to regular NR devices. In addition, RedCap was introduced to meet the low-cost, large-bandwidth, medium data rate, and no latency no delay tolerance IoT service requirements [29]. Hence, RedCap inherits the majority of the key advantages of NR. These include the ability to connect to the 5G core network, which is a cloud-based platform with a service-based architecture, support for a very broad range of frequency bands (FR1 and FR2 and millimeter-wave bands), network energy efficiency due to the ultra-flexible design, forward-compatible and beam-based air interfaces, and support for millimeter-wave bands [28]. As depicted in Fig. 7, enhancements have been incorporated in each release of RedCap. The applications use cases that are targeted include wearables, medical sensors, remote surgery, industrial sensors, surveillance cameras, and others. Rel. 17 of RedCap offers a multitude of enhancements that make it a cutting-edge solution for IoT applications. One of the most notable features is its ability to provide slicing capabilities, creating virtual networks within a single physical network, increasing network efficiency, and ensuring optimal resource utilization [67]. The positioning component of Rel. 17 has also been improved, providing more accurate location-based services and enabling new location-based applications.

Furthermore, this release boasts a large capacity for storing and processing data, making it ideal for handling large volumes of IoT data. The UE energy-efficient operation component ensures that the end-user experience is optimized for energy efficiency, reducing the overall carbon footprint of IoT devices [28]. In addition, Rel. 17 is highly cost-effective and offers low latency, making it an attractive solution for a wide range of IoT applications and budgets [109]. In Fig. 7, one of the key advancements in Rel. 18 is supporting higher transmission rates, providing faster data transfer, and enabling new applications that require higher bandwidth. Another major improvement is the support for the unlicensed spectrum, which expands the available spectrum for IoT devices and enables new use cases. Advanced positioning technology has also been incorporated, further improving location-based services and enabling new location-based applications [27]. Integrating sidelink near-field communications allows for direct communication between devices, providing a new level of convenience and enabling new use cases. In addition, it takes steps to reduce the complexity of RedCap UE further, making it even more user-friendly and accessible. Finally, the addition of device-to-device (D2D) communication expands the communication options for IoT devices, making it easier to connect and communicate with other devices in a local network. These enhancements and new features make Rel. 18 of RedCap CIoT necessary for anyone aiming to remain at the forefront of IoT technology. RedCap has unique features incorporated with 5G NR services and was objectively designed to maintain lower com-

Table 7: RedCap use cases with fundamental parameters

	Wearables	**Video Surveillance**	**Industrial Wireless Sensors**
UL-DL Bandwidth	≥5 MHz	≥5 MHz	≥5 MHz
Data Rate	5 Mb/s (DL/UL); peak 150/50 Mb/s (DL/UL)	2–4 Mb/s (UL) and 7.5–25 Mb/s	≤2 Mb/s
Latency	<10 ms	<500 ms	<100 ms, 10 ms
Service Availability	-	From 99% to 99.9%	99.99%
Battery Life	1 to 2 weeks	Not applicable	At least few years
Mobility	Non-stationary	Non-stationary	Stationary
Energy- Efficient Solution	eDRX for RRC idle and inactive states, RRM relaxation for stationary devices	eDRX for RRC idle and inactive states, RRM relaxation for stationary devices	eDRX for RRC idle and inactive states, RRM relaxation for stationary devices
Application Examples	Live video feed, visual production control and process automation	Remote vehicle operation cooperative farm machinery, economic video high-end video	Time-critical sensing & feedback augmented reality and safety-related sensors remote drone operation
References	[29][110][28][109][111]	[29][110][28][109][111]	[29][110][28][109][111]

plexity devices with 20 or 100 MHz maximum bandwidth in sub-7 or millimeter-wave with one or two Rx antennae. Additionally, 3GPP introduced this standard [61] due to RedCap's ability to coexist with URLLC features, use higher frequency bands, and apply other 5G features, such as network slicing. For instance, RedCap is designed to provide significantly faster data rates than previous CIoT technology compared to the data rate specified in Rel. 17 using a higher frequency band, multiple-input multiple-output technology, advanced modulation techniques, advanced beamforming features, and network slicing. Use cases for RedCap are less battery-life-intensive than mMTC use cases, but they are more demanding for throughput and latency. However, a higher data rate of up to 100 Mbps is required to accommodate live video feed, visual production, and process automation [28]. This approach enables new use cases and applications that were previously impossible [9].

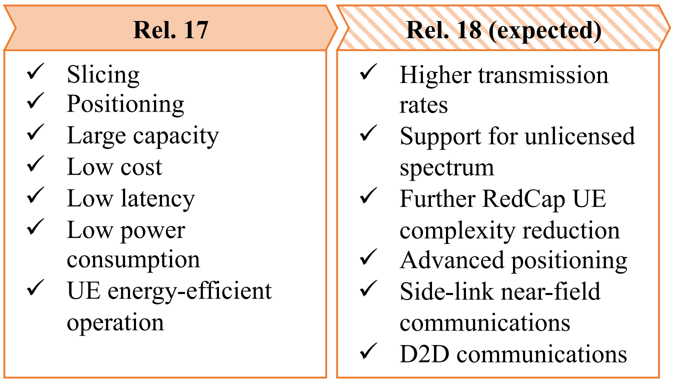

Figure 7: RedCap release enhancement features.

In addition to the transmission rate, in machine-to-machine collaboration and real-time remote control, ultra-low communication latency is expected at around 1 ms. Communication latency can be raised from the physical layer latency and scheduling latency problems [112]. However, for the time being, in the higher requirement scenario, it is possible to achieve a latency of 10 to 30 ms to support applications like remote drone operation, cooperative farm machinery, time-critical sensing and feedback, and remote vehicle operations. Higher communication reliability in mission and time-critical applications, for example, autonomous vehicles, remote surgery, and smart factories, is not an option to compromise but should be kept stable [9]. In IIoT, data transmission security is the top demand to make sensitive information extremely secure and highly available on demand. For Rel. 17 RedCap features [111], 3GPP also added extra features in future Rel. 18 work, depicted in Fig. 7.

Furthermore, localization or positioning increases network complexity, potential overhead, and accuracy degradation and can include power, time, and space domain localization [66]. Positioning or localization in the MTC has become difficult due to the complication of environments, sensor errors, and device motions, as Le *et al.* [23] investigated. Supporting location-based service applications is crucial for some IoT applications, such as tracking items. Although a smaller BS density has an advantage in the IoT scenario, a higher BS density is an important factor in localization with small BSs. In addition to environment complexity, other problems in positioning are end device-related errors, environment-related errors, BS-related errors, and data-related errors [23]. Hence, positioning accuracy can be supported by different mechanisms, including received signal strength (RSS), time difference of arrival [23], and channel -state information [113].

Regarding the D2D Protocol, communication between devices, such as wearables, that can directly communicate with nearby smartphones or connected vehicles is supported by RedCap [114]. It is enabled via sideline communication over a shared RF channel in which the cellular BS provides a synchronization signal that enables direct D2D communication, which can also improve communication efficiency, reduce latency, and extend network coverage and capacity. Most importantly, RedCap supports the Unlicensed Spectrum. In 3GPP's EC-GSM-IoT, LTE-M, and NB-IoT, there is no support for sub-GHz license-free frequency bands (unlicensed spectrum). There have been efforts, such as MulteFire Alliance [115] that have been working on expanding IoT services with LPWAN support in the 800/900 MHz band (902 to 928 MHz band in the United States and 863 to 870 MHz band in the European Union) with NB-IoT unlicensed and 2.4 GHz with extended MTC unlicensed. RedCap uses unlicensed spectrum bands under both licensed and unlicensed standards and regulatory requirements to address spectrum scarcity issues.

Due to its lower cost and low-complexity features, RedCap is further becoming manifested in IoT applications that target mission-critical aspects (that require low latency, ultra-reliability, high security, and high data rates) [57] and time-sensitive IoT connectivity like emergency response, health-care services, disaster mitigation, and related cases in which these applications require faster and more reliable performance than other applications, and their connectivity must be guaranteed to be safe and resilient. Industrial wireless sensor networks, video surveillance cameras, and wearables (e.g., smartwatches, rings, eHealth-related devices, and medical monitoring devices) are some use cases for RedCap [108, 67].

RedCap contributes to services that require more capabilities than the EC-GSM-IoT, LTE-M, and NB-IoT but are lower than URLLC and eMBB machines including process monitoring (pressure sensors, humidity sensors, and thermometers), self-diagnosis and maintenance (motion sensors, accelerometers, and actuators), and video-assisted applications (asset monitoring and augmented reality) [108]. According to TR 22.832, TS 22.104, and TR 22.804, [110] as summarized in Table 7, reference use cases and requirements are as follows. End-to-end latency is less than 100 ms, and communication services are 99.99% available. For all usage situations, the reference bit rate is less than 2 Mbps, and the device is immobile. This reference bit rate may be asymmetric, such as in high UL traffic [111]. At least a couple of years should pass between charges. Safety-related sensors, such as smart factories, require less delay (5 to 10 ms). Generally, time-critical sensing and feedback, augmented reality, safety-related sensors, and remote drone operations are applications in industrial sensors. For instance, the goal of the smart grid is to create a more sustainable and efficient-energy infrastructure that can meet the needs of an increasingly connected and energy-intensive world. In IIoT, a specific application known as the power IoT focuses on smart grids to attain automatic optimized data collection and exchange of information, as well as smart energy management [116].

6. Focuses of CIoT Technologies

One of the focuses of the CIoT is to provide extended coverage in areas where traditional cellular networks may not reach, including indoor and underground locations and remote or rural areas. This reach is achieved using a narrowband frequency for better signal penetration and greater range. Another key role of the CIoT is to offer efficient and cost-effective connectivity for a broad scope of IoT applications, from smart cities and homes to agriculture, transportation, and healthcare. With its low- power consumption and ability to facilitate numerous connected devices, the CIoT enables a broad range of use cases, including asset tracking, remote monitoring, and sensor networks [38].

For instance, international roaming can be considered one important focus of the EC-GSM-IoT, minimizing device complexity and cost. Because the EC-GSM-IoT has coexisted with 2G mobile networks, it has benefited significantly from all the security and privacy features provided by mobile networks including various measures to ensure user confidentiality and privacy, such as the protection of user identity, authentication protocols, data encryption to ensure confidentiality, measures to maintain data integrity, and identification of mobile equipment [73].

LTE-M, on the other hand, targets medium-sized IoT applications supporting voice and video services. Therefore, it is a better candidate technology for over-the-air firmware updates during the life span of IoT devices [24]. Unlike the NB-IoT, LTE-M is better suited for mobile devices to avoid connection and data loss and provides higher data rates that would enable more use cases, such as VoLTE vehicles, fleet management, tracking devices, and related use cases [117]. Moreover, LTE-M can be used in video surveillance systems because it supports higher data rates and can transmit real-time video data.

In addition, the NB-IoT is primarily designed for ultralow-end and latency insensitive or delay tolerant IoT applications [68]. It focuses on fixed indoor coverage in areas where signal loss and multitiered layers have posed problems. NB1 UE, for example, operates only in the 200 kHz bandwidth with IoT devices imposing ultralow complexity for services without strict data rate, latency, or mobility requirements but that requires a massive deployment of low-cost devices [65].

Lastly, according to 3GPP and Ericsson [51, 44], RedCap has many use cases and is highly necessary to work in extremely harsh environments. RedCap was introduced with lower hardware complexity at more affordable prices. It aims for terrestrial coverage and targets exchanging data over the satellite with the aim of ubiquitous coverage area (referred to as NTN communication) [109]. It is possible to run a RedCap device on an NR carrier optimized for eMBB or time-critical communications. The objective of the study group on the NR-RedCap has been emphasizing reduced UE complexity, such as a reduced number of antennae, reduced UE bandwidth, HD-FDD, and other aspects. Compared to high-end eMBB and URLLC devices of Rel. 15/16, the primary driving force of the new device type is to reduce device cost and complexity, which is true for industrial sensors [109]. The standard must allow for a device design with a compact form factor to support most use cases, and all FR1/FR2 bands for FDD and time division duplex should be supported by the system [110]. As shown in Table 7, video cameras, for instance, lead to higher data-rate requirements than can be satisfied by the EC-GSM-IoT, LTE-M, and NB-IoT. Smart cities, smart farming, smart factories, and other industrial locations have increasingly installed surveillance cameras. According to TR 22.804, a reference economic video bitrate would be 2 to 4 Mbps with a latency of 500 ms or less and a reliability of 99% to 99.9% [110]. High-quality video, for example, for farming, would require 7.5 to 25 Mbps [28]. As explained in [3], reference bitrates for smart wearable applications can range from 5 to 50 Mbps in the DL and 2 to 5 Mbps in the UL. The device's peak bit rates can reach 150 Mbps in the DL and 50 Mbps in the UL [28]. The battery should last one to two weeks for wearables, as reviewed in Fig. 7. Rel. 17 for RedCap devices introduced power-saving techniques to extend battery life and enable longer usage times. These are; eDRX for RRC idle and inactive states and RRM relaxation for stationary devices. In eDRX, when DRX cycles are utilized, it can achieve up to 10485.76 seconds, almost 3 hours when the RRC is idle, and up to 10.24 seconds when the RRC is inactive. In demanding RedCap use cases, such as industrial wireless sensors, eDRX proves to be a valuable solution in meeting the battery lifetime requirements. Regarding the RRM relaxation, in RRC idle and inactive states, the device is required to regularly conduct RRM measurements. These measurements are necessary to determine and select the best available cell for the device to establish a connection. In spite of this, the battery will be depleted even if there is no active data transmission. Thus, skip performing RRM measurements under certain thresholds of reference signal received power (RSRP) and reference signal received quality (RSRQ) values are employed [28]. In addition, the other optional power-saving features, standardized in Rel 15 and Rel. 16, are also made available for RedCap devices which offer power-saving capabilities to enhance the battery performance. Because of the fast-growing need for personal care devices and diagnostics, such as sports, healthcare, and fitness devices, wearables have garnered more attention. Devices that are too small in size, such as smartwatches, rings, e-health-related devices, and medical monitoring devices, are supported by RedCap, which can collect and relay health information. The CIoT plays an immense role in healthcare, and healthcare IoT (HIoT) is developed and supported by AI, big data, software-defined networks, and blockchains [118] with the driving technology; the Internet of Nano Things and tactile Internet. The HIoT is implemented in the form of wrist-worn smart wearables [119]. As with other IoT application requirements, HIoT prompts low latency that can be obtained through edge computing implementation using a large volume of data through cloud and edge computing. As most medical applications are private, the blockchain has been a solution to secure patient data from third-party access risks [120]. In healthcare-based medical operations, it is highly recommended to securely transmit sensitive healthcare data to the fog and cloud for processing. Ullah *et al.* [121] recommended fog and cloud-assisted computing as the appropriate candidate solutions for these issues. RedCap has an immense role in remote surgery applications by integrating wearables, medical sensors, industrial sensors incorporating surveillance cameras, and more. For more, we briefly present their detailed features in the following sections.

7. Features of CIoT Technologies

To guarantee that CIoT technologies can efficiently provide connectivity solutions for various use cases ranging from Massive IoT to Critical IoT, this section outlines essential requirements that must be met for the large-scale deployment of these services. These include extended coverage areas, low deployment costs, extended battery life, affordable device costs, support for a vast number of connected devices (scalability), and robust security and privacy measures, we discuss in detail as follows.

Wide Coverage: Delivering a wider and more extended coverage area is one of the main aims of the CIoT. In a wide coverage area, the path range is an important parameter that varies inversely with frequency, offering tens of kilometers of coverage. Carrier frequency has a significant effect on CE. Although the path loss is directly dependent on the size of the carrier frequency, if the carrier frequency is high, the propagation loss becomes high. Maintaining a lower carrier frequency is important to maximize the coverage in the CIoT to lessen propagation loss. For instance, the EC-GSM-IoT is based on the GSM; thus, the frequency band of the GSM is highly globally deployed with the four known global frequency bands 850, 900, 1800, and 1900 MHz, where coverage is ultimately enhanced [73]. Ericsson, Orange, and Intel have tried extending coverage on smart agriculture use cases using the EC-GSM-IoT, confirming that it is possible to enhance indoor coverage by deploying new software on the existing cellular networks [122]. Moreover, CE techniques should be implemented to achieve a wide or deep coverage area (it is primarily accomplished by sacrificing the data rate for coverage), which is required for two reasons. Implementing reduction techniques in device complexity (e.g., minimizing to a single-antenna Rx and lower maximum transmission power) may result in performance degradation that directly produces coverage loss. The loss of coverage can be maintained by scaling transport block size (TBS), HARQ retransmissions for the physical DL shared channel (PDSCH), PUSCH, physical UL control channel (PUCCH), and PDCCH [9, 67]. Second, some CIoT devices could encounter extremely difficult coverage circumstances. Hence, transmission time interval bundling, sending a limited, predefined number of transmissions without feedback instead of sending a block of transmissions once, and narrowband retuning are key feature techniques to achieve higher and more extensive coverage. In widening the coverage, the objective is to attain a CE of +15 dB compared to GSM and LTE [123]. The 3GPP measures CE using the MCL standard, which is the discrepancy between the power levels transmitted and received before the signal is lost. Coverage can be measured as “kilometers of coverage” but according to the analysis presented in [124], it is not adequate since it heavily relies on the carrier frequency and environmental factors such as the type of location, whether it is indoors, outdoors, urban, suburban, or rural. In contrast, MCL is an appropriate measure because it is not influenced by the frequency and environmental aspects. At extreme coverage, it is expected to attain +20 dB from the normal LTE or GSM coverage, and it is very important to determine exactly how much coverage the CIoTs can provide.

Apparently, for evaluation, Ericsson, AT and T, KT, SK Telecom by Korea, Nokia, Verizon, Altair, Docomo, Sony, SoftBank, TELKOMSEL by Telecom Indonesia, Virtuosys, Sequans Communications, KDDI, and Orange conducted a thorough link-level simulation inspection to assess the actual coverage performance of 3GPP’s LTE-M technology. Their findings discovered that LTE-M is capable of achieving a coverage gain of 21 dB compared to older LTE devices, which is higher than the 3GPP target of 18 dB. This increase of 21 dB corresponds to a data rate of 1400 bps in the DL and 250 bps in the UL. If IoT applications can tolerate slower data rates and longer acquisition times, it is possible to achieve a coverage gain beyond 21 dB without using the BS power spectral density (PSD) boosting [124]. With a 21-dB gain with 23 dBm UE (the maximum coverage) and less conservative noise figures, LTE-M is a strong competitor for IoT applications that require extensive coverage, with a maximum MCL of 164 dB, and where the demands for low latency, high mobility, and fast data transfer are less stringent. Moreover, LTE-M has two specifications in its CE strategy: Modes A and B. The former mode is mandatory and supports only moderate CE, whereas the latter mode, B, supports deep and extended coverage that can be considered optional. Common coverage techniques are employed to provide CE for the LTE-M specification. The Tx power (e.g., Class 3 power amplifier 23 dBm and Class 5 power amplifier 20 dBm) is increased by considering the increasing cost management, repetition by optimizing accurate channel estimations, and frequency tracking to manage the downside of repetition in linearly increasing the latency. In addition, PSD boosting improves the DL coverage and reduces the power by employing a maximum amount of PSD boosting to 4 dB. These methods are the most feasible in CE, as illustrated in [124]. In B5G CIoT [125], a programmable metasurface can significantly improve coverage with an intelligent reflecting surface. Through the IoT non terrestrial network (NTN) work item in Rel. 17 [91], 3GPP has already addressed NTN support for LTE-M and the NB-IoT [114]. Overall, LTE-M can support extensive IoT deployments, covering the maximum distance and beyond with the approved QoS and minimum maintenance provisions.

From the 3GPP standard specification, the range of the NB-IoT covers urban and rural areas, outlined as 1 to 2 and 10 to 15 km, respectively [126], enabling better signal propagation in basements (aiming for +20 dB improvement over legacy cellular systems) [127]. A transmission time interval bundling, repetition (retransmission, such as 128 and 2,048 times in the UL and DL, respectively [89]), and narrowband retuning are employed as key features to achieve higher and more extensive coverage. The number of repetitions of a transmission is determined by the desired CE level (CEL) for a given set of devices. The CEL is the signal strength at a particular location and can be influenced by the distance between the Tx and Rx, the transmit power, the Rx sensitivity, and interference. The number of tones and sub-carrier spacing, which are the number of different frequency components used to transmit data and the distance in frequency between adjacent sub-carriers, respectively, also affect the CEL and spectral efficiency of a wireless communication system [22]. The increased number of retransmissions lowers the spectral efficiency [128], which requires reducing the number of retransmissions. However, three CELs are supported by NB-IoT devices: CEL-0 for 0 dB with an MCL of 144 dB with a subcarrier spacing of 15 kHz, CEL-1 for 10 dB with an MCL of 154 dB with 15 kHz spacing, and CEL-2 for 20 dB with an MCL of 164 dB with 3.75 kHz carrier spacing [79]. In the CE of the NB-IoT, the objective is to attain a coverage capacity of 164 dB [129],[123] and guarantee that it can enhance the 164-dB coverage achieved through repetitions in time, with power amplification in in-band and guard-band operation modes [65]. In general, this is preserved by implementing repetition, boosting the PSD, reducing the system acquisition time, and random-access range enhancement. Based on the findings in [21], the coverage of NB-IoT [882 MHz] can be boosted by up to 398% with a mere 10% enhancement in Rx sensitivity. Enhancing the coverage by implementing machine learning methods using reinforcement learning-based dynamic spectrum access [130] is also feasible. The NB-IoT increases the link budget by over 20 dB, significantly enhancing penetration. Although reducing the device capabilities can lower the device cost and reduce the device size, it has an adverse influence on coverage. For instance, in RedCap, reducing the number of antennae and limiting the number of spectrum bands can affect device coverage. It is vital to secure the device cost and lower complexity simultaneously to enhance the coverage. In RedCap, it is expected to extend 10 to 15 dB compared to URLLC.

Low Power Consumption: Most IoT devices are powered by batteries. Therefore, conserving energy to extend their lifespan is vital. It is exceptionally demanding to reserve the main power supply by implementing longevity in the battery life of the device before recharging is mandated. Devices that support lower power consumption have a longer device battery life. In many use cases, the CIoTs are supposed to achieve a battery life of up to 10 years. The battery usage directly relates to how long the device spends sending and receiving data. As research [58] has noted, to maintain a battery life of 5 years, for example, a device with a 5000 mAh battery capacity should use no more than 2.74 mAh per day. This limit can be achieved by restricting daily battery consumption to below 5000 mAh/5/365 [58]. Achieving long battery life and reducing maintenance costs are critical in applications and equipment with limited battery capacity, which makes low energy consumption essential. However, the battery life depends on coverage [131]. The objective of 3GPP standards for battery life in the CIoT is to achieve ≥10 years of service life in most extreme coverage situations at 164 dB MCL [47] (11.9 years is achievable) and 35.7 years at normal coverage (144 dB MCL) [84]. This feature can also save costs in areas where replacing batteries can be a challenging task, such as basements or subterranean tunnels.

In minimizing power consumption, EC-GSM-IoT, LTE-M, and NB-IoT utilize techniques including the power-saving mode (PSM) [132, 133, 134], long periodic tracking area updates (TAU), and eDRX which are developed by the 3GPP standards to reduce energy consumption and enable an extended life for these devices [80]. The PSM allows modules to enter a sleep mode that consumes very little energy (only a few microamps) while sending TAU messages at long intervals to remain registered on the network. This approach eliminates the need for reregistration when the module wakes. The eDRX feature allows devices to enter a low-power paging mode for an extended period of time, during which they can receive data from the server but do not need to send data, saving power when the device does not need to transmit. In eDRX, an extension of ~52 min is possible. The PSM can use paging in the DRX or jointly use paging and routing area updates (via incoming SMS, voice call, or data) to reach the CIoT devices on the network. For devices that prefer a lower periodicity of reachability, using eDRX is more advantageous; however, for devices that can tolerate longer intervals of inaccessibility, the PSM emerges as an appealing alternative. Furthermore, implementing GMSK modulation in the EC-GSM-IoT, for instance, influences power and energy efficiency. The enhanced coverage common control channel (eCCCH)can also contribute to energy efficiency, providing long battery life. Other energy-saving techniques besides PSM and eDRX have been developed and employed, such as energy-efficient TAU, user and control plane optimizations, energy-efficient paging reception, wake-up signal (WUS) calls, and techniques for monitoring cells less frequently.

Furthermore, RedCap power consumption is anticipated to be significantly (2 to 4 times) lower than that of Rel. 16 eMBB, resulting in minimized power usage. The battery life is expected to span 1 to 3 years. In Rel. 17, 3GPP suggested improvements for UE power conservation in the idle or inactive mode while considering system performance factors to address the power consumption problem. They studied and specified improvements to power-saving methods for connected UE, with the least possible influence on system performance [3]. Based on power-saving techniques proposed in Rel. 17 for RedCap devices, in the idle and inactive state, eDRX cycles are almost 3 h and 10.24 s, respectively. This approach better extends the battery life [67] in the stringent use case of industrial wireless sensors, for example. In addition to eDRX, the relaxation of frequent radio resource management (RRM) to secure the exact camping in its idle and inactive state can avoid the drainage of batteries, primarily in stationary devices. In general, potential power consumption-saving techniques include reducing the duration the device spends checking the control channel for scheduling, lengthening the device sleep time by extending the DRX period, and allowing for less frequent measurements for stationary devices. In the long run, a very high energy-efficiency technology is expected, supporting battery-free IoT devices, such as self-driving cars, drones, and auto-robots [135]. The most important area of research in the IoT is energy efficiency, especially in IIoT, to preserve moderate power consumption [136].

According to [26], energy-saving methods can be maintained in three ways: configurations (including traffic models, connectivity periods, and DRX cycles), software modification (comprising improved radio layer protocols, changes have been made to the scheduling request procedures for accessing radio channel resources, as well as the introduction of new software entities in the core network to improve communication in both the UL and DL directions), and hardware integration (embedding a low-power Rx by deactivating the main Rx). In [137], energy efficiency or low power consumption can be achieved by eliminating transmission between nodes using the star topology, maintaining a straightforward node design, and using narrowband channels for reduced noise and an extended transmission range. Based on [138], the joint optimization of user selection, power allocation, and antenna selection while fulfilling the QoS requirements has a prior role in maximizing energy efficiency under imperfect channel state information. In most IoT devices, the channel state information is imperfect due to the functional limitations and mobility, as stated in [139]. In addition, an advanced energy-harvesting technique called simultaneous wireless information and power transfer is another promising solution to achieve energy-efficient green communication. Chen *et al.* developed a two-layer iterative algorithm to manage inter- and intra-beam interferences by leveraging the Dinkelbach method[140] for energy maximizing by allocating power at the base station and splitting power at each IoT node.

The other promising solution is HARQ feedback. Transmitting a positive HARQ-ACK over MPDCCH in a UL data center interconnect is now possible [141]. This approach enables early termination of the UL (PUSCH) transmission or early termination of the DL (MPDCCH) monitoring (for FD-FDD or time division duplex but not HD-FDD). It allows the BS to notify the UE that UL data have been successfully received using two HARQ processes and 10 HARQ processes with a beneficial effect. In addition, cell reselection with relaxed monitoring is a good option. When enabled, the UE can reduce neighbor cell measurements to once every 24 h [31]. This approach can significantly lower power usage, especially for fixed UE in difficult coverage situations. Moreover, resynchronization signal (RSS) better improves energy economy when a device needs to regain synchronization with a cell's time and frequency [5]. Researchers from academics and industry have been studying solutions and techniques to address power consumption issues, including energy harvesting [142], [143], [144], sporadic transmission, resource allocation, clustering, zonal thermal pattern analysis for smart agriculture, and energy-efficient adaptive health monitoring system for smart health applications [14]. In [145], RF energy harvesting on the strength of RF signals was cheaper to implement and available in difficult-to-reach places where other popular sources, such as solar or wind, may not be accessible. Moreover, accurate computation and efficient communication are critical for numerous devices to reduce power usage. Developing communication systems that are energy-efficient, both in terms of system design and hardware is vital to mitigate power problems [146]. Over-the-air computation was proposed as a promising solution [147]. In [148], energy-harvesting strategies for operating low-power network devices using long-lasting IoT devices and sensors were studied, enabling them to be self-powered and providing devices with long standby intervals. Network parameter settings affect energy consumption and network performance, and [149] found that the paging interval set by the BS has the greatest effect on energy consumption when the device is connected.

Low Cost: In the CIoT, installing or maintaining local networks or gateways is unnecessary. The sensor can connect directly to the desired system or network, which maintains the cost [25]. Maintaining low power consumption facilitates low device costs, which can be achieved by reducing Tx and Rx bandwidths. Current costs run between \$10 and \$15 per module, with a long-term goal of reaching \$5. The GSM, for instance, is the main player in machine-to-machine communications because of its reduced cost compared to other technology. As a result of the expiration of the device module patents in GSM networks, compared to other 3GPP-defined technology, the cost of the EC-GSM-IoT module is the most economical in developing countries [52, 25], less than $10, where 2G, 3G are deployed. The EC-GSM-IoT module cost is $5.5 and $2.9 in 2016 and 2020 [150, 151], respectively. It is because of the overall cost of deployment, network coverage (which can balance the economy of vendors, particularly in the Asian and African continents), maturity (the presence of a more mature ecosystem comprising a wide range of compatible devices, and applications), lower complexity, and lower frequency band specificity. The other player in achieving ultralow-cost devices is the implementation of a GMSK-only modulation. Moreover, for cost reduction, according to the analysis of [152], the trend reveals a 10-times reduction in 1G and 2G, respectively, and a 1,000-times reduction from 3G to 6G).

In contrast, the NB-IoT has many design trade-offs to achieve low-cost goals, resulting in a simplified, low-complexity system with a lower data rate. One of these trade-offs is the lack of carrier aggregation, a technique that combines multiple carriers (or frequency bands) to increase the available data rate. Carrier aggregation requires additional hardware and processing resources, increasing the cost and complexity of NB-IoT devices. Similarly, NB-IoT does not support voice services or multi-stream transmissions in the DL/UL direction. These features would also require additional hardware and processing resources, which would be incompatible with the low-power and low-cost requirements of the NB-IoT. Instead, the NB-IoT provides simple, low-data-rate communication for IoT applications that do not require high-bandwidth or real-time services [80]. However, the NB-IoT can operate alongside the existing GSM and LTE networks, which can help lower deployment costs. The device cost is related to the complexity of baseband processing, memory consumption, and RF requirements. Valuable cost reductions can be achieved from various modifications associated with narrowband operations, power reduction mechanisms, and the simplification of a physical layer [14]. The NB-IoT module cost is achieved $4 and $2-3 in 2016 and 2020 [150, 151] per module, respectively which is more effective in urban environments where 5G requirements are in hand.

Regarding LTE-M devices, they could achieve a similar cost to GSM devices by simplifying the design of the end devices. Due to its compatibility with existing LTE radio systems, LTE-M can be easily deployed through a simple software upgrade to meet the cost optimization needs of IoT applications, building upon the foundation of LTE technology. Taking into consideration the market scale, the module cost for LTE-M is less than $10, making it an affordable option [153] by incorporating various optimizations to enhance efficiency and reduce complexity. These optimizations include incorporating half-duplex operations (i.e., less complex and less costly), reduced transmission mode (TM) support, minimizing the number of blind decodings required for control channel reception, and eliminating simultaneous reception. As elaborated in [150, 151], the LTE-M module cost achieved $5 in 2016 and $3.3 in 2020.

On the other hand, compared to standard NR UE, RedCap UE is substantially simpler due to the half-duplex operation, which means that the UE is not required to transmit and receive simultaneously, a smaller number of radio RX antenna branches (reducing the antenna configuration, can reduce the device size), and a smaller radio Tx bandwidth. As a result of the projected decreased complexity, devices are expected to be more affordable, enabling the use of NR in novel applications, such as industrial sensor networks [44]. In conclusion, these requirements are achieved through careful configurations, properly adjusting the traffic profile (the frequency and number of data transmitted and received by the UE), coverage situation (under normal, robust, and extreme coverage scenarios), and network settings [154].

***Low Complexity*:** Simplified network topology and deployment is one component of the CIoT that the EC-GSM-IoT, for instance, highly fulfills. It only requires software upgrades in the existing GSM networks [122]. In addition, by simplifying the modulation scheme used for transmitting data over the air instead of using more complex modulation schemes, such as 16 quadrature amplitude modulation (QAM) or 64 QAM used in traditional GSM networks, the low-complexity mode of EC-GSM-IoT employs a simpler modulation scheme called GMSK. This approach reduces the complexity of the transceiver hardware required to implement the technology. Keeping the device complexity ultralow to secure a low-cost device is expected to support the large-scale deployment of millions of devices. Indeed, the EC-GSM-IoT technology, for example, is an advanced version of the EGPRS technology, which already satisfies the necessary requirements without any need for further complexity reduction [73]. The goal of LTE-M, for example, was to drastically reduce the complexity and cost compared to the preceding LTE device categories. In addition to reducing complexity, LTE-M aims to handle a broad range of mMTC use cases, including demanding high-throughput and low-latency applications. Under the 3GPP cost reduction analysis and techniques [155], employing the following methods can provide remarkable complexity reductions in LTE-M: reduction of the maximum bandwidth (from 20 to 1.4 MHz), a single-receive radio frequency (RF) chain (from 2 to 1), a reduction of the peak rate (from 10 to 1 Mbps), a reduction of transmit power (from 23 to 20, or 14 dBm), half-duplex instead of a full-duplex operation, and a reduction of supported DL transmission modes. Furthermore, securing low device complexity is required to boost the QoE and QoS in IoT applications. The device complexity is related to the complexity of baseband processing, memory consumption, and transmit-and-receive antenna (RF requirements). In NB-IoT, for instance, low complexity can be secured by reducing the TBS, accommodating only single-stream transmissions, supporting only a single HARQ process for both the DL and UL, adapting only one redundancy version in the DL, applying a low sampling rate due to lower UE bandwidth NB-IoT support, and allowing only HD-FDD operation [68]. Additionally, synchronization in the modulation and demodulation process requires higher computation. However, the NB-IoT has been specifically designed to facilitate low-complexity Rx processing in such operations. The RedCap, in addition, is also developed to be lower in complexity compared to the standard NR via narrowing the bandwidth, reducing the number of DL

MIMO layers, the transmit antennas, the receive antennas, and so on.

Mass Device Connection and Global Deployment: Massive connectivity is the key component in IoT applications to provide and offer the intended services to society. Mass device connectivity pertains to the number of devices that meet a specific QoS within a given area, typically measured in terms of square kilometers. As a result of the CIoT's low complexity features and high demands and expectations, deploying a massive number of IoT devices is demanded. As concluded in [147], the present CIoT technology is efficient, and developing 6G CIoT is essential. Massive numbers of device connections are vital when expanding coverage is needed. According to [101], low-orbit satellites have been identified as an efficient option for delivering long-range IoT services with good coverage and latency by supporting numerous connections. Furthermore, the International Telecommunication Union Radiocommunication Sector (ITU-R) [41] has established a firm requirement for International Mobile Telecommunications (IMT) 2020 systems that mandates a connection density of one million devices per square kilometer. For instance, the GSM has been deployed for over 30 years. A round 50% and 25% of subscriptions are made in developing countries in Africa and the Middle East, respectively, according to Ericsson's November 2022 report [156]. The GSM networks are widely covered and deployed worldwide, making connecting devices feasible, which means that the EC-GSM-IoT can be deployed in most regions without significant additional infrastructure. Hence, the deployment of the EC-GSM-IoT is feasible worldwide. It can also accommodate massive device connections with at least 50,000 nodes per cell [66]. 3GPP has been developed enhancements to support more devices per cell. For instance, optimizing resource allocation in IoT communication systems is critical in supporting many IoT devices. In [157], the authors devised a two-step optimization technique for UL transmission using convolutional neural networks (CNNs) based on deep learning. This approach is capable of optimizing the assignment of sub-bands and controlling transmit power with outcomes of low complexity, and it can accommodate a large number of devices. Moreover, regarding enabling numerous IoT device connections, [158] introduced leveraging the unlicensed spectrum in addition to exploiting the licensed spectrum. From the Technical Specifications Group RAN work group of TR-45.820 [43, 159, 32], for only one PRB (12x15 kHz), the NB-IoT, for example, can hold more than 52,500 pieces of UE per cell, in some scenarios, it also supports 72,000 devices ([160]). NB-IoT enables the connection of up to 100,000 end devices at the expense of complexity and cost[75, 134, 26] within single-cell, and its capacity can be obtained by incorporating multiple NB-IoT carriers of 200 KHz. In this configuration, one anchor carrier is dedicated to carrying the always-on broadcast signaling, while additional carriers (non-anchor carriers) are utilized for offloading data traffic and enhancing capacity. Moreover, enhancement objectives include designing positioning support (horizontal) targeting at least 50-m accuracy; extending the single cell point to multi-point network to support the CIoT for multicast DL transmissions (namely firmware or software updates and group message delivery); specifying new UE power classes (e.g., 14 dBm) to enable lower maximum transmit power suitable for small form-factor batteries, mobility, and service continuity enhancements; UL enhancements to reduce device power consumption further; and enhancements to support voice [93].

***Improved Security*:** Given the growing importance of IoT devices in various industries such as healthcare, manufacturing, and transportation, ensuring the security of things is critical to protecting sensitive data and ensuring the safe operation of these devices. Every CIoT technology option necessitates that both the network and the mobile station employ an enhanced and strong security framework. They have got a significant benefit from all the security and privacy mobile network features comprising user identity confidentiality, authentication, confidentiality, data integrity, and mobile equipment identification since it is operating in the licensed spectrum sharing all the advantages of standards-based technologies. For instance, EC-GSM-IoT has an LTE-grade security to improve end user security for the sake of removing any security concerns. The security measures currently in place for GSM technology have significantly contributed to enhancing security in EC-GSM-IoT. These procedures involve mutual authentication of both the device and the network during connection establishment, employment of 64-bit long encryption and 128-bit ciphering algorithms for better encryption, rejection of incompatible networks, and protection of control plane integrity [75]. Most importantly, the integration of existing CIoT technologies with 5G is done. This integration allows for enhanced security mechanisms across the network, addressing issues of authentication, authorization, and accounting (AAA) for a wide range of interconnected IoT devices. In general, in CIoT, extending coverage, reducing power consumption, lowering device complexity, reducing device cost, enhancing massive connectivity, and enhancing positioning are the foremost required features to maintain during CIoT communication by all mobile network operators, organizations, and companies. As shown in Fig. 8, coverage extension techniques can be incorporated, such as repetition and bundling, direct interface side-links or relays, and reducing the subcarrier spacing. For example, asset tracking, fleet management, and smart cities all rely on accurate positioning data to function effectively and maintain position enhancement. Hence, observed time-difference-of-arrival positioning, enhanced cell-ID positioning, UL time difference of arrival positioning, location positioning protocol, assisted global navigation satellite systems, and centimeter-level positioning techniques have been integrated. Solutions for reducing power consumption include lowering the transmit power by introducing new classes of UE, enhancing power-saving modes (PSM, eDRX, and WUS), and limiting mobility and handovers. Narrowing the bandwidth and reducing the number of DLs, multiple-input multiple-output layers, and Tx or Rx antennae minimize device complexity. Moreover, reducing signaling overhead, simplifying the core network architecture (network elements, interfaces, and protocols), and employing better resource management techniques can enhance network efficiency. Further, reducing device costs and Tx and Rx bandwidths, min-

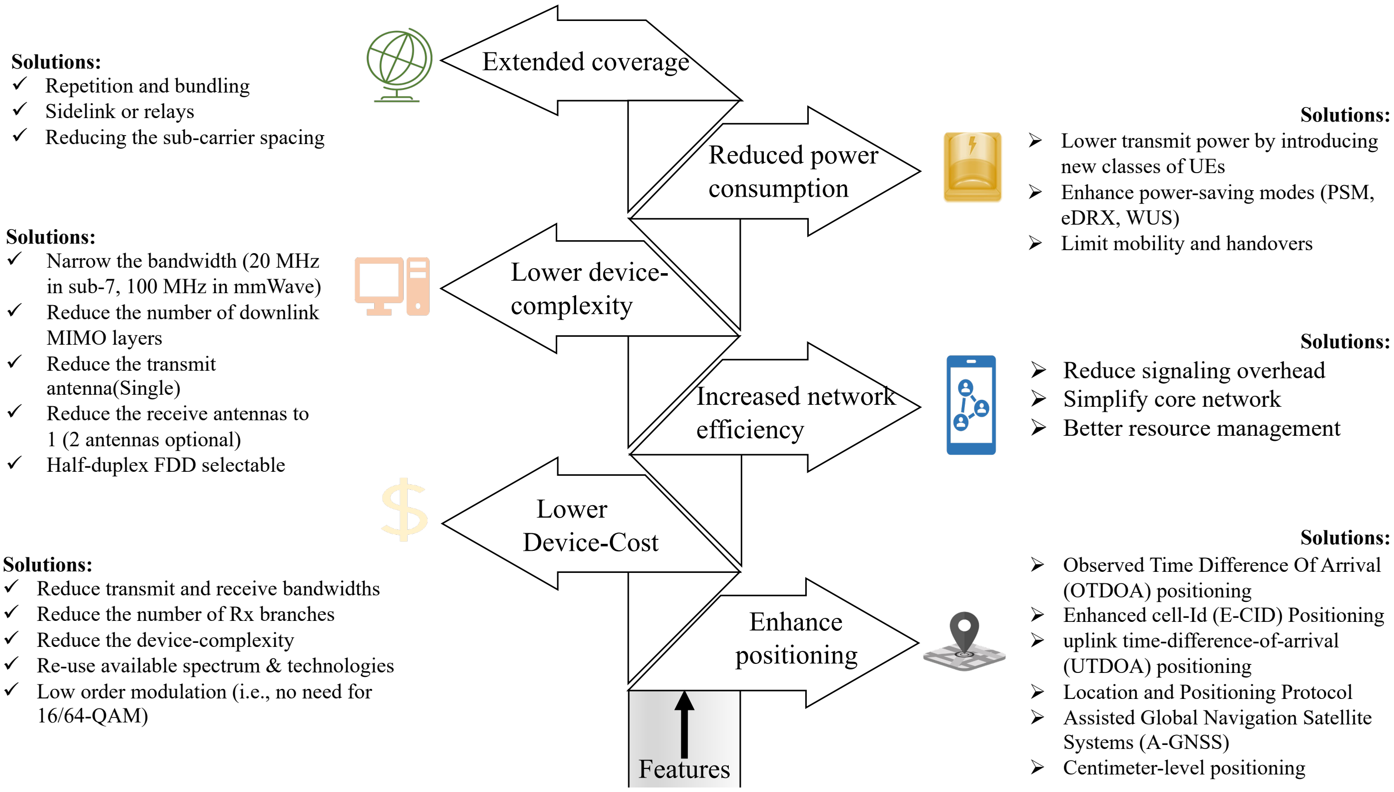

Figure 8: Common CIoT features enhancement techniques.

imizing the device complexity, reusing the available spectrum and technology, and lowering order modulations can play a vital role in using the devices and removing marketing barriers.

8. Applications of CIoT Technologies

CIoT technologies have a wide range of applications and can be used to improve efficiency, reduce costs, and enhance the quality of life in various industries and sectors. Table 8 presents applications better suited for the EC-GSM-IoT, LTE-M, NB-IoT, and RedCap. The EC-GSM-IoT is fundamentally designed to offer coverage for machine-to-machine communications (direct communication with each other without the need for human involvement) in areas with challenging radio coverage conditions. However, the 2G-GSM and 3G-Universal Mobile Telecommunications System (UMTS) wireless networks are winding down, and some mobile network operators plan to phase out their GSM and UMTS networks soon [83]. The EC-GSM, LTE-M, NB-IoT, and RedCap can be employed in areas of applications including; smart cities (waste and traffic management), smart environments (building automation; urban safety; and intelligent environment monitoring), smart metering (electricity, water, gas, and parking spot meters), asset tracking and smart logistics [154], localization, farming (monitoring livestock), forestry, industry pallets and pipelines [18], [161], and intelligent transportation (e.g., logistics services, and traveling time estimation) [30]. Moreover, the LTE and NB-IoT can work with the low and geostationary earth orbit satellites to support NTN, studied in Rel. 17 on the NB-IoT and LTE-M for NTN [29]. Under the IoT over NTN projects [91], for instance, UAVs [162] can use LTE-M to develop low-latency energy-efficient communication techniques and power-efficient computing modules [163] in military applications to track enemy locations. The feasibility of integrating the NB-IoT into the NTN [70] was investigated to extend the coverage in challenging environments like mountains, deserts, and oceans [164]. In the same objective, NR-RedCap is designed based on the 5G NR requirements, so its application is vital. The 5G is becoming prominent in the healthcare industry, automotive industry, smart cars, manufacturing sector, smart factories, smart grids, and smart cities [53], which substantially affects the IoT but has high costs and complexity issues compared to RedCap. Due to its lower cost and low-complexity features, RedCap is further becoming manifested in IoT applications that target mission-critical aspects (that require low latency, ultra-reliability, high security, and high data rates) [57] and time-sensitive IoT connectivity like emergency response, health-care services, disaster mitigation, and related cases in which these applications require faster and more reliable performance than other applications, and their connectivity must be guaranteed to be safe and resilient. Industrial wireless sensor networks, video surveillance cameras, and wearables (e.g., smartwatches, rings, eHealth-related devices, and medical monitoring devices) are some use cases for RedCap [108, 67]. Hence, these envisioned use cases have specific requirements regarding data rate, latency, battery life, reliability, and other factors. As of today, CIoTs are being applied in the following application areas.

Smart Agriculture: Smart agriculture is one of the key application scenarios in the IoT industry [165]. Via CIoTs connectivity, farmers and cities can capture data from environmental sensors for management. The reason is that they can access places that are hard to reach, such as remote areas where agriculture or infrastructure sensors are installed. Due to this, monitoring the soil temperature and humidity and tracking the existing land features, rain, and pollution are some of the activities farmers can perform using EC-GSM-IoT, LTE-M, NB-IoT, and RedCap [23, 166]. In Africa, specifically, farmers are utilizing multiple interconnected sensors in their fields to identify the optimal planting and harvesting periods for specific crops by leveraging EC-GSM-IoT technology [76, 167]. LTE-M and NB-IoT have a role in smart agriculture. Moreover, RedCap is expected to be used in cooperative farm machinery in the near future. Minimizing water waste will be vital to advancing agricultural processes based on real-time monitoring and predictive data analytics via remote sensing [13].

Smart Grid and Meter: CIoT technologies play a significant role in application areas, such as smart metering, smart grid management with strong coverage requirements, and low power use scenarios (e.g., water and gas) since they can access places that are hard to reach, such as deep basements where smart meters are installed. They are well-suited for connecting many remote smart meters to a central data collection point, allowing utility companies to remotely monitor energy consumption and manage their networks more efficiently, leading to cost savings and improved customer service [168]. Through the EC-GSM-IoT, LTE-M, NB-IoT, and RedCap, in smart grid applications; electricity is efficiently transmitted and distributed, power is recovered rapidly after a fault occurs, maintenance costs are reduced, and security and protection. They can remotely control and monitor energy-consuming devices, such as air-conditioning and heating systems, to reduce energy consumption during peak demand periods [169, 170, 171, 37] with the support of numerous (more than 10,000 devices in a cell) smart grid devices. Indeed, a smart grid management system is the main operational demand for power control, enabling two-way communication between providers and consumers. For instance, according to the investigation in [171], demand-response techniques are pivotal to addressing power outage problems, reducing cost, and increasing reliability.

Intelligent Transportation: Tracking and monitoring vehicles intelligently is crucial for transportation companies and vehicle owners. Hence, 3GPP identified the vehicle-to-everything communication types [33]: vehicle to vehicle, vehicle to infrastructure, vehicle to pedestrian, and vehicle to network. In intelligent transportation, vehicle-to-vehicle communication, vehicle-to-infrastructure communication, autonomous/semi autonomous driving, and in-car infotainment systems emerged [57]. The CIoT technologies can also assist drivers in various ways, such as providing real-time traffic and weather information, route planning, and parking assistance; improving the driving experience; and reducing the risk of accidents. In intelligent transportation, fleet management applications are most in demand [172] including; monitoring fuel consumption and scheduling maintenance and repairs. Moreover, LTE-M is well-suited for applications requiring voice and data communications, such as telemetry and remote control systems. Hence, LTE-M is well-suited for fleet management applications because it supports voice and data communication and can track the location and status of vehicles in real-time. For transportation systems to be effective, they need to be quick, dependable, and adaptable. By implementing the CIoT-based Internet of Vehicles, drivers can receive real-time traffic updates, monitor speed limits, and subsequently reduce traffic congestion and accidents. In *smart parking*, for instance, data can be transmitted and received in real-time, enabling immediate updates to park availability and other information. The available CIoTs can improve efficiency, reduce parking costs, and improve the overall user experience [173]. For some IoT use cases with stationary mobility in intelligent transportation, for instance, all CIoT technologies are applicable. NB-IoT, despite its limited mobility characteristics, can be considered applicable for smart transportation. The devices are often deployed in fixed locations, such as road sensors, infrastructure components, or stationary objects along roadways. These devices collect and transmit various transportation-related data including real-time tracking, traffic analysis (traffic conditions, environmental factors), parking space reservation (often involves parking in the basement), location navigation, vehicle management, and enable communication between vehicles [174]. Overall, using EC-GSM-IoT, LTE-M, NB-IoT, and RedCap for intelligent transportation systems helps reduce travel time, fuel consumption, and environmental effects and can improve the overall travel experience for passengers and drivers.

Smart City: Smart cities have a high level of technology integration and are distinguished by the extensive use of information and communication methods [175]. Due to the current urbanization demands worldwide, the smart city concept has been extended from smart offices and smart homes to smart buildings. In the framework of smart cities, applications, such as environmental sensors, smart grids, predictive maintenance, utility meters, high-definition security cameras, smart parking, smart traffic management, smart city sensors system for irrigation, and smart street lighting are included, and supported by CIoT systems [176, 177, 153]. A smart city cuts costs, increases resource consumption efficiency, engages with inhabitants more actively during emergencies, and greatly reduces labor costs. Controlling street lights, assessing free parking spaces, monitoring environmental conditions, and inspecting road conditions are some of the daily administrative tasks performed by city bodies. Furthermore, in each layer of IoT applications (i.e., in smart cities), security and privacy are daily concerns for safety [178]. Noteworthy to know a smart city can be considered a package comprising applications, including intelligent environmental monitoring, intelligent transportation, smart street lighting, smart grid, smart metering, smart homes, and the like. These applications are demanding the use of deep learning-based techniques, for example, in smart lighting [179, 23]of smart garbage detection systems that can recognize garbage more accurately, reducing the necessary deployment costs and material resources.

Smart Homes and Buildings: One of CIoT's rapidly expanding markets is smart homes. The primary focus behind the smart home philosophy is preserving energy [79]. Recently, the CIoT has offered a powerful and flexible way to control and monitor various aspects of the home, providing convenience, energy reduction, and enhanced security [180]. Various ECGSM-IoT, LTE-m, NB-IoT, and RedCap devices can be deployed in the living room, kitchen, bathrooms, and other rooms. In addition, the devices can be used for video surveillance monitoring [177]. For example, homeowners can access remote lighting controls, monitor their children, and turn devices on and off while commuting to and from work. In emergencies, such as smoke and hazard incidents, installing CIoT devices in a smart home is beneficial. Examples of applications that can utilize these CIoT's building penetration capability include monitoring utility usage (e.g., smart heat), enhancing security in residential properties, smoke detectors, and managing energy consumption in household appliances [23].

Smart Environmental Monitoring: Environmental monitoring is a wider concept comprising both natural and human environmental phenomena involving rural-agricultural and urban-city-oriented monitoring. It includes monitoring air, soil, water, traffic volumes, city infrastructure, and other aspects. The existing CIoT cellular network can provide intelligent services [181] by incorporating a wireless sensor network to automate data acquisition for easy data analysis. These intelligent services optimize resource usage, reduce waste, and increase energy efficiency by providing real-time data on environmental conditions [182, 183]. It can also be used for monitoring the location of wild animals, observing their habitats, and recognizing their behaviors. Furthermore, the role of the EC-GSM-IoT, LTE-M, NB-IoT, and RedCap in intelligent environment monitoring involves public health and safety in identifying and mitigating possible environmental hazards and extreme weather conditions.

Smart Tracking: Vertical industries, including transportation, logistics, and manufacturing, have a high demand for tracking and monitoring the location and movement of physical assets, such as vehicles, equipment, and inventory. Installing or attaching global positioning system trackers or RF identification tags onto assets and communicating their location and status to the central system optimizes operations (e.g., routes in logistics companies) by delivering real-time updates on the location, movement, and condition of the assets (e.g., temperature). Hence, EC-GSM-IoT, LTE-M, NB-IoT, and RedCap are useful in tracking shipping, monitoring drivers and goods, and obtaining diagnostics and reports across moving operations in industry [153, 184], contributing to efficiency improvement, cost reduction, and customer service enhancement. Note that when continuous tracking is not required NB-IoT can be taken as a good method. In addition to enabling real-time tracking and monitoring, they can also provide other benefits in asset tracking systems, such as the ability to monitor the condition of the assets and alert maintenance personnel when repairs are needed, reducing downtime and improving the overall efficiency of the tracking system.

Smart Hospitals: Healthcare is the most important concern in the era of smart life projects, with a high priority [177]. Wearable devices, such as fitness trackers or sports wearables, smartwatches, and smart clothing, can track and monitor location and movements and provide identification, authentication, data collection, and sensing, including patient vital signs, such as heart rate, blood pressure, and body temperature. Moreover, implantable devices, such as pacemakers and defibrillators, can monitor the heart, or sensors can monitor a segment of an organ (i.e., the lungs or kidneys). A periodic update of training data and message reception is possible with the NB-IoT and LTE-M in normal conditions [190]. Similar to LTE-M and NB-IoT, EC-GSM-IoT is also suitable for low data rate healthcare applications**??**. To enhance patient outcomes and lower healthcare expenses through the implementation of telemedicine and remote patient monitoring systems, EC-GSM-IoT, NB-IoT, LTE-M, and RedCap are suggested for healthcare applications. These technologies offer swift data transfer, energy efficiency, broad communication coverage, dependable performance, the ability to handle large data volumes, and human tissue safety. Their accurate localization capabilities enable them to address clinical care in the hospital and remote patient care. Furthermore, they can be utilized to acquire medical reports at regular intervals and receive alerts triggered by specific events. Additionally, it enables real-time, two-way medical control and monitoring of health conditions through live video feeds. General applications in health care systems, including remote patient monitoring, medical asset tracking, wellness-tracking wearables, and secure data collection protecting patient data privacy [16], can be supported by the current CIoT technologies.

Wearables: Devices equipped with NB-IoT technology enable real-time monitoring of energy consumption, enabling utilities to enhance energy management and improve the efficiency of health monitoring. Moreover, in the context of wearables, the ability to support mobility and high data rates is critical, as is the ability to support VoLTE. For this reason, LTE-M and RedCap are emerging as strong candidates for powering the next generation of wearable devices. In applications such as smartwatches, fitness trackers, and medical wearables, crucial data can be extracted based on various metrics, including heart rate, sleep patterns, and activity levels. These real-time data are sent over LTE-M and RedCap networks to be analyzed by the responsible authorized individuals (e.g., doctors and caregivers) or organizations [118]. Importantly, LTE-M and RedCap support movement so that it is possible to monitor users anywhere in motion, such as runners, to track their well-being [189]. The utilization of wearable devices potentially simplifies self-care for elderly individuals, for instance. Hence, wearable devices equipped with NB-IoT, LTE-M, and RedCap technology have the capability to track and record an individual's physical activity, heart rate, body temperature, and other health-related data.

Video Surveillance Cameras: Due to their support of high data rate and video capturing, LTE-M and RedCap are the candidate CIoT technologies in video surveillance camera services. Smart cities, smart farming, smart factories, and other industrial locations have increasingly installed surveillance cameras. In LTE-M, for example, the Cat-M2 UE category supports multimedia IoT applications such as voice and video which have a

Table 8: CIoT Applications

Applications	**EC-GSM-IoT**	**LTE-M**	**NB-IoT**	**RedCap**	**Contributions**
Smart Agriculture[23, 76, 167]	✓	✓	✓	✓	It monitors environmental factors, including temperature and humidity, where the GSM network is applied for EC-GSM-IoT. Smart LTE-M & NB-IoT solutions maximize yield and lower agricultural input costs, such as efficiently managing water used for irrigation. RedCap extends to collaborative farm equipment as well.
Smart Grid and Meter [38, 66, 76, 167, 170, 185, 186]	✓	✓	✓	✓	They can support numerous smart grid devices (more than 10,000 devices in a cell). For instance, managing whether electricity is efficiently transmitted and distributed, power is recovered rapidly after a fault occurs, maintenance costs are reduced, security and protection improve, and so on. The CIoTs are the preferred options for smart metering, which stand out due to their capability to handle large data amounts, accommodates high load scalability, provide extensive coverage, and offer exceptional obstruction penetration over broad regions.
Intelligent Transportation [28, 76, 167]	✓	✓	✓	✓	In the automotive industry, they improve vehicle performance, fuel efficiency, and safety through real-time monitoring and analysis of vehicle data, and are able to quickly distribute warning messages through a relay system. RedCap is ideal technology in remote drone operations as well.
Smart City [23, 76, 167, 168, 117, 175]	✓	✓	✓	✓	The EC-GSM-IoT, LTE-M, NB-IoT, and RedCap can be utilized for broad smart city applications including smart traffic management, smart parking, smart energy management, smart waste management systems, and so on.
Smart Homes and Buildings [66, 161, 76, 167, 187]	✓	✓	✓	✓	In smart building use cases, comfort, safety, and building integrity can be supported by the EC-GSM-IoT, LTE-M, NB-IoT, and RedCap based on reliability, communication range, and low power consumption.
Smart Environmental Monitoring [66, 76, 167]	✓	✓	✓	✓	Smart environmental management applications benefit from the CIoT's reduced delay, excellent reliability, better obstruction penetration, high scalability for heavy traffic, and extended transmission coverage.
Smart Tracking [66, 76, 167, 153]	✓	✓	✓	✓	EC-GSM-IoT, LTE-M, NB-IoT, and RedCap play a pivotal role in tracking and monitoring assets and their states in industries (transportation, logistics, and manufacturing).
Smart Hospitals [61, 66, 167, 188]	✓	✓	✓	✓	Because of their fast data transfer, optimized energy consumption, rapid data transfer, wide-ranging communication reach, high reliability, capacity to handle significant data loads, and safety for human tissue, the EC-GSM-IoT, NB-IoT, LTE-M, and RedCap are recommended for healthcare applications to improve patient outcomes and reduce healthcare costs by implementing telemedicine and remote patient monitoring systems.
Video Surveillance Cameras [153, 110]		✓		✓	LTE-M and RedCap are used for remote monitoring and surveillance applications in various industries, in cooperative farm machinery for example, to assist in monitoring crops, livestock, and so on.
Industry IoT [8, 66, 111]		✓	✓	✓	NB-IoT, LTE-M, and RedCap are used in monitoring equipment status, controlling processes, and ensuring factory safety.
Wearables [1, 189]		✓	✓	✓	LTE-M, NB-IoT, and RedCap have the ability to provide assistance for wearable devices, such as smartwatches, which typically necessitate voice functionality, portability, and fast data transfer rates for connectivity to the Internet.

maximum TBS of 4008 bits in the DL and 6968 bits in the UL good for video surveillance applications. Moreover, for high-quality video, RedCap plays a significant role.

Industry IoT: The LTE-M, NB-IoT, and RedCap sensors can be used in the prediction of machine failure in the factory. Note that the NB-IoT is not suitable for moving objects, so the device is assumed to be battery-powered in a fixed location in the factory, requiring two-way communication to upgrade the firmware and software [191]. It has a significant role in real-time applications and is more suitable for industrial systems that require real-time communication without mobility requirements. Even though the NB-IoT supports only up to QPSK modulation that limits its data rate, spectral efficient frequency division multiplexing has been proposed, which uses higher modulation formats; however, it has drawbacks in energy consumption. The authors of [192] developed a two-dimensional channel-aware adaptive modulation scheme that improves network performance while maintaining energy efficiency to solve this problem. On the other hand, LTE-M and RedCap are the prominent technologies for IIoTs since they support mobility and high data rates. Moreover, RedCap is objectively developed for such use cases including wearables and video surveillance cameras, which we discuss under the RedCap section in detail.

9. Future Challenges

The proposed solutions are explicitly explored as part of the CIoT use-case specifications by the 3GPP working group. Most requirements set by the study groups in various release versions have been met as promised and planned. Indeed, CIoT has gained attention globally due to its cost-effective, ubiquitous coverage with ease of deployment of massive MTC and URLLC and several feasible reasons. However, there are further challenges that need to be resolved.

Congestion Problems: Overcrowding or congestion is a significant challenge in the CIoT with a very high concentration of devices, as there are limited resources available to handle the numerous sporadic access attempts made by a diverse range of MTC devices [24]. With a massive number of devices, an enormous number of simultaneous access requests occurs, causing congestion in the physical random-access channel, resulting in network access delays [193]. For instance, if multiple machine-type devices transmit the same preamble simultaneously, they cause the access requests to fail so that access efficiency decreases and the number of supported devices reduces. Hence, optimized node clustering and data aggregation have been employed as candidate solutions to address congestion [194]. Kim and Bang [195] proposed a random-access parallelization technique to support multiple preambles, enabling each IoT device to attempt multiple instances of random access in parallel to mitigate collisions. In addition, the preamble (re)transmission limit [196] is adopted in the UE MAC layer. In contrast, network slicing is another promising method to improve the efficiency of resource utilization [197, 57] by allocating resources dynamically between slices, providing QoS in congestion situations and end-to-end communication. Furthermore, a study [198] introduced a recursive access class barring technique to use the available resources optimally, obtaining an optimized service time and average access delay compared to the conventional access class barring schemes. Despite these solutions, as the massive number of devices expands, the reliability of access, data transmission, and energy consumption are inevitably questioned.

Very High Signaling Overhead per Data Packet: In the CIoT, signaling overhead becomes a significant issue when considerable signaling is required for each data packet a device sends. Very high signaling overhead per data packet can occur when frequent updates or small amounts of data are sent from the device. Cellular networks are optimized for larger data packets, and when small data packets are sent frequently, the overhead required to establish and maintain the connection becomes a significant proportion of the overall communication. However, it is particularly problematic in scenarios where devices are battery-powered and have limited energy resources, such as IoT devices where a device sends small data packets infrequently. The signaling required to establish and maintain the connection can become a bottleneck. It can significantly increase network traffic, causing issues, such as network congestion, increased latency, and energy consumption [52] on the device and network sides, and reduced overall performance. Although data packets transmitted by IoT devices are typically small, the high signaling overhead required per packet can always become a significant issue for IoT devices [199]. Various signaling reduction techniques can address these issues, such as message queuing, efficient protocols, and optimized network coverage [200]. Studying more appropriate methods is crucial for scheduling transmissions and reducing signaling overhead in extremely dense environments using advanced techniques, such as machine learning to overcome these challenges in the ultra-dense CIoT to meet service requirements, such as latency, battery life, and accuracy.

Scalability/Massive Connection: There has been a surge in demand for CIoT connectivity, especially in the healthcare, transportation, and manufacturing industries, according to the future market insight projections [201]. Hence, numerous connected devices, sensors, and machines must be handled simultaneously. The main challenge facing the CIoT is the need to support numerous devices with a broad range of capabilities and requirements to mitigate problems, such as network congestion, power consumption, security, and cost. This challenge requires significant investments in network infrastructure and management systems to ensure that the network can scale to meet the demands of the IoT. Providing connectivity for many devices can be a challenge for CIoT networks, where the system scalability [112] comprises the network capacity, processing power, data storage, and security. In [202], mobile edge computing (MEC) based CIoT (MECIoT) is taken as one of the promising solutions for scalability. Thus, techniques including developing low-power devices, designing and implementing smart system architecture involving leveraging distributed computing, cloud-based infrastructure, and other advanced technology, such as edge computing and AI might help and should be further investigated.

Privacy and Security: Security cameras, biometric sensors, and authentication devices, electronic door locks and access control systems, fire alarm and detection systems, intrusion detection and prevention systems, industrial control systems used in critical infrastructure such as energy, water, and transportation systems, medical devices such as pacemakers and insulin pumps are security-sensitive devices that could harm owners if their security is threatened by intruders [118]. It is because, the limited resources of CIoT devices can make it challenging to implement robust security measures, leaving them vulnerable to attacks [203]. CIoT devices are often deployed in physically vulnerable locations, making them susceptible to tampering. In addition, the low power and low data rates of CIoT devices can make it difficult to implement strong security protocols, leaving them open to network-based attacks. Moreover, the lack of uniform standards for security in CIoT can lead to inconsistencies in security measures across different devices and networks, potentially exposing vulnerabilities. To address these risks, it is essential to implement strong security measures such as encryption, secure authentication, and access control, while also establishing industry standards for securing the devices [204]. Moreover, Ni *et al.* [205] proposed a security authentication system to protect device security during network slicing by isolating IoT applications. Savic *et al.* [206] proposed a deep learning-based anomaly detection, the anomaly detection module (ADM) for IoT devices (ADM-EDGE) and the ADM at the mobile core network (ADM-FOG), to enhance the CIoT security and the mobile core network, respectively, by demonstrating it on smart logistics use cases. However, the trial is on small-scale real-world use cases that should be examined on a large scale. In [161], quantum resistance access authentication is developed to achieve privacy protection and anti-quantum attacks. However, numerous IoT devices with high-speed mobility still have security issues relating to moving from one cell to another.

Interoperability and Integration Issues: Enabling different IoT devices and applications to communicate with each other and with the CIoT networks seamlessly is another barrier facing the CIoT. Due to the requirements for the device, network, standardization, and security and the heterogeneity of the protocols, there are a variety of interoperability types, including infrastructure (device interoperability), architecture (network interoperability), design (syntactical and semantic interoperability), and platform interoperability [207], in which intelligent algorithms should be implemented. However, ensuring seamless and interoperable communication among numerous devices is challenging because of its various data formats, protocol interfaces and application, and the complexity increases if two or more devices communicate simultaneously [208]. It is necessary to create a multifaceted technology approach to handle the interoperability concerns. This approach requires the development of standards, protocols, software tools and interfaces, data formats, and more that can be used across networks and devices.

Energy Efficiency/Power Consumption: One of the most critical constraints for CIoT devices is battery life. Most CIoT devices are battery-powered require constant sources of power and need low power consumption with many years of deployment lifecycle in remote locations where supplying power is spectacularly difficult. The reason why many years of deployment are employed is that activities include charging batteries regularly, devices that are hard-wired to maintain electricity, and a complete device replacement which causes human interaction too costly for the business case. For battery-powered IoT devices, energy efficiency is a highly critical factor [154]. Often, IoT devices are designed to be low-power and energy-efficient, but this is not easy to achieve with cellular networks, which requires new approaches to network design and management to ensure the network can support low-power devices while providing the necessary performance and coverage. However, there are still compromising power consumption issues in the CIoT. One method of saving energy in the age of AI is applying the recommended deep neural network techniques. However, due to frequent memory access, executing power-intensive deep neural networks on low-resource IoT devices increases power consumption. To address these problems, a study [209] suggested that reducing the number of MAC operations and data precision saves energy. In addition, the recursive access class barring technique provides resource-efficiency and energy-efficiency solutions [198]. However, a trade-off occurs between energy efficiency and other performance factors, such as high data transfer rates, poor network coverage, and complex data processing (to mention a few that could be balanced), and further investigation is required.

Cost: As the deployment of numerous IoT devices increases exponentially, it can result in high costs for network providers and end users. Network providers and IoT device manufacturers explore partnerships and collaborations to reduce costs, share resources, and leverage each other's expertise and capabilities. Among other solutions, significant factors of the CIoT to make IoT devices more accessible and affordable for a wider range of applications and use cases are using low-cost devices and employing technology that stabilizes the costs for the device, network, maintenance, data management, and others [25, 28, 155]. Often, IoT devices are designed to be low cost, which requires new approaches to network design and management to ensure that the network can be deployed and maintained at a low cost. However, a low-cost design negatively affects CIoT performance, spectral efficiency, and energy consumption. In [210], the authors proposed a time allocation algorithm to avoid the problem. Nonetheless, the support for a massive number of devices can become limited.

Spectrum Efficiency: As IoT devices use a small amount of bandwidth, the spectrum is a limited resource that must be shared among a massive number of connecting devices. Efficient spectrum allocation is vital for connecting many IoT devices and preventing network disruptions. The author [211] investigated power-domain nonorthogonal multiple access as the best multiple access technique for efficiently utilizing the existing spectrum resources in IoT networks from the multiple-user scenario by assigning different power levels. However, the number of frequency blocks in the IoT network in the framework is limited. Al-Dweik *et al.* [212] mentioned that power-domain nonorthogonal multiple access could be a prominent solution for spectral efficiency from the same user perspective in which nonidentical power values can be assigned. However, in large-scale IoT networks, spectral efficiency requires new robust approaches to spectrum management to ensure that the network can support numerous low-power devices.

Quality of Service: The level of services and performance of a network provider guarantees its customers to make the IoT devices reliable is a highly important factor in the CIoT. The technical challenges in the CIoT regarding the bandwidth, power, delay, and error rate should be optimized to attain the various QoS requirements, including reliability, low latency, high throughput, low power consumption, security, scalability, cost-effectiveness, and more. Indeed, IoT devices require low-latency and high reliability communication, which is challenging to provide in cellular networks. Network optimization, traffic management, and service-level agreement strategies are good for preserving QoS [199]. Furthermore, deploying fixed and mobile small cells due to the reduced Tx-to-Rx distance is expected to improve the QoS with the ever-increasing data demands [213]. However, challenges still exist, such as interference and resource management. Hence, new and robust approaches to network design and management are required to ensure the network can support low-latency, high-reliability communication to achieve QoS.

10. Conclusion

In recent years, the CIoT has emerged as a promising solution for providing a scalable, reliable, and secure infrastructure connecting a broad range of devices and applications. The CIoT enables billions of devices to connect and share information, creating new services and applications. With the ongoing full deployment and integration of 5G networks, CIoT is poised to gain further significance. The fact that 5G offers higher data rates, lower latency, and massive device connectivity, which unlock new possibilities for CIoT applications, 3GPP and Ericsson have been working on standardization of CIoT technologies to improve connectivity and communication between devices. The LTE-M and NB-IoT have confirmed that they can efficiently be integrated into the 5G and share its ultimate benefits. The URLLC capabilities of 5G enable mission-critical CIoT use cases, such as autonomous vehicles, remote surgery, and industrial automation, that require real-time, reliable connectivity is now achieved. Moreover, the CIoT is valuable because it reduces the cost and complexity of deploying and maintaining IoT networks, provides a global and standardized solution for connecting IoT devices, and enables interoperability while ensuring the security and privacy of data transmitted over the CIoT network. To this end, in this paper, we have compared the existing literature on CIoT technologies and discussed their general network architecture. Moreover, we have elaborated on the existing CIoT technologies with a complete overview from the perspectives of their features and current state-of-the-art including release enhancements, focuses, and applications. Finally, we have identified the major challenges in CIoT technology that researchers, academics, and industry operators might find interesting for further studies and efforts.

References

[1] N. Xia, H.-H. Chen, C.-s. Yang, Emerging technologies for machine-type communication networks, IEEE Network 34 (1) (2019) 214–222.

[2] M. Condoluci, G. Araniti, T. Mahmoodi, M. Dohler, Enabling the IoT machine age with 5G: Machine-type multicast services for innovative real-time applications, IEEE Access 4 (2016) 5555–5569.

[3] G. T. RAN, Revised WID UE Power Saving Enhancements for NR, Tech. Rep. RP-200938, 3GPP (June 29 - July 3 2020).
URL `https://www.3gpp.org/ftp/TSG_RAN/TSG_RAN/TSGR_88e/Docs/RP-200938.zip`

[4] 3GPP, Technical Specification Group Services and System Aspects Service requirements for Machine-Type Communications (MTC) stage 1, Tech. Rep. TR 22.368, 3GPP (December 2014).

[5] 3GPP, 3rd generation partnership project; technical specification group services and system aspects; release 15 description; summary of rel-15 work items (release 15), 3GPP TR 21.915 (September 2019).

[6] K. Samdanis, T. Taleb, The road beyond 5G: A vision and insight of the key technologies, IEEE Network 34 (2) (2020) 135–141.

[7] Y. Chen, Y. A. Sambo, O. Onireti, M. A. Imran, A Survey on LPWAN-5G Integration: Main Challenges and Potential Solutions, IEEE Access 10 (2022) 32132–32149.

[8] S. A. Gbadamosi, G. P. Hancke, A. M. Abu-Mahfouz, Building upon NB-IoT networks: A roadmap towards 5G new radio networks, IEEE Access 8 (2020) 188641–188672.

[9] S. Moloudi, M. Mozaffari, S. N. K. Veedu, K. Kittichokechai, Y.-P. E. Wang, J. Bergman, A. Höglund, Coverage evaluation for 5G reduced capability new radio (NR-RedCap), IEEE Access 9 (2021) 45055–45067.

[10] Y. Kim, Y. Kim, J. Oh, H. Ji, J. Yeo, S. Choi, H. Ryu, H. Noh, T. Kim, F. Sun, et al., New radio (NR) and its evolution toward 5G-advanced, IEEE Wireless Communications 26 (3) (2019) 2–7.

[11] Ericsson, Ericsson mobility report, June (2018).
URL `https://www.ericsson.com/491e17/assets/local/mobility-report/documents/2018/ericsson-mobilityreport-june-2018.pdf`

[12] Peter, Jonsson and Steven, Davis and Peter, Linder and Amir, Gomroki and Ali, Zaidi and Anders, Carlsson, P and Miljenko, Opsenica and Ida, Sorlie and Sebastian, Elmgren and Greger, Blennerud and Harald, Baur and Ritva, Svenningsson and Brian, Heath, "Ericsson mobility report" , `https://www.ericsson.com/assets/local/reports-papers/mobility-report/documents/2020/november-2020-ericsson-mobility-report.pdf`, Accessed On: 2023-01-27 (June 2020).

[13] K. Mekki, E. Bajic, F. Chaxel, F. Meyer, A comparative study of lpwan technologies for large-scale iot deployment, ICT express 5 (1) (2019) 1–7.

[14] S. Popli, R. K. Jha, S. Jain, A survey on energy-efficient narrowband internet of things (NBIoT): architecture, application, and challenges, IEEE Access 7 (2018) 16739–16776.

[15] A. Azari, Č. Stefanović, P. Popovski, C. Cavdar, On the latency-energy performance of NB-IoT systems in providing wide-area IoT connectivity, IEEE Transactions on Green Communications and Networking 4 (1) (2020) 57–68.

[16] V. Kumar, R. K. Jha, S. Jain, NB-IoT security: A survey, Wireless Personal Communications 113 (4) (2020) 2661–2708.

[17] J. Sanchez-Gomez, D. G. Carrillo, R. Sanchez-Iborra, J. L. Hernandez-Ramos, J. Granjal, R. Marin-Perez, M. A. Zamora-Izquierdo, Integrating LPWAN technologies in the 5G ecosystem: A survey on security challenges and solutions, IEEE Access 8 (2020) 216437–216460.

[18] E. M. Migabo, K. D. Djouani, A. M. Kurien, The narrowband Internet of Things (NB-IoT) resources management performance state of art, challenges, and opportunities, IEEE Access 8 (2020) 97658–97675.

[19] M. Kanj, V. Savaux, M. Le Guen, A tutorial on NB-IoT physical layer design, IEEE Communications Surveys & Tutorials 22 (4) (2020) 2408–2446.

[20] G. Hu, Z. Yi, L. Lu, Y. Huang, Y. Zhai, J. Liu, B. Yang, Self-powered 5G NB-IoT system for remote monitoring applications, Nano Energy 87 (2021) 106140.

[21] A. Ikpehai, B. Adebisi, K. M. Rabie, K. Anoh, R. E. Ande, M. Hammoudeh, H. Gacanin, U. M. Mbanaso, Low-power wide area network technologies for Internet-of-Things: A comparative review, IEEE Internet of Things Journal 6 (2) (2019) 2225–2240.

[22] S. R. Pokhrel, J. Ding, J. Park, O.-S. Park, J. Choi, Towards enabling critical mMTC: A review of URLLC within mMTC, IEEE Access 8 (2020) 131796–131813.

[23] Y. Li, Y. Zhuang, X. Hu, Z. Gao, J. Hu, L. Chen, Z. He, L. Pei, K. Chen, M. Wang, et al., Toward location-enabled IoT (LE-IoT): IoT positioning techniques, error sources, and error mitigation, IEEE Internet of Things Journal 8 (6) (2020) 4035–4062.

[24] S. K. Sharma, X. Wang, Toward Massive Machine Type Communications in Ultra-Dense Cellular IoT Networks: Current Issues and Machine Learning-Assisted Solutions, IEEE Communications Surveys & Tutorials 22 (1) (2020) 426–471.

[25] M. I. Hossain, J. I. Markendahl, Comparison of LPWAN technologies: Cost structure and scalability, Wireless Personal Communications 121 (1) (2021) 887–903.

[26] M. T. Abbas, K.-J. Grinnemo, J. Eklund, S. Alfredsson, M. Rajiullah, A. Brunstrom, G. Caso, K. Kousias, Ö. Alay, Energy-Saving Solutions for Cellular Internet of Things-A Survey, IEEE Access 10 (2022) 62073–62096.

[27] R. Ratasuk, N. Mangalvedhe, G. Lee, D. Bhatoolaul, Reduced Capability Devices for 5G IoT, in: 2021 IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2021, pp. 1339–1344.

[28] S. N. K. Veedu, M. Mozaffari, A. Höglund, E. A. Yavuz, T. Tirronen, J. Bergman, Y.-P. E. Wang, Toward Smaller and Lower-Cost 5G Devices with Longer Battery Life: An Overview of 3GPP Release 17 RedCap, IEEE Communications Standards Magazine 6 (3) (2022) 84–90.

[29] J. Tan, X. Sha, T. Lu, B. Dai, A Short Survey on Future Research of AI and IoT Technologies, in: 2022 International Wireless Communications and Mobile Computing (IWCMC), IEEE, 2022, pp. 190–195.

[30] B. E. Benhiba, A. A. Madi, A. Addaim, Comparative study of the various new cellular iot technologies, in: 2018 International Conference on Electronics, Control, Optimization and Computer Science (ICECOCS), IEEE, 2018, pp. 1–4.

[31] A. Hoglund, D. P. Van, T. Tirronen, O. Liberg, Y. Sui, E. A. Yavuz, 3GPP release 15 early data transmission, IEEE Communications Standards Magazine 2 (2) (2018) 90–96.

[32] M. Vaezi, A. Azari, S. R. Khosravirad, M. Shirvanimoghaddam, M. M. Azari, D. Chasaki, P. Popovski, Cellular, wide-area, and non-terrestrial IoT: A survey on 5G advances and the road toward 6G, IEEE Communications Surveys and Tutorials 24 (2) (2022) 1117–1174.

[33] F. J. Dian, R. Vahidnia, LTE IoT technology enhancements and case studies, IEEE Consumer Electronics Magazine 9 (6) (2020) 49–56.

[34] B. Lorenzo, J. Garcia-Rois, X. Li, J. Gonzalez-Castano, Y. Fang, A robust dynamic edge network architecture for the internet of things, IEEE network 32 (1) (2018) 8–15.

[35] Z. Alavikia, M. Shabro, A comprehensive layered approach for implementing internet of things-enabled smart grid: A survey, Digital Communications and Networks (2022).

[36] R. S. Sinha, Y. Wei, S.-H. Hwang, A survey on lpwa technology: Lora and nb-iot, Ict Express 3 (1) (2017) 14–21.

[37] S. Ahmadzadeh, G. Parr, W. Zhao, A review on communication aspects of demand response management for future 5G IoT-based smart grids, IEEE Access 9 (2021) 77555–77571.

[38] A. Ali, G. A. Shah, M. O. Farooq, U. Ghani, Technologies and challenges in developing machine-to-machine applications: A survey, Journal of Network and Computer Applications 83 (2017) 124–139.

[39] W. Ayoub, A. E. Samhat, F. Nouvel, M. Mroue, J.-C. Prévotet, Internet of mobile things: Overview of lorawan, dash7, and nb-iot in lpwans standards and supported mobility, IEEE Communications Surveys & Tutorials 21 (2) (2018) 1561–1581.

[40] J.-M. Liang, P.-Y. Chang, J.-J. Chen, Energy-efficient scheduling scheme with spatial and temporal aggregation for small and massive transmissions in LTE-M networks, Pervasive and Mobile Computing 52 (2019) 29–45.

[41] ITU, Guidelines for evaluation of radio interface technologies for IMT-2020, Tech. Rep. ITU-R M.2412-0, ITU (2017).

[42] 3GPP, Technical Specification Group Radio Access Network Study on Provision of Low-Cost Machine-Type Communications (MTC) User Equipments (UEs) Based on LTE, Tech. Rep. TR 36.888, 3GPP (Jun. 2013).

[43] G. TSG-RAN, Study on Cellular system support for ultra Low Complexity and low throughput Internet of Things (CIoT), Tech. Rep. TR-45.820, 3GPP (2016).

[44] R. Imadur, R. Sara Modarres, L. Olof, H. Christian, W. Henning, T. Claes, S.-B. Paul, P. Patrik, G. Dirk, The 5G Evolution: 3GPP Releases 16-17, `https://www.ericsson.com/4a92c5/assets/local/reports-papers/ericsson-technology-review/docs/2021/an-overview-of-3gpp-releases-17-and-18.pdf`, October (2021).

[45] O. Liberg, M. Sundberg, E. Wang, J. Bergman, J. Sachs, G. Wikström, Cellular internet of things: from massive deployments to critical 5G applications, Academic Press, 2019.

[46] B. S. Khan, S. Jangsher, A. Ahmed, A. Al-Dweik, URLLC and eMBB in 5G Industrial IoT: A survey, IEEE Open Journal of the Communications Society 3 (2022) 1134–1163.

[47] S. W. Ericsson, IMT-2020 self-evaluation: mMTC coverage, data rate, latency & battery life, Tech. Rep. R1-1903119, 3GPP TSG-RAN1 Meeting #96 (2019).

[48]

[49] Q. Chen, J. Wu, J. Wang, H. Jiang, Coexistence of URLLC and eMBB Services in MIMO-NOMA Systems, IEEE Transactions on Vehicular Technology 72 (1) (2022) 839–851.

[50] L. Ericsson, Cellular IoT evolution for industry digitalization, White Paper 17 (2019).

[51] Ericsson, New WID on support of reduced capability NR devices, February (2021).
URL `https://www.ericsson.com/en/blog/2021/2/reduced-cap-nr`

[52] S. W. H. Shah, A. N. Mian, A. Aijaz, J. Qadir, J. Crowcroft, Energy-efficient MAC for cellular IoT: state-of-the-art, challenges, and standardization, IEEE Transactions on Green Communications and Networking 5 (2) (2021) 587–599.

[53] M. Attaran, The impact of 5G on the evolution of intelligent automation and industry digitization, Journal of Ambient Intelligence and Humanized Computing (2021) 1–17.

[54] 5G Americas, LTE progress leading to the 5G massive Internet of things, `https://www.5gamericas.org/wp-content/uploads/2019/07/LTE_Progress_Leading_to_the_5G_Massive_Internet_of_Things_Final_12.5.pdf`, December (2017).

[55] K. Christian, R. Bela, Z. Ali, H. Marie, ”Cellular networks for Massive IoT”, `https://www.ericsson.com/4ac671/assets/local/reports-papers/white-papers/massive_iot_whitepaper.pdf`, Accessed on: 03-02-2023 (January 2020).

[56] Ericsson, Ericsson mobility report, November (2021).
URL `https://amta.org.au/wp-content/uploads/2021/12/Ericsson-Mobility-Report-November-2021-ericsson-mobility-repor`
`pdf`

[57] S. Wijethilaka, M. Liyanage, Survey on network slicing for Internet of Things realization in 5G networks, IEEE Communications Surveys & Tutorials 23 (2) (2021) 957–994.

[58] W. Yang, M. Wang, J. Zhang, J. Zou, M. Hua, T. Xia, X. You, Narrowband wireless access for low-power massive internet of things: A bandwidth perspective, IEEE wireless communications 24 (3) (2017) 138–145.

[59] R. A. Khalil, N. Saeed, Network optimization for industrial Internet of Things (IIoT), IEEE Sensors Letters 4 (7) (2020) 1–4.

[60] C. Paniagua, J. Delsing, Industrial frameworks for internet of things: A survey, IEEE Systems Journal 15 (1) (2020) 1149–1159.

[61] A. Mahmood, L. Beltramelli, S. F. Abedin, S. Zeb, N. I. Mowla, S. A. Hassan, E. Sisinni, M. Gidlund, Industrial IoT in 5G-and-beyond networks: Vision, architecture, and design trends, IEEE Transactions on Industrial Informatics 18 (6) (2021) 4122–4137.

[62] R. A. Khalil, N. Saeed, M. Masood, Y. M. Fard, M.-S. Alouini, T. Y. Al-Naffouri, Deep learning in the industrial internet of things: Potentials, challenges, and emerging applications, IEEE Internet of Things Journal 8 (14) (2021) 11016–11040.

[63] H. Wu, H. Tian, G. Nie, P. Zhao, Wireless powered mobile edge computing for industrial internet of things systems, IEEE Access 8 (2020) 101539–101549.

[64] H. Huawei, Rel-17 enhancements for NB-IoT and LTE-MTC, Tech. Rep. RP-193264 (2019).

[65] A. Hoglund, X. Lin, O. Liberg, A. Behravan, E. A. Yavuz, M. Van

Der Zee, Y. Sui, T. Tirronen, A. Ratilainen, D. Eriksson, Overview of 3GPP release 14 enhanced NB-IoT, IEEE network 31 (6) (2017) 16–22.

[66] B. Buurman, J. Kamruzzaman, G. Karmakar, S. Islam, Low-power wide-area networks: Design goals, architecture, suitability to use cases and research challenges, IEEE Access 8 (2020) 17179–17220.

[67] 3GPP, Study on support of reduced capability NR devices (Release 17), Tech. Rep. TR 38.875 (March 2021).

[68] Y.-P. E. Wang, X. Lin, A. Adhikary, A. Grovlen, Y. Sui, Y. Blankenship, J. Bergman, H. S. Razaghi, A primer on 3GPP narrowband Internet of Things, IEEE communications magazine 55 (3) (2017) 117–123.

[69] C. B. Mwakwata, H. Malik, M. Mahtab Alam, Y. Le Moullec, S. Parand, S. Mumtaz, Narrowband Internet of Things (NB-IoT): From physical (PHY) and media access control (MAC) layers perspectives, Sensors 19 (11) (2019) 2613.

[70] O. Liberg, S. E. Löwenmark, S. Euler, B. Hofström, T. Khan, X. Lin, J. Sedin, Narrowband Internet of Things for non-terrestrial networks, IEEE Communications Standards Magazine 4 (4) (2020) 49–55.

[71] E. Dahlman, S. Parkvall, J. Skold, 5G NR: The next generation wireless access technology, Academic Press, 2020.

[72] S. Ugwuanyi, G. Paul, J. Irvine, Survey of iot for developing countries: Performance analysis of lorawan and cellular nb-iot networks, Electronics 10 (18) (2021) 2224.

[73] GSMA, 3GPP Low Power Wide Area Technologies, https://halberdbastion.com/technology/iot/iot-protocols/ec-gsm-iot, Accessed on: 2023-01-11.

[74] G. GSM, 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Mobile radio interface layer 3 specification; GSM/EDGE Radio Resource Control (RRC) protocol , Tech. Rep. 3GPP TS 44.018, 3GPP (2022).

[75] O. Liberg, M. Sundberg, E. Wang, J. Bergman, J. Sachs, Cellular Internet of things: technologies, standards, and performance, Academic Press, 2017.

[76] R. Ratasuk, N. Mangalvedhe, A. Ghosh, B. Vejlgaard, Narrowband LTE-M system for M2M communication, in: 2014 IEEE 80th vehicular technology conference (VTC2014-Fall), IEEE, 2014, pp. 1–5.

[77] Ericsson, Ericsson mobility report, November (2022).
URL https://www.ericsson.com/en/reports-and-papers/mobility-report/reports

[78] GSMA, "Extended Coverage – GSM – Internet of Things (EC-GSM-IoT)", https://www.gsma.com/iot/extended-coverage-gsm-internet-of-things-ec-gsm-iot/, Accessed on: 03-02-2023 (January 2023).

[79] S. A. A. Abir, A. Anwar, J. Choi, A. Kayes, Iot-enabled smart energy grid: Applications and challenges, IEEE access 9 (2021) 50961–50981.

[80] A. Deutsche Telekom, NarrowBand IoT The Game Changer for The Internet of Things, Tech. rep., Tech. Rep. October (2017).

[81] G. TSG-RAN, Summary for WI Further enhanced MTC for LTE, Tech. Rep. RP-171441, Ericsson ML (2017).

[82] G. TSG-RAN, Further Enhanced MTC for LTE, Tech. Rep. RP-170532, 3GPP (2017).

[83] Andrew Worth, A Complete Overview of 2G & 3G Sunsets, https://1ot.mobi/resources/blog/a-complete-overview-of-2g-3g-sunsets, Accessed on: 2023-02-17.

[84] R. Ratasuk, N. Mangalvedhe, D. Bhatoolaul, A. Ghosh, LTE-M evolution towards 5G massive MTC, in: 2017 IEEE Globecom Workshops (GC Wkshps), IEEE, 2017, pp. 1–6.

[85] A. Sørensen, H. Wang, M. J. Remy, N. Kjettrup, R. B. Sørensen, J. J. Nielsen, P. Popovski, G. C. Madueño, Modeling and Experimental Validation for Battery Lifetime Estimation in NB-IoT and LTE-M, IEEE Internet of Things Journal 9 (12) (2022) 9804–9819.

[86] A. Ahmed, A. Al-Dweik, Y. Iraqi, H. Mukhtar, M. Naeem, E. Hossain, Hybrid automatic repeat request (HARQ) in wireless communications systems and standards: A contemporary survey, IEEE Communications Surveys & Tutorials 23 (4) (2021) 2711–2752.

[87] P. Reininger, 3GPP Standards for the Internet-of-Things, in: IoT Business & Technologies Congress, Singapore, November, Vol. 30, 2016.

[88] G. TSG-RAN, Even further enhanced MTC for LTE, Tech. Rep. RP-172811, Ericsson and Qualcomm (2017).

[89] M. B. Hassan, S. Alsharif, H. Alhumyani, E. S. Ali, R. A. Mokhtar, R. A. Saeed, An enhanced cooperative communication scheme for physical uplink shared channel in NB-IoT, Wireless Personal Communications 120 (3) (2021) 2367–2386.

[90] G. TSG-RAN, Study on Scenarios and Requirements for Next Generation Access Technologies, Tech. Rep. TR-38.913, 3GPP (2017).

[91] 3GPP, Summary of Rel-17 Work Items, Tech. Rep. TR 21.917, 3GPP (January 2023).

[92] G. Medina-Acosta, L. Zhang, J. Chen, K. Uesaka, Y. Wang, O. Lundqvist, J. Bergman, 3gpp release-17 physical layer enhancements for lte-m and nb-iot, IEEE Communications Standards Magazine 6 (4) (2022) 80–86.

[93] G. TSG-RAN, Enhancement of NB-IoT, Tech. Rep. RP-160813, Vodafone, Huawei,and HiSilicon (2016).

[94] G. TSG-RAN, New WI proposal for L1/L2 eMTC and NB-IoT Enhancements, Tech. Rep. RP-160878, Ericsson (2016).

[95] G. T. RAN, Study on new radio access technology physical layer aspects, Tech. Rep. TR.38.802, 3GPP (2017).
URL https://www.3gpp.org/ftp/Specs/archive/38_series/38.802/.

[96] A. Chakrapani, NB-IoT uplink receiver design and performance study, IEEE Internet of Things Journal 7 (3) (2019) 2469–2482.

[97] G. Stanco, A. Botta, F. Frattini, U. Giordano, G. Ventre, On the performance of iot lpwan technologies: the case of sigfox, lorawan and nb-iot, in: ICC 2022-IEEE International Conference on Communications, IEEE, 2022, pp. 2096–2101.

[98] G. Caso, Ö. Alay, L. De Nardis, A. Brunstrom, M. Neri, M.-G. Di Benedetto, Empirical models for NB-IoT path loss in an urban scenario, IEEE Internet of Things Journal 8 (17) (2021) 13774–13788.

[99] G. TSG-RAN, Narrowband IoT, Tech. Rep. RP-151621, Qualcomm (2015).

[100] A. I. Sulyman, S. M. Oteafy, H. S. Hassanein, Expanding the cellular-IoT umbrella: An architectural approach, IEEE Wireless Communications 24 (3) (2017) 66–71.

[101] M. Centenaro, C. E. Costa, F. Granelli, C. Sacchi, L. Vangelista, A survey on technologies, standards and open challenges in satellite IoT, IEEE Communications Surveys & Tutorials 23 (3) (2021) 1693–1720.

[102] A. Larmo, A. Ratilainen, J. Saarinen, Impact of CoAP and MQTT on NB-IoT system performance, Sensors 19 (1) (2018) 7.

[103] R. Singh, Y. Yan, An Experimental Evaluation of NB-IoT Coverage and Energy Consumption, in: 2020 IEEE Computing, Communications and IoT Applications (ComComAp), IEEE, 2020, pp. 1–6.

[104] L. Chettri, R. Bera, J. K. Barauh, Performance Analysis of 3GPP NB-IoT Downlink System towards 5G Machine Type Communication (5G-MTC), J. Commun. 16 (8) (2021) 355–362.

[105] D. C. Nguyen, M. Ding, P. N. Pathirana, A. Seneviratne, J. Li, D. Niyato, O. Dobre, H. V. Poor, 6G Internet of Things: A comprehensive survey, IEEE Internet of Things Journal 9 (1) (2021) 359–383.

[106] 5G Americas, The 5G Evolution: 3GPP Releases 16-17, https://www.5gamericas.org/wp-content/uploads/2020/01/5G-Evolution-3GPP-R16-R17-FINAL.pdf, Jan. (2020).

[107] G. Caso, K. Kousias, Ö. Alay, A. Brunstrom, M. Neri, Nb-iot random access: data-driven analysis and ml-based enhancements, IEEE Internet of Things Journal 8 (14) (2021) 11384–11399.

[108] 3GPP, Revised SID on Study on support of reduced capability NR devices, Tech. Rep. RP-191386 (September 14-18 2020).

[109] A. Ghosh, A. Maeder, M. Baker, D. Chandramouli, 5G evolution: A view on 5G cellular technology beyond 3GPP release 15, IEEE access 7 (2019) 127639–127651.

[110] G. T. RAN, Revised SID on Study on support of reduced capability NR devices, Tech. Rep. RP-201677, 3GPP, Ericsson (2020).

[111] Boost IoT with 5G NR RedCap, https://www.keysight.com/us/en/assets/7122-1119/white-papers/Boost-IoT-with-5G-NR-RedCap.pdf, Accessed On: 2023-02-14 (February 2023).

[112] Z. Jiang, S. Fu, S. Zhou, Z. Niu, S. Zhang, S. Xu, AI-assisted low information latency wireless networking, IEEE Wireless Communications 27 (1) (2020) 108–115.

[113] S. Montella, B. Berruet, O. Baala, V. Guillet, A. Caminada, F. Lassabe, A Funnel Fukunaga-Koontz Transform for Robust Indoor-Outdoor Detection Using Channel State Information in 5G IoT Context, IEEE Internet of Things Journal (2022).

[114] M. Beale, H. Uchiyama, J. C. Clifton, IoT Evolution: What's Next?,

IEEE Wireless Communications 28 (5) (2021) 5–7.

[115] Overall Description; Stage 2 (Release 1.1); MulteFire MFA Technical Specification 1.1, MulteFire Alliance, Fremont, CA, USA, `https://www.mfa-tech.org/technology/multefire-release-1-1-specification/`, Accessed On: 2023-01-27 (February 2019).

[116] X. Yang, Z. Zho, B. Huang, URLLC key technologies and standardization for 6G power Internet of Things, IEEE Communications Standards Magazine 5 (2) (2021) 52–59.

[117] M. El Soussi, P. Zand, F. Pasveer, G. Dolmans, Evaluating the performance of eMTC and NB-IoT for smart city applications, in: 2018 IEEE international conference on communications (ICC), IEEE, 2018, pp. 1–7.

[118] Y. A. Qadri, A. Nauman, Y. B. Zikria, A. V. Vasilakos, S. W. Kim, The future of healthcare internet of things: a survey of emerging technologies, IEEE Communications Surveys & Tutorials 22 (2) (2020) 1121–1167.

[119] H. Qiu, X. Wang, F. Xie, A survey on smart wearables in the application of fitness, in: 2017 IEEE 15th Intl Conf on Dependable, Autonomic and Secure Computing, 15th Intl Conf on Pervasive Intelligence and Computing, 3rd Intl Conf on Big Data Intelligence and Computing and Cyber Science and Technology Congress (DASC/PiCom/DataCom/CyberSciTech), IEEE, 2017, pp. 303–307.

[120] H. M. Hussien, S. M. Yasin, N. I. Udzir, M. I. H. Ninggal, S. Salman, Blockchain technology in the healthcare industry: Trends and opportunities, Journal of Industrial Information Integration 22 (2021) 100217.

[121] A. Ullah, M. Azeem, H. Ashraf, A. A. Alaboudi, M. Humayun, N. Jhanjhi, Secure healthcare data aggregation and transmission in IoT—A survey, IEEE Access 9 (2021) 16849–16865.

[122] Ericsson and Orange in the Internet of Things Trial with EC-GSM-IoT, `https://www.ericsson.com/en/press-releases/2016/2/ericsson-and-orange-in-internet-of-things-trial%20-%20with%20-%20ec-gsm-iot`, accessed: 2023-01-10.

[123] M. Chen, Y. Miao, Y. Hao, K. Hwang, Narrow band Internet of Things, IEEE access 5 (2017) 20557–20577.

[124] Sierra Wireless, Ericsson, Altair A, SONY company, Telenor,Sprint, AT&T, Verizon and SK Telecom, Coverage Analysis of LTE-M Category-M1, Tech. rep. (March 2018).

[125] G. Yu, X. Chen, C. Zhong, D. W. K. Ng, Z. Zhang, Design, analysis, and optimization of a large intelligent reflecting surface-aided B5G cellular Internet of Things, IEEE Internet of Things Journal 7 (9) (2020) 8902–8916.

[126] W. Ayoub, A. Ellatif Samhat, M. Mroue, H. Joumaa, F. Nouvel, J.-C. Prévotet, Technology selection for iot-based smart transportation systems, in: Vehicular ad-hoc networks for smart cities, Springer, 2020, pp. 19–29.

[127] F. Muteba, K. Djouani, T. Olwal, A comparative survey study on LPWA IoT technologies: Design, considerations, challenges and solutions, Procedia Computer Science 155 (2019) 636–641.

[128] F. Guo, F. R. Yu, H. Zhang, X. Li, H. Ji, V. C. Leung, Enabling massive IoT toward 6G: A comprehensive survey, IEEE Internet of Things Journal 8 (15) (2021) 11891–11915.

[129] M. B. Hassan, E. S. Ali, R. A. Mokhtar, R. A. Saeed, B. S. Chaudhari, NB-IoT: concepts, applications, and deployment challenges, in: LPWAN Technologies for IoT and M2M Applications, Elsevier, 2020, pp. 119–144.

[130] M. Chafii, F. Bader, J. Palicot, Enhancing coverage in narrow band-IoT using machine learning, in: 2018 IEEE Wireless Communications and Networking Conference (WCNC), IEEE, 2018, pp. 1–6.

[131] Evaluation of LTE-Mtowards 5g iot requirements for category-m1 devices.

[132] B. Martinez, F. Adelantado, A. Bartoli, X. Vilajosana, Exploring the performance boundaries of NB-IoT, IEEE Internet of Things Journal 6 (3) (2019) 5702–5712.

[133] P. Andres-Maldonado, M. Lauridsen, P. Ameigeiras, J. M. Lopez-Soler, Analytical modeling and experimental validation of NB-IoT device energy consumption, IEEE Internet of Things Journal 6 (3) (2019) 5691–5701.

[134] A. K. Sultania, C. Blondia, J. Famaey, Optimizing the energy-latency tradeoff in NB-IoT with PSM and eDRX, IEEE Internet of Things Journal 8 (15) (2021) 12436–12454.

[135] K. B. Letaief, W. Chen, Y. Shi, J. Zhang, Y.-J. A. Zhang, The roadmap to 6G: AI empowered wireless networks, IEEE communications magazine 57 (8) (2019) 84–90.

[136] W. Mao, Z. Zhao, Z. Chang, G. Min, W. Gao, Energy-efficient industrial internet of things: Overview and open issues, IEEE Transactions on Industrial Informatics 17 (11) (2021) 7225–7237.

[137] E. Sisinni, A. Saifullah, S. Han, U. Jennehag, M. Gidlund, Industrial internet of things: Challenges, opportunities, and directions, IEEE transactions on industrial informatics 14 (11) (2018) 4724–4734.

[138] J. A. Ansere, G. Han, L. Liu, Y. Peng, M. Kamal, Optimal resource allocation in energy-efficient Internet-of-Things networks with imperfect CSI, IEEE Internet of Things Journal 7 (6) (2020) 5401–5411.

[139] Y. Mao, E. Piovano, B. Clerckx, Rate-splitting multiple access for overloaded cellular internet of things, IEEE Transactions on Communications 69 (7) (2021) 4504–4519.

[140] L. Chen, B. Hu, G. Xu, S. Chen, Energy-efficient power allocation and splitting for mmWave beamspace MIMO-NOMA with SWIPT, IEEE Sensors Journal 21 (14) (2021) 16381–16394.

[141] X. Sun, W. Zhan, W. Liu, Y. Li, Q. Liu, Sum Rate and Access Delay Optimization of Short-Packet Aloha, IEEE Open Journal of the Communications Society 3 (2022) 1501–1514.

[142] M. Min, L. Xiao, Y. Chen, P. Cheng, D. Wu, W. Zhuang, Learning-based computation offloading for IoT devices with energy harvesting, IEEE Transactions on Vehicular Technology 68 (2) (2019) 1930–1941.

[143] A. M. Alqasir, A. E. Kamal, Cooperative small cell HetNets with dynamic sleeping and energy harvesting, IEEE Transactions on Green Communications and Networking 4 (3) (2020) 774–782.

[144] Y. Cheng, J. Zhang, J. Zhang, H. Zhao, L. Yang, H. Zhu, Small-Cell Sleeping and Association for Energy-Harvesting-Aided Cellular IoT With Full-Duplex Self-Backhauls: A Game-Theoretic Approach, IEEE Internet of Things Journal 9 (3) (2021) 2304–2318.

[145] M. A. Kishk, H. S. Dhillon, Joint uplink and downlink coverage analysis of cellular-based RF-powered IoT network, IEEE Transactions on Green Communications and Networking 2 (2) (2017) 446–459.

[146] A. Lombardo, S. Parrino, G. Peruzzi, A. Pozzebon, LoRaWAN versus NB-IoT: Transmission performance analysis within critical environments, IEEE Internet of Things Journal 9 (2) (2021) 1068–1081.

[147] Q. Qi, X. Chen, C. Zhong, Z. Zhang, Integration of energy, computation and communication in 6G cellular internet of things, IEEE Communications Letters 24 (6) (2020) 1333–1337.

[148] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, M. Zorzi, Toward 6G networks: Use cases and technologies, IEEE Communications Magazine 58 (3) (2020) 55–61.

[149] F. Michelinakis, A. S. Al-Selwi, M. Capuzzo, A. Zanella, K. Mahmood, A. Elmokashfi, Dissecting energy consumption of nb-iot devices empirically, IEEE Internet of Things Journal 8 (2) (2020) 1224–1242.

[150] V. Tikhvinskiy, G. Bochechka, A. Gryazev, A. Aitmagambetov, Comparative analysis of qos management and technical requirements in 3gpp standards for cellular iot technologies, Journal of Telecommunications and Information Technology (2018).

[151] N. S. Chilamkurthy, O. J. Pandey, A. Ghosh, L. R. Cenkeramaddi, H.-N. Dai, Low-power wide-area networks: A broad overview of its different aspects, IEEE Access (2022).

[152] S. Zhang, C. Xiang, S. Xu, 6G: Connecting everything by 1000 times price reduction, IEEE Open Journal of Vehicular Technology 1 (2020) 107–115.

[153] S. R. Borkar, Long-term evolution for machines (LTE-M), in: LPWAN technologies for IoT and M2M applications, Elsevier, 2020, pp. 145–166.

[154] A. Sørensen, H. Wang, M. J. Remy, N. Kjettrup, R. B. Sørensen, J. J. Nielsen, P. Popovski, G. C. Madueño, Modelling and Experimental Validation for Battery Lifetime Estimation in NB-IoT and LTE-M, IEEE Internet of Things Journal (2022).

[155] 3GPP, 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on provision of low-cost Machine-Type Communications (MTC) user equipments (UEs) based on LTE (release 12), Tech. Rep. TR 36.888 (2013).

[156] Ericsson, Ericsson mobility report, November (2022).
URL `https://www.ericsson.com/en/reports-and-papers/mobility-report/reports`

[157] H. W. Kim, H. J. Park, S. H. Chae, Sub-band assignment and power

control for IoT cellular networks via deep learning, IEEE Access 10 (2022) 8994–9003.

[158] H. Zhang, B. Di, K. Bian, L. Song, IoT-U: Cellular Internet-of-Things networks over unlicensed spectrum, IEEE Transactions on Wireless Communications 18 (5) (2019) 2477–2492.

[159] S. Winalisa, M. I. Nashiruddin, Designing nb-iot (internet of things) network for public iot in batam island, in: 2020 8th International Conference on Information and Communication Technology (ICoICT), IEEE, 2020, pp. 1–6.

[160] R. Ratasuk, B. Vejlgaard, N. Mangalvedhe, A. Ghosh, Nb-iot system for m2m communication, in: 2016 IEEE wireless communications and networking conference, IEEE, 2016, pp. 1–5.

[161] J. Cao, P. Yu, X. Xiang, M. Ma, H. Li, Anti-quantum fast authentication and data transmission scheme for massive devices in 5G NB-IoT system, IEEE Internet of Things Journal 6 (6) (2019) 9794–9805.

[162] Z. Wang, R. Liu, Q. Liu, J. S. Thompson, M. Kadoch, Energy-efficient data collection and device positioning in uav-assisted iot, IEEE Internet of Things Journal 7 (2) (2019) 1122–1139.

[163] A. Kumar, Embedded Sensors, Communication Technologies, Computing Platforms and Machine Learning for UAVs: A Review (2022).

[164] X. Fang, W. Feng, T. Wei, Y. Chen, N. Ge, C.-X. Wang, 5G embraces satellites for 6G ubiquitous IoT: Basic models for integrated satellite terrestrial networks, IEEE Internet of Things Journal 8 (18) (2021) 14399–14417.

[165] F. K. Shaikh, S. Karim, S. Zeadally, J. Nebhen, Recent trends in internet of things enabled sensor technologies for smart agriculture, IEEE Internet of Things Journal (2022).

[166] S. Qazi, B. A. Khawaja, Q. U. Farooq, IoT-equipped and AI-enabled next generation smart agriculture: a critical review, current challenges and future trends, IEEE Access (March 2022).

[167] E. Rastogi, N. Saxena, A. Roy, D. R. Shin, Narrowband internet of things: A comprehensive study, Computer networks 173 (2020) 107209.

[168] D. Milovanovic, V. Pantovic, N. Bojkovic, Z. Bojkovic, Advanced human-centric 5g-iot in a smart city: Requirements and challenges, in: Human Centered Computing: 5th International Conference, HCC 2019, Čačak, Serbia, August 5–7, 2019, Revised Selected Papers 5, Springer, 2019, pp. 285–296.

[169] Y. Li, X. Cheng, Y. Cao, D. Wang, L. Yang, Smart choice for the smart grid: Narrowband Internet of Things (NB-IoT), IEEE Internet of Things Journal 5 (3) (2017) 1505–1515.

[170] Y. Saleem, N. Crespi, M. H. Rehmani, R. Copeland, Internet of things-aided smart grid: technologies, architectures, applications, prototypes, and future research directions, IEEE Access 7 (2019) 62962–63003.

[171] A. K. Sultania, F. Mahfoudhi, J. Famaey, Real-time demand response using NB-IoT, IEEE Internet of Things Journal 7 (12) (2020) 11863–11872.

[172] R. Salazar-Cabrera, Á. P. De La Cruz, J. M. M. Molina, Fleet management and control system from intelligent transportation systems perspective, in: 2019 2nd Latin American Conference on Intelligent Transportation Systems (ITS LATAM), IEEE, 2019, pp. 1–7.

[173] F. Al-Turjman, A. Malekloo, Smart parking in IoT-enabled cities: A survey, Sustainable Cities and Society 49 (2019) 101608.

[174] D. Cheng, C. Li, N. Qiu, The application prospects of nb-iot in intelligent transportation, in: 2021 4th International Conference on Advanced Electronic Materials, Computers and Software Engineering (AEMCSE), IEEE, 2021, pp. 1176–1179.

[175] Y. Mehmood, F. Ahmad, I. Yaqoob, A. Adnane, M. Imran, S. Guizani, Internet-of-things-based smart cities: Recent advances and challenges, IEEE Communications Magazine 55 (9) (2017) 16–24.

[176] H. Fattah, 5G LTE Narrowband Internet of Things (NB-IoT), CRC Press, 2018.

[177] L. Chettri, R. Bera, A comprehensive survey on Internet of Things (IoT) toward 5G wireless systems, IEEE Internet of Things Journal 7 (1) (2019) 16–32.

[178] J. L. Hernandez-Ramos, J. A. Martinez, V. Savarino, M. Angelini, V. Napolitano, A. F. Skarmeta, G. Baldini, Security and privacy in internet of things-enabled smart cities: Challenges and future directions, IEEE Security & Privacy 19 (1) (2020) 12–23.

[179] W. Xu, J. Zhang, J. Y. Kim, W. Huang, S. S. Kanhere, S. K. Jha, W. Hu, The design, implementation, and deployment of a smart lighting system for smart buildings, IEEE Internet of Things Journal 6 (4) (2019) 7266–7281.

[180] M. Mahbub, Nb-iot: applications and future prospects in perspective of bangladesh, International Journal of Information Technology 12 (4) (2020) 1183–1193.

[181] X. Chen, X. Wang, H. Shen, Design of greenhouse environment monitoring system based on NB-IoT and edge computing, in: 2021 IEEE 5th Advanced Information Technology, Electronic and Automation Control Conference (IAEAC), Vol. 5, IEEE, 2021, pp. 1319–1324.

[182] M. Klymash, T. Maksymyuk, S. Dumych, O. Yaremko, Designing the industrial and environmental monitoring system based on the internet of things architecture, in: 2018 IEEE 4th International Symposium on Wireless Systems within the International Conferences on Intelligent Data Acquisition and Advanced Computing Systems (IDAACS-SWS), IEEE, 2018, pp. 187–190.

[183] Y. Zhao, Y. Yu, J. Kang, Y. Zhang, Intelligent irrigation system based on nb-iot, in: 2022 IEEE International Conference on Mechatronics and Automation (ICMA), IEEE, 2022, pp. 1419–1424.

[184] P. Deligiannis, S. Koutroubinas, G. Koronias, Predicting energy consumption through machine learning using a smart-metering architecture, IEEE Potentials 38 (2) (2019) 29–34.

[185] A. M. Abbas, K. Y. Youssef, I. I. Mahmoud, A. Zekry, NB-IoT optimization for smart meters networks of smart cities: Case study, Alexandria Engineering Journal 59 (6) (2020) 4267–4281.

[186] Y. Li, W. Zhan, L. Dai, Rate-Constrained Delay Optimization for Slotted Aloha, IEEE Transactions on Communications 69 (8) (2021) 5283–5298.

[187] F. Al-Turjman, E. Ever, H. Zahmatkesh, Small cells in the forthcoming 5G/IoT: Traffic modelling and deployment overview, IEEE Communications Surveys & Tutorials 21 (1) (2018) 28–65.

[188] H. Zhang, J. Li, B. Wen, Y. Xun, J. Liu, Connecting intelligent things in smart hospitals using NB-IoT, IEEE Internet of Things Journal 5 (3) (2018) 1550–1560.

[189] F. J. Dian, R. Vahidnia, A. Rahmati, Wearables and the internet of things (iot), applications, opportunities, and challenges: A survey, IEEE access 8 (2020) 69200–69211.

[190] O. Apilo, J. Mäkelä, A. Kuosmonen, Evaluation of cellular IoT for sport wearables, in: 2019 IEEE 30th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC Workshops), IEEE, 2019, pp. 1–7.

[191] GSMA, DEVELOPMENT GUIDE FOR INDUSTRIAL USING NB-IoT, Accessed on: 31-01-2023.
URL `https://www.gsma.com/iot/wp-content/uploads/2019/08/201902_GSMA_IoT-Development_Guide_NB-IoT_for_Industrial.pdf`

[192] E. Migabo, K. Djouani, A. Kurien, Energy Efficient Data Rate Enhancement Channel Coding Technique for Narrowband Internet of Things (NB-IoT), in: 2021 IEEE AFRICON, IEEE, 2021, pp. 1–6.

[193] H. G. Moussa, W. Zhuang, RACH performance analysis for large-scale cellular IoT applications, IEEE Internet of Things Journal 6 (2) (2018) 3364–3372.

[194] H. G. Moussa, W. Zhuang, Energy-and delay-aware two-hop NOMA-enabled massive cellular IoT communications, IEEE Internet of Things Journal 7 (1) (2019) 558–569.

[195] T. Kim, I. Bang, Random access parallelization based on preamble diversity for cellular IoT networks, IEEE Communications Letters 24 (1) (2019) 188–192.

[196] W. Zhan, X. Sun, X. Wang, Y. Fu, Y. Li, Performance Optimization for Massive Random Access of mMTC in Cellular Networks With Preamble Retransmission Limit, IEEE Transactions on Vehicular Technology 70 (9) (2021) 8854–8867.

[197] V. P. Kafle, Y. Fukushima, P. Martinez-Julia, T. Miyazawa, H. Harai, Adaptive virtual network slices for diverse IoT services, IEEE Communications Standards Magazine 2 (4) (2018) 33–41.

[198] H. S. Jang, H. Jin, B. C. Jung, T. Q. Quek, Resource-optimized recursive access class barring for bursty traffic in cellular IoT networks, IEEE Internet of Things Journal 8 (14) (2021) 11640–11654.

[199] H. Yahya, A. Al-Dweik, Y. Iraqi, E. Alsusa, A. Ahmed, A power and spectrum efficient uplink transmission scheme for QoS-constrained IoT networks, IEEE Internet of Things Journal 9 (18) (2022) 17425–17439.

[200] O. Hayat, Z. Kaleem, M. Zafarullah, R. Ngah, S. Z. M. Hashim, Signaling overhead reduction techniques in device-to-device communications:

Paradigm for 5g and beyond, IEEE Access 9 (2021) 11037–11050.

[201] Cellular IoT Module Market outlook (2023 to 2033, `https://www.futuremarketinsights.com/reports/cellular-iot-module-market`, Accessed On: 2023-03-16 (March 2023).

[202] S.-H. Pan, S.-C. Wang, Enhancing the reliability of cellular internet of things through agreement, Applied Sciences 10 (21) (2020) 7699.

[203] M. Elkhodr, S. Shahrestani, H. Cheung, The internet of things: New interoperability, management and security challenges, arXiv preprint arXiv:1604.04824 (2016).

[204] T. Alladi, V. Chamola, B. Sikdar, K.-K. R. Choo, Consumer iot: Security vulnerability case studies and solutions, IEEE Consumer Electronics Magazine 9 (2) (2020) 17–25.

[205] J. Ni, X. Lin, X. S. Shen, Efficient and secure service-oriented authentication supporting network slicing for 5G-enabled IoT, IEEE Journal on Selected Areas in Communications 36 (3) (2018) 644–657.

[206] M. Savic, M. Lukic, D. Danilovic, Z. Bodroski, D. Bajović, I. Mezei, D. Vukobratovic, S. Skrbic, D. Jakovetić, Deep learning anomaly detection for cellular IoT with applications in smart logistics, IEEE Access 9 (2021) 59406–59419.

[207] A. Ahmad, S. Cuomo, W. Wu, G. Jeon, Intelligent algorithms and standards for interoperability in internet of things (2019).

[208] R. Khan, I. Ali, M. A. Jan, M. Zakarya, M. A. Khan, S. S. Alshamrani, M. Guizani, A hybrid approach for seamless and interoperable communication in the internet of things, IEEE Network 35 (6) (2021) 202–208.

[209] Z. Zhang, A. Z. Kouzani, Implementation of DNNs on IoT devices, Neural Computing and Applications 32 (2020) 1327–1356.

[210] G. Yu, X. Chen, D. W. K. Ng, Low-cost design of massive access for cellular Internet of Things, IEEE Transactions on Communications 67 (11) (2019) 8008–8020.

[211] W. U. Khan, J. Liu, F. Jameel, V. Sharma, R. Jäntti, Z. Han, Spectral efficiency optimization for next generation NOMA-enabled IoT networks, IEEE Transactions on Vehicular Technology 69 (12) (2020) 15284–15297.

[212] A. Al-Dweik, Y. Iraqi, High throughput wireless links for time-sensitive WSNs with reliable data requirements, IEEE Sensors Journal 21 (21) (2021) 24890–24898.

[213] S. Jaffry, R. Hussain, X. Gui, S. F. Hasan, A comprehensive survey on moving networks, IEEE Communications Surveys & Tutorials 23 (1) (2020) 110–136.