

Cellular Internet of Things: Principles, Potentials and Use Cases

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Abstract

Internet of things (IoT) can either be deployed over existing cellular networks or their own custom-built standalone networks. Based on the infrastructure, IoT can be classified into two types: cellular and non-cellular categories. In the cellular form, IoT network needs the support of cellular infrastructure of the mobile service providers. Currently, three forms of cellular IoT are being deployed across the world. They are: narrowband Internet of things (NB-IoT), extended coverage GSM (EC-GSM), long term evolution for machines (LTE-M), and 5G Reduced Capacity IoT (RedCap). Out of these three, NB-IoT and EC-GSM are low energy and low resource consuming versions of cellular IoT. They need narrow bandwidths for their operations. Their energy consumption is also very low and thus suitable for low energy applications. Both NB-IoT and EC-GSM are compatible with all types of cellular communication infrastructure such as 2G, 3G, 4G and 5G. They can cover a large area with a very small amount of power. Both these forms are popular low power wide area (LPWA) technologies. Due to their LPWA features, they are popular for the connected living applications at home and workplace surroundings. Their LPWA features make them popular green technology for digital transformation. LTE-M and RedCap use comparatively larger bandwidth and higher power. They are suitable for higher bandwidth and higher data rate applications. We survey the recent literature on cellular IoT and present their key principles, potentials and applications. We provide their main characteristics, deployment options, standards, and some specific applications in different sectors.

Keywords: Cellular IoT, NB-IoT, EC-GSM, LTE-M, RedCap, low power wide area technology, applications of cellular IoT.

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1. Introduction

The Internet of things (IoT) is now an integral part of the modern digital ecosystem. It has the ability to connect every object and living beings with the Internet [1]. As a leading technology in the ongoing global digital transformation, IoT is witnessing widespread deployment of its components, including sensors, actuators, servers, edge computing infrastructure, and more. This proliferation clearly indicates a substantial demand for energy and other IoT resources. To address this demand and reduce resource consumption, there is a growing need for leaner and more efficient versions of

IoT that are as ubiquitous as cellular networks. Cellular IoT represents this resource-efficient evolution, providing a viable solution for deployment over existing cellular networks [2]. They had evolved from the need of massive machine type communications (mMTC) over the LTE networks [3–5]. Currently, there are three popular cellular IoT solutions are available for deployment: narrowband IoT (NB-IoT), extended coverage GSM (EC-GSM), long term evolution for machines (LTE-M), and 5G Reduced Capacity (RedCap). NB-IoT and EC-GSM are among the most popular low power wide area (LPWA) technologies [6]. These IoTs do not have adverse effects on humans or upon other living beings [2], which is why they are considered as main technologies for ambient living ecosystems. They are

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preferred for the large scale deployments over a large coverage area [5]. Cost wise, they are among the economical forms of the available IoT [4]. Their deployment is simpler when compared with other types of IoT [7]. Their standardization has been completed and new provisions are added with the new application demands. Cellular IoT can be deployed over the cellular infrastructure as well as in the standalone mode in case of NB-IoT [7]. They have enormous potential for low power applications and assist in the sustainability of the environment in several ways [8–51]. They are among the most attractive LPWA technologies in a large number of applied technology and non-technology sectors [9]. Therefore, a lot of applications of cellular IoT is found in the low power regime [7–11]. Cellular IoT is very popular in many pervasive applications such as healthcare, smart cities, smart grids, smart homes, industries, agriculture, localization, tracking and several other domains [14–43]. All these applications are the testimony of the importance of the cellular IoT.

Large scale machine to machine communication is a primary requirement in the beyond 4G networks [11]. In order to handle these connectivity issues several solutions have been proposed. In the mobile cellular framework, there are three different solutions viz. NB-IoT, LTE-M, and EC-GSM. There are a few differences between these cellular IoTs [5]. Though they are designed for the emerging demands of 5G and beyond 5G networks, they are also compatible with the legacy networks such as 2G, and 3G and 4G [14]. Different cellular IoTs were proposed by the Third Generation Partnership Project (3GPP) for machine type communications in the LTE framework in Release 13 [5]. These cellular IoTs were custom designed to be compatible with the LTE networks and their legacy systems [17]. Their main goal was to compete with the existing low power non-cellular IoT technologies such as LoRa and SigFox. New physical layer signals and channels were designed for cellular IoT to fulfil the demands of LPWA applications [5]. Their LTE features make it suitable for rural, urban and remote deployments over the mobile cellular infrastructure. Due to their low energy consumption characteristics, NB-IoT and EC-GSM are considered as green technologies [14]. They are applied in a wide range of applications such as agriculture, healthcare, cattle tracking, localization in logistics, policing, utility management, traffic management, smart cities, smart grids, retail management, waste management, and smart homes [14–51]. These applications of cellular IoT indicate a lot about their popularity in recent years. These IoTs are also sustainable technologies of the long term [11–14]. Energy and bandwidth efficiency are essential for the global sustainability of the telecommunications industry [12]. NB-IoT and EC-GSM have both the attributes and they are essential for the global sustainability in the mMTC sectors [18–20]. Security and privacy aspects of cellular IoT are essential for their sustained applications in the coming decades [21–27]. In this regard, cellular IoTs are currently better placed than majority of the non-cellular IoTs in practice. Cellular IoTs use the security provisions of LTE and some new initiatives at the upper layers [29]. Several new

security initiatives have also been proposed for NB-IoT and LTE-M which are going to be the game changers in coming years [1–11]. NB-IoT and EC-GSM are custom built for low data rates. However, in some of the applications higher data rates are needed. LTE-M is preferred for higher data rates, voice and video communications [11]. In such cases, cellular IoT data has to be compressed using efficient techniques. IoT and other low bandwidth networks need support of the advanced compression techniques. These efficient compression techniques are essential for the overall success of NB-IoT, EC-GSM, and other low bandwidth IoT networks [3]. It shows that effective compression techniques are essential to overcome several difficulties of low bandwidth networks [3]. Resources for cellular IoT such as the bandwidth for practical deployment, and transmitted power are scarce [1]. Bandwidth scarcity is a modern reality in the large cities and places with high density population. Several options for new bandwidths and management of existing bandwidths have been proposed for emerging services in the recent years [3]. Cellular IoTs can be deployed over the cellular networks in different ways which we have discussed with more clarity in the deployment section of this paper.

Due to the large size and large traffic, cellular IoT needs some supporting technologies such as software defined networking (SDN) for proper control and management. Main issues related to the SDN approaches in IoT networks have been presented in some recent works [15, 16]. These works show that a dedicated slice for IoT based services is essential for the future demands [1]. Various emerging issues of cellular IoT such as the physical layer design, cloud implementation and future complexities are to be considered for their practical deployment [3, 11]. Centralized clouds are not suitable for NB-IoT due to its wide coverage. Fog or edge nodes and with small cloud facilities are better than the centralized cloud facilities [3]. RedCap is the new 5G based advanced IoT technology which can provide high data rate services like the LTE-M [5]. In fact, RedCap uses the 5G-based framework to improve the range and quality services at higher data rates using higher bandwidth [53]. There are several emerging applications of the IoT and cellular networks both on the earth and beyond the earth. These services need the support of advanced technologies to provide good quality services at the expected levels. In [5], we have presented some of those advanced services.

In this paper, we present the main principles of cellular IoT. Subsequently, we present their standardization, features, and deployment related issues with practical focus. We show the potentials of cellular IoT for the low power digital ecosystem and large scale digital transformation. We also show that cellular IoT is the prime technology for the large scale LPWA applications and use cases.

The remainder of this paper is organized in four different sections. In the next section, we present the main principles of cellular IoT. After that, we present the standardization and deployment related issues of different types of cellular IoT. Then we present the potentials and applications of these cellular IoT in the practical scenarios.

2. Principles of Cellular IoT

Cellular IoTs are widely regarded as the value-added services over the cellular network platforms [47]. These cellular IoTs can be deployed over the cellular infrastructure and also have their own networks [2, 7]. Cellular IoT typically refers to a network of connected devices that communicate with each other and with central network systems using cellular technology principles. Its main objective is interconnecting everyday objects and devices (which are not computers) to the Internet, allowing them to collect and exchange data for various purposes [1]. Cellular IoT specifically depends on cellular networks to enable this connectivity. There are several key principles that underpin the operation and functionality of cellular IoT. These principles are pivotal in the deployment of efficient and reliable connectivity for a wide range of devices and applications.

Cellular IoT relies on existing cellular network infrastructure, such as 4G LTE, 4.5G, 5G, and other cellular technologies [7]. Some cellular IoT are compatible with the legacy cellular infrastructure such as 3G, 2G, WiFi and WiMAX [14]. This infrastructure includes a network of cell towers, base stations, and core network elements that provide coverage over a specific geographic area. Majority of the cellular IoT devices are designed to operate with low power consumption. They are often battery-powered and designed to conserve energy to extend the device's lifespan [2]. Low power consumption is certainly essential for applications where frequent battery replacement or recharging is impractical. Cellular IoTs offer wide area coverage, making them suitable for applications that require connectivity over a broad geographic area [17, 27]. This is especially important for applications like asset tracking, remote healthcare, agriculture, and smart cities that may span large regions. Normally, cellular IoT networks are highly scalable and can support a large number of connected devices [5]. This scalability is essential for accommodating the growing number of IoT devices deployed in various industries and domestic applications. Security is a fundamental requirement of IoT and cellular IoT shares the similar security mechanism as the parent cellular network [41]. We see that cellular networks incorporate encryption and authentication mechanisms to protect data transmitted between devices and the network [14]. This is also utilized in cellular IoT which ensures the confidentiality and integrity of data. Cellular networks are known for their reliability and high availability [40]. They offer robust connections that are suitable for mission-critical applications. These aspects of reliability are also found in the cellular IoT [48]. It is crucial in scenarios such as healthcare, industrial automation, and public safety. Cellular IoT networks can provide different levels of quality of service (QoS) to meet the requirements of diverse applications [48]. Some applications may prioritize low latency, while others may prioritize low data rates and energy efficiency. Based on these priorities the QoS aspects are set for different cellular IoT. It is noteworthy that cellular IoTs follow the principles of the cellular network technologies. For instance, the cellular IoT over 4G networks follow the principles of 4G technologies. The evolution of

cellular networks to 5G brings advancements to cellular IoT as well. However, the specific benefits depend on the host system where the IoT device is deployed. Notably, advanced cellular standards like 4.5G and 5G offer significant improvements in Quality of Service (QoS) compared to legacy systems. These advancements often include features that enhance the user experience. Cellular IoT applications can leverage these features in certain scenarios.

Cellular IoT technologies follow the cellular standards such as the LTE and 5G which adhere to industry standards, ensuring interoperability between devices and networks from different manufacturers [48]. Standardization helps prevent vendor lock-in and promotes a competitive ecosystem in the cellular IoT market. Cellular IoT networks typically include features for remote device management. This allows the operators and network administrators to monitor and update devices over the air and perform tasks like firmware updates and troubleshooting without physical access to the devices [40]. Cellular IoT devices often require data plans and may involve billing based on data usage. This aspect of cellular IoT is typically managed by service providers and network operators [41]. Cellular IoT devices can roam between different cellular networks and operators, enabling seamless connectivity as devices move across coverage areas. Regulatory bodies allocate specific frequency bands and spectrum for cellular IoT usage [48]. These allocations are managed to prevent interference and ensure efficient use of radio resources. Overall, cellular IoT offers a robust, energy efficient, and versatile solutions for connecting a wide range of devices and sensors to the Internet, enabling data-driven decision-making and automation in various industries [7]. The deployment of 5G networks further enhances the capabilities and potential applications of cellular IoT. In fact, large scale IoT deployment is a strategic focus in 5G [50].

3. Types of Cellular IoT

Cellular IoT is popular for the long-term deployment of IoT services over the existing cellular infrastructure. According to the current trends, cellular IoT can be classified in to three

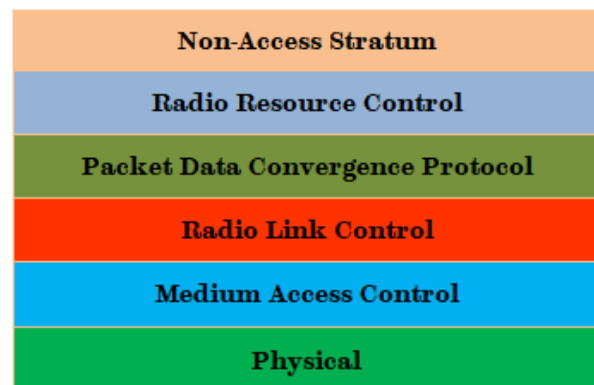


Figure 1. The typical OSI model of cellular IoT (compatible with the LTE architecture).

different types. They are: NB-IoT, EC-GSM, and LTE-M [48]. The first two are narrowband IoTs (bandwidth is much lower than the commonly used LTE bandwidth) and they consume fewer resources. However, LTE-M is significantly different as it uses comparatively wider bandwidths, and higher data rates for communication [49].

3.1 NB-IoT

NB-IoT has been designed to provide mMTC services in the LTE environment. However, it is compatible with the legacy cellular systems and the emerging networks such as 5G [47]. NB-IoT has a systematic technological framework, and it can be explained with the help of its different functional layers just like the Internet. The Open Systems Interconnection (OSI) model shows its layers according to their functions [41]. According to the OSI model of the NB-IoT, it has six different layers as shown in Figure 1. The lower most layer in the OSI model of NB-IoT is the physical layer. It has several wireless channels used for NB-IoT communications. These channels facilitate the communication between the NB-IoT end devices and the NB-IoT servers [14]. Above the physical layer we find the medium access control (MAC) layer. This MAC layer is very similar to the MAC layer of the Internet and the LTE networks. It provides the common functions such as coding and decoding of the information and facilitates the multiple access techniques. Radio link control (RLC) is just above the MAC layer. Its main function is to establish and terminate the radio links for NB-IoT communications [41]. It normally uses the user datagram protocol (UDP) for its functions. Packet data convergence protocol (PDCP) layer is situated just above the RLC layer [41]. It provides the order sequencing and convergence of the incoming packets which are received by the RLC layer. Radio resource control (RRC) is just above the PDCP layer. Its function is to allocate and control the available radio resources for the NB-IoT communications [41]. At the top of the OSI model, is the non-access stratum layer. It deals with several control and security mechanisms at the upper level [14]. It also provides the sessions for communication between the user equipment (UEs) and the servers.

However, for the practical implementation of an NB-IoT system or technical applications points of views this OSI model is not much helpful. Rather the protocol based version shown in Figure 2 is more realistic and appropriate for deployment [41]. Similar to the OSI model, the lower most layer in this model is the physical layer. For NB-IoT, it is the wireless channel through which it communicates with different ports, nodes, devices and components. Just above the physical layer is the Internet protocol (IP) layer in its lighter form (because the NB-IoT systems and components do not have large memory to carry the original form of the IPv6). It is called IPv6 over Low Power Wireless Personal Area Network (6LoWPAN). This lighter version is suitable for bandwidth limited applications such as NB-IoT [43]. Above that, we find the UDP layer. It is the transmission control protocol for the connectionless mediums. Above the UDP layer, we find the datagram transport layer security (DTLS)

layer. Its function is to provide the security to the datagrams using appropriate mechanisms [41]. Above the DTLS layer, we find the constrained application protocol (CoAP) layer. This is very much similar to the hypertext transfer protocol (HTTP). But CoAP is much lighter than the HTTP. CoAP uses only UDP information in its functions [41]. It is optimized to function in the constrained resource scenarios. The uppermost layer is the end objects layer. It deals with the end objects such as the sensors, actuators, UEs, and other end objects. This practically implementable model is very popular in the real deployments. It is adopted in almost all the practical deployments [41]. It saves a lot of time and provides better system efficacy in design and implementation.

3.2 EC-GSM

EC-GSM is also known as extended coverage GSM Internet of things (EC-GSM-IoT). It is a popular LPWA cellular IoT just like the NB-IoT [18]. EC-GSM is a cellular technology designed to extend the coverage and enhance the performance of GSM (2G) networks for different IoT applications. It is also compatible with all the legacy networks such as the 3G, 4G. However, in the 5G regime, it is not very popular due to the advent of RedCap which provides several new use cases based on the 5G requirements. Its features include high capacity, low complexity, low energy, long range, and wider coverage. Since 2017, it has been deployed commercially in several countries.

EC-GSM is also known as GPRS (General Packet Radio Service) phase 2, as it is built upon the existing GSM infrastructure [48]. It is enabled through the electronic GPRS (eGPRS) protocols. It operates in the 2G spectrum and is compatible with existing GSM networks, making it a cost-effective option for upgrading IoT connectivity without requiring a complete network overhaul. EC-GSM is an LPWA technology, optimized for low data rate applications that require extended coverage and long battery life for IoT devices [49]. It provides improved signal reachability, allowing devices to transmit data over longer distances from the cellular base stations compared to traditional GSM.

EC-GSM is particularly suitable for IoT applications in challenging environments or remote areas where cellular coverage is limited [50]. It supports downlink and uplink data rates of 60 kbps, which is sufficient for many IoT applications that require periodic data transmission, such as utility metering and environmental monitoring. However, the data rate enhancement provisions have been added to its features. EC-GSM can coexist with existing GSM services, utilizing the same infrastructure and spectrum, thus ensuring backward compatibility with legacy devices [48]. It uses the same security features as GSM, providing data protection and ensuring the integrity of communications for IoT devices. EC-GSM improves indoor coverage, making it ideal for applications deployed within buildings, underground facilities, or other environments with weak radio signals [48]. Although EC-GSM is an improvement over traditional GSM for IoT applications, it has been largely superseded by other

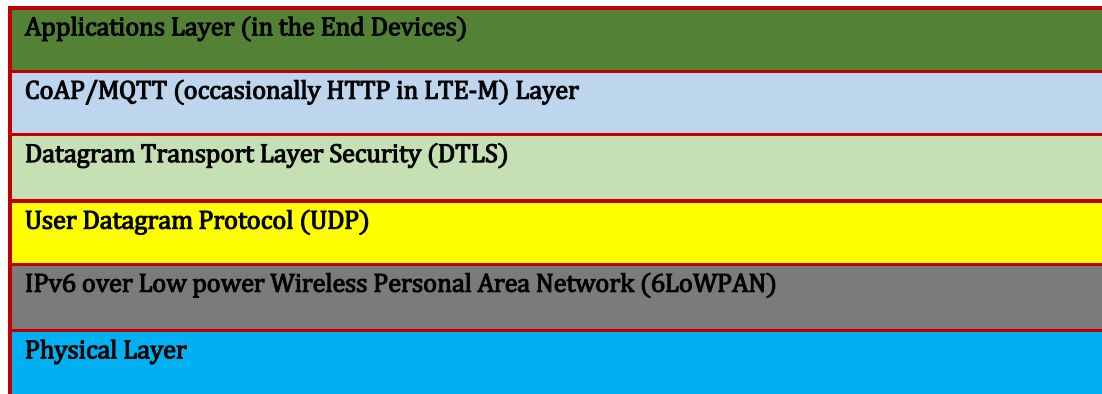


Figure 2. The protocol based practically implementable layers of NB-IoT, EC-GSM and LTE-M (this model applies to all the typical cellular IoTs, though a few protocol based changes may apply).

LPWA cellular IoTs like NB-IoT and LTE-M. NB-IoT is preferred for lower data rates and LTE-M is chosen for higher data rates. Both are found to be better than EC-GSM in performance. EC-GSM plays an important role in extending the capabilities of GSM networks for IoT before the widespread adoption of dedicated LPWA technologies. However, other cellular IoT technologies emerged, and the industry shifted towards more specialized solutions to meet the diverse demands [50].

EC-GSM offers several advantages that make it a suitable choice for certain IoT applications. EC-GSM significantly extends the coverage area compared to traditional GSM networks which is particularly advantageous for IoT devices deployed in remote or challenging environments with limited cellular coverage [48]. EC-GSM builds upon the existing GSM infrastructure, making it a cost-effective upgrade for operators looking to enhance their IoT connectivity without requiring a complete network overhaul. EC-GSM is designed to coexist with GSM networks, ensuring backward compatibility with legacy devices that operate on the GSM standard. This ensures a smooth transition for existing devices and services. EC-GSM is optimized for low-power operation, making it suitable for IoT devices that need to operate on batteries for extended periods. The technology allows devices to have long battery life, reducing the maintenance and replacement costs. EC-GSM gained widespread adoption during its time, which means that it was available in many regions and had existing infrastructure support, making it easier for IoT devices to connect in those areas.

EC-GSM data rates might not be ideal for high-bandwidth applications, but, it is perfectly sufficient for many IoT use cases that require periodic data transmission, such as environmental monitoring or utility metering. EC-GSM improves indoor coverage, which is beneficial for IoT applications deployed within buildings, underground facilities, or other locations where radio signals may struggle to penetrate. EC-GSM leveraged from the existing standards and helped extend the reach of cellular connectivity for IoT

devices worldwide. EC-GSM plays a crucial role in paving the way for cellular IoT connectivity and serve its purpose where other forms of cellular IoT are not available.

3.3 LTE-M

LTE-M is a cellular technology designed specifically for higher data rates in IoT applications. LTE-M is part of the 3GPP's Release 13 and beyond, which defines a set of cellular IoT technologies. It operates in licensed spectrum bands and leverages existing LTE infrastructure, allowing for efficient and cost-effective deployment. LTE-M is an LPWA technology, optimized for IoT devices that require extended coverage, long battery life, and moderate to high data rates. It supports both half-duplex and full-duplex communication modes, allowing devices to transmit and receive data efficiently. LTE-M offers data rates up to 5 Mbps in the downlink and up to 1 Mbps in the uplink, which is ideal for applications requiring higher bandwidth than traditional LPWA technologies like NB-IoT. Of course the data rate enhancement provisions have been added in the subsequent releases of 3GPP LTE. One of the key advantages of LTE-M is its enhanced mobility support, making it suitable for applications involving moving IoT devices, such as asset tracking and logistics.

It provides better penetration through buildings and other obstacles, offering improved indoor coverage compared to regular LTE. LTE-M supports voice over LTE (VoLTE) and other real-time services, allowing for more diverse IoT use cases, including voice-enabled applications. It offers extended battery life for IoT devices, allowing them to operate for several years on a single battery charge, depending on the usage patterns. LTE-M enables firmware updates and over-the-air software upgrades, making it easier to maintain and manage large-scale IoT deployments. Security is a fundamental aspect of LTE-M, with features like end-to-end encryption and authentication ensuring the integrity and confidentiality of data transmitted over the network. LTE-M has found applications in various industries, including asset tracking, smart meters, smart cities,

agriculture, healthcare, and industrial monitoring, among others. Overall, LTE-M addresses the requirements of a broad range of IoT use cases, combining the advantages of cellular networks with low-power operation and extended coverage. It provides a compelling solution for IoT applications that need higher data rates and mobility support while still benefiting from the efficiency and reliability of cellular connectivity.

LTE-M offers several significant advantages that make it a compelling choice for various IoT applications. LTE-M provides greater coverage and range compared to traditional cellular technologies, making it suitable for IoT devices deployed in remote or hard-to-reach areas. It enables connectivity in locations where regular cellular signals might struggle to reach. LTE-M is designed to be highly energy-efficient, optimizing battery life for IoT devices. This efficiency allows IoT devices to operate for extended periods on a single battery charge, reducing maintenance and operational costs. LTE-M utilizes existing LTE infrastructure, which means that the investment in network deployment is less extensive compared to deploying entirely new networks. This cost-effectiveness makes it an attractive option for large-scale IoT deployments.

LTE-M offers higher data rates compared to some other LPWA technologies like LoRa, Sigfox, NB-IoT and EC-GSM. This higher bandwidth allows for applications that require more data-intensive communications, such as firmware updates, real-time sensor data streaming, and VoLTE services. LTE-M provides improved mobility support, enabling applications with moving IoT devices. This makes it suitable for use cases like asset tracking, vehicle telematics, and logistics. LTE-M exhibits better penetration through buildings and obstacles, resulting in improved indoor coverage. This capability is essential for IoT devices deployed within structures where cellular signals may be attenuated. LTE-M supports QoS mechanisms, allowing network operators to prioritize traffic and ensure that critical IoT data is given preferential treatment. LTE-M inherits the robust security features of LTE, including authentication and encryption, ensuring that data transmitted over the network remains secure and confidential. As a part of the 3GPP standard, LTE-M is a globally accepted and standardized technology. This standardization ensures interoperability and makes it easier for manufacturers and developers to create devices and applications that can work worldwide. LTE-M is part of the evolving LTE ecosystem, which means it will continue to benefit from ongoing advancements in cellular technology. As LTE networks evolve, LTE-M devices will be able to take advantage of these improvements without requiring significant changes.

LTE-M's unique combination of power efficiency, extended coverage, and moderate data rates has propelled it to the forefront of industrial adoption. This versatile technology empowers a vast array of IoT applications across diverse sectors like asset tracking, smart metering, industrial automation, smart cities, healthcare, and agriculture.

3.3 RedCap

5G RedCap, is a feature of 5G technology designed to support a wide range of IoT devices that require lower complexity, reduced power consumption, and cost efficiency. Unlike traditional 5G, which focuses on high-speed data and low latency for applications like video streaming and gaming, RedCap targets devices such as wearables, smart meters, and industrial sensors. It offers a balanced compromise between performance and efficiency, enabling these devices to leverage 5G networks without the need for extensive resources. This makes 5G RedCap ideal for massive IoT deployments and enhances the scalability of connected solutions. Since its arrival in 3GPP Release 17, RedCap has found several popular use cases across sectors [5]. In Release 17, several performance parameters of RedCap have been enhanced to accommodate new use cases. 5G RedCap is aimed at supporting a diverse range of IoT devices with moderate data requirements. It is specifically designed to balance performance and efficiency, making it ideal for applications where high speed and bandwidth are unnecessary. RedCap has all the main key features of 5G at a reduced level as shown in Figure 3. Key features of 5G RedCap have been presented below.

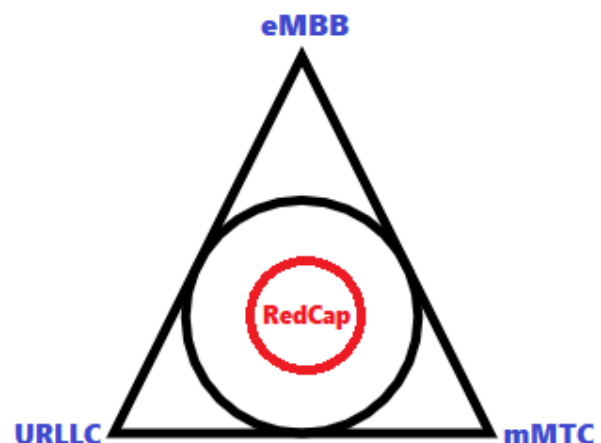


Figure 3. RedCap IoT having the hybrid (i.e., hybrid of eMBB, mMTC and URLLC) and reduced capabilities of 5G, making it suitable for large scale IoT applications across many sectors.

RedCap devices feature a simplified design compared to traditional 5G devices, which results in lower costs. This makes it feasible for manufacturers to produce a broader array of affordable IoT solutions. The architecture of RedCap is optimized to consume less power, extending battery life for devices such as wearables, smart meters, and industrial sensors. This feature is crucial for applications requiring long-term deployments without frequent maintenance. By utilizing narrower bandwidth and supporting lower data rates, RedCap ensures efficient spectrum usage, making it suitable for massive IoT deployments that require connectivity for numerous devices simultaneously. RedCap is designed to integrate smoothly with existing 5G networks, allowing for

backward compatibility with LTE-M and NB-IoT standards, thus providing a unified platform for diverse IoT applications. The RedCap technology supports various deployment scenarios, including private networks, public networks, and hybrid setups, offering adaptability to meet the unique needs of different industries. In Table 1, we have compared the key performance parameters of NB-IoT, LTE-M and RedCap.

Table 1. Comparison among NB-IoT, LTE-M and RedCap

Parameters	NB-IoT	LTE-M	RedCap
Bit Rate	Up to 250 Kb/s	1 – 5 Mb/s	Up to 150 Mb/s
Bandwidth	~ 200 KHz	Up to 5 MHz	~ 20/100 MHz
No. of Antennas*	1	1	1 or 2
Sensitivity	-164 dBm	-156 dBm	-145 dBm
Modulation*	BPSK	Up to 16 QAM	Up to 64 QAM
Range*	~50 Km	~10 Km	~8 Km

* These are the normal values are under typical scenarios.

5G RedCap is mainly used in applications that require moderate data rates and efficient resource use. Its key applications include wearable devices such as fitness trackers and smartwatches, smart sensors for industrial automation, smart meters for utilities, and connected healthcare devices for remote monitoring. RedCap is also used in smart cities for traffic management and environmental monitoring, as well as asset tracking in logistics. Its balance of cost-efficiency and performance makes it ideal for widespread IoT deployments in the 5G era.

4. Standardisation of Cellular IoT

NB-IoT, EC-GSM, LTE-M, and RedCap are standardized technologies. They have been designed for mMTC applications over the LTE and 5G based cellular networks [48]. In fact, they were evolved from the LTE for machine type communication (LTE-Cat1). In LTE Release 12, LTE-Cat1 was proposed for long range applications of LTE in the IoT related applications. Several problems were found in the LTE-Cat1 framework such the bandwidth allocation and resource sharing. In Release 12, LTE-Cat1 was designed for high data rates which are normally not useful in majority of the mMTC cases. Bandwidth for LTE-Cat1 was provided from within the cellular bands. It was directly interfering with the cellular services during the peak hours. Also, the non-3GPP standards such as LoRa and SigFox performed better than LTE-Cat1 in several LPWA applications. Therefore in Release 13, NB-IoT, EC-GSM and LTE-M were proposed as the new cellular solutions for mMTC for long range communications. EC-GSM was also proposed as an alternative of LTE-Cat1 for the IoT related application in the cellular framework. However, NB-IoT was preferred due to its low bandwidth, easy deployment, lower costs, and low power requirements [41]. The LPWA features of NB-IoT were introduced in Release 13. Some of the adaptive features of NB-IoT were enhanced in Release 14 [5]. In Release 15 and

Release 16 also a few enhancements have been done to improve the performances of NB-IoT and LTE-M. In Release 17, several provisions for the integration into non-terrestrial networks have been added.

In Release 13, all the main operational standards of NB-IoT, EC-GSM and LTE-M were framed. These standards were very much different from the provisions of LTE-Cat1 (in Release 12). Of course, in Release 13, LTE-M inherited the main features of LTE-Cat1 and also a lot of changes were brought in. The three mMTC solutions developed in the LTE framework were made competitive for the long term mMTC applications. Both EC-GSM and NB-IoT are designed for large coverage. But, in practice, NB-IoT has several advantages over EC-GSM in the LPWA applications. The coverage area of each node in NB-IoT is tremendously large and matches the coverage ranges of EC-GSM. However, the threshold power levels at the end devices are the same for both. In terms of power, its sensitivity is -164 dBm, meaning the power difference between the NB-IoT node and the end sensors can be as large as 144 dB [41]. Both the EC-GSM and NB-IoT are provisioned with long battery lives. Energy efficiency was improved using suitable duty cycles in which the sleep period is long when the end nodes and devices are not in active operation. EC-GSM normally deals with higher output power than NB-IoT. Therefore, EC-GSM uses larger power transmitters (i.e., up to 33 dBm) than NB-IoT [48]. For NB-IoT two power levels have been specified: 20 dBm, and 23 dBm [10]. In the optimized conditions, NB-IoT and EC-GSM battery lives outperform LTE-M battery lives. The bandwidth allocated for NB-IoT channel is just 200 kHz and out of this only 180 kHz is used for data transmission. The data rates for NB-IoT vary between 150 kbps to 250 kbps. In the large coverage area, it is limited to 150 kbps. However, when a high data rate is needed it can be enhanced to 250 kbps. In case of EC-GSM, the bandwidth allocated per channel is 200 kHz, but the typical data rates are 60 kbps and 70 kbps. The modulation techniques used in NB-IoT are: binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK). Normally BPSK is used in the majority of the cases. QPSK is proffered when there is a demand for higher data rates. Gaussian minimum shift keying (GMSK) is the most popular modulation scheme in EC-GSM. In case of EC-GSM the modulation technique has a higher spectral efficiency. In addition to GMSK, it can also use QPSK and 8-PSK modulation technique which provides it to communicate with higher data rates. However, these data rates are very rarely used in EC-GSM because these modulation schemes make the transceivers complex. LTE-M uses higher data rates (normally in the range of 1 Mbps to 5 Mbps) and higher bandwidths (normally in the range of 1 MHz to 5 MHz) [48]. The downlink packet sizes are same for all these three cellular IoT and it is 65 bytes long. However, two different uplink packet sizes (50 bytes and 200 bytes) have been specified for the NB-IoT, EC-GSM, and LTE-M in Release 13 [48]. In terms of latency, EC-GSM is slightly better than NB-IoT as it uses higher power levels. Also its higher spectral efficiency and higher data rates help in reducing the latency. According to Release 13, NB-IoT can be deployed in three different ways

[41]. More about these issues have been presented in the next section. NB-IoT and EC-GSM were designed for half-duplex communications in both the up and downlinks. However, in Release 14, they were enhanced for full-duplex and higher data rate communications. These enhancements are utilized in some specific applications.

In Release 14 and Release 15, several operational parameters and specifications were revised for NB-IoT and LTE-M to enhance their performances. In Release 14, new multicasting facilities were introduced for NB-IoT. Device mobility and peak data rates were enhanced to make it suitable for several complex applications. New carriers and frequency bands were allocated for NB-IoT. Location and positioning protocol (LPP) was introduced in NB-IoT in Release 14 to improve the location and tracking applications. LPP supports new positioning techniques which can be shared with other localization methods and then further improved using the locations of the NB-IoT nodes [17]. In Release 15, some for the compatibility issues of NB-IoT with the 5G new radio were introduced. In 5G, the LPWA technologies are going to play important roles. NB-IoT and LTE-M were enhanced for time division duplex and better connectivity with the new radio provisions for 5G and beyond 5G application scenarios [47].

RedCap was standardized in 3GPP Release 17, which introduced specifications to enhance 5G's capability for IoT applications. This standardization ensures interoperability and consistency across devices and networks, focusing on reduced complexity, lower power consumption, and efficient spectrum utilization. By defining the technical framework,

3GPP enables manufacturers and network operators to deploy RedCap solutions globally, supporting various IoT use cases with uniform performance standards.

5. Deployment of Cellular IoT

There are several issues in the practical deployment of cellular IoT. First of all, they are deployed over the cellular infrastructure. However, the bandwidth through which the cellular IoT services have to be provided is determined by the cellular operators [41]. Based on their choice, three different types of deployments are possible as shown in Figure 3. However, in case of the urban scenarios, a more complex hybrid deployment is preferred where a lot of users subscribe for the cellular IoT services. Similarly, the edge computing facilities and appropriate sensor and actuator deployments are important for the overall effectiveness of the cellular IoT performances [43].

5.1 Deployment Bands of NB-IoT, EC-GSM and LTE-M

NB-IoT can be deployed in different forms. In terms of the bandwidth, it can be deployed in three different ways: standalone deployment, guard band deployment, and in-band deployment [10]. In the standalone deployment, the NB-IoT bands are normally not used by the LTE networks. Rather a dedicated band is provided for this type of deployment. Normally standalone deployments are preferred in the areas

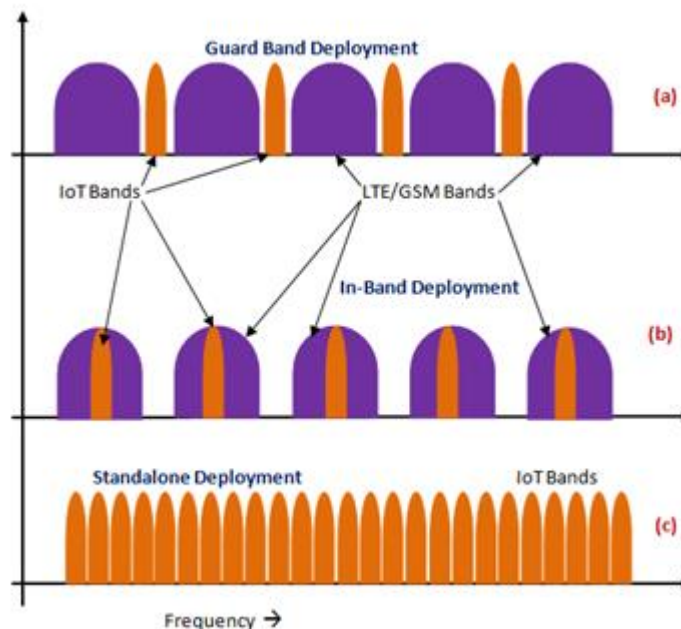


Figure 4. Different types of bandwidth deployment of NB-IoT [in (a) guard band deployment, (b) in-band deployment, and (c) standalone deployment are shown]. EC-GSM can also be deployed just like the NB-IoT in three different options shown in (a), (b) and (c), but (b) is the typically preferred option. LTE-M can only be deployed in option (b) due to its higher bandwidth requirements.

where there is no LTE coverage is available or the LTE bands remain occupied most of the time [1]. In the guard band deployment scheme, the guard bands of the LTE

MTS GSM are allocated for the NB-IoT deployment. It is an efficient use of the spectrum as the guard bands in these networks remain unused. In the recent survey of Grand View Research, more than 70% of deployments of NB-IoT were in the guard bands. This trend is expected to remain as the top priority in the coming years according to Grand View Research. In the in-band deployment, the NB-IoT bands are part of the allocated LTE bands. Normally when the LTE bands are not in use, they are provided for the NB-IoT services [1]. Whenever the LTE bands are back in use, the NB-IoT services are shifted from that band to another LTE band which is not in use. This is done using frequency hopping mechanisms [1]. All these deployment schemes have been depicted in Figure 3. In addition to the above, the hybrid deployment schemes are also possible in which more than one of the above schemes can be used. Normally for the in-band deployment, during the peak times, we see all the LTE bands remain completely occupied by the LTE users. Therefore, there needs to be an alternative band for the NB-IoT services. It is possible if hybrid arrangements are placed instead of just the in-band scheme. In fact, most of the in-band deployments are now shifted towards the hybrid deployments [1]. EC-GSM can also be deployed in the three different ways just like the NB-IoT. However, it is optimized for in-band deployment, and thus option (b) in Figure 3 is the preferred option for EC-GSM. LTE-M uses higher bandwidth than the other two cellular IoTs. So it cannot be deployed in guard bands and the standalone options are also not popular for it. So, LTE-M is also deployed in the LTE bands the in-band option as shown in Figure 3.

In the hybrid deployments, two or more of the above mentioned schemes are utilized. Normally, hybrid deployments are essential for the multiple service-providing NB-IoT networks [1]. Real-time applications also demand the hybrid deployments. Any disruption or obstruction in the services may result in big losses. Therefore hybrid deployment is essential to avoid such unwanted incidents. It is noteworthy that hybrid deployments are more expensive than the simple one-type of deployment [1]. They are also more complex and demand more resources than the simple one-type deployment. For high priority services such as mission critical applications and real-time critical applications, hybrid deployments are preferable. In almost all the hybrid deployments guard band usage is common.

RedCap can be deployed in various frequency bands designed to optimize performance and efficiency. These bands include Sub-6 GHz frequency Range 1 (R1) bands such as n5, n7, n8, n12, n13, n14, n15, n16, n17, n18, n19, n20, n21, n22, n23, n24, n25, n26, n27, n28, n29, n30, n31, n32, n33, n34, n35, n36, n37, n38, n39, n40, n41, n42, n43, n44, n45, n46, n47, n48, n49, n50, n51, n52, n53, n54, n55, n56, n57, n58, n59, n60, n61, n62, n63, n64, n65, n66, n67, n68, n69, n70, n71, n72, n73, n74, n75, n76, n77, n78, n79, n80, n81, n82, n83, n84, n85, n86, n87, n88, n89, n90, n91, n92, n93, n94, n95, n96, n97, n98, n99, n100, n101, n102, n103, n104, n105, n106, n107, n108, n109, n110, n111, n112, n113, n114, n115, n116, n117, n118, n119, n120, n121, n122, n123, n124, n125, n126, n127, n128, n129, n130, n131, n132, n133, n134, n135, n136, n137, n138, n139, n140, n141, n142, n143, n144, n145, n146, n147, n148, n149, n150, n151, n152, n153, n154, n155, n156, n157, n158, n159, n160, n161, n162, n163, n164, n165, n166, n167, n168, n169, n170, n171, n172, n173, n174, n175, n176, n177, n178, n179, 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different network environments. Currently, R1 provides bandwidth up to 100 MHz, and R2 provides up to 100 MHz for the RedCap applications.

5.2 Large Scale Deployment and Edge Computing

LPWA features of cellular IoT make it a primary choice for the large scale deployment over a large area. In such large scale deployments there are several challenges such as long latency, delay in decision making, poor control over the remote nodes, and poor resource allocation [15]. In such cases local control and better resource sharing mechanism are essential for better quality of service. Edge computing is essential for the large scale deployment of cellular IoT. In the large projects, the central control of the sensors and actuators become very much complex. Therefore, the decentralization of the control and management related functions are essential. Edge computing infrastructure provides these decentralized facilities [41]. When the cellular IoT network is stretched beyond a certain limit the edge computing facilities are needed to keep the performances intact. Edge facilities provide all the common control and management related support to the edge nodes which are normally far away from the central facilities. Small scale cloud support can also be provided to the edge facilities if they deal with significantly large amount of data. Such edge facilities are known as fog computing centers. For large networks, network slicing and other softwarized services are needed to make the operations smoother [16]. This is normally not simple without edge or fog computing. Thus SDN approaches are preferred using the edge computing facilities [15]. For large scale projects such as smart cities or smart grids these edge facilities are essential.

6. Potentials of Cellular IoT

Cellular IoTs have strong potentials for several practical applications [14]. Especially, in the long range and low power regime NB-IoT and EC-GSM are the best choices in the wider scope of the connected living paradigm. Their LPWA features are the main attractions for their business potentials. As we have seen in the previous sections, NB-IoT has excellent sensitivities. The bandwidth needed for its operations is just 180 KHz and the data rate needed is 150 Kbps [47]. Its data rate can be increased by using spectrally efficient modulation schemes. Its low power requirements make it the primary choice for the safe digital ecosystem. Therefore, it is preferred over other forms of IoTs for healthcare, smart homes, pet tracking and parking. In addition to that its LPWA features make it suitable for smart cities and smart grids [25]. EC-GSM too is a very low resource consuming IoT. However, its data rates can be scaled up to 355 kbps. The lower costs make NB-IoT and EC-GSM the premier choices in the developing countries. Both these IoTs are essential for the widespread digital transformation of developing countries. They can provide the expected digitalization goals in the industries, retail management, and

logistics. The low energy consumption makes them green technology. They are preferred in all the green applications. Overall, they are the front runners in many applications. However, LTE-M and RedCap are preferred where a higher data rate is needed. These high data rate IoT can transfer audio files, pictures, frames, and videos unlike NB-IoT and EC-GSM.

Artificial intelligence (AI) is widely used to enhance the performances of the engineering systems. It optimizes the system performances and reduces the costs. It has scopes for NB-IoT as well. Using AI several new and advanced services can be included in the broad cellular IoT domain. Machine learning (ML) is used for the improvement of the operations. It has the ability to provide optimized outcomes. Using ML several optimal outcomes are possible in IoT [8]. Cellular IoT is a suitable tool to make the systems intelligent using the advanced algorithms based on AI and ML. Many such smart systems such as smart classrooms and IoT based smart grids are popular in different application sectors [19]. Cellular IoT is equally supportive in such intelligent applications. Many of such applications have been presented in some of the recent works which show the tremendous potentials of cellular IoT [2, 47].

Several new frontiers of cellular IoT emerge in the recent years. For instance, the satellite based cellular IoT applications for large scale surveillance and monitoring are new and their demands are high. Satellite based cellular IoT applications have several advantages over the existing satellite based applications [21, 39]. Similarly, under-water applications of cellular IoT to measure and monitor the ocean surface ecosystem is very new. It opens up new frontiers for

the ecosystem monitoring. Applications of cellular IoT in the mining and other difficult terrains find popularity due to the LPWA and high longevity of the systems. Cellular IoT can also be deployed faster and comparatively with less difficulty in these environments. Every year several new applications are found and the real potential of cellular IoT is explored with these new services.

7. Use Cases of Cellular IoT

There are several applications of cellular IoT. Every year, we find new applications of cellular IoT emerge in different fields. In the LPWA domain, it is considered as a prime choice. The low power regime of cellular IoTs make them suitable choice for the connected living applications. In this section, we show a list of applications of cellular IoT in which it is one of the prime choices. In Figure 5, we show the main list of applications of cellular IoT in recent years. However, there are many more applications of cellular IoT than what are shown in Figure 5.

Large-scale smart city initiatives require a dense network of sensors and actuators, extending beyond the core urban center to encompass surrounding areas. These projects demand significant power and complex infrastructure. Cellular IoT technologies like NB-IoT, RedCap, LTE-M and EC-GSM offer ideal solutions by providing ubiquitous network coverage without the high cost of deploying entirely new infrastructure. By leveraging these technologies, smart city initiatives can achieve large-scale deployments with reduced energy consumption and bandwidth requirements [19, 45, 47]. Cellular IoT networks offer a plug-and-play approach to smart city deployments. Compared to complex deployments

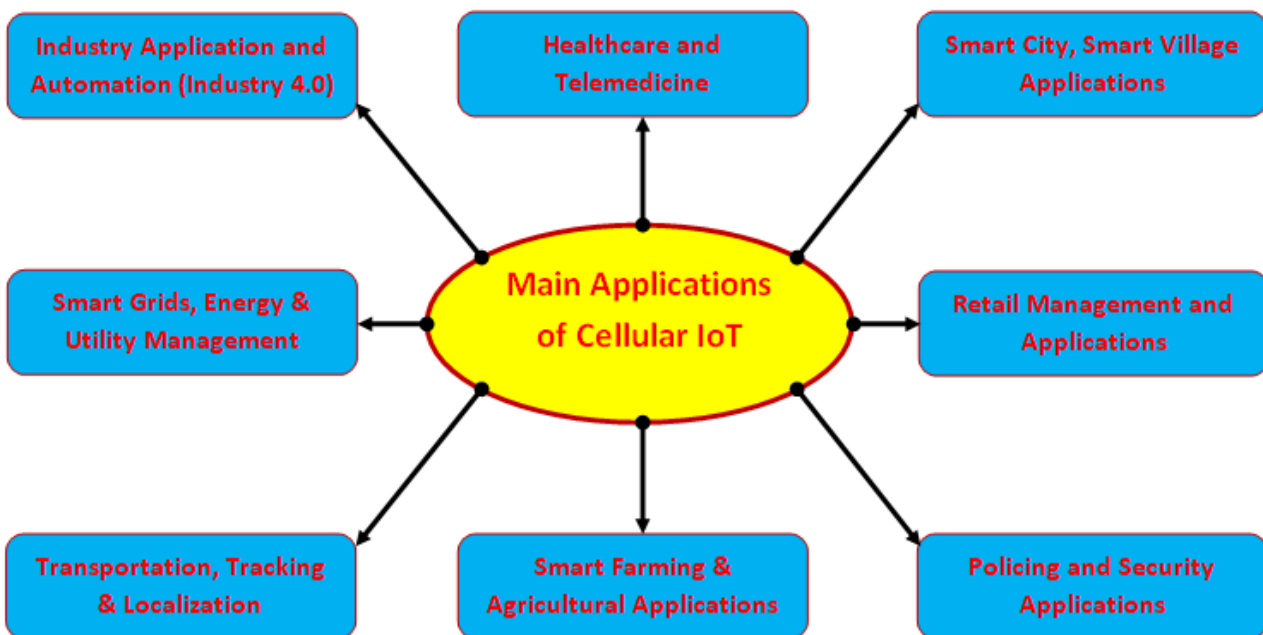


Figure 5. Some of the typical applications of cellular IoT.

of other IoT networks, cellular IoT offers a refreshingly simple solution for smart cities.

The vast healthcare sector, serving individuals across all demographics, increasingly relies on low-power sensors for patient monitoring and condition management. Remote health monitoring and pre-hospital care, often delivered outside traditional hospital settings, demand efficient solutions. Cellular IoT technologies, with their low-power consumption and cost-effectiveness, are ideally suited to address these needs [2]. In emergency healthcare, continuous monitoring is essential, and the use of sensors and actuators should not present any unwanted effects on the patients. In such situation, NB-IoT is the right solution which does not have adverse effects on the patients [11].

Digital transformation and industrialization need large scale IoT deployment. Cellular IoTs are potential solutions for the widespread digital transformation [19]. This can drive the industrial digital transformation forward. In the developing countries, cellular IoTs are the main choices due to their cost effective solutions. Cellular IoT can improve the resource and utilities management such as water, electricity and gas distributions in the cities and villages [25]. Leakage and wastage can be minimized using appropriate sensors and alarm systems. In agriculture, NB-IoT is preferred for its fast deployment and LPWA features. It can help the farmers in the monitoring and management of the crops [34].

In transportation, cellular IoT plays a significant role in tracking and localization tasks. Logistics and supply chain operations require extensive sensing and information exchange. Due to the high volume of these tasks, an economical IoT solution is essential for cost-effective operations. Cellular IoT offers reliability comparable to other cellular services and non-cellular IoT alternatives. Recently, there has been an increased demand for improved accuracy in tracking and localization. By leveraging multiple sensors, cellular IoT can provide more precise tracking and localization than existing methods [17]. The sensors can localize and track in the areas where the cellular networks do not provide good accuracies. Thus cellular IoT provides added advantages in these applications.

In the retail industries, cellular IoTs can help in the rack and inventory management. It can provide the information on time so that the retail space can be managed properly. It is estimated that the use of NB-IoT would improve the inventory management in retail sector to the extent of 40% which is certainly significant. Similarly, parking in the cities and other public places can be managed using NB-IoT [14]. It has already become popular in many cities now. Policing and surveillance related applications are very much popular in the cellular IoT application domain [32].

Smart grids are essential in the modern context due to the major short-comings of the conventional grids. These smart grids need a lot of support functions which are not common in the traditional grids. For the smart city operations, smart

grids are essential. Smart grids are large networks and their control, operation, and monitoring needs the support of IoT. In addition to that smart metering functions can also be carried out using NB-IoT and RedCap. Due to the LPWA nature, cellular IoTs fit well in the smart grid applications such as the remote measurement, control and large scale monitoring of the smart grid parameters [25]. Extension of the cellular IoT related applications is possible using hybrid systems such as the satellite integration [39]. Satellite based cellular IoT systems cover a large area and provide better network availability, reliability, and flexibility [39]. Satellite based cellular IoT systems are good for monitoring large scale projects and to provide multi-layer support [27]. In agriculture, healthcare, smart cities, smart grids, military applications, and in several other areas these systems get high demands [21]. These satellite based services will get better in the 5G and beyond 5G frameworks. In beyond 5G and 6G, each cluster head of the cellular IoT networks are expected to be connected with the satellites [47]. Of course that is going to common when 6G is expected to be rolled out commercially in the 2030s. However, recent developments in satellite integration and non-terrestrial communications have paved the way for these applications in the 5G framework [27].

Every year, we find new applications of cellular IoT get added to the existing pool of applications. From these viewpoints, it is clear that cellular IoT will have new applications in the emerging fields of science and engineering. In the previous section, we have shown the potentials of cellular IoT in the emerging areas such as satellite conjugation, under water monitoring and difficult terrains. These applications will further get enhanced with the new standards and requirements [25]. Non-cellular and cellular IoT both have entered into several critical applications in industries. Even, power electronics also gets better through IoT [25]. The edge computing facilities make cellular IoT a popular choice for large scale deployment. Edge computing servers can be spread around the main server and deployed at the proper locations where the data acquisition from the IoT nodes becomes efficient and flexible [41]. Edge servers can be connected with the main central servers through high data rate communication channels such as the optical fibers.

While considering the large pool of applications of cellular IoTs, it is noteworthy that there are some limitations as well. For instance, NB-IoT and EC-GSM use low data rates and thus they cannot send the high definition information which demands large data rates [41]. Similarly, its bandwidth is a natural limitation for higher data rates. Of course using quadrature amplitude modulation (QAM) and QPSK techniques the data rates are increased as per the provisions of Release 14 [14]. But still the scope is very limited. Large constellation QAM still has not been incorporated in the NB-IoT and EC-GSM standards. In addition to that, latency is comparatively high for the NB-IoT based systems. For low latency applications NB-IoT and EC-GSM are not the first choice. For critical low latency applications, broadband IoT

services such as LTE-M are preferred over NB-IoT and EC-GSM. Data compression is a basic need of cellular IoTs. However, the advanced data compression schemes cannot be implemented in their full form in cellular IoT nodes due to their small sizes. Those schemes may be implemented in their standard form in the edge computing facilities [36]. It is expected that some of the limitations of cellular IoTs will be removed in coming years.

8.1 Future Scope

Currently, cellular IoTs are popular LPWA technologies which have several applications in both the domestic and industrial environments. Their new applications emerge every year and they provide new smart services in almost all the domains. We expect many new applications of cellular IoT in the coming years. Both AI and ML are proposed to enhance the abilities of cellular IoT for new applications. Starting from the domestic applications to the large projects such as the smart cities there are a lot of new applications for cellular IoT. AI and ML have the capabilities to enhance the functions of cellular IoT in several frontiers. 5G and cellular IoT are very much compatible with each other. It is predicted that 5G in this decade and 6G in the 2030s will open the new frontiers for mMTC [47]. Cellular IoTs have great prospects in the future mMTC applications in the mobile cellular frameworks. Large projects like smart cities and smart grids will need the support of cellular IoT for their long term sustainability. Currently, several smart city and smart grid projects have already deployed cellular IoT for sensing, actuation, and communication functions. In the future, it will be further enhanced at a larger scale.

8. Conclusion

Cellular IoTs are energy-efficient forms of IoT that are as widespread as cellular networks. They offer large-scale compatibility with existing cellular infrastructure and are extremely resource-efficient, requiring only a small bandwidth. This makes them more economical than other forms of IoT and ideal for large-scale deployment in connected living applications. Their deployment is less complex compared to other IoT forms, and their LPWA features are particularly attractive for large-scale projects like smart cities, smart grids, agriculture, and healthcare. Cellular IoTs hold great potential for future applications across multiple sectors and are especially suitable for developing countries due to their cost-effectiveness. In the long term, they promise significant contributions to digital transformation and are pivotal tools for large-scale digital change in developing regions. Overall, cellular IoTs are sustainable technologies that provide long-term benefits for both humans and the environment.

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Conflict of Interest

The authors declare that they do not have any conflict of interest with regard to this paper.

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