STUDY PAPER ON

CELLULAR LOW POWER WIDE AREA TECHNOLOGIES

TELECOMMUNICATION ENGINEERING CENTRE
KHURSHID LAL BHAWAN, JANPATH
NEW DELHI - 110001 INDIA

MT Division, TEC

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Scope

This study paper focuses on the role and evolution of Low Power Wide Area (LPWA) technologies within the 3rd Generation Partnership Project (3GPP) ecosystem. It specifically examines four key technologies: Narrowband Internet of Things (NB-IoT), LTE-M (Long-Term Evolution for Machines), EC-GSM-IoT (Extended Coverage GSM IoT), and RedCap (Reduced Capability NR). These technologies, introduced across multiple 3GPP releases starting from Release 13, have been designed to address the connectivity needs of massive Machine-Type Communications (mMTC) — characterized by large numbers of low-cost, low-power IoT devices requiring extended coverage, long battery life, and efficient spectrum use.

The paper explores the standardization history, technical features, deployment modes, 5G compatibility, and evolving use cases of these LPWA technologies. It also provides a comparative analysis to support strategic planning for IoT deployments. Finally, it highlights the future direction of LPWA evolution under 5G and beyond, with emphasis on AI/ML integration, non-terrestrial networks (NTN), and policy frameworks shaping global adoption. The intent is to provide a technology-centric reference for stakeholders including regulators, service providers, equipment manufacturers, and researchers involved in the planning and adoption of 3GPP-based IoT solutions.

Abstract

The rapid growth of the machine-to-machine communication has led to an increasing demand for standardized, scalable, and efficient wireless communication technologies that support diverse use cases and deployment environments. The 3rd Generation Partnership Project (3GPP) has developed a suite of cellular IoT technologies—NB-IoT LTE-M, EC-GSM-IoT, and RedCap - to meet the unique requirements of massive Machine-Type Communications (mMTC) and other emerging IoT applications.

This study paper explores the evolution, technical foundations, and strategic importance of these technologies within the 3GPP ecosystem. Each technology is tailored to support specific use cases based on parameters such as power efficiency, coverage, data rate, mobility, and device complexity. NB-IoT and LTE-M were introduced in 3GPP Release 13 as part of the effort to address low-power wide-area (LPWA) connectivity. NB-IoT offers deep coverage, low power consumption, and cost-effective module design, making it ideal for stationary applications such as smart metering and environmental monitoring. LTE-M, on the other hand, provides higher data rates and support for mobility and voice services (e.g., VoLTE), making it suitable for asset tracking and wearables.

EC-GSM-IoT builds upon the existing GSM infrastructure and provides extended coverage and improved spectral efficiency for IoT applications in regions where GSM remains prevalent. It offers a migration path for operators with legacy 2G networks to support IoT without significant infrastructure changes. Although its adoption is more limited globally compared to NB-IoT and LTE-M, it plays a critical role in certain markets.

With the advent of 5G, 3GPP introduced RedCap in Release 17 to address the needs of mid-tier IoT devices that do not require the full capabilities of enhanced mobile broadband (eMBB) but still benefit from higher throughput, lower latency, and the advanced features of 5G NR. RedCap devices are characterized by reduced bandwidth, simplified hardware, and optimized power consumption, making them suitable for industrial sensors, surveillance cameras, and wearables that require moderate data rates and improved performance over legacy LPWA technologies.

The paper also presents a comparative analysis of these technologies in terms of deployment scenarios, spectral efficiency, battery life, cost, and standardization status. It highlights their complementarity rather than competition, with each technology addressing a distinct segment of the IoT landscape. Furthermore, the study examines their interoperability, evolution paths, and role in supporting the broader vision of a connected society under 5G and future 6G frameworks.

This paper aims to provide policymakers, industry stakeholders, network operators, and technology developers with an in-depth understanding of the capabilities and applications of NB-IoT, LTE-M, EC-GSM-IoT, and RedCap. By analyzing their technical characteristics and deployment experiences, the study facilitates informed decision-making for IoT strategy, spectrum planning, and long-term network evolution in alignment with the 3GPP roadmap.

Chapter: 1 Introduction

1.1 Background

The rapid proliferation of connected devices has accelerated the demand for scalable, energy-efficient, and cost-effective wireless communication solutions. Traditional cellular technologies like 3G and 4G LTE, while successful in delivering high-speed data for smartphones and broadband services, are often ill-suited for the requirements of Internet of Things (IoT) applications that transmit small, infrequent data packets and must operate in remote or signal-challenged environments.

Recognizing this gap, the 3rd Generation Partnership Project (3GPP) initiated efforts to standardize Low Power Wide Area (LPWA) communication technologies that could serve massive numbers of IoT devices efficiently within licensed spectrum. These efforts culminated in Release 13 (2016), which introduced the first wave of three cellular LPWA technologies: - NB-IoT (Narrowband IoT) and LTE-M (also referred to as eMTC) under the LTE system, and EC-GSM-IoT as an enhancement to legacy GSM networks. These technologies were designed to offer ultra-low power consumption, deep indoor and rural coverage, reduced device complexity, and optimized support for delay-tolerant, low-throughput communication—meeting the essential requirements outlined in 3GPP TR 45.820, TS 36.300 and related 36-series specifications.

These technologies enable a range of use cases across utilities, agriculture, healthcare, logistics, and smart cities — all of which require long battery life, low device costs, and robust signal performance, often in remote or underground locations.

NB-IoT and LTE-M have since continued to evolve in subsequent 3GPP releases, with enhancements such as power-saving improvements, multicast capabilities, and support for non-terrestrial networks (NTN) starting in Release 17 to further extend coverage in remote or underserved areas. EC-GSM-IoT, leveraging the widespread footprint of GSM networks, provides a backward-compatible LPWA option where LTE coverage may not be fully available.

As cellular networks evolve towards 5G New Radio (NR), LPWA technologies continue to play a pivotal role in supporting massive Machine-Type Communications (mMTC) — one of 5G's three core service categories, alongside enhanced Mobile Broadband (eMBB) and Ultra-Reliable Low-Latency Communications (URLLC). To complement existing LPWA solutions and address the requirements of mid-tier IoT applications—those needing moderate data rates and lower latency, 3GPP introduced RedCap (Reduced Capability NR) devices in Release 17 as specified in 3GPP TS 38.306 and TR 38.840. Although not formally classified as LPWA, RedCap bridges the gap between traditional LPWA technologies and full-featured 5G, offering reduced device complexity and power consumption with higher throughput.

Together, these technologies form the backbone of scalable, future-proof IoT connectivity, ensuring a smooth transition from 4G to 5G and beyond without compromising efficiency or reach.

1.2 Introduction

The IoT revolution is redefining connectivity by enabling billions of devices — from smart meters and wearables to industrial sensors — to connect and communicate efficiently. A central requirement for IoT growth is the availability of LPWA communication technologies that support small data transmissions over long distances, with extended battery life and minimal costs. These technologies must also offer robust coverage in diverse environments, including remote rural areas, deep indoor locations, and industrial zones. Furthermore, they must scale to support massive numbers of concurrently connected devices while ensuring reliability and security.

To address this, the 3GPP initiated a series of LPWA standards as part of its global cellular specifications. Starting in Release 13, 3GPP introduced three foundational technologies for IoT:

- Narrowband IoT (NB-IoT)
- LTE-M (also known as Cat-M1 or eMTC)
- EC-GSM-IoT, an enhancement of legacy GSM systems.

These technologies are designed to support the growing class of mMTC — one of the key service categories in both 4G LTE and 5G. Also, these are designed to operate within licensed spectrum, ensuring coexistence with traditional mobile services while leveraging existing cellular infrastructure for rapid and cost-effective deployment. Each technology was engineered with specific use cases in mind, targeting different performance, deployment, and migration needs.

In more recent releases, 3GPP introduced RedCap under 5G NR. While not a pure LPWA technology, RedCap enables lightweight 5G devices with reduced complexity, bridging the gap between LPWA and full-scale 5G applications. RedCap is intended to bridge the gap between traditional LPWA and high-speed 5G use cases by enabling lightweight 5G NR devices with reduced complexity.

This paper explores the evolution, features, and deployment landscape of NB-IoT, LTE-M, EC-GSM-IoT, and RedCap. It provides a detailed analysis of each technology's role, capabilities, 5G compatibility, and practical applications, as standardized across multiple 3GPP releases. The paper also discusses the comparative strengths and trade-offs of these technologies to assist in strategic deployment planning and system design.

Chapter 2: Narrowband IoT (NB-IoT)

NB-IoT, as defined by 3GPP, is a cellular-based low-power wide-area (LPWA) technology designed to enable wide deployment of IoT devices that need low data rates, long battery life, low device complexity, and robust coverage. It is a 3GPP-standardized LPWA technology, first introduced in Release 13, developed to address the specific requirements of massive-scale, low-bandwidth, and delay-tolerant IoT applications. Unlike traditional cellular technologies designed for high-throughput services, NB-IoT is purpose-built for devices that generate small, infrequent data packets, typically operate in coverage-constrained environments, and require ultra-long battery life with minimal maintenance.

Operating within a narrow 180 kHz bandwidth, NB-IoT facilitates deep indoor and rural penetration, achieving Maximum Coupling Loss (MCL) values up to 164 dB—surpassing the capabilities of legacy GSM systems. Its flexible deployment options including standalone mode (reusing GSM spectrum), in-band mode (within LTE carriers), and guard-band mode (using unused LTE guard bands)—enable operators to roll out NB-IoT cost-effectively without significant infrastructure changes.

Originally designed for static applications, NB-IoT has evolved to support connected and idle mode mobility beginning with Release 14, enhancing applicability for mobile sensors and trackers. Its seamless integration into 5G networks began with Release 15, which declared NB-IoT and LTE-M as part of the 5G standard and allowed NB-IoT devices to connect via the 5G Core (5GC). Later enhancements in Release 17 extended its applicability to Non-Terrestrial Networks (NTNs)—including LEO satellite-based connectivity—opening up use cases in remote sensing, agriculture, and disaster recovery.

As of Releases 16 through 18, NB-IoT continues to advance in terms of power efficiency, device simplicity, control signaling reduction, and multicast delivery capabilities. Release 16 focused on efficiency improvements (reduced signaling, enhanced multicast, improved coexistence with 5G spectrum), while Release 18 (2024–25) introduces multicast/broadcast enhancements, mobility upgrades, and coexistence optimization with RedCap. With these developments, NB-IoT remains a cornerstone of mMTC services in the 5G era, especially in countries like India where rural coverage, cost sensitivity, and spectrum reuse are critical.

Table 1: -Key Features by Release for NB-IoT

Feature	Description	Release
Bandwidth Efficiency	Operates on a narrow 180 kHz channel for efficient spectrum usage and coexistence with GSM/LTE networks	Release 13
Deployment Flexibility	Supports three modes—standalone (refarmed GSM), in-band (LTE), and guard-band (LTE unused gaps)	Release 13

Deep Coverage	Provides Maximum Coupling Loss (MCL) up to 164 dB, suitable for indoor, rural, and underground use	Release 13
Battery Life	Supports 10–15 years of battery operation through Power Saving Mode (PSM) and eDRX (Extended Discontinuous Reception)	Release 13
Mobility Support	Initially static (Rel-13); connected and idle mode mobility added in Rel-14 onward	Release 14–17
Positioning	Uses OTDOA (Observed Time Difference of Arrival) and E-CID (Enhanced Cell ID positioning) for location tracking and asset monitoring (with limited accuracy, in the order of hundreds of meters)	Release 14
5G Integration	Declared part of 5G standard and supported on 5G Core (5GC) since Release 15, ensuring backward compatibility and longevity	Release 15
Satellite Support (NTN)	Enabled in Release 17, allowing NB-IoT to function via LEO satellites in areas lacking terrestrial signal	Release 17
Future Enhancements	Release 18 adds multicast/broadcast features, mobility upgrades, and RedCap coexistence optimization	Release 18

Table 2:- Release-wise Evolution for NB-IoT

3GPP Release	Key Enhancements for NB-IoT
Release 13	Initial NB-IoT spec with basic LPWA capabilities.
Release 14	Added mobility, positioning, multicast.
Release 15	Integration into 5G system architecture.
Release 16	Power and coverage optimizations; NR coexistence.
Release 17	Extended device support, 5G core compatibility.
Release 18	Broadcast, RedCap optimization, mobility upgrades

2.1 NB-IoT Use Cases and Coexistence with 5G NR:-

NB-IoT is ideally suited for applications that require low-throughput, long-range, and energy-efficient connectivity, especially in environments where traditional cellular or Wi-Fi networks are impractical. Its design support static or low-mobility devices that operate for years on battery power, making it a key enabler for various IoT use cases across industries. There are many use cases of NB-IoT, few are detailed below:-

- In the utilities sector, NB-IoT is widely used for smart metering of gas, electricity, and water, enabling automated and remote data collection even from basements or rural installations.
- In agriculture, it connects soil moisture sensors, crop health monitors, and irrigation controllers, supporting precision farming and resource optimization.

- Building management systems leverage NB-IoT for HVAC controls, smoke alarms, and intrusion detection—where small data packets must be transmitted reliably over long periods.
- In urban infrastructure, the technology powers smart parking systems, waste bin level monitoring, and adaptive street lighting.
- Additionally, environmental monitoring applications, such as air quality sensors, flood alerts, and temperature/humidity tracking, benefit from NB-IoT's extended coverage and battery efficiency.

NB-IoT's compatibility with both existing and next-generation mobile network architectures ensures long-term deployment viability. From its inception in 3GPP Release 13, it has supported integration with the EPC of LTE networks. With Release 15, NB-IoT was formally included in the 5G Core architecture, ensuring interoperability with 5G Standalone (SA) (while coexisting with LTE/NR NSA networks, NB-IoT itself is not dependent on NSA operation). The technology also supports Non-IP Data Delivery (NIDD), which allows ultra-lightweight payloads to be sent efficiently without the need for IP-based protocol stacks. These features collectively make NB-IoT a highly scalable, interoperable, and future-ready solution for mMTC within the 5G ecosystem.

2.2 Modes of Operations of NB-IoT: -

NB-IoT supports three deployment modes that allow flexible integration into existing mobile network infrastructure:

I. **Standalone Mode:** In this mode, NB-IoT operates on re-farmed GSM spectrum, typically 200 kHz wide (channel spacing), and functions independently of LTE infrastructure. This makes it suitable for legacy 2G networks.

II. **In-band Mode:** NB-IoT is deployed within an LTE carrier's existing spectrum using a dedicated 180 kHz resource block. This mode enables shared infrastructure and efficient spectrum reuse with minimal impact on LTE performance.

III. **Guard-band Mode:** NB-IoT utilizes the unused guard bands between LTE carriers. This mode achieves minimal disruption to LTE services and enables efficient spectrum utilization. These deployment options offer adaptability for operators based on spectrum availability and network evolution strategy.

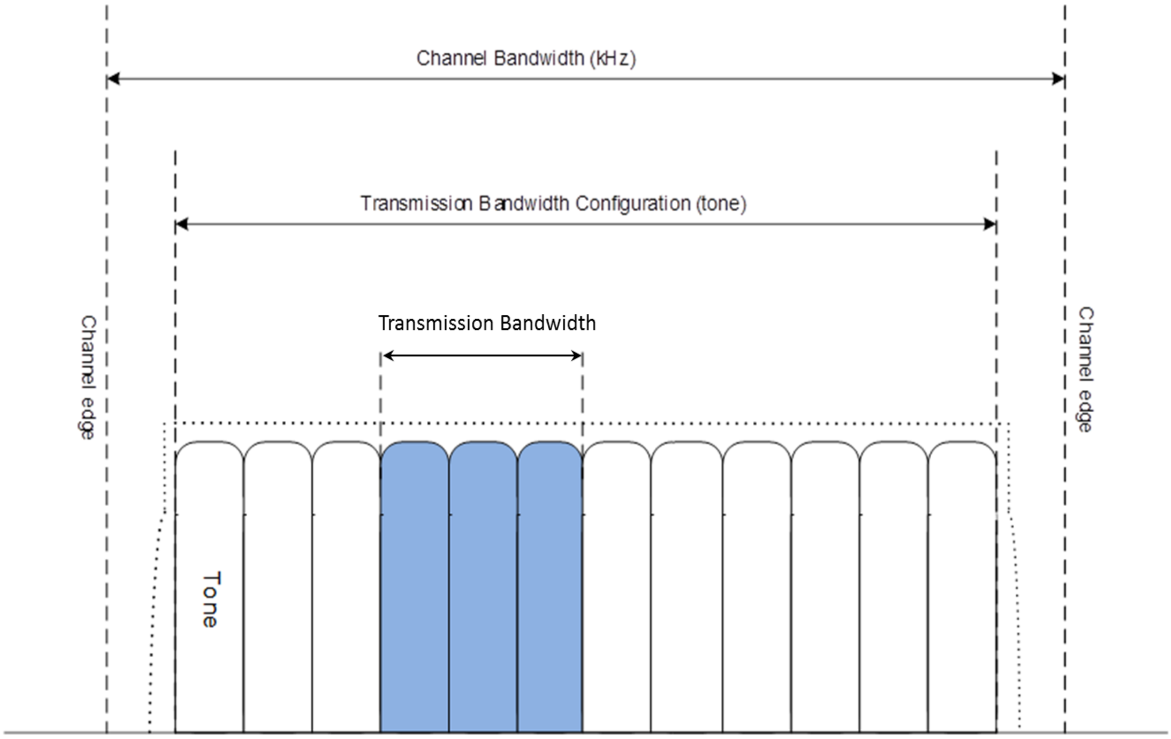

Figure 1:- Definition of Channel Bandwidth and Transmission Bandwidth Configuration for one NB-IoT carrier

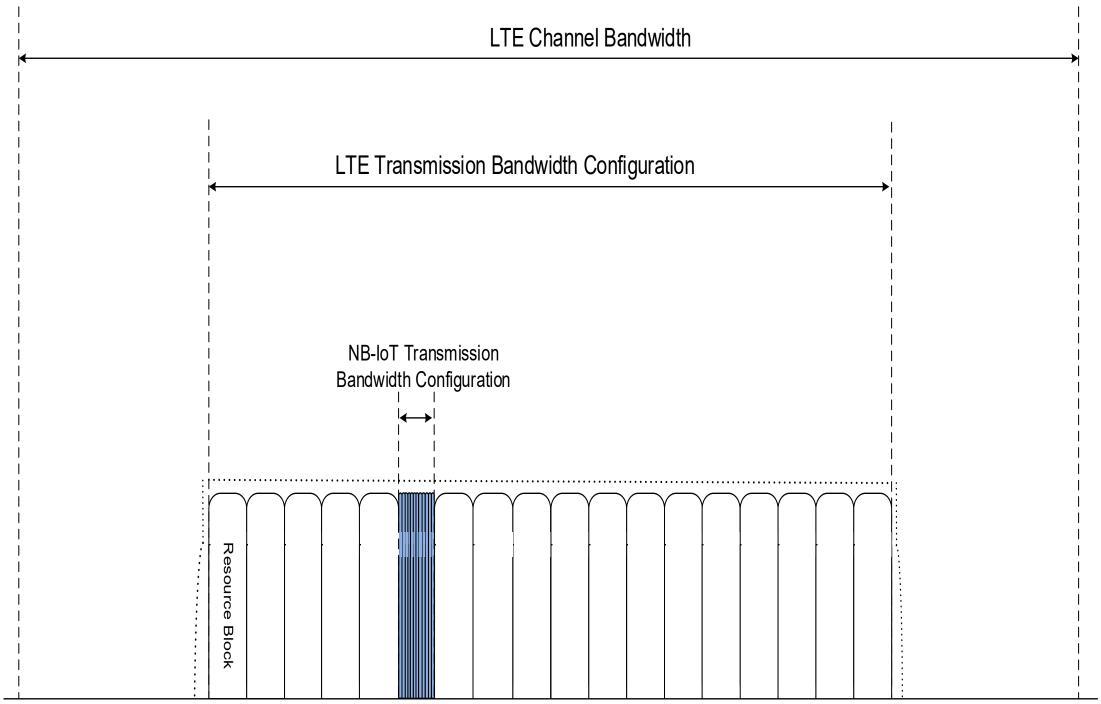

Figure 2:- Definition of Channel Bandwidth for LTE and NB-IoT Channel Bandwidth for NB-IoT In-band operation

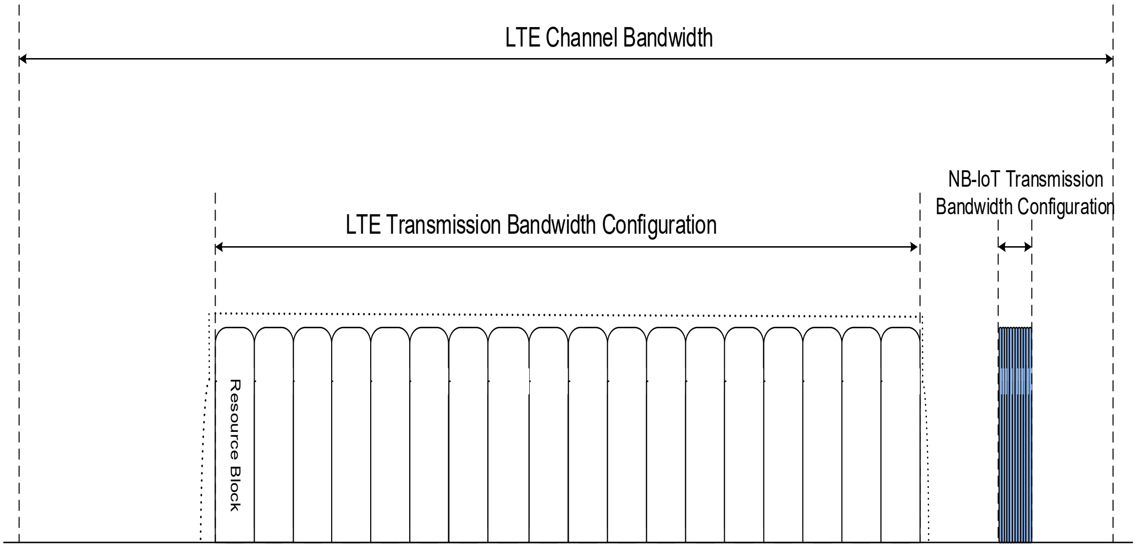

Figure 3:- Definition of Channel Bandwidth for LTE and NB-IoT Channel Bandwidth for NB-IoT in guard band operation

Specifically, in NB-IoT, the following features will be supported in all modes of operation:

- The user equipment (UE) will use a 180 kHz bandwidth for both downlink and uplink transmissions.
- The downlink will utilize OFDMA with 12 Subcarriers at 15 kHz subcarrier spacing (180KHz bandwidth) across all operating modes, supporting both normal and extended cyclic prefixes (CP).
- For the uplink:
    - Single-tone transmission will be enabled, with two numerologies configurable by the network: 3.75 kHz (48 subcarriers) and 15 kHz (12 subcarriers) subcarrier spacing. A cyclic prefix will be applied, and sinc pulse-shaping will be used in the frequency domain at the physical layer.
    - Multi-tone uplink transmission will also be supported using SC-FDMA with 15 kHz subcarrier spacing.
    - There is a work-in-progress regarding additional methods to reduce Peak-to-Average Power Ratio (PAPR).
    - The UE will be required to indicate its capability to support single-tone, multi-tone, or both modes—details to be finalized by 3GPP RAN working groups.
- An NB-IoT UE will only operate in half-duplex mode, meaning it can transmit and receive, but not simultaneously.
- A common synchronization signal design will be used across different operating modes, with mechanisms to manage potential overlap with legacy LTE signals.

2.3 Operating bands and channel arrangements for NB-IoT: -

NB-IoT is designed for deployment flexibility and can operate in numerous 3GPP-defined E-UTRA bands, including but not limited to Bands 1-5, 7-8, 11-14, 17- 21, 24-26, 28, 31, 41- 43, 48, 54, 65, 66, 70-74, 85, 87, 88, 103, and 106. NB-IOT is designed to operate in the frequency bands defined in Table 3

Table 3: -NB-IOT frequency bands

NB-IOT Operating Band	Uplink (UL) operating band BS receive UE transmit	Downlink (DL) operating band BS transmit UE receive	Duplex Mode
	F_{UL_low} – F_{UL_high}	F_{DL_low} – F_{DL_high}	
1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	HD-FDD
3	1710 MHz – 1785MHz	1805 MHz – 1880 MHz	HD-FDD
5	824 MHz – 849 MHz	869 MHz – 894MHz	HD-FDD
8	880 MHz – 915 MHz	925 MHz – 960 MHz	HD-FDD
12	699 MHz – 716 MHz	729 MHz – 746 MHz	HD-FDD
13	777 MHz – 787 MHz	746 MHz – 756 MHz	HD-FDD
17	704 MHz – 716 MHz	734 MHz – 746 MHz	HD-FDD
19	830 MHz – 845 MHz	875 MHz – 890 MHz	HD-FDD
20	832 MHz – 862 MHz	791 MHz – 821 MHz	HD-FDD
26	814 MHz – 849 MHz	859 MHz – 894 MHz	HD-FDD
28	703 MHz – 748 MHz	758 MHz – 803 MHz	HD-FDD

Channel edge arrangements, raster (100 kHz), and spacing rules ensure NB-IoT can coexist robustly with LTE and legacy systems in both contiguous and non-contiguous spectrum allocations. The requirements and arrangements are designed to guarantee flexible yet standardized NB-IoT deployments, efficient frequency planning, and reliable spectrum sharing across mobile, indoor, and IoT-specific environments.

Table 4: -Bandwidth support for three deployment modes of NB-IoT

Deployment Mode	Channel Bandwidth	Resource Block Configuration	Subcarrier Configuration	Channel Placement
Standalone	200 kHz	1 NB-IoT RB	12 × 15 kHz or 48 × 3.75 kHz	Dedicated/Narrowband (often replacing GSM)
In-band	≥1.4/3 MHz (LTE)	1 NB-IoT RB within LTE RB	12 × 15 kHz or 48 × 3.75 kHz	Within LTE carrier
Guard-band	≥3 MHz (LTE)	1 NB-IoT RB in guard band	12 × 15 kHz or 48 × 3.75 kHz	LTE guard band area

2.4 Requirements for NB-IoT: -

A. Base Station (BS)/E-UTRA Requirements

Transmitter Characteristics:-

The base station transmitter requirements are crucial to ensure proper signal quality and coexistence with existing cellular technologies. NB-IoT BS transmitters are expected to comply with strict power emission limits, including defined Adjacent Channel Leakage Ratio (ACLR) and spectral emission masks. These requirements differ slightly depending on the deployment mode—standalone, in-band, or guard-band—to mitigate the risk of interference to adjacent carriers.

In standalone deployments, the RF mask needs to meet either the GSM mask or the Multi-Standard Radio (MSR) spectral mask, depending on the operator configuration. For in-band and guard-band scenarios, additional requirements address coexistence with LTE carriers operating in adjacent frequency resources.

3GPP TS 36.104 defines key transmitter behaviour for base stations with respect to NB-IoT operation modes. It focuses on output power dynamics, specifying the minimum NB-IoT resource block (RB) power dynamic range to ensure robust signal separation and coverage when NB-IoT operates in in-band, guard band, or standalone modes.

For in-band and guard band operation, a minimum dynamic range of +6 dB must be achieved, except for 5 MHz guard band scenarios where the manufacturer must declare the supported range. It also sets requirements for transmitter ON/OFF behaviour: the mean power spectral density during the OFF state must be less than -85 dBm/MHz, and the transition time between ON and OFF states must not exceed 17 µs. These controls minimize interference and enable energy-efficient, prompt transitions needed for NB-IoT's IoT applications.

Table 5: - BS transmitter characteristics in NB-IoT

Parameter	NB-IoT Requirement
RB Power Dynamic Range	≥ +6 dB for in-band/guard band (except 5 MHz guard band, value declared by manufacturer)
Transmitter OFF Power	< -85 dBm/MHz spectral density during OFF period
Transmitter Transient Period	OFF↔ON transition time ≤ 17 µs
Applicability	All requirements apply for in-band, guard band, and standalone NB-IoT base station operations

For NB-IoT, specific power limits are set for emissions both at the band edge and beyond, and these requirements apply to in-band, guard band, and standalone operation modes. For NB-IoT, strict emission limits at and beyond the band edge for all three modes (standalone, in-band, guard-band) are defined. These ensure the NB-IoT transmitter will not interfere with adjacent frequencies or other services.

- The Operating Band Unwanted Emissions (sometimes called Spectrum Emission Mask, SEM) are defined from 10 MHz below the lowest downlink frequency of the operating band up to 10 MHz above the highest downlink frequency.
- Spurious emissions (outside those ranges) must comply from 9 kHz to 12.75 GHz with measurement bandwidths that change by frequency range. For instance, in Category A: from 9 kHz-150 kHz the limit is −13 dBm /1 kHz, in 150 kHz-30 MHz the limit is −13 dBm /10 kHz, etc. Category B limits are stricter (e.g. −36 dBm /1 kHz in 9 kHz-150 kHz).
- For protection of other base station receivers, there are very low out-of-band emission (spurious) limits. For example, for a Wide Area BS, emissions must be ≤ −96 dBm /100 kHz at frequencies inside its uplink/downlink band (when protecting another BS). For Local Area or Home BS, the limit is relaxed to around −88 dBm /100 kHz.

The emission thresholds ensure that NB-IoT transmitters do not interfere with neighboring frequencies, other communication systems, or services, complying with both global 3GPP technical standards and potentially stricter regional regulations. Detailed limits exist for each NB-IoT base station class and operational scenario, ensuring robust coexistence in shared spectrum environments

Table 6: - Emission Requirements for BS in NB-IoT

Emission Aspect	NB-IoT Requirement	Applicability	Notes
Out-of-Band Emission	Power limits at specific offsets from NB-IoT channel	All NB-IoT modes	Protects adjacent frequencies (in-band, guard band, standalone)
Spurious Emissions	Strict maximum power limits in remote bands	All NB-IoT modes	Includes harmonics and intermodulation products
Standalone Operation	Dedicated emission masks by station class and offset	Standalone NB-IoT BS	Wide Area, Local, Home, Medium class BS scenarios
Regional Requirements	Possible tighter limits or added protections	As set by regulators	Examples: safety, broadcast, satellite, TV protection
Multi-band Operation	Aggregate unwanted emission limits across bands	Multi-band BS	Cumulative out-of-band and spurious calculations

The table below summarizes the core unwanted emission criteria relevant for each base station class operating with NB-IoT: -

Table 7: - Emission Requirements for different class of BS in NB-IoT

Emission Aspect	Wide Area BS	Medium Range BS	Local Area BS	Home BS	Notes/Applicability
Out-of-Band Emission	Strict power limits at band edge & offsets	Limits vary with output power; cumulative for non-contiguous ops	Tighter limits; focus on local use	Most restrictive to prevent home interference	In-band, guard band, standalone
Spurious Emissions	≤-13dBm (Cat A, 1MHz BW), stricter for Cat B	Stricter (up to -25dBm/100kHz/1MHz)	Up to -32dBm/100kHz/1MHz	Up to -50dBm/100kHz/1MHz	9kHz–12.75GHz, all NB-IoT modes
Standalone Operation	Dedicated emission masks by frequency offset	Separate emission masks based on rated power	As per operation with close-in/remote offsets	Specific masks; strongest out-of-band suppression	By NB-IoT BS class & band
Regional Requirements	May require added filtering/tighter limits	As set locally/regionally	Dependent on local regulation	Dependent on local regulation	E.g., TV, satellite, safety services
Multi-band Operation	Cumulative unwanted emission limits	Aggregate PM for multi-band/gap	Cumulative for sub-block/inter-band gaps	Cumulative for multi-band BS	Applies when bands share hardware

Receiver Characteristics: -

For the NB-IoT Base Station receiver, 3GPP defines parameters such as reference sensitivity, adjacent channel selectivity (ACS), blocking, and intermodulation performance. These ensure the BS can reliably receive uplink NB-IoT signals even when there are strong interfering signals from adjacent bands or other RATs—important for achieving the high link budgets / extended coverage NB-IoT targets while coexisting with LTE/other services. Some key values (for Wide Area NB-IoT BS) are:

- **Reference Sensitivity (PREFSENS[1])**: This is the minimum received NB-IoT uplink signal power at which the BS must support a given error-rate/throughput. The exact value depends on subcarrier spacing, channel conditions etc., and is defined in TS 36.104.
- **Blocking Requirement**: For NB-IoT, wide area BS in in-band, guard band, or standalone modes, there is a requirement that the BS must maintain ≥ 95 % of reference

[1] PREFSENS : Preferred Sensitivity

throughput when there is an interfering signal of a specified power. For example, in in-band operation for wide area NB-IoT, the interfering signal can be at PREFSENS [2]+ 6 dB, while the interfering frequency offset and type are specified (e.g. CW or E-UTRA signal).

- **Adjacent Channel Selectivity (ACS) / Narrowband Intermodulation**: For NB-IoT wide area base stations, the adjacent channel selectivity (ACS) and intermodulation performance are specified with reference to the BS receiver sensitivity level. In all modes—standalone, guard-band, and in-band—the wanted signal is set at the reference sensitivity level plus 6 dB. Under these conditions, the interfering signal power is typically set to –52 dBm, placed at defined frequency offsets that correspond to adjacent channel positions. The BS must maintain at least 95 % of the reference throughput in the presence of these interferers. For intermodulation tests, two interfering signals are applied at specified frequency offsets, again with each interferer at –52 dBm, while the wanted NB-IoT signal remains at reference sensitivity plus 6 dB. The BS must continue to meet throughput requirements despite the combined effect of these intermodulation products. These requirements apply consistently across the three NB-IoT deployment modes, ensuring that the receiver maintains robustness against strong adjacent channel signals and nonlinear distortion, which is critical for dense spectrum environments where NB-IoT coexists with LTE and other RATs.
- **Intermodulation Performance**: Outside the BS RF bandwidth edges or sub-block gaps, NB-IoT wide area BS are required to meet intermodulation rejection limits. For example, for standalone NB-IoT, interfering signal levels of PREFSENS + 6 dB must still allow ≥ 95 % throughput under intermodulation conditions with interfering signals placed at given offsets.

B. Radio Resource Management (RRM) Requirements

NB-IoT supports simplified yet efficient RRM procedures aligned with LTE standards but optimized for narrowband operation. These include mechanisms for cell selection and reselection, measurement reporting, and mobility handling. The parameters are tuned to favor static or low-mobility scenarios typical of IoT deployments. This section ensures that NB-IoT devices can remain connected and switch cells effectively without excessive signaling, thus preserving battery life.

C. Performance Requirements

Performance requirements for NB-IoT are designed to achieve its core objectives of low power consumption, extended coverage, and reliable connectivity in challenging conditions. To support long battery life and operation in deep-indoor or remote areas, enhanced receiver sensitivity is combined with power-saving mechanisms such as Power Saving Mode (PSM) and Extended Discontinuous Reception (eDRX). The

[2] It is a reference minimum receiver sensitivity requirement defined for NB-IoT and LTE devices. In simple words, it's the weakest signal level (in dBm) that a UE (or BS receiver) must be able to detect and still meet performance targets like BLER (block error rate).

specifications, notably 3GPP TS 36.104, define robust RF and system performance requirements covering uplink (UL), downlink (DL), and transmitter behavior.

On the uplink, NB-IoT relies on NPUSCH and NPRACH, with targets set at a Block Error Rate (BLER) of ≤10% for NPUSCH, along with strict missed detection and false alarm limits for random access. Coverage enhancement techniques ensure reliable decoding under low SINR, with defined test cases for fading and path-loss, while uplink control includes ACK/NACK signaling and random access benchmarks across static and deep-coverage scenarios. On the downlink, performance requirements apply to NPDSCH, NPDCCH, NPBCH, NPSS, and NSSS, where BLER must remain within ≤10% for NPDSCH and NPDCCH, and synchronization signals must achieve high detection reliability.

Reference sensitivity levels and coverage enhancement modes further enable decoding under fading and interference, supporting deep-indoor and extended-range IoT deployments. From a transmitter perspective, base stations must ensure stable NB-IoT resource block power, comply with strict unwanted emission masks, and maintain class-specific spurious emission limits across standalone, in-band, and guard-band operation modes. Section 6.6 of 3GPP TS 36.104 specifies thresholds for Wide Area, Medium Range, Local Area, and Home BS, ensuring coexistence with legacy systems. Low "OFF" power operation and rapid Tx/Rx switching further enhance energy efficiency and minimize interference. Together, these uplink, downlink, and transmitter requirements form the foundation of NB-IoT's ability to deliver massive, reliable, and scalable IoT connectivity across diverse and interference-prone environments.

Table 8: -Key Transmitter & Emission Requirements

Requirement Aspect	Wide Area BS	Medium Range BS	Local Area BS	Home BS	Applicability/Notes
RB Power Dynamic Range	≥ +6 dB	≥ +6 dB	≥ +6 dB	≥ +6 dB	In-band, guard band; exception for 5MHz scenario
Tx "OFF" Power	< -85 dBm/MHz	< -85 dBm/MHz	< -85 dBm/MHz	< -85 dBm/MHz	During OFF state; all modes
Tx Switch Time	≤ 17 µs	≤ 17 µs	≤ 17 µs	≤ 17 µs	OFF↔ON transitions; all modes
OOB/Spurious Emissions	Class-specific masks	Stricter for local ops	Most restrictive	Most restrictive	Class- and region-dependent

2.5 Technical features and Functional Design of NB-IoT: -

A. Radio Access Network (RAN) Design

From a radio perspective, NB-IoT reuses the LTE eNodeB with minor software modifications, lowering network upgrade costs. Its air interface employs a fixed narrow bandwidth of 180 kHz. The downlink uses Orthogonal Frequency Division Multiplexing (OFDM), while the uplink relies on Single Carrier Frequency Division Multiple Access (SC-FDMA), which is more power-efficient for small IoT devices. Peak data rates are approximately 66 kbps for uplink and 26 kbps for downlink. NB-IoT employs simplified, static scheduling and supports data repetition and robust encoding for coverage and reliability.

B. Protocol Stack

The protocol stack in NB-IoT is a streamlined version of LTE's to reduce complexity and improve power efficiency. At the physical layer, modulation and transmission are handled, followed by the MAC layer responsible for resource scheduling. RLC manages segmentation and error correction, while PDCP takes care of header compression and encryption. RRC manages connection setup and mobility, and NAS enables session control between the UE and core network. A key optimization is the use of SRB1bis, a lightweight signalling bearer introduced in NB-IoT to transmit messages before security activation, minimizing signalling load.

C. Core Network Integration

NB-IoT integrates with both LTE and 5G core networks. Initially, deployments relied on the LTE Evolved Packet Core (EPC), using standard LTE elements such as the Mobility Management Entity (MME), Serving Gateway (S-GW), and Packet Gateway (P-GW). Starting from 3GPP Release 15, NB-IoT can be connected to the 5G Core (5GC) using the Service-Based Architecture (SBA), enabling operators to future-proof their IoT deployments. Furthermore, NB-IoT supports Non-IP Data Delivery (NIDD), allowing the transmission of small binary payloads without the overhead of IP protocols—enhancing efficiency for low-bandwidth applications.

D. Power Efficiency Mechanisms

To ensure long battery life, NB-IoT employs Power Saving Mode (PSM) and eDRX. PSM allows devices to enter a deep sleep state, during which the device is unreachable but maintains registration with the network. This state can last from hours to weeks, drastically conserving power. eDRX lets devices sleep for extended intervals and periodically wake up to receive messages, trading latency for energy savings. These power-saving techniques are critical for long-term operations in applications such as smart metering.

E. Positioning and Mobility

NB-IoT initially supported only static devices under Release 13. However, Releases 14 to 17 introduced enhancements for mobility, including support for idle and connected mode mobility, making NB-IoT suitable for use cases involving movement, such as asset tracking. In terms of positioning, NB-IoT supports OTDOA (Observed Time Difference of Arrival) and Enhanced Cell ID (E-CID) techniques to estimate device location.

F. Security and Reliability

Security in NB-IoT is inherited from LTE, providing mutual authentication between the device and network, encryption of data via the PDCP layer, and integrity protection for signaling messages. These security features ensure secure communication in large-scale IoT deployments.

G. Scalability and Network Density

NB-IoT is built to scale. It supports more than 50,000 devices per cell, thanks to enhanced random-access procedures (RA) that help manage contention in dense deployments such as smart cities and industrial environments. This massive connectivity capability ensures that NB-IoT can meet the demands of the evolving Internet of Things landscape (3GPP TS 36.300).

2.6 NB-IoT support for Non-Terrestrial Networks (NTN):

IoT Non-Terrestrial Networks Overview: -

The integration of IoT technologies, particularly NB-IoT, within NTN represents a major advancement in extending global connectivity. NTNs are mobile networks that employ spaceborne and airborne platforms—such as satellites in geostationary, medium, or low Earth orbits, as well as high-altitude platforms—to provide or supplement communication services where terrestrial infrastructure is limited or absent. By leveraging NB-IoT over NTN, IoT applications can achieve seamless global reach, enabling device connectivity in remote, rural, maritime, and disaster-stricken regions. This integration allows for reliable worldwide tracking, monitoring, and data exchange for critical sectors such as logistics, agriculture, environmental monitoring, and emergency response, making NB-IoT over NTN a cornerstone of truly ubiquitous IoT services.

- **Satellite Orbits**:
    - **Low Earth Orbit (LEO)**: 300–1,500km altitude, provides relatively low latency and small beam footprints (100–1,000km).
    - **Geostationary Earth Orbit (GEO)**: 35,786km in altitude, fixed relative to Earth, with much larger beam footprints (200–3,500km)

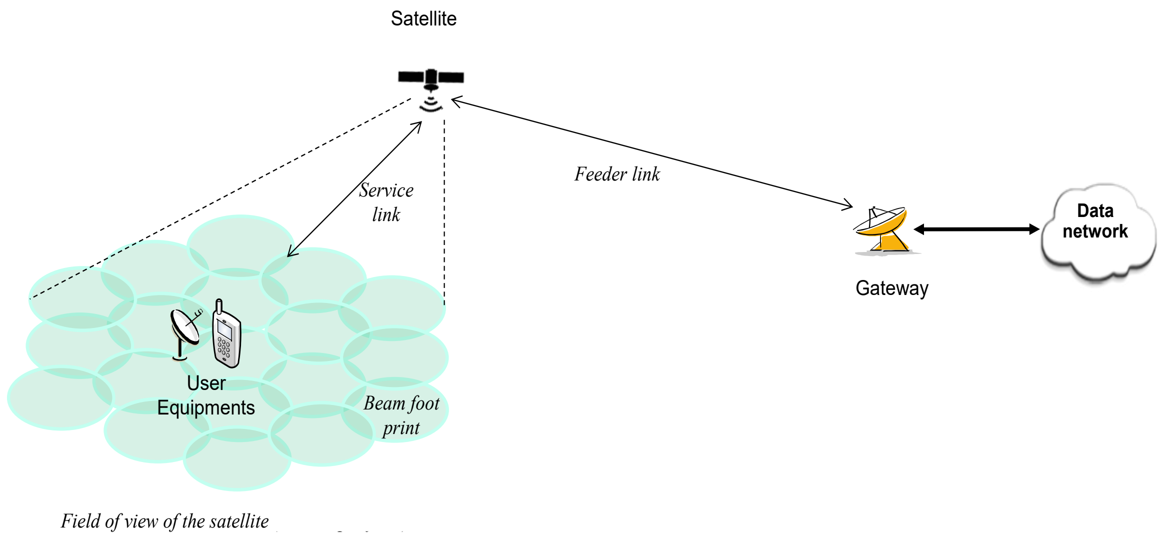

Figure4: -Non-terrestrial network typical scenario based on transparent payload

Non-Terrestrial Network typically features the following elements:

- One or several sat-gateways that connect the Non-Terrestrial Network to a public data network
- a GEO satellite is fed by one or several sat-gateways which are to enable satellite coverage over the targeted area (e.g. regional or even continental coverage). It is assumed that UE in a cell are served by only one sat-gateway
- A Non-GEO satellite served successively by one or several sat-gateways at a time. The system ensures service and feeder link continuity between the successive serving sat-gateways with sufficient time duration to proceed with mobility anchoring and hand-over. Service discontinuity can also be deployed.
- A Feeder link or radio link between a sat-gateway and the satellite
- A service link or radio link between the user equipment and the satellite.
- A satellite which implements a transparent payload. The satellite typically generate several beams over a given service area bounded by its field of view. The beam could be either earth fixed beam or earth moving beam for LEO. The footprints of the beams are typically of elliptic shape. The field of view of a satellite depends on the on board antenna design and minimum elevation angle.
- A transparent payload: Radio Frequency filtering, Frequency conversion and amplification. Hence, the waveform signal repeated by the payload is un-changed;
- User Equipment are served by the satellite within the targeted service area.

2.6.1 IoT NTN Architecture: -

The architecture of IoT over NTN builds upon a layered integration of satellites, gateways, and user equipment to enable seamless connectivity for NB-IoT devices beyond terrestrial coverage. At the system level, satellites in different orbital regimes—including Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Orbit (GEO)—serve as relay nodes that link user devices with the terrestrial core network. These satellites forward uplink and downlink signals between IoT user equipment (UE) and NTN gateways, which function as the terrestrial interface to the operator's core network (EPC/5GC). On the device side, NB-IoT UEs are equipped with specialized antennas and transceiver chains designed to handle the higher latency, Doppler shifts, and variable link budgets characteristic of satellite channels.

Depending on the payload configuration, NTN deployments can adopt two modes: (i) transparent payloads, where the satellite acts as a simple bent-pipe relay with minimal onboard processing, a widely used approach due to reduced complexity and cost; and (ii) regenerative payloads, where the satellite performs partial signal processing tasks such as demodulation, decoding, or header stripping before forwarding data to the gateway. While transparent payloads dominate current NB-IoT NTN implementations, regenerative payloads are expected to gain importance in future releases as satellite payload capabilities evolve. This architecture ensures that NB-IoT devices can operate efficiently over NTN links while remaining interoperable with terrestrial infrastructures, thereby extending IoT service coverage to global and hard-to-reach environments.

2.6.2 IoT NTN UE Capabilities: -

In the context of IoT over Non-Terrestrial Networks (NTN), specific radio and device-level parameters have been standardized to ensure robust NB-IoT operation under satellite conditions. NB-IoT operates with a fixed downlink bandwidth of 180 kHz, while uplink transmissions can use flexible allocations as narrow as 3.75 kHz to accommodate low-data-rate IoT traffic efficiently. By contrast, eMTC supports wider bandwidths of up to 1,080 kHz on the downlink, alongside multiple smaller allocations to balance flexibility and efficiency. User equipment (UE) in NTN scenarios typically conforms to defined power classes, such as 23 dBm (200 mW) and 20 dBm (100 mW), with the assumption of omnidirectional antennas offering 0 dBi gain. A key challenge arises from the extended propagation delays inherent to satellite communication, which vary significantly with orbital altitude—ranging from approximately 25–42 ms in Low Earth Orbit (LEO) systems to over 500 ms in Geostationary Orbit (GEO). Mobility is also accounted for, with NB-IoT devices supporting both stationary operation and moderate mobility up to 120 km/h, enabling applications across land, maritime, and low-speed aerial platforms. To counteract the large Doppler shifts and time-varying delays associated with satellite links, NB-IoT devices employ Global Navigation Satellite System (GNSS)-based frequency pre-compensation, advanced synchronization techniques, and protocol-level adaptations. Together, these mechanisms ensure reliable uplink and downlink communication across diverse NTN environments, thereby extending IoT coverage well beyond terrestrial boundaries.

Table 9: -Key features for NB-IoT in NTN Scenario

Characteristic	LEO Scenario	GEO Scenario
Altitude	600–1,200km	35,786km
DL Bandwidth (NB-IoT)	180kHz	180kHz
UE Max Tx Power	23 dBm/200mW or 20 dBm/100mW	Same
Max RTT Delay	~26–42ms	~541ms
Beam Footprint	50–1,000km	200–3,500km

2.6.3 Channel Bandwidth and Frequency Allocation: -

NB-IoT over NTN maintains compatibility with the same 3GPP-defined bandwidth and subcarrier spacing parameters as terrestrial deployments, ensuring interoperability and simplified integration with existing cellular ecosystems. However, these air interface configurations are carefully adapted to account for satellite-specific challenges such as increased propagation delays, large round-trip times, and variable Doppler shifts caused by satellite motion.

To support reliable communication under these conditions, NB-IoT incorporates delay-tolerant signaling and synchronization techniques while preserving the narrowband channelization that underpins its power efficiency and scalability. In terms of spectrum, NTN deployments for NB-IoT predominantly operate in sub-6 GHz frequency ranges, with the S-band around 2 GHz being particularly important for both uplink and downlink transmissions. The use of these bands offers favorable propagation characteristics, supporting reliable coverage in wide geographic areas while ensuring coexistence with other terrestrial and satellite services.

Chapter 3: LTE-M (Long Term Evolution for Machines / Cat-M1)

LTE-M, short for Long Term Evolution for Machines, is a 3GPP standardized LPWA technology introduced in Release 13 under the term eMTC (enhanced Machine-Type Communications) as part of the broader MTC effort. Marketed as Cat-M1, LTE-M provides an efficient balance between low power, extended coverage, and broadband-like capabilities. LTE-M is designed to cater to IoT applications that require medium data rates, extended coverage, long battery life, real-time communication, or mobility such as smart meters, asset tracking, health monitors, wearables, and industrial sensors.

Unlike NB-IoT, LTE-M typically uses a ~1.4 MHz channel bandwidth in LTE spectrum, supporting higher throughput and mobility, as well as voice/SMS in some deployments, making it more suitable for mid-complexity IoT applications.

Table 10: -Key Features of LTE-M by Release

Feature	Description	Release
Bandwidth	Uses 1.4 MHz bandwidth (compared to 180 kHz in NB-IoT) for broader capabilities	Release 13
Deployment Modes	Operates within standard LTE spectrum as a part of the LTE network	Release 13
Battery Life	Supports 10+ years of battery life using Power Saving Mode (PSM) and eDRX	Release 13
Coverage	Offers ~155 dB MCL, providing improved indoor and rural coverage	Release 13
Data Rate	Peak uplink/downlink data rates up to 1 Mbps	Release 13
Mobility	Full mobility support including connected mode mobility	Release 13
Voice Support (VoLTE)	Enables voice support in IoT devices	Release 13
Positioning	OTDOA and enhanced signal timing for improved positioning	Release 14
Multicast (eMBMS)	Efficient group communication via LTE multicast	Release 14
Reduced Latency	Low latency (~10–15 ms)	Release 13
5G Core Network Integration	LTE-M support in 5GC for 5G readiness	Release 15
Non-Terrestrial Networks (NTN)	Satellite IoT support	Release 17
Advanced Power Optimization	Additional power savings in signaling and sleep modes	Releases 16 & 17
Reduced Complexity Devices	Protocol and hardware simplifications for low-cost modules	Release 17

Table 11: -Release-wise Evolution for LTE-M

3GPP Release	Key Enhancements for LTE-M
Release 13	Introduction of LTE-M (Cat-M1) - Narrowband operation (1.4 MHz) - Power Saving Mode (PSM) and eDRX - Basic mobility (cell reselection) - MCL up to 155 dB
Release 14	VoLTE support for Cat-M1 - Connected mode mobility (intra-frequency handovers) - Higher data rates (up to 1 Mbps) - Multicast/eMBMS support OTDOA and GNSS-based positioning
Release 15	LTE-M integration with 5G Core (5GC) - Enhanced QoS and signaling - Support for 5G system architecture (non-standalone IoT deployment)
Release 16	Initial support for Non-Terrestrial Networks (NTN) - Enhanced coverage techniques - Improved positioning accuracy for IoT devices
Release 17	Enhanced LTE-M over NTN (e.g., mobility and p ower optimization) - Support for Power Class 5 (14 dBm) - Positioning and coverage improvements for satellite IoT
Release 18	Continued LPWA support in 5G context - Coexistence and harmonization with 5G RedCap - Alignment with 5G mMTC roadmap

3.1. LTE-M Categories: -

To meet the needs of LPWA technology, 3GPP defined two special categories of LTE User Equipment (UE):

A. Category M1 (Cat-M1)

Cat-M1 is the first generation of LTE-M devices introduced by 3GPP in Release 13 and is the most widely deployed LTE-M category today. It operates with a bandwidth of 1.4 MHz (6 Resource Blocks) and offers maximum data rates of around 375 kbps in both uplink (with QPSK) and downlink. It supports multiple duplex modes, including FDD, TDD, and HD-FDD, and uses QPSK modulation with optional 16QAM. Cat-M1 devices fall under three power classes: 3 (23 dBm), 5 (20 dBm), and 6 (14 dBm). Additionally, Cat-M1 supports power-saving mechanisms such as Power Saving Mode (PSM) and Extended Discontinuous Reception (eDRX), as well as coverage enhancement techniques like repetitions. With sub-second latency, it is suitable for interactive IoT applications and also supports VoLTE with longer DRX cycles.

B. Category M2 (Cat-M2)

Cat-M2 was introduced in Release 14 as an enhancement over Cat-M1, offering higher throughput for more demanding IoT applications. While it retains the same bandwidth of 1.4 MHz (6 Resource Blocks) and low power profiles, it provides uplink and downlink data rates that can reach up to ~1 Mbps or more depending on conditions. Cat-M2 also enables improved performance with more flexible scheduling and channel usage. Furthermore, it offers enhanced modulation support, making better use of 16QAM, thereby extending its utility to IoT scenarios requiring higher data rates and performance compared to Cat-M1.

Table 12: - Comparison between Cat-M1 & Cat-M2

Feature	Cat-M1	Cat-M2
Introduced in	3GPP Release 13	3GPP Release 14
Max Data Rate	~375 kbps	~1 Mbps
Power Class	3/5/6	3/5/6
DL/UL Bandwidth	1.4 MHz (6 RBs)	1.4 MHz (6 RBs)
Modulation Support	QPSK, 16QAM (optional)	QPSK, 16QAM (enhanced)
Complexity	Lower	Slightly higher
Power Usage	Very low	Low
Target Devices	Basic IoT, meters	Mid-Range IoT, Video-less wearables, tracking with more data

Both categories of devices share several common features that make them well-suited for IoT applications. They are designed with reduced UE complexity, enabling cost-effective deployment and simpler device architectures. Both categories support enhanced coverage through the use of repetitions, ensuring reliable communication even in challenging environments. Low power operation is achieved with mechanisms like Power Saving Mode (PSM) and Extended Discontinuous Reception (eDRX), which extend device battery life significantly. They also utilize narrowband operation, ensuring efficient use of spectrum resources, and maintain interoperability with existing LTE networks, allowing seamless integration into current mobile infrastructures.

Operating Bands for UE Category M1 and M2: - UE Categories M1 and M2 are designed to operate within the standard LTE frequency bands defined by 3GPP, ensuring seamless coexistence with existing LTE networks. They can be deployed in low, mid, and high LTE bands depending on regional spectrum availability, which typically includes bands below 1 GHz (such as Band 5, Band 8, Band 12, Band 13, Band 20, and Band 28) for extended coverage and improved penetration, as well as higher frequency bands (such as Band 3, Band 4, and Band 25) for capacity-focused deployments. The flexibility to operate across multiple LTE bands allows Cat-M1 and Cat-M2 devices to support global roaming, wide deployment scenarios, and compatibility with diverse operator spectrum holdings.

Table 13: - Operating Bands for UE Category M1 and M2

Mode	E-UTRA Operating Bands
FDD (Full/Half Duplex)	1, 2, 3, 4, 5, 7, 8, 11, 12, 13, 14, 18, 19, 20, 21, 24, 25, 26, 27, 28, 31, 54, 66, 71, 72, 73, 74, 85, 87, 88, 106
TDD	39, 40, 41, 42, 43, 48

Remarks:-

- *These bands refer to the E-UTRA (Evolved Universal Terrestrial Radio Access) frequency bands.*
- *Both Cat-M1 and Cat-M2 UEs support half-duplex and full-duplex FDD operation depending on device configuration.*
- *TDD (Time Division Duplex) bands are supported for devices and networks capable of operating in TDD spectrum.*

TX–RX frequency separation for category M1 and M2:-

For both Category M1 and Category M2 devices, the TX–RX frequency separation follows the same principle as standard LTE operation, since they are designed to work within the existing LTE spectrum framework. The separation between transmit (TX) and receive (RX) frequencies depends on the specific LTE band in use, as defined by 3GPP. Typically, in Frequency Division Duplex (FDD) mode, a fixed duplex spacing is maintained between the uplink and downlink frequencies, while in Time Division Duplex (TDD) mode, the same frequency is used for both transmission and reception but separated in time. Thus, Cat-M1 and Cat-M2 leverage the standardized LTE band allocations for TX–RX separation, ensuring compatibility and coexistence with legacy LTE systems.

Table14: - Default UE TX-RX frequency separation

E-UTRA Operating Band	TX – RX carrier centre frequency separation
1	190 MHz
2	80 MHz.
3	95 MHz.
4	400 MHz
5	45 MHz
6	45 MHz
7	120 MHz
8	45 MHz
9	95 MHz
10	400 MHz
11	48 MHz
12	30 MHz
13	-31 MHz
14	-30 MHz
17	30 MHz
18	45 MHz
19	45 MHz
20	-41 MHz
21	48 MHz
22	100 MHz
23	180 MHz
24	-101.5[1], -120.5 MHz
25	80 MHz
26	45 MHz
27	45 MHz
28	55 MHz
30	45 MHz
31	10 MHz
65	190 MHz
66	400 MHz
68	55 MHz
...	
70	295, 300MHz[1]
71	-46 MHz
72	10 MHz
73	10 MHz
74	48 MHz
85	30 MHz
87	10 MHz
88	10 MHz
103	-30 MHz
106	39 MHz

3.2 Requirements of LTE-M: -

Based on the document 3GPP TS 36.101, the key radio frequency (RF) requirements for LTE-M devices, referred to in the specification as UE Category M1 and UE Category M2 are as follows:-

a) **Transmitter Characteristics: -** Transmitter characteristics define the minimum requirements for the device's signal transmission, ensuring signal quality and minimizing interference. The transmit power requirements for UE in Categories M1 and M2 are defined across several parameters. The maximum output power is specified for two nominal power classes: 23 dBm ±2 dB (Power Class 3) and 20 dBm ±2 dB (Power Class 5), each with defined tolerances. In addition, the UE may apply Maximum Power Reduction (MPR), which allows it to lower its maximum output power depending on the modulation scheme (such as QPSK or 16QAM) and the number of allocated resource blocks, in order to meet spectrum emission limits. For LTE-M, MPR (Maximum Power Reduction) typically ranges from 1–2 dB depending on the configuration, while Additional MPR (A-MPR) of up to 1–3 dB can be applied based on band-specific regulatory requirements.

The power control requirements cover several tolerance parameters. Absolute power tolerance is ±2 dB for Pout >17 dBm and ±2.5 dB for lower power levels, defines how accurately the UE must set its maximum output power when configured by the network. Relative power tolerance specifies the accuracy with which the UE adjusts its power level in response to incremental network commands. Aggregate power tolerance determines the overall accuracy for transmit power adjustments across a sequence of power control commands, ensuring consistency over time.

The signal quality requirements address both frequency and modulation performance. The UE's transmitted carrier frequency must remain within ±0.1 parts per million (PPM) for normal condition (up to ±0.3 ppm under extreme conditions) of the reference frequency provided by the network. Transmit modulation quality is evaluated using parameters such as Error Vector Magnitude (EVM), with strict limits defined for different modulation schemes: for QPSK the EVM must be ≤17.5%, and for 16QAM it must be ≤12.5% to preserve signal fidelity. Additional requirements are specified for minimizing carrier leakage and controlling in-band emissions, further ensuring high-quality transmissions.

b) Receiver Characteristics: - Receiver characteristics specify the minimum performance for the device's receiver, which determines its ability to decode signals successfully, especially in weak or noisy conditions. The reference sensitivity (REFSENS) is a critical receiver metric that specifies the minimum signal strength at which the UE must still be able to achieve the required data throughput. For both Category M1 and Category M2 devices, detailed REFSENS power levels are defined across all supported operating bands in the 3GPP specifications. For LTE-M, the REFSENS is typically around –100 dBm (1.4 MHz bandwidth, QPSK, BLER ≤10%), with slight band-to-band variations.

The adjacent channel selectivity (ACS) requirement defines the receiver's ability to correctly receive a desired signal on its assigned channel even in the presence of a strong interfering signal in an adjacent channel. This ensures reliable operation in environments with high spectral congestion. For LTE-M, the ACS requirement is ≥33 dB, measured with an adjacent interferer at a level of –49 dBm.

The blocking characteristics describe the receiver's capability to manage strong, unwanted signals. This includes both in-band blocking, where interferers are present within the same operating band, and out-of-band blocking, where interfering signals originate from other frequency bands. For LTE-M, in-band blocking must tolerate interferers at levels up to –15 dBm, while out-of-band blocking covers interferers from 9 kHz to 12.75 GHz with levels between –15 dBm and –30 dBm depending on frequency separation.

The intermodulation characteristics requirement specifies the receiver's robustness when exposed to two or more interfering signals that can combine within the receiver circuitry to produce distortion products. These requirements ensure that the UE can still detect and decode the wanted signal in such scenarios. In LTE-M, the UE must meet performance with two interferers at –43 dBm each, located at ±10 MHz and ±20 MHz from the carrier.

Finally, the spurious response requirement measures the receiver's ability to reject spurious or unwanted signals across a range of frequencies, ensuring that they do not degrade overall performance. For LTE-M, spurious response rejection is required up to 12.75 GHz, with interferer levels typically at –30 dBm.

c) Performance Requirements: - Performance requirements ensure that LTE-M devices can reliably demodulate data, especially when utilizing coverage enhancement features. In the context of coverage enhancement, several key performance requirements are defined for different channels. For demodulation in coverage enhancement, the Physical Downlink Shared Channel (PDSCH) must meet the minimum required Signal-to-Noise Ratio (SNR) to ensure successful decoding of the main data channel in both CE Mode A and Mode B, which rely on signal repetition to extend coverage. For LTE-M, the PDSCH BLER requirement is ≤10% at an SNR of about –4 dB for QPSK, with coverage enhancement repetitions enabling operation down to around –14 dB SNR.

Similarly, the MTC Physical Downlink Control Channel (MPDCCH) has defined performance requirements for decoding the dedicated LTE-M control channel, with tests specified under various interference conditions for both CE modes. The MPDCCH must be decoded with ≤10% BLER at an SNR of about –6 dB in CE Mode A, and down to around –12 dB in CE Mode B with repetitions.

The Physical Broadcast Channel (PBCH) must also meet minimum performance requirements to ensure reliable decoding of essential system information in coverage enhancement scenarios.

For LTE-M, PBCH decoding must succeed with ≤10% BLER at an SNR threshold of about –6.5 dB.

For channel state reporting, the Channel Quality Indicator (CQI) specifies the conditions under which a UE in coverage enhancement mode must report channel quality back to the network, with tests typically conducted under Additive White Gaussian Noise (AWGN) conditions. CQI reporting is required to be accurate within ±1 dB under AWGN at SNR ≥ –3 dB for QPSK. Additionally, the Precoding Matrix Indicator (PMI) sets out the requirements for reporting the recommended precoding matrix used in multi-antenna transmission schemes, where applicable for UEs supporting coverage enhancement. For LTE-M, PMI reporting applies only to Cat-M2 devices with 2Rx, and must remain within ±1 dB accuracy under reference test conditions.

3.3 LTE-M Coexistence with NR and Use Cases: -

LTE-M is a fully supported technology within the 5G massive Machine-Type Communications (mMTC) framework, ensuring its continued relevance in next-generation networks. According to 3GPP specifications, LTE-M remains operational within 5G networks through seamless integration with the 5G Core (5GC). It is designed to coexist with 5G New Radio (NR) deployments, supporting features such as dual connectivity and network slicing, which enable differentiated service environments tailored to specific IoT applications. This forward compatibility provides a stable migration path, allowing existing LTE-M deployments to remain future-proof without the need for immediate transition to NR-based IoT technologies like Reduced Capability (RedCap). As a result, LTE-M protects legacy IoT investments while aligning with the long-term evolution of 5G ecosystems.

From a deployment perspective, LTE-M addresses use cases that require a balance between extended coverage, mobility support, and moderate throughput. Typical applications include wearables such as smartwatches with VoLTE, healthcare devices like portable ECG monitors, and asset tracking and logistics, where mobility and reliability are essential. It also plays a key role in smart city infrastructure (for example, mobile meters and intelligent traffic control), industrial automation requiring both mobility and low latency, and connected retail solutions such as point-of-sale terminals and vending machines. By supporting real-time communication and enhanced reliability, LTE-M effectively bridges the gap between low-power, static IoT use cases typically served by NB-IoT and more demanding mobile IoT scenarios, making it a versatile choice for diverse industries.

Table15: -Specific LTE-M Use Cases

Use Case	Description	Why LTE-M?
Smart Metering (Electricity/Gas/Water)	Central entity polls metering devices for data collection. Devices remain mostly idle and respond only when queried.	Infrequent data transmission- Small payloads- Network-triggered communication

Time-Controlled Communication	Devices send/receive data only during specific time intervals (e.g., low traffic periods), to reduce network load and cost.	Scheduled data bursts- Time-controlled access via LTE-M features- Lower communication costs
Theft/Vandalism Detection for MTC Devices	Stationary devices (e.g., meters) report movement, indicating possible theft.	Location monitoring- Secure connectivity- Low-power tracking
Mass Sensor Data Upload (Bridge Monitoring, Flood Sensors)	Thousands of sensors send data simultaneously in response to a trigger (e.g., train crossing or heavy rain).	Efficient overload control- Small data bursts- Group-based MTC handling
Nationwide Payment Terminals	Devices like vending/payment machines become active at the same time (e.g., after a power outage or during peak hours).	Control signaling storm with Extended Access Barring (EAB)- Group-based policing
Cargo/Animal/Asset Tracking	High mobility devices like animal trackers, prison monitors, or cargo tags operate under severe power constraints.	Ultra-low power support- Long battery life- Location tracking
Gas Meters vs. Electricity Meters	Gas meters (battery-operated) need far stricter power saving than electricity meters (which may be powered).	LTE-M low-power modes like PSM/eDRX- Efficient small data transmission
Access Control with Billing Restrictions	Devices must use specific USIMs matched to particular terminals (e.g., vending machines) to enforce usage policies.	Network-managed access control- Secure identity binding
Roaming Devices with End-to-End Security	Payment terminals or trackers operating globally require secure data links even over untrusted roaming networks.	End-to-end encryption- Roaming support with trusted domain control

3.4 Technical features and Functional Design of LTE-M: -

A. Deployment and Spectrum

LTE-M operates directly within the LTE carrier's spectrum, making it easy to deploy on existing LTE networks. It uses a 1.4 MHz bandwidth and can operate across various LTE frequency bands, such as Band 3 or Band 20. As it is deployed fully in-band, LTE-M can reuse existing LTE base stations and antennas, allowing operators to upgrade the network through software without requiring additional hardware investment.

B. Radio Access Network (RAN) Architecture

LTE-M shares its core air interface with LTE, employing OFDM for downlink and SC-FDMA for uplink. It supports both single-tone and multi-tone operations for uplink, offering greater flexibility in data rates and power efficiency. LTE-M supports full connected mode mobility from Release 13, making it well suited for applications like fleet management and mobile medical monitoring. Peak data rates reach up to 1 Mbps, offering significantly higher throughput than NB-IoT.

C. Protocol Stack

The LTE-M protocol stack is based on standard LTE but includes enhancements for power and complexity reduction. The PHY layer supports 1.4 MHz narrowband operation.The MAC, RLC, and PDCP layers handle radio resource management, segmentation, and header compression. RRC manages the device's state transitions, while NAS enables secure session management. LTE-M devices typically operate in half-duplex FDD mode with single antenna, reducing device cost and complexity. Sleep modes such as eDRX and PSM extend battery life for IoT devices.

D. Core Network Integration

LTE-M seamlessly integrates with the existing Evolved Packet Core (EPC) used in LTE, enabling reuse of the LTE core network infrastructure. It supports standard EPS bearers and Quality of Service (QoS) management, and from 3GPP Release 15 onward, LTE-M is also compatible with the 5G Core (5GC), enabling long-term evolution and transition into 5G networks.

E. Power Efficiency

Power efficiency in LTE-M is achieved via Power Saving Mode (PSM) and extended Discontinuous Reception (eDRX). PSM allows devices to sleep while retaining registration, while eDRX enables scheduled wake-ups to receive data. These features allow LTE-M devices to achieve 10+ years of battery life in low-data-rate scenarios.

F. Voice and Mobility Support

LTE-M is unique among LPWA technologies in supporting Voice over LTE (VoLTE), enabling its use in wearables, health monitors, and emergency communication devices. It also supports mobility from Release 13, including handover in connected mode and cell reselection in idle mode, which is essential for moving IoT devices.

G. Positioning

Positioning capabilities in LTE-M were enhanced in Release 14 with the support of OTDOA (Observed Time Difference of Arrival) and Enhanced Cell ID (E-CID), offering better accuracy compared to NB-IoT and enabling applications in tracking and navigation.

H. Security

Security in LTE-M leverages LTE’s proven mechanisms, including USIM-based mutual authentication, encryption of user and signaling data, and integrity protection. These features ensure that LTE-M meets the requirements of secure IoT communication.

I. Device Complexity and Cost

LTE-M devices are more complex than NB-IoT devices due to wider bandwidth and mobility features. However, LTE-M still retains a relatively low-cost profile, supporting single antenna, half-duplex operation, and simplified hardware design suitable for mass production.

J. Scalability and Performance

LTE-M supports tens of thousands of devices per cell and provides latency in the range of 50–100 ms. Unlike NB-IoT, LTE-M supports QoS differentiation, enabling services that require prioritization, such as emergency alerts or high-reliability messaging.

3.5 LTE-M Support for Non-Terrestrial Networks (NTN)

3GPP has progressively enhanced LTE-M to extend beyond terrestrial cellular infrastructure into Non-Terrestrial Networks (NTN), recognizing the growing need for global, seamless IoT connectivity. While LTE-M was originally optimized for terrestrial LPWA deployments, later releases, particularly 3GPP Release 17, introduced adaptations for NTN operation over satellite (LEO, MEO, GEO) and high-altitude platforms (HAPS). These adaptations address NTN-specific challenges such as large round-trip delays (tens to hundreds of milliseconds, depending on orbit), Doppler shifts (caused by satellite mobility, especially in LEO), and intermittent visibility due to satellite passes.

To overcome these challenges, several technical enhancements were standardized:

- Timing and Synchronization Adjustments: LTE-M procedures, such as random access and HARQ timing, were modified to accommodate long propagation delays typical in satellite links.
- Doppler Compensation: Support for frequency error tolerance and enhanced synchronization mechanisms ensures reliable operation under high Doppler shifts in LEO environments.
- Extended Coverage Enhancements: LTE-M's inherent support for signal repetition and coverage enhancement modes (CE Mode A/B) is leveraged to maintain connectivity under high path loss conditions.
- Protocol Adaptations: Modifications in control signaling, power-saving mechanisms (PSM, eDRX), and mobility handling were introduced to ensure efficiency under intermittent satellite coverage.

From a use case perspective, LTE-M over NTN significantly broadens the scope of IoT applications. It supports global asset tracking (shipping containers, logistics fleets), maritime and aviation monitoring, remote industrial operations (oil rigs, mining, energy distribution), and public safety/emergency communications in disaster-hit or underserved regions. Additionally, NTN support enables ubiquitous coverage for wearable health devices and connected agriculture, ensuring IoT continuity across urban, rural, and remote geographies.

Importantly, LTE-M over NTN is fully compatible with 5G Core (5GC), allowing it to integrate with terrestrial LTE-M deployments and coexist with 5G NR NTN solutions. This ensures a smooth migration path for operators and enterprises already invested in LTE-M, while also positioning it as a practical complement to NB-IoT in NTN environments. Compared to NB-IoT, LTE-M provides higher mobility support, lower latency, and VoLTE capability, making it more suitable for mobile NTN use cases like aviation, connected vehicles, and mission-critical communications.

By extending LTE-M into the NTN domain, 3GPP has effectively created a globally scalable, future-proof IoT ecosystem that combines terrestrial and non-terrestrial infrastructures, offering near-universal coverage for massive IoT applications.

Chapter 4: EC-GSM-IoT (Extended Coverage GSM for IoT)

EC-GSM-IoT is a 3GPP-standardized Low Power Wide Area (LPWA) technology introduced in Release 13, alongside NB-IoT and LTE-M. It is designed to extend the lifespan and capabilities of legacy GSM/GPRS networks for IoT use cases. By reusing the existing 850/900 MHz GSM bands, EC-GSM-IoT provides enhanced coverage, low complexity, and low power consumption for massive Machine-Type Communications (mMTC).

Unlike LTE-based technologies (NB-IoT and LTE-M), EC-GSM-IoT is based on circuit-switched GSM infrastructure, making it suitable for regions where LTE deployment is sparse or legacy GSM remains in operation. It achieves this by leveraging existing GSM networks and introducing new procedures, measurements, and control mechanisms tailored for low power, cost-efficient, and wide-area IoT deployments. Its primary benefit lies in offering LPWA IoT services without requiring LTE upgrades.

Table 16: -Key Features by Release

Feature	Description	Release
Legacy GSM Reuse	Operates over existing GSM networks (850/900 MHz bands), reducing deployment cost	Release 13
Extended Coverage	Provides up to 164 dB MCL for deep indoor and rural areas	Release 13
Low Power Operation	Uses PSM and eDRX for 10+ years of battery life	Release 13
Data Rates	Uplink speeds up to 350 kbps using EC-PAC or GMSK; optimized for small payloads	Release 13
Low Complexity Devices	Designed for low-cost, low-capability modules	Release 13
Security	GSM SIM-based authentication and encryption	Release 13
SMS Support	May support SMS for signaling or fallback depending on operator setup	Release 13
Mobility	Inherits GSM mobility (cell reselection, handovers)	Release 13
Backward Compatibility	Fully compatible with legacy GSM base stations with software updates	Release 13
Deployment Simplicity	Enables rapid rollout without major hardware changes	Release 13
5G Core (5GC) Support	Not supported; remains a 2G LPWA solution	Confirmed through Releases 14–17
Evolution Beyond R13	No major feature additions in later releases; considered stable and complete	Releases 14–17

4.1 Key Operational Features and Enhancements of EC-GSM-IoT:

The technical framework of EC-GSM-IoT is designed to extend the capabilities of existing GSM networks for supporting IoT applications in challenging coverage scenarios. Operating over traditional GSM frequency bands such as 900 MHz and 1800 MHz, the technology leverages network-specific configurations to ensure compatibility with existing infrastructure. To facilitate enhanced coverage operation, dedicated logical channels—including EC-BCCH, EC-SCH, and EC-CCCH—are introduced, which extend the conventional GSM channel structure and enable reliable performance under extended coverage conditions.

A defining feature of EC-GSM-IoT is its ability to tolerate a maximum coupling loss of up to 164 dB. This significantly enhances link robustness, allowing devices to remain connected even in deep indoor environments or remote rural areas where traditional GSM coverage would not suffice. Complementing this, the system employs coverage classes, ranging from CC1 to CC4, with an optional fifth class. These classes can be dynamically selected by the device or network, depending on prevailing link conditions, thereby ensuring adaptability across a wide range of deployment scenarios.

Signal measurement is another critical aspect. The RLA_EC (Received Level Average for Extended Coverage) metric, which reflects the linearly averaged received signal strength under EC operation, spans from –122 dBm to –48 dBm. Coverage class assignment is guided by thresholds based on such measurements, ensuring efficient utilization of both downlink and uplink resources. To further improve energy efficiency—an essential requirement for IoT devices—EC-GSM-IoT integrates mechanisms such as extended Discontinuous Reception (eDRX) and Power Efficient Operation (PEO), allowing devices to optimize their battery consumption while maintaining reliable connectivity.

On the transmission side, initial access is supported through open-loop power control, where the starting transmission power for EC-RACH procedures is derived from a specific calculation formula. The system also enforces stringent requirements for measurement accuracy: error margins are confined to ±3 dB for RLA_EC and SLA values down to –122 dBm, as well as for SINR measurements down to –7 dB. Such precision ensures that device behavior and network coordination remain highly reliable, even under adverse conditions.

Beyond these parameters, EC-GSM-IoT employs a range of control values broadcast by the network, covering aspects such as access regulation, power thresholds, and operating conditions. Importantly, the standard also incorporates mechanisms for multi-RAT cell selection, enabling seamless mobility and interoperability across GSM, UTRAN, and LTE systems. This cross-technology support makes EC-GSM-IoT a practical solution for operators seeking to extend IoT coverage without compromising compatibility with their broader network ecosystem.

4.2 <u>Coverage Class Selection in EC-GSM-IoT</u>: -

In EC-GSM-IoT (Extended Coverage GSM for Internet of Things), a coverage class represents a classification used to describe and manage the radio link conditions of an IoT device within a GSM network. The concept allows both the network and the device (Mobile Station, MS) to dynamically adapt transmission procedures, power levels, and resource allocation based on the device's real-time radio environment, particularly in challenging coverage scenarios like deep indoor or rural areas.

Coverage classes enable EC-GSM-IoT networks to extend service reach and maintain reliable connectivity for devices with varying link qualities, supporting robust operation even where path loss and signal degradation would normally prevent successful communication.

Coverage classes allow EC-GSM-IoT to efficiently manage a vast range of deployment scenarios, from urban environments with strong signal availability to remote or indoor locations where path loss is significant. By quantifying the link condition and aligning device operation accordingly, the technology delivers energy-efficient, scalable, and reliable IoT connectivity over existing GSM infrastructure.

Typical Coverage Classes:- There are four coverage classes defined as per the table given below: -

Table 17: -Coverage Classes for EC-GSM-IoT

Coverage Class	Description
CC1	Best coverage, normal operation
CC2	Moderate coverage enhancement
CC3	Significant coverage extension
CC4	Deepest coverage, system limit
CC5*	Extreme coverage extension (optional and if broadcast by network)

*Note: *CC5 is supported only if the network is configured accordingly and the device supports it.*

Coverage class selection operates separately for the downlink (network to device) and uplink (device to network):

- **Downlink Coverage Class Selection:**

Before each network access, the UE measures the received signal or Signal-to-Interference-and-Noise Ratio as indicated by the network. It then uses configured broadcast thresholds to map the measurement to a specific coverage class (CC1–CC4). The MS communicates this selected class to the network, which uses it to determine how to page or allocate resources for the device. If the measured level is on the boundary between two classes, the higher class is selected.

- **Uplink Coverage Class Selection:**

For uplink (device to network), the UE estimates the likely received signal strength at the base station, factoring in its own output power and BTS-configured parameters. Using broadcast thresholds, the MS maps this value to an uplink coverage class (typically CC1–CC4 or CC5 if supported). The MS uses this class when initiating access on EC-RACH and reports it to the network.

Table18: - Downlink Coverage Class Selection for EC-GSM-IoT

Downlink Coverage Class	Range for RLA_EC or SLA	Description
CC1	≥ BT_Threshold_DL	Best coverage, standard EC operation
CC2	< BT_Threshold_DL and ≥ (BT_Threshold_DL − CC2_Range_DL)	Moderate coverage extension
CC3	< (BT_Threshold_DL − CC2_Range_DL) and ≥ (BT_Threshold_DL − CC2_Range_DL − CC3_Range_DL)	Significant coverage extension
CC4	< (BT_Threshold_DL − CC2_Range_DL − CC3_Range_DL)	Deepest coverage; triggers re-selection if too low

- BT_Threshold_DL: Broadcasts the signal threshold for blind transmissions and entry to extended coverage.
- CC2_Range_DL / CC3_Range_DL: Broadcasts the range widths for selection of classes 2 and 3.
- If the measured value falls between boundaries, the higher class is chosen.

Table19: Uplink Coverage Class Selection

Uplink Coverage Class	Range for BS_RX_PWR (dBm)	Description
CC1	≥ BT_Threshold_UL	Best uplink coverage, normal operation
CC2	< BT_Threshold_UL and ≥ (BT_Threshold_UL − CC2_Range_UL)	Moderate extension, some path loss
CC3	< (BT_Threshold_UL − CC2_Range_UL) and ≥ (BT_Threshold_UL − CC2_Range_UL − CC3_Range_UL)	Significant uplink extension, high loss environments
CC4/5	Progressively lower ranges, if CC4_Range_UL broadcast and device supports CC5	Deepest coverage; approach limits for system access

- BT_Threshold_UL: Threshold for required uplink signal at base station.
- CC2/3/4_Range_UL: Range widths for class boundaries, determined by the network.
- Selection uses the same "higher class on boundary" rule.

These selection mechanisms, based on real-time radio measurements and broadcast network parameters, ensure EC-GSM-IoT devices achieve operational efficiency and deep coverage vital for IoT deployment.

4.3 5G Compatibility: -

EC-GSM-IoT, unlike NB-IoT and LTE-M, does not have native integration with the 5G Core (5GC). It remains rooted in the 2G GSM layer and was designed primarily as a low-power wide-area solution to extend the life of GSM networks by enhancing coverage and optimizing performance for IoT-specific use cases. While NB-IoT and LTE-M have been standardized as part of the 5G massive Machine-Type Communication (mMTC) family, enabling them to connect directly to the 5G Core and evolve alongside 5G New Radio, EC-GSM-IoT lacks such a migration path. This limits its scalability and long-term relevance in the global IoT ecosystem, as it cannot be future-proofed within the 5G framework.

Despite these limitations, EC-GSM-IoT continues to serve as a practical short-term option in regions where GSM coverage remains strong. It provides cost-effective and reliable connectivity for applications that require deep indoor penetration, such as smart metering, agriculture monitoring, and basic sensor networks. Moreover, it offers operators an opportunity to maximize the return on investment from their existing GSM infrastructure by extending its commercial life. However, as more networks worldwide phase out 2G services in favor of LTE and 5G, the role of EC-GSM-IoT will gradually diminish, leaving NB-IoT and LTE-M as the primary long-term LPWA technologies within the 5G ecosystem.

4.4 Use Cases:-

EC-GSM-IoT is best suited for simple, delay-tolerant applications in legacy markets, such as:

- Utility metering (water, gas, electricity)
- Environmental monitoring (air, soil sensors)
- Agricultural telemetry
- Basic asset tracking
- Smart parking.

Table20: Use Cases of EC-GSM-IoT

Sector / Domain	Application Examples	Benefits of EC-GSM-IoT
Utility Metering	Smart water, gas, electricity meters	Deep indoor coverage, long battery life
Smart Cities	Street lighting, waste bins, parking sensors	Efficient city operations, extensive urban/rural coverage
Asset/Vehicle Tracking	Logistics, fleet management, livestock tracking	Reliable global tracking, reach in remote areas
Agriculture	Soil sensors, weather stations, wildlife monitoring	Connectivity without new infrastructure, power efficiency
Industrial Automation	Remote equipment/pipelines monitoring, predictive maintenance	Persistent supervision in hard-to-reach locations
Consumer IoT	Wearables, personal and pet trackers, safety alarms	Small form factor, years-long battery, reliable everywhere
Health & Medical	Remote patient monitors and sensors	Secure, consistent data reporting from any environment

4.5 Technical Features and Functional design of EC-GSM-IoT: -

A. Deployment and Spectrum Use

EC-GSM-IoT is designed to operate within the standard GSM 200 kHz channels, which allows seamless reuse of existing spectrum. This approach ensures coexistence with ongoing GSM voice and data services, enabling operators to introduce IoT offerings without the need for additional spectrum allocations. A key advantage of this technology lies in its ability to leverage the existing GSM infrastructure, including base transceiver stations (BTS), antennas, and spectrum resources. With only a software upgrade required in the GSM Radio Access Network (RAN), operators can deploy EC-GSM-IoT at minimal cost. This feature makes it particularly appealing in developing countries, where operators can achieve rapid and cost-effective deployment of wide-area and rural IoT networks while maximizing the value of their existing GSM investments.

B. Air Interface Enhancements - Modulation and Coding

EC-GSM-IoT retains Gaussian Minimum Shift Keying (GMSK), the same modulation used in traditional GSM. Optionally, it supports 8-Phase Shift Keying (8PSK) to enable higher data throughput when needed. These modulation schemes are optimized for low data rate but highly reliable IoT communication.

C. Data Throughput

Typical uplink and downlink data rates range between 70 kbps and 240 kbps, depending on the modulation technique and the number of repetitions used. The system is well-suited for transmitting small, infrequent data packets typical of IoT use cases.

D. Coverage Enhancements- Extended Coverage Modes

EC-GSM-IoT introduces three levels of coverage: Normal, Extended, and Extreme. These modes employ increased repetition levels to ensure data is successfully transmitted and received even under weak signal conditions.

E. Maximum Coupling Loss (MCL)

The system can achieve a Maximum Coupling Loss of up to 164 dB, which is significantly higher than standard GSM and even surpasses NB-IoT by about 20 dB. This enhanced link budget makes it suitable for deep-indoor and remote-area deployments.

F. Power Efficiency Features (Power Saving Mode)

Similar to NB-IoT and LTE-M, EC-GSM-IoT supports PSM, allowing devices to disable their radio interfaces while remaining registered with the network. This drastically reduces power consumption during idle periods.

G. Extended Discontinuous Reception (eDRX)

With eDRX, devices periodically wake up to check for downlink messages, maintaining connectivity while minimizing energy use. Together with optimized signaling procedures, these features can enable battery lives of up to 10 years using typical AA batteries.

H. Security Features

EC-GSM-IoT retains the GSM authentication framework, using SIM/USIM-based A3/A8 algorithms for user verification. Signalling and user data are protected using Kc-based encryption, making the system fully interoperable with existing GSM security mechanisms. This allows secure, trusted communications without the need for new security infrastructure.

I. Mobility and Roaming

EC-GSM-IoT benefits from GSM's mature mobility management features, including support for both idle and connected mode handovers. International roaming is fully supported due to its operation over the global GSM footprint. These characteristics make it an excellent choice for asset tracking and fleet management, especially across national borders.

J. Device and Network Complexity

Device complexity in EC-GSM-IoT is comparable to legacy GSM handsets, helping reduce costs. Modules are simpler and cheaper than LTE-M equivalents, supporting single-antenna, half-duplex operation. This simplicity also makes the technology more suitable for mass-scale, cost-sensitive IoT deployments.

K. Positioning and Timing

The positioning capabilities of EC-GSM-IoT are based on traditional GSM methods, such as timing advance and cell ID. While the system does not support advanced location technologies like OTDOA (Observed Time Difference of Arrival), it can still provide basic location functionality for many IoT applications.

Table21: NB-IoT vs LTE-M vs LTE Capability

Feature / Capability	NB-IoT (Cat-NB1/NB2)	LTE-M (Cat-M1)	LTE (Broadband, eMBB)
Channel Bandwidth	180 kHz (1 PRB of LTE)	1.4 MHz (can scale up)	1.4 – 20 MHz (scalable)
Deployment Modes	Standalone (GSM refarmed), In-band, Guard-band	In-band within LTE carriers	Native LTE spectrum
Max Data Rate	~26 kbps (UL), ~64 kbps (DL)	~1 Mbps (UL/DL)	100 Mbps – 1 Gbps+
Latency	1.5 – 10 seconds (not real-time)	~50 – 150 ms	<10 ms

Mobility	No seamless handover (supports cell reselection only)	Supports handover, mobility, VoLTE	Full mobility, seamless handover
Voice Support	Not supported	Supported (VoLTE for low-rate voice)	Fully supported
Coverage Enhancement (CE)	Up to +20 dB gain vs LTE (deep indoor, rural)	Up to +15–20 dB gain vs LTE	Standard LTE coverage
Typical Cell Radius	15 – 35 km (rural extended)	5 – 15 km (up to ~20–30 km with CE)	~2 – 10 km (depends on band and deployment)
Battery Life	10+ years (PSM, eDRX)	5 – 10 years (PSM, eDRX)	Limited (designed for smartphones)
Device Complexity	Very low (cheapest modules)	Low (slightly higher than NB-IoT)	High (complex, expensive devices)
Use Cases	Smart meters, sensors, static low-power devices	Asset tracking, wearables, logistics, healthcare	Smartphones, video streaming, broadband IoT
3GPP Release Introduction	Rel-13	Rel-13	Rel-8 (evolved continuously)

Chapter 5: RedCap (Reduced Capability NR)

Reduced Capability (RedCap) is a feature introduced in 3GPP Release 17 to address the need for mid-tier devices that fall between low-power wide-area (LPWA) technologies like NB-IoT/LTE-M and full-scale enhanced Mobile Broadband (eMBB) devices. It is designed for IoT applications that require higher data rates and lower latency than LPWA but do not need the full complexity, cost, or power consumption of 5G eMBB devices. RedCap devices operate with reduced bandwidth, fewer antennas, and simplified processing requirements, making them more affordable and energy efficient.

The target applications for RedCap include industrial sensors, wearables, video surveillance, and healthcare devices, where reliable connectivity and moderate throughput are essential. By simplifying hardware requirements, RedCap lowers device costs while still delivering the benefits of 5G, such as improved reliability, spectrum efficiency, and support for massive connectivity. Importantly, RedCap is natively integrated into the 5G Core (5GC), ensuring future-proof evolution and smooth coexistence with other 5G services.

In practical terms, RedCap is expected to enable a broad range of IoT and enterprise applications that demand a balance of performance and affordability. Its introduction fills a critical gap in the 5G ecosystem, creating a scalable pathway for mass IoT adoption across industries.

Table 22: -3GPP Release wise Evolution for RedCap

3GPP Release	Key Enhancements for RedCap (Reduced Capability UE)
Release 17	Introduction of RedCap UE as a new 5G NR device category with reduced complexity and power consumption.
	Bandwidth limits: Maximum 20MHz in FR1 and 100MHz in FR2
	Support for up to 8 Data Radio Bearers (DRBs).
	Simplified MIMO: 1 DL MIMO layer with 1 Rx; 2 DL MIMO layers with 2 Rx.
	Exclusion of advanced features such as Carrier Aggregation (CA), Multi-Radio Dual Connectivity (MR-DC), Dual Active Protocol Stack (DAPS), Conditional PSCell Addition/Change (CPAC), and Integrated Access Backhaul (IAB).
	Mandatory indication of RedCap capability (supportOfRedCap-r17).
	Optional enhancements: support for 16 DRBs, 18-bit PDCP and RLC sequence numbers.

	Special provision for RedCap-specific signaling parameters.
	Focus on moderate data rates, improved latency, and reduced device cost/complexity compared to standard 5G NR UEs.
Release 18	Continued definition of RedCap in line with Release 17, maintaining core limitations on bandwidth, DRBs, and feature set.
	Introduction of eRedCap (Enhanced RedCap) as an extension, allowing for selected enhancements while preserving low-complexity goals.
	Further parameter refinements and signaling specific to both RedCap and eRedCap categories.
	eRedCap definition includes optional support for certain features and the possibility for modest performance improvements.
	Refinements to signaling, measurement, mobility, and physical layer operations for improved network interoperability and device performance.
	Backward compatibility maintained for standard RedCap capabilities

5.1 Key Features by Release for RedCap:

Reduced Capability (RedCap) was formally introduced in 3GPP Release 17 as a new category of 5G NR devices specifically designed to lower complexity and cost while meeting the needs of mid-tier IoT and enterprise applications. Unlike NB-IoT and LTE-M, which focus on ultra-low data rates and coverage extension, RedCap balances affordability with moderate performance, making it an attractive option for industries that require more capability than LPWA but less than full 5G eMBB devices.

In terms of spectrum use, RedCap devices can operate with bandwidths of up to 20 MHz, which is significantly higher than LPWA technologies but still reduced compared to high-end 5G devices. This bandwidth enables a notable boost in throughput while keeping device design and cost manageable. To further reduce complexity, RedCap supports 64-QAM modulation and simplifies processing requirements, resulting in nearly 50% lower complexity than full NR implementations. This allows for reduced hardware costs and energy consumption without sacrificing essential 5G capabilities.

Performance-wise, RedCap can achieve downlink data rates of up to 100 Mbps, a level sufficient for applications like wearables, video surveillance, and industrial monitoring. Its design also prioritizes low-latency operation, with response times around 10 milliseconds, supporting time-sensitive use cases such as healthcare devices and mission-critical industrial sensors.

Mobility support is another strong feature of RedCap. It provides full 5G mobility, including seamless handover and cell reselection, ensuring that devices remain connected even in dynamic environments like transportation and logistics. Complementing this, power-saving features such as Discontinuous Reception (DRX) and optimized idle modes help extend battery life, making RedCap suitable for long-term field deployments.

Crucially, RedCap is a native 5G technology, operating entirely within the 5G NR and 5G Core (5GC) framework. This ensures compatibility with future network upgrades and provides operators with a streamlined way to support RedCap alongside other 5G services. It also integrates 5G positioning capabilities, including Positioning Reference Signals (PRS), allowing for enhanced location accuracy in applications such as asset tracking, emergency response, and logistics.

The targeted use cases for RedCap are diverse, spanning industrial IoT, wearable devices, smart healthcare, and surveillance applications. By striking a balance between performance, cost, and power efficiency, RedCap fills a crucial gap in the 5G ecosystem and is expected to accelerate the adoption of mid-tier IoT solutions across multiple sectors.

5.2 Benefits over Legacy IoT Technologies

- **Enhanced Performance:** RedCap offers higher data rates, better latency, and improved reliability compared to LTE-M or NB-IoT. This makes it suitable for a wider range of use cases, including those requiring periodic medium-rate data transfers and devices with more demanding performance needs.
- **Broader Ecosystem Support:** RedCap operates within standard 5G NR frameworks, providing seamless integration, mobility enhancement, and better forward compatibility compared to legacy IoT technologies.
- **Reduced Complexity and Lower Cost:** By supporting a subset of features from standard NR UEs, RedCap strikes a balance between capabilities and power/complexity/cost, aiming for greater device longevity and scalability in deployments.

5.3 RedCap UEs: -

RedCap UEs, are a category of 5G NR devices specifically designed to offer reduced complexity and cost while maintaining essential 5G connectivity. These UEs are intended for use cases such as wearables, industrial sensors, smart meters, and other Internet of Things (IoT) applications, where high data rates and advanced features are not critical.

Capability of RedCap UE :-

- **Bandwidth Limitation:**

  RedCap UEs are specifically designed with a streamlined feature set to support low to mid-range performance use cases. These UEs are limited in their bandwidth support: the maximum supported bandwidth is 20 MHz in Frequency Range 1 (FR1) and 100 MHz in Frequency Range 2 (FR2). This is significantly lower than what is supported by standard 5G UEs, which may utilize bandwidths of 100 MHz or more in FR1 and up to 400 MHz in FR2. Any UE features or capabilities requiring wider bandwidths than these thresholds are not supported by RedCap devices. This restriction aligns RedCap UEs with simpler, more power- and cost-efficient use cases.

- **Data Radio Bearer (DRB) and Sequence Number Support:**

  RedCap UEs support a maximum of 8 Data Radio Bearers (DRBs), which is lower than in full-featured UEs, ensuring reduced complexity in data management. For data transmission protocols, RedCap UEs mandatorily support 12-bit PDCP (Packet Data Convergence Protocol) sequence numbers, with 18-bit PDCP SNs being optional. Similarly, in the RLC (Radio Link Control) Acknowledged Mode, 12-bit sequence numbers are mandatory, with the 18-bit variant being optional. This simplified sequence number support reflects the reduced processing and memory requirements of RedCap UEs.

- **MIMO and Antenna Configuration:**

  In terms of antenna capabilities, RedCap UEs support 1 DL MIMO (Downlink Multiple-Input Multiple-Output) layer if the UE has 1 receive branch, and 2 DL MIMO layers if it has 2 receive branches. However, features involving more than 2 receive branches or more than 2 DL MIMO layers are not supported. Similarly, RedCap UEs do not support more than 2 transmit branches or more than 2 UL MIMO (Uplink MIMO) layers. This further reduces hardware complexity and cost, targeting less demanding use cases.

- **Unsupported Features and Compatibility:**

  Several advanced 5G features are explicitly not supported by RedCap UEs. These include Carrier Aggregation (CA), Multi-RAT Dual Connectivity (MR-DC), Dual Active Protocol Stack (DAPS), Conditional PDCCH (CPAC), and Integrated Access and Backhaul (IAB)—the RedCap UE is not expected to act as an IAB node. These features, while typical for eMBB-capable UEs, are optional for RedCap and generally not implemented to maintain simplicity and power efficiency. Despite these exclusions, RedCap UEs continue to support all other relevant features and capability groups as defined in 3GPP TR 38.822 and the main 3GPP specification, unless stated otherwise. This ensures that while RedCap UEs are simplified, they remain interoperable and standards-compliant within the broader 5G ecosystem.

- **Reduced Power Consumption: -**

  While RedCap UEs can participate in basic RRC procedures and support necessary MAC and PHY functions for network access, they are not required to implement enhanced MAC features such as HARQ optimizations, logical channel prioritization, or multi-cell scheduling. These simplifications help reduce device power consumption and enable more efficient radio design.

Table23:- RedCap UE vs. Regular NR UE

Feature / Capability	RedCap UE	Regular NR UE	Notes
Max Bandwidth (FR1)	Up to 20 MHz	Up to 100 MHz or more	RedCap is capped at 20 MHz to simplify RF design
Max Bandwidth (FR2)	Up to 100 MHz	Up to 400 MHz	RedCap is limited in mmWave too
Carrier Aggregation (CA)	Optional / Not Required	Supported	RedCap may skip CA to reduce complexity
MIMO (DL/UL Layers)	1 or 2 Layers (Low Rank)	Up to 8 Layers (High Rank)	RedCap may only support rank-1 or no MIMO
Dual Connectivity	Optional / Not Required	Often supported	RedCap typically operates with a single connection
Mobility Support	Basic	Full (including SCG/MCG handovers)	RedCap can support basic mobility
Target Use Cases	IoT, wearables, smart meters, sensors	eMBB, URLLC, mMTC	RedCap focuses on cost/efficiency rather than high data rate

5.4 eRedCap (enhanced Reduced Capability NR): -

The evolution of 5G has focused not only on delivering extreme performance for high-speed mobile broadband but also on supporting a wide spectrum of devices with varying requirements. While NB-IoT and LTE-M were designed for low-power, narrowband IoT applications, and full-featured 5G devices serve data-intensive services, there remains a substantial segment of devices that need moderate data rates, reduced latency, and long battery life, but without the complexity or cost of premium UEs. This gap was initially addressed by Reduced Capability (RedCap) devices in 3GPP Release 17. Building on that foundation, 3GPP Release 18 introduced enhanced RedCap, or eRedCap, which refines the original design and makes it better suited for a broader range of consumer and industrial use cases in the 5G Advanced era.

The motivation for eRedCap stems from the limitations of the original RedCap specification. RedCap devices in Release 17 offered simplified designs, with bandwidth capped at 20 MHz in Frequency Range 1 (FR1) and 100 MHz in Frequency Range 2 (FR2), limited MIMO support, and a reduced set of advanced 5G features. While this made RedCap ideal for low-cost devices such as wearables, sensors, and simple industrial equipment, it restricted its suitability for scenarios that required greater flexibility, higher reliability, and more robust connectivity. With the growth of industrial IoT, mission-critical communication, and advanced consumer applications, there was a clear need for a mid-tier 5G device class with improved performance while retaining affordability and efficiency. eRedCap was therefore defined in Release 18 to close this gap.

One of the major enhancements in eRedCap is the expansion of spectrum and bandwidth flexibility. While still limited compared to full 5G devices, eRedCap offers more configurable bandwidth options, enabling it to make better use of fragmented spectrum and shared network environments. This is especially useful in private networks, enterprise campuses, and industrial deployments where spectrum availability may be constrained. The ability to operate more flexibly across different bandwidth configurations makes eRedCap a more scalable and adaptable solution than its predecessor.

Power efficiency is another area where eRedCap introduces significant improvements. Since many of the target devices are battery-powered and deployed in the field for long durations, eRedCap adds features such as improved discontinuous reception (DRX) cycles, optimized idle modes, and enhanced wake-up signal (WUS) handling. These improvements reduce the need for constant network monitoring, thereby conserving energy. Additionally, better uplink power adaptation helps minimize transmission overheads, further extending device battery life. These capabilities make eRedCap particularly attractive for wearables, healthcare devices, and industrial sensors where long battery life is a primary requirement.

Latency and reliability have also been refined in eRedCap. While RedCap supported moderate latency in the range of around 10 milliseconds, eRedCap optimizes scheduling, uplink procedures, and hybrid automatic repeat request (HARQ) mechanisms to deliver more consistent low-latency performance. This improvement is critical for industrial IoT applications such as robotic control, process automation, and smart manufacturing, where faster and more reliable response times directly impact operational efficiency and safety.

Mobility support is another enhancement introduced in eRedCap. Unlike RedCap, which had limited mobility capabilities, eRedCap supports more robust handovers and, in selected scenarios, dual connectivity (MR-DC). This means eRedCap devices can maintain better service continuity in dynamic environments such as logistics, transport, or connected vehicles. The improved mobility performance expands eRedCap's utility beyond stationary or semi-fixed devices, opening up new opportunities in areas such as fleet management and mobile healthcare.

eRedCap also broadens feature support compared to RedCap. While RedCap intentionally excluded many advanced 5G features to keep complexity low, eRedCap selectively adds back certain functions in simplified forms. For example, limited carrier aggregation support is included to improve throughput where needed, and enhancements to uplink transmission options provide greater flexibility. In addition, eRedCap devices benefit from improved support for positioning and localization features, which are valuable for asset tracking and location-based services in logistics, smart cities, and industry.

Overall, eRedCap represents the natural evolution of Reduced Capability UEs by striking a more effective balance between performance, cost, and efficiency. It maintains the affordability and lower complexity that make RedCap attractive, but it extends the feature set to support a wider range of applications in both consumer and industrial domains. By addressing the shortcomings of the initial RedCap design, eRedCap strengthens the role of 5G in enabling mass adoption of IoT and mid-tier devices, ensuring that operators and industries can deploy scalable solutions that align with their performance and cost requirements.

As the 5G Advanced phase unfolds, eRedCap will become an important part of the ecosystem, complementing LPWA technologies at the low end and full 5G devices at the high end. Its ability to offer moderate data rates, lower latency, enhanced mobility, and improved power efficiency makes it a key enabler of future IoT services, bridging the gap between ultra-low-power devices and high-capability smartphones and broadband terminals.

Table24: - RedCap vs. eRedCap

Feature / Aspect	**RedCap UE (Release 17)**	**eRedCap UE (Release 18)**
Standard Release	Release 17	Release 18
Design Purpose	Low-cost, low-complexity 5G NR for IoT-type devices	Enhanced RedCap to support broader use cases with modest increases in capability
Bandwidth Support (FR1, FR2)	Up to 20 MHz for FR1 Up to 100 MHz for FR2	Can support higher effective throughput, including relaxed limits in some configurations for FR1. FR2 Operation is not supported.
Baseband Capability	Reduced baseband bandwidth only	May support non-reduced baseband bandwidth (optional)
Minimum Data Rate (DL/UL)	Minimum floor defined for RedCap	New minimum floor defined for eRedCap (based on formulas with lower bounds)
Optional Feature Support	Limited (e.g., no carrier aggregation, no DC)	Can optionally support more PHY/MAC features
Use Cases	Wearables, smart meters, sensors	Smart logistics, industrial devices requiring slightly more capacity
Flexibility in Modulation/MIMO	Restricted	Slightly relaxed restrictions possible
Backward Compatibility	RedCap UEs compliant with Rel-17 networks	eRedCap UEs expected to function in Rel-18-compliant networks

5.5 Target Use Cases

The development of RedCap (Reduced Capability) devices began as a study item in 3GPP Release 17. During this phase, three primary IoT use cases were identified: wearables (such as smartwatches, AR/VR goggles, and health monitoring devices), industrial wireless sensors (including motion detectors, actuators, and pressure sensors), and video surveillance systems (used in smart cities, factories, and industrial setups).

Each of these use cases has specific performance requirements in terms of data rate, latency, availability/reliability, and battery life, as summarized in Table I [2]. While RedCap requirements are less demanding than those for enhanced Mobile Broadband (eMBB) or Ultra-Reliable Low-Latency Communication (URLLC), they are also not as battery-efficient as those targeted by massive Machine-Type Communication (mMTC). The range of performance needs among the three use cases is quite broad, yet there is a strong motivation to support all of them with a single RedCap device type. This unified approach helps minimize market fragmentation and improves cost-efficiency through economies of scale.

Table25:- The specific Requirements for RedCap use cases

	Wearables	Industrial wireless sensors	Video surveillance
Data rate (Reference bit rate)	5-50 Mbps in DL and 2-5 Mbps in UL[1]	2 Mbps	2-4 Mbps for economic video 7.5-25 Mbps for high-end video
Latency	-	100 ms	500 ms
Availability/reliability	-	99.99%	99%-99.9%
Device battery lifetime	At least few days and up to 1-2 weeks	At least few years	-
Traffic pattern	-	UL heavy	UL heavy
Stationarity	Non-stationary	Stationary	Stationary
Note 1: Peak bit rate for wearables can be up to 150 Mbps in DL and 50 Mbps in UL.			

It's important to note that the use cases listed in Table 24 are representative examples; RedCap is also suitable for other use cases with similar technical demands. Beyond these specific requirements, RedCap is designed to offer lower cost, reduced complexity, and smaller device size compared to high-end eMBB and URLLC devices. However, RedCap is not meant for low-power wide-area (LPWA) applications, which are already addressed by LTE-M and NB-IoT technologies.

RedCap aims to provide coverage comparable to 3GPP Release 15/16 NR devices and should be deployable across all FDD and TDD frequency bands in both Frequency Range 1 (FR1: 0.4–7.1 GHz) and Frequency Range 2 (FR2: 24.2–52.6 GHz).

5.6 COEXISTENCE, COVERAGE, AND CAPACITY IMPACTS: -

5.6.1 Coexistence with other NR devices: -

To ensure smooth operation, one of the main goals in designing RedCap devices was to nsure their seamless coexistence alongside regular NR (New Radio) devices. However, a few challenges were identified during this process. The first issue was how to identify RedCap devices early during the random-access procedure, especially when they share the same carrier with regular NR devices. Normally, the network only learns about a device's full capabilities after it connects, but this can lead to inefficient scheduling. To solve this, Release 17 introduced a way for RedCap devices to indicate their reduced capability earlier in the process—through dedicated indications in the random-access messages rather than waiting until full connection.

The second challenge was related to how RedCap devices use bandwidth. Since they operate on narrower bandwidths than regular NR devices, using the same initial bandwidth settings could cause interference and waste resources. To fix this, Release 17 allows RedCap devices to have their own special initial bandwidth settings (called BWPs), and even lets the network disable certain features like PUCCH frequency hopping, which previously caused issues. These changes help place RedCap transmissions in a way that avoids disturbing other users on the network.

In addition, the design takes into account trade-offs between flexibility, device performance, and signaling overhead. For example, using shared bandwidth settings between RedCap and other devices reduces the need for extra signals and improves energy efficiency. Also, if needed, the network can block RedCap devices from accessing the carrier by using a setting in the system information. This can be helpful in situations such as congestion management or scenarios where RedCap traffic may degrade higher-priority services.

5.6.2 Coverage impacts: -

RedCap (Reduced Capability) devices are designed to be smaller and more affordable by using simpler hardware, such as fewer antennas and narrower bandwidth. While this helps reduce cost and size, it can also affect how well these devices connect to the network—especially in terms of coverage. To evaluate this, a detailed study was conducted to understand how much the reduced capabilities impact RedCap's performance in different real-world scenarios.

The analysis looked at both uplink (device to network) and downlink (network to device) communication. It included various network messages involved in the connection process and considered deployment environments like rural and urban areas (both large and small cells) in lower frequency bands (FR1), as well as indoor environments in higher frequency bands (FR2).

A key measure used in the study was Maximum Coupling Loss (MCL)**,** which reflects how much signal loss a device can handle while still maintaining a connection. The performance of RedCap devices was compared to that of a standard 5G device (from earlier releases) with basic features. If any channel on a RedCap device had worse coverage than the weakest channel on the reference device, that channel was marked as needing improvement.

The main findings were:

- **Uplink (UL):** RedCap devices performed well in both FR1 and FR2 with no need for coverage improvement.
- **Downlink (DL) in FR1:** Some improvements were needed for specific messages in crowded urban areas if the device had only one receiving antenna. Devices with two antennas didn't face this issue.

- **Downlink (DL) in FR2:** Whether improvements were needed depended on how much power the device could transmit. At higher power (23 dBm), some downlink channels might need help. At lower power (12 dBm), they generally performed well.

In the early study, it was assumed that RedCap devices would have slightly less efficient antennas, due to their smaller size. This made the results more cautious. However, this assumption was not used in the final conclusions.

Importantly, no new methods were needed to fix the coverage gaps. Existing techniques from earlier 5G standards—like retransmitting messages or adjusting message sizes—were found to be sufficient. Additional improvements from Release 17 can also be applied if necessary. Overall, RedCap devices can achieve acceptable coverage with proper configuration, without requiring major changes to the network.

5.6.3 Capacity impacts: -

There may be concerns that RedCap devices, because of their lower capabilities, could negatively affect the performance of other users in the network—particularly those using enhanced Mobile Broadband (eMBB) services.

To examine this, system-level simulations were conducted using typical network conditions. The study focused on how eMBB users' downlink (DL) data speeds are affected as the proportion of RedCap users in a cell increases (up to 90%) in a 2.6 GHz frequency band. The results showed that eMBB users with strong signal quality (top 5%) experienced little to no change in their download speeds, even as the number of RedCap devices increased. However, users with average or weaker signals saw a slight drop in speed as more RedCap devices were added. This is mainly because RedCap devices are less efficient in using network resources, requiring more bandwidth for the same amount of data. Still, since RedCap devices generate much less traffic—about 50 times less than an eMBB user—their overall impact on the network is minimal.

In fact, significant performance differences only appeared when RedCap devices made up 90% of the users in a cell, which is unlikely in real-world situations. Overall, the presence of RedCap devices is not expected to seriously affect the experience of eMBB users under normal network conditions.

5.7 Future Direction

RedCap represents a strategic direction for scalable, future-ready IoT deployments that align with 5G’s core goals: flexibility, ultra-reliability, and low latency. It is not a direct replacement for NB-IoT or LTE-M but rather an expansion of the 5G IoT portfolio, giving operators and manufacturers a continuum of options based on cost, performance, and network environment.

As 5G matures globally, RedCap is expected to serve as the natural migration path for LTE-M and NB-IoT applications needing more capability — especially in regions phasing out legacy LTE networks.

Table26:- Comparison of LPWA Technologies

Feature	NB-IoT	LTE-M	EC-GSM-IoT	RedCap
Standardization Release	Rel-13 (2016), enhanced up to Rel-18	Rel-13 (2016), enhanced up to Rel-18	Rel-13 (2016), stable after Rel-14	Rel-17 (2021), evolving in Rel-18
Spectrum/Bandwidth	180 kHz (Standalone, In-band, Guard-band)	1.4 MHz (in LTE spectrum)	Reuses GSM bands (850/900 MHz)	5G NR, reduced bandwidth (20 MHz FR1, 100 MHz FR2)
Peak Data Rate	Uplink ~66 kbps, Downlink ~26 kbps	Up to 1 Mbps	Up to 350 kbps	Up to ~150 Mbps
Link Budget (MCL)	Up to 164 dB	Up to ~155 dB	Up to 164 dB	Standard NR coverage (lower than NB-IoT/EC-GSM)
Battery Life	10-15 years (PSM, eDRX)	10+ years (PSM, eDRX)	10+ years (PSM, eDRX)	Optimized but lower than NB-IoT (multi-year with duty cycling)
Mobility Support	Initially static (Rel-13), mobility from Rel-14	Full mobility (Rel-13 onwards)	GSM-based mobility	Yes (full NR mobility)
Voice Support	No	Yes (VoLTE)	No (SMS fallback possible)	Yes
5G Integration	Rel-15 (5GC support)	Rel-15 (5GC support)	Not supported	Native NR technology (5GC)
NTN Support	Rel-17 (LEO/GEO satellite support)	Rel-17 (satellite IoT support)	Not supported	Yes (designed for NTN use cases)
Use Cases	Smart metering, agriculture, environment monitoring, smart cities	Wearables, healthcare, asset tracking, industrial sensors	Emerging markets with GSM infra, utilities, basic IoT	Industrial IoT, surveillance cameras, wearables needing mid-rate data

Chapter 6: Role of 5G in IoT & 3GPP Release 18 – Key Innovations

6.1 Role of 5G in IoT

The fifth generation of mobile networks, or 5G, represents a fundamental shift in the capabilities of wireless connectivity and its application to the Internet of Things (IoT). 5G was designed with three primary categories of service in mind: Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC), and Massive Machine Type Communications (mMTC). Among these, mMTC holds the most relevance for IoT applications, as it targets the need to connect a vast number of devices that are low-cost, low-power, and often transmit data intermittently—such as smart meters, environmental sensors, and tracking devices. The flexibility and scalability of 5G make it uniquely suited to support this massive IoT deployment.

6.1.1 LPWA Technologies in the 5G Ecosystem

Low Power Wide Area (LPWA) technologies such as NB-IoT and LTE-M were standardized in earlier 3GPP releases but have now been officially incorporated into the 5G standards beginning with Release 15. According to documentation from 3GPP and GSMA, both NB-IoT and LTE-M are considered compliant with 5G and can be deployed over either the LTE Evolved Packet Core (EPC) or the 5G Core (5GC). This dual compatibility ensures a seamless evolution for existing deployments while enabling new deployments to benefit from the advanced features of 5GC.

Retaining NB-IoT and LTE-M in the 5G ecosystem is strategic. These technologies provide extended battery life of over 10 years, deep indoor coverage due to high Maximum Coupling Loss (MCL), and ultra-low device costs—features not addressed by standard 5G NR. Furthermore, NB-IoT and LTE-M benefit from global roaming and an established vendor and operator ecosystem, making them invaluable for international and scalable IoT applications.

6.1.2 Timeline and Migration Path

The evolution of LPWA technologies in the 5G context follows a structured roadmap defined by successive 3GPP releases. Release 13 in 2016 saw the introduction of NB-IoT and LTE-M as foundational LPWA solutions. Releases 14 and 15 brought significant enhancements in mobility, voice support, multicast capabilities, and the initial steps toward integration with the 5G core network. Releases 16 and 17 introduced further optimizations such as power-saving techniques, satellite connectivity (NTN), and paved the way for the new RedCap (Reduced Capability NR) device category. Release 18 and beyond focus on advancing 5G for industrial and vertical-specific use cases.

6.2 3GPP Release 18 – Key Innovations

Release 18 marks the transition into 5G Advanced, bringing significant improvements to RedCap and LPWA technologies:

A. RedCap Enhancements

Release 18 introduces a set of important enhancements to RedCap devices, aimed at improving both performance and efficiency. One of the key upgrades is the improvement in uplink throughput and coverage, which enables RedCap terminals to deliver more reliable data transmission even in challenging radio environments. This ensures better support for applications that require consistent connectivity without significantly increasing device complexity.

Another notable enhancement is the simplification of RF requirements, which makes it easier and more cost-effective for manufacturers to design and produce RedCap devices. By reducing hardware complexity while maintaining compliance with 5G standards, Release 18 encourages wider adoption of RedCap in cost-sensitive markets such as industrial sensors, wearables, and smart utilities.

Additionally, mobility and dormancy management have been significantly improved. These enhancements allow RedCap devices to handle transitions between different network states more efficiently, conserving power while maintaining seamless connectivity in dynamic environments. This is particularly valuable for mobile and energy-constrained applications, ensuring that RedCap continues to balance affordability, performance, and efficiency in the evolving 5G ecosystem.

B. NB-IoT and LTE-M Upgrades

Release 18 also brings notable upgrades to NB-IoT and LTE-M, strengthening their role in the evolving 5G ecosystem. One of the key additions is the introduction of multicast capabilities for firmware over-the-air (FOTA) delivery, which allows operators to update a large number of NB-IoT endpoints simultaneously, reducing network load and improving efficiency in device management. Alongside this, idle-mode mobility tracking has been enhanced, a feature that is particularly crucial for asset-tracking applications where devices frequently change locations and need continuous connectivity with minimal signaling overhead. Furthermore, Release 18 introduces initial support for cross-RAT mobility, enabling devices to transition seamlessly between NB-IoT and RedCap in areas where coverage is mixed. This ensures more reliable service continuity and smooth interoperability across different IoT technologies.

C. Satellite (NTN) Support Expansion

Release 18 significantly expands support for non-terrestrial networks (NTN), enabling NB-IoT and LTE-M to operate across GEO, MEO, and LEO satellite constellations. This advancement provides truly ubiquitous coverage, extending the reach of IoT services to remote and underserved areas where terrestrial networks are limited or unavailable. By integrating satellite connectivity, IoT applications such as agriculture, logistics, maritime, and environmental monitoring can benefit from seamless global connectivity.

In addition, the release introduces improvements in timing advance handling and differential signal processing, which are essential for devices operating in NTN environments. These refinements address challenges caused by longer propagation delays and varying signal conditions in satellite communication. As a result, NB-IoT and LTE-M devices can maintain reliable connections with better efficiency and performance, even under the demanding conditions of satellite links.

D. Power Efficiency and Slicing

Release 18 also strengthens RedCap and LTE-M by introducing updates that enable network slicing support, allowing these devices to benefit from differentiated Quality of Service (QoS). This feature is particularly important for industrial automation and healthcare applications, where guaranteed reliability and priority handling of data traffic are critical. With slicing, operators can dedicate specific network resources to RedCap and LTE-M devices, ensuring that mission-critical services are delivered with the necessary performance and consistency.

Alongside slicing, improvements have been made to Discontinuous Reception (DRX) mechanisms, which optimize power-saving modes for LPWA devices connected to 5G networks. These updates allow devices to spend longer periods in low-power states without compromising responsiveness, thereby extending battery life while maintaining reliable connectivity. Together, these enhancements make RedCap and LTE-M better suited for power-sensitive IoT deployments that also demand high service reliability.

Chapter 7: Global and India-Specific Deployment Scenarios of LPWA IoT Technologies

The global deployment of LPWA technologies such as NB-IoT, LTE-M, EC-GSM-IoT, and now RedCap, has accelerated due to their ability to support massive-scale IoT with high energy efficiency and wide coverage. RedCap is newer and still being standardized; its global deployment is limited compared to NB-IoT and LTE-M. Regional preferences, spectrum availability, and existing network infrastructure have influenced the adoption patterns across continents. According to GSMA Intelligence, smart utilities IoT connections are expected to reach approximately 3.5 billion by 2030, up from around 1.7 billion in 2021.

7.1 Global Deployment Overview

By mid-2025, more than 147 operators across 68 countries had launched or deployed NB-IoT and LTE-M networks, and around 176 operators in 84 countries were actively investing in NB-IoT. These figures are consistent with GSMA Intelligence data; additionally, approximately 448 public LPWA networks were planned or operating in 87 countries at the start of 2023, with NB-IoT accounting for roughly half of all LPWA deployments.

- Europe

  European countries have broadly embraced NB-IoT and LTE-M. Germany has extensive coverage through Deutsche Telekom and Vodafone, supporting smart meters and logistics. Vodafone Spain, for instance, has covered the entire country with NB-IoT and supports over 9 million devices. Other countries such as Italy, Netherlands, UK, and Hungary have nationwide NB-IoT and LTE-M rollouts. These deployments are mostly in-band or guard-band within LTE spectrum, enabling integration with existing infrastructure and supporting industrial IoT, utilities, and smart city applications.

- United States & Canada

  In North America, major operators like AT&T, T-Mobile, and Verizon have deployed both NB-IoT and LTE-M. AT&T, for instance, had over 117 million NB-IoT connections before shifting focus to LTE-M for future IoT services. LTE-M is preferred in the US for applications requiring better mobility and lower latency, such as wearables, mobile asset tracking, and healthcare. Canadian operators such as Telus and Rogers have also rolled out both technologies, providing nationwide coverage, particularly on bands 4, 5, and 12. The North American market shows a relative preference for LTE-M due to its enhanced mobility and support for higher-end IoT applications.

- Asia-Pacific (Outside China)

  Several Asia-Pacific nations have made significant progress in LPWA deployments. South Korea’s KT and LG Uplus have launched NB-IoT nationwide, while SK Telecom has deployed LTE-M. Japan, led by NTT Docomo and SoftBank, has LTE-M and NB-IoT for transportation, logistics, and utilities. NTT Docomo terminated its NB-IoT network in

2020; SoftBank focuses on LTE-M. In Southeast Asia, countries like Singapore, Malaysia, Thailand, Indonesia, and Vietnam have launched NB-IoT and/or LTE-M services through operators such as Singtel, Maxis, and Telkomsel. Most deployments in this region use LTE in-band strategies for smart city applications and rural agricultural IoT.

- Australia & New Zealand

  In Australia, both Telstra and Optus have rolled out NB-IoT and LTE-M networks. Telstra uses NB-IoT on bands 3 and 28 and offers nationwide LTE-M coverage. These networks support applications like smart agriculture, water metering, and infrastructure monitoring. Similarly, New Zealand's major providers, including Vodafone NZ and Spark, have deployed NB-IoT, primarily for smart utilities and environmental monitoring, operating mainly on bands 3 and 28, per verified sources.

- Latin America

  NB-IoT is growing steadily across Brazil, Argentina, Chile, Colombia, and Mexico, primarily through operators like Claro, Movistar, and Entel. These deployments often serve utilities, asset tracking, and environmental monitoring. LTE-M is limited but increasing, particularly in urban centers; Movistar Colombia launched LTE-M in Feb 2024, Entel Chile introduced NB-IoT in Oct 2023. Countries are generally using a standalone or in-band deployment mode, depending on spectrum availability and operator strategy.

- Africa

  LPWA adoption in Africa is emerging but still limited in scope. Countries like South Africa (Vodacom) and Kenya (Safaricom) have launched NB-IoT services using bands like 3, 8, and 28. NB-IoT is primarily applied in agriculture, utility metering, and logistics. Sigfox, a non-cellular LPWA technology operated by UnaBiz, provides coverage in parts of North and West Africa. LTE-M deployment remains sparse but is anticipated to grow as urban digitization progresses.

7.2 Deployment Scenarios in India

India represents a unique market for LPWA technologies, given its vast geography, diverse network infrastructure, and strong push for digital public infrastructure. In India, the deployment of Low Power Wide Area (LPWA) technologies is still emerging, with Narrowband IoT (NB-IoT) gradually becoming the preferred technology for large-scale low-power IoT use cases. NB-IoT deployment is primarily driven by government and enterprise projects; LTE-M is not yet widely deployed. Cellular LPWA initiatives are primarily led by government and enterprise contracts, particularly in smart utility metering, smart city infrastructure, and agricultural monitoring. The focus in India is primarily on NB-IoT due to its compatibility with existing GSM networks and suitability for deep rural coverage.

While TRAI and DoT have not published granular subscriber-level NB-IoT figures, operator announcements combined with market studies indicate steady progress. The National Smart Grid Mission has partially rolled out smart electricity meters across states that leverage cellular connectivity like NB-IoT, though precise penetration data is not yet available in public government releases.

LPWA deployment in India is often facilitated through enterprise and utility contracts rather than individual consumer subscriptions, highlighting its enterprise-led model.

Technical and Strategic Advantages

NB-IoT with its use of licensed sub-GHz spectrum (e.g., 900 MHz) delivers deep indoor and rural penetration, making it well-suited for utility metering and urban sensor networks. This approach avoids the complexity and cost associated with deploying mesh or proprietary LPWA networks, especially in areas with Right-of-Way constraints

In summary, LPWA deployment in India is principally NB-IoT-focused, driven by state-level and utility contract-based implementations. Government missions and regulatory bodies provide a supportive policy and standards framework, while commercial interest centers on pilots that are gradually translating into enterprise deployments. While LTE-M awaits broader rollout, NB-IoT is seen as the cornerstone of India's cellular IoT strategy, especially for smart meters, environmental sensing, and municipal infrastructure.

Chapter 8: Government Initiatives and Regulatory Aspects

GSMA 2023 report on IoT and Essential Utility Services: India market case study explores how India is harnessing Internet of Things (IoT) technologies to improve delivery and efficiency across essential utility services such as energy, water, sanitation, waste management, and transport. These developments are largely supported by the Indian government's Digital India initiative, the Smart Cities Mission, and schemes like the Production Linked Incentive (PLI), which have created a favourable policy and investment climate. Additionally, India benefits from a rapidly maturing mobile ecosystem.

In the energy sector, India is undertaking one of the world's largest smart meter rollouts, aiming to replace 250 million traditional meters by 2025. These smart meters, many of which are now manufactured locally, provide real-time usage data, reduce losses in transmission and distribution, and support advanced features like time-based tariffs.

In the water sector, India stands out as a leader among its peers. The Ministry of Jal Shakti has introduced several pilots using IoT to monitor rural drinking water systems, including through partnerships with solution providers like Vassar Labs. These systems track groundwater levels, water quality, pressure, and flow, sending real-time data via mobile or satellite networks to centralized platforms. IoT is also used in smart water meters, water ATMs, and treatment systems, although large-scale deployment of smart water meters remains limited due to the low pricing of water.

The sanitation sector is seeing innovation under the Swachh Bharat Mission (SBM) and its successor SBM 2.0. IoT-enabled solutions such as smart public toilets (like those from GARV Toilets) and sensor-based sewer monitoring systems are being deployed in urban areas to enhance cleanliness and operational efficiency. Cities, such as Gurugram, have implemented alert systems for manhole overflow detection, though challenges like short device battery life and limited LPWAN infrastructure persist.

India's waste management infrastructure is being digitally transformed using IoT for better route planning, container fill level monitoring, and tracking of waste collection vehicles. For instance, Lucknow Municipal Corporation has successfully used IoT to increase door-to-door garbage collection from 60% to 100% by integrating NFC tags, GPS, and fill-level sensors. These systems improve service delivery, reduce overflow incidents, and support predictive planning.

In the transport sector, the Indian government is integrating IoT into urban mobility through smart public transport systems, vehicle tracking, electronic fare collection, and more. Companies like NEC have partnered with local authorities to digitize bus rapid transit systems in cities like Ahmedabad, Pune, and Surat. Additionally, India's growing focus on electric vehicles (EVs) and drone deliveries is opening new use cases for IoT—ranging from tracking EV usage and battery health to enabling last-mile delivery services.

Government Initiatives

Table27:- List of Government initiatives

Initiative	Focus Technologies	Deployment Area	Highlights
Smart Cities Mission	LPWA (NB-IoT, LoRa)	100+ cities	Smart metering, lighting, sensors, digital infrastructure
Digital India & IoT Centers	LPWA, 5G-RedCap	Nationwide, R&D centers	IoT incubation, hardware labs, manufacturing incentives
Smart Meter Roll-Out	LPWA (NB-IoT)	Utilities/All India	Mandatory local value addition, grid digitization
Spectrum & Regulatory Framework	LPWA, 5G-RedCap	National	Adaptation of spectrum policies, technology trials, regulatory support
Pollution Control Monitoring	LPWA	Urban/Rural	Air/water quality monitoring via LPWA-based IoT
5G Use Case Labs	5G-RedCap	Academic / R&D institutions	Technology pilots, industrial applications, government-funded labs
Make in India for IoT/5G/RedCap	LPWA, 5G-RedCap	Nationwide, manufacturing	Manufacturing incentives for hardware, chip, module, and network equipment production

Use Cases

Table28:- Use Cases for LPWA Tech

Sector	Applications	Preferred LPWA Tech
Utilities	Smart water/electric meters	NB-IoT
Agriculture	Soil moisture, crop health monitoring	NB-IoT, EC-GSM-IoT
Transportation	Asset tracking, toll booth automation	LTE-M
Healthcare	Wearables, remote vitals monitoring	LTE-M, RedCap
Industry 4.0	Condition-based monitoring in factories	RedCap (trial stage)

Spectrum Utilization in India

- **NB-IoT**: 900 MHz (Band 8) and 1800 MHz (Band 3) re-farmed spectrum from GSM.
- **LTE-M**: Trials using 1.4 MHz channels on LTE bands (Band 40, Band 3).
- **RedCap**: Will use existing 5G NR spectrum (Band n78) with reduced complexity.

Chapter 9: Conclusion

The evolution of Low Power Wide Area (LPWA) technologies—namely NB-IoT (Narrowband Internet of Things), LTE-M (Long Term Evolution for Machines), EC-GSM-IoT (Extended Coverage GSM IoT), and RedCap (Reduced Capability 5G NR)—has laid a strong foundation for India's digital transformation in the Internet of Things (IoT) domain. These technologies are enabling critical infrastructure, smart city solutions, and industry-specific automation to scale sustainably and affordably across diverse Indian geographies. As India positions itself as a digital-first, self-reliant economy, the confluence of policy interventions, market readiness, and indigenous innovation has created a dynamic and promising future for LPWA technologies in India.

NB-IoT: Cementing Its Role in Utility and Rural Connectivity

NB-IoT has emerged as a front-runner for wide-area IoT deployments, particularly due to its deep penetration, low energy consumption, and compatibility with existing GSM infrastructure. Its licensed spectrum operation ensures minimal interference, making it a preferred technology for mission-critical applications such as smart metering, utility grid automation, and rural monitoring.

The Indian government has already made significant strides in embracing NB-IoT through initiatives such as the National Smart Grid Mission and the Revamped Distribution Sector Scheme (RDSS). With over 250 million smart meters projected to be deployed by 2030, NB-IoT is poised to become the de facto protocol for meter connectivity due to its high spectral efficiency, energy-saving features, and wide rural reach. Network operators like Reliance Jio have established near-national NB-IoT coverage, enabling not only public utilities but also private players to launch scalable IoT services in agriculture, logistics, and environmental monitoring.

Additionally, NB-IoT's relevance in precision farming and rural IoT is becoming increasingly evident. The Ministry of Agriculture, in collaboration with ICAR and TRAI, has initiated NB-IoT pilots for soil monitoring, remote irrigation, and livestock tracking. These applications address India's core challenges of agricultural productivity, water conservation, and food security, while leveraging NB-IoT's low power footprint and long battery life.

In the coming years, NB-IoT will form the backbone of rural connectivity solutions, especially in combination with the BharatNet optical fiber backhaul and L-band satellite LPWA. Such hybrid models will ensure that even remote and underserved locations are integrated into the national IoT framework.

LTE-M: Bridging Massive IoT and Mobile Mobility

While NB-IoT focuses on static, low-bandwidth, and delay-tolerant use cases, LTE-M fills the gap for IoT applications that require mobility, voice support, and relatively higher data rates. LTE-M offers better latency and supports handover, which is crucial for asset tracking, mobile health monitoring, and connected vehicles.

In India, LTE-M remains in a nascent stage compared to NB-IoT, with limited commercial deployments. However, Bharti Airtel and Vi have been exploring LTE-M in controlled environments, particularly for industrial IoT and private campus networks. Given its backward compatibility with LTE infrastructure, LTE-M can be rapidly scaled without substantial spectrum reallocation or hardware overhaul.

As 5G networks continue to roll out, LTE-M could serve as a bridge technology, offering affordable, reliable mobile IoT services in areas where RedCap adoption is still maturing. Moreover, LTE-M's strong encryption and QoS capabilities make it suitable for applications in digital health, wearable tracking, and public safety, where reliability and data integrity are paramount.

Despite the relatively low uptake in India thus far, LTE-M is expected to play a strategic role in urban mobility, healthcare logistics, and emergency communication, especially as India advances toward a multi-tiered IoT ecosystem.

EC-GSM-IoT: Low-Cost Coverage for Legacy Networks

EC-GSM-IoT is designed to extend the life and reach of existing 2G networks, offering low-cost, backward-compatible LPWA connectivity. This makes it particularly relevant for low-bandwidth rural deployments, where infrastructure upgrade costs remain a constraint.

India's vast 2G footprint, covering more than 90% of the population, offers fertile ground for EC-GSM-IoT, particularly in remote sensing, agricultural telemetry, and basic utility metering. While not as commercially prominent as NB-IoT or RedCap, EC-GSM-IoT serves as a cost-effective entry point for small-scale or resource-constrained IoT projects, especially in mountainous and tribal areas with limited network upgrades.

The government and rural development agencies may continue to support EC-GSM-IoT for its affordability and alignment with legacy systems, ensuring inclusive digital participation across the nation.

RedCap: 5G's Optimized Edge for Industrial and Mission-Critical IoT

RedCap, or Reduced Capability NR, is a relatively recent 3GPP enhancement tailored for low-cost, moderate-complexity IoT devices within 5G networks. It is engineered to deliver a balance of performance and power efficiency, targeting devices that are too demanding for NB-IoT or LTE-M but do not require the full capabilities of 5G eMBB or URLLC.

India's LPWA roadmap increasingly acknowledges RedCap as a cornerstone for next-generation industrial automation, smart logistics, and private 5G networks. Sectors such as steel, cement, pharmaceuticals, and ports are early candidates for RedCap-based connectivity. With the n78 band being widely earmarked for 5G deployments, RedCap will allow these industries to roll out private 5G networks that support condition-based maintenance, autonomous guided vehicles, and intelligent robotics, while keeping device costs manageable.

Moreover, RedCap is expected to benefit from PLI schemes focused on chipset manufacturing, allowing India to nurture a local hardware ecosystem that aligns with Make in India and

Atmanirbhar Bharat missions. As device standardization and mass production accelerate, RedCap will become the default LPWA choice for high-performance yet cost-sensitive industrial use cases.

Convergence and Interoperability: The Path Ahead

A key insight from India's LPWA evolution is the need for interoperability across technologies and networks. NB-IoT and EC-GSM-IoT may dominate in utilities and rural segments, while RedCap and LTE-M find relevance in urban and industrial deployments. Thus, a layered architecture that allows devices to seamlessly switch between LPWA protocols based on location, application, and network availability will become essential.

This convergence will also be driven by cloud-native IoT platforms, edge computing, and AI-based analytics, which will aggregate data from multi-protocol sources for real-time decision-making. Mobile operators and system integrators will play a crucial role in managing this complex ecosystem, offering end-to-end LPWA solutions bundled with connectivity, cloud hosting, analytics, and device management.

Abbreviations

Abbreviation	Full Form
3GPP	3rd Generation Partnership Project
ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
AWGN	Additive White Gaussian Noise
BT_Threshold	Broadcast Threshold
BS	Base Station
CC	Coverage Class
Cat-M1	Category M1 (LTE-M UE Category)
Cat-M2	Category M2 (LTE-M UE Category)
CQI	Channel Quality Indicator
DL	Downlink
E-CID	Enhanced Cell ID
EAB	Extended Access Barring
EC-GSM-IoT	Extended Coverage GSM for Internet of Things
eDRX	Extended Discontinuous Reception
eMBMS	evolved Multimedia Broadcast Multicast Service
eMTC	enhanced Machine-Type Communication
EPC	Evolved Packet Core
EUTRA	Evolved Universal Terrestrial Radio Access
GEO	Geostationary Earth Orbit
GSM	Global System for Mobile Communications
IoT	Internet of Things
LEO	Low Earth Orbit
LPWA	Low Power Wide Area
LTE	Long Term Evolution
LTE-M	Long Term Evolution for Machines
MCL	Maximum Coupling Loss
MEO	Medium Earth Orbit
mMTC	massive Machine-Type Communications
NAS	Non-Access Stratum
NB-IoT	Narrowband Internet of Things
NIDD	Non-IP Data Delivery
NR	New Radio
NTN	Non-Terrestrial Networks
OFDMA	Orthogonal Frequency Division Multiple Access
OTDOA	Observed Time Difference of Arrival
PDCP	Packet Data Convergence Protocol
PEO	Power Efficient Operation
PMI	Precoding Matrix Indicator
PSM	Power Saving Mode

QoS	Quality of Service
RAN	Radio Access Network
RB	Resource Block
RedCap	Reduced Capability (NR)
REF-SENS	Reference Sensitivity
RLC	Radio Link Control
RRC	Radio Resource Control
SC-FDMA	Single Carrier Frequency Division Multiple Access
SINR	Signal to Interference plus Noise Ratio
SRB	Signaling Radio Bearer
TR	Technical Report
TS	Technical Specification
TDD	Time Division Duplex
UE	User Equipment
UL	Uplink
VoLTE	Voice over LTE

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