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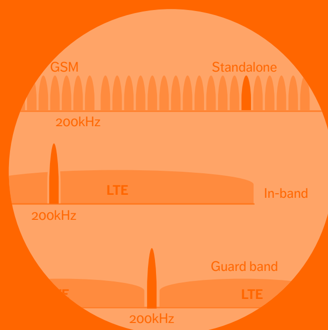
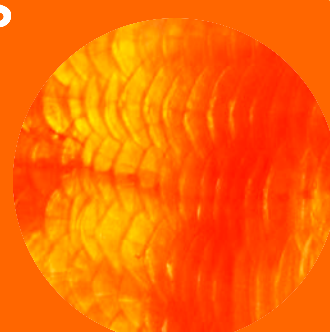
Review

ERICSSON TECHNOLOGY



NB-IOT: A SUSTAINABLE TECHNOLOGY FOR CONNECTING BILLIONS OF DEVICES



ERICSSON

NB-IoT:

A SUSTAINABLE TECHNOLOGY FOR **CONNECTING BILLIONS OF DEVICES**

Under the umbrella of 3GPP, radio-access technologies for mobile broadband have evolved effectively to provide connectivity to billions of subscribers and things. Within this ecosystem, the standardization of a radio technology for massive MTC applications – narrowband IoT (NB-IoT) – is also evolving. The aim is for this technology to provide cost-effective connectivity to billions of IoT devices, supporting low power consumption, the use of low-cost devices, and provision of excellent coverage – all rolled out as software on top of existing LTE infrastructure. The design of NB-IoT mimics that of LTE, facilitating radio network evolution and efficient coexistence with MBB, reducing time to market, and reaping the benefits of standardization and economies of scale.

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THE BEST WAY to provide MTC applications with cost-effective connectivity is to design the radio-access network accordingly. What is needed is a radio-access network that minimizes battery usage, covers a wide area, and functions with simplified low-cost devices while efficiently matching the varying spectrum allocations of operators. 3GPP release 13 specifications includes the NB-IoT feature, with a large degree of deployment flexibility to maximize migration possibilities and allow the technology to be deployed in GSM spectrum, in an LTE carrier, or in a WCDMA or LTE guard band.

The IoT embeds a broad range of MTC applications, and among the different types, it is widely accepted that massive MTC will be the first to take off. This segment includes applications like smart metering, agriculture and real estate monitoring, as well as various types of tracking and fleet management. Often referred to as low power wide area (LPWA), networks that provide connectivity to massive MTC applications require a radio-access technology that can deliver widespread coverage, capacity, and low power consumption.

Massive MTC devices typically send small amounts of data, and tend to be placed in signal-challenged locations like basements and remote rural areas. Due to the sheer numbers of devices deployed in typical scenarios, per-device and life-cycle costs need to be kept to a minimum, and measures that promote battery longevity are essential for ensuring the overall cost-effectiveness of the system.

The coverage and throughput needs for massive MTC applications are quite different from those of MBB. The need to support high bitrates, for example, applies to MBB scenarios, but seldom to massive MTC. The precise nature of massive MTC allows for a significant degree of optimization in the design of radio access.

Standardization of NB-IoT began in 2014 with a 3GPP study. The objective of this study was to determine the requirements for massive MTC, to choose an evaluation methodology, and to investigate whether proposed radio-access designs could meet the set requirements. This study led to work on the specification of NB-IoT [1], with a number of design targets – as illustrated in *Figure 1*.

In addition to the design targets, extensive deployment flexibility and use of industry competence to meet time-to-market requirements

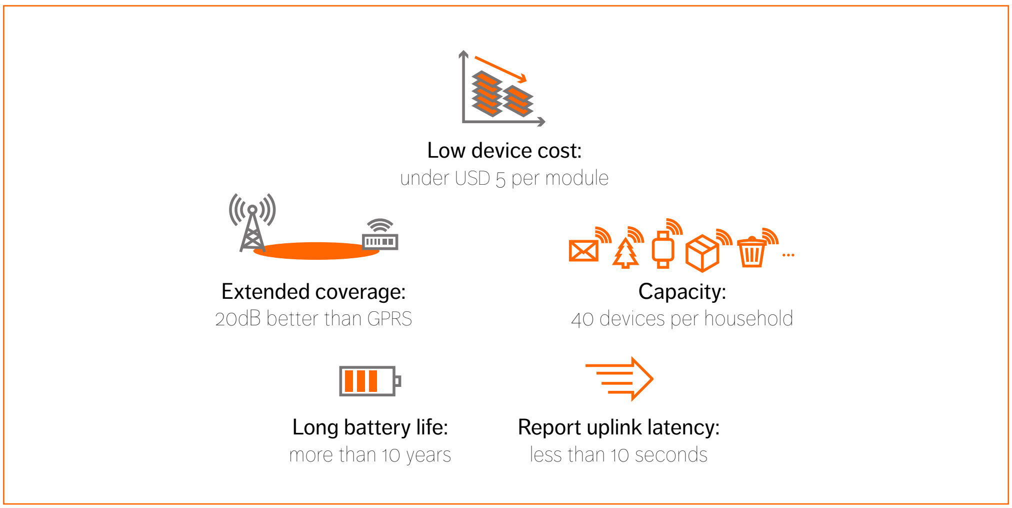

Figure 1: IoT design targets

Terms and abbreviations

CS–circuit-switched | **DL**–downlink | **DRX**–discontinuous reception | **eDRX**–extended DRX | **eMBMS**–evolved multimedia broadcast multicast service | **eMTC**–enhanced machine-type communications | **EPC**–Evolved Packet Core | **E-UTRA**–Evolved Universal Terrestrial Radio Access | **IoT**–Internet of Things | **LPWA**–low power wide area | **MAC**–media/medium access control | **MBB**–mobile broadband | **MTC**–machine-type communications | **NB-IoT**–narrowband Internet of Things | **OFDMA**–Orthogonal Frequency-Division Multiple Access | **PA**–power amplifier | **PRB**–physical resource block | **PSM**–power save mode | **RF**–radio frequency | **RLC**–Radio Link Control | **RRC**–Radio Resource Control | **SC-FDMA**–single-carrier frequency-division multiple access | **TCO**–total cost of ownership | **UE**–user equipment | **UL**–uplink have been included as key considerations in the specification of NB-IoT. To future-proof the technology, its design exploits synergies with LTE by reusing the higher layers (RLC, MAC, and RRC), for example, and by aligning numerology (the foundation of the physical layer) in both the uplink and downlink. However, the access procedures and control channels for NB-IoT are new.

Prior to NB-IoT specification, work had already begun on the design of another radio access for massive MTC to support Cat-M1 – a new UE category. With completion also targeted for release 13, the resulting standardization work item – eMTC – covers bitrates, for example, ranging from hundreds of kbps to 1Mbps. These requirements are broader than NB-IoT, which has been streamlined for applications with widely varying deployment characteristics, lower data rates, and operation with simplified low-cost devices.

With a carrier bandwidth of just 200kHz (the equivalent of a GSM carrier), an NB-IoT carrier can be deployed within an LTE carrier, or in an LTE or WCDMA guard band*. The link budget of NB-IoT has a 20dB improvement over LTE Advanced. In the uplink, the specification of NB-IoT allows for many devices to send small amounts of data in parallel.

*Guard band is a thin band of spectrum between radio bands that is used to prevent interference.

Release 13 not only includes standards for eMTC and NB-IoT, it also contains important refinements, such as extended discontinuous reception (eDRX) and power save mode (PSM). PSM was completed in release 12 to ensure battery longevity, and is complemented by eDRX for use cases involving devices that need to receive data more frequently.

Deployment flexibility and migration scenarios

As a finite and scarce natural resource, spectrum needs to be used as efficiently as possible. And so technologies that use spectrum tend to be designed to minimize usage. To achieve spectrum efficiency, NB-IoT has been designed with a number of deployment options for GSM, WCDMA, or LTE spectrum, which are illustrated in *Figure 2*.

- **standalone – replacing a GSM carrier with an NB-IoT carrier**
- **in-band – through flexible use of part of an LTE carrier**
- **guard band – either in WCDMA or LTE**

Starting with standalone

The standalone deployment is a good option for WCDMA or LTE networks running in parallel with

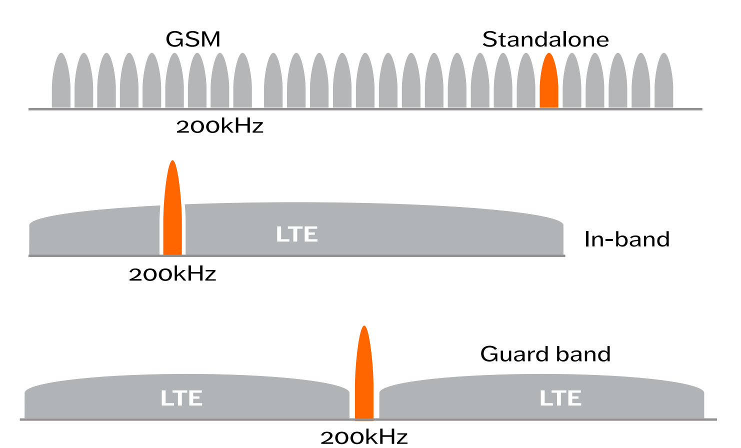

Figure 2: Spectrum usage deployment options

GSM. By steering some GSM/GPRS traffic to the WCDMA or LTE network, one or more of the GSM carriers can be used to carry IoT traffic. As GSM operates mainly in the 900MHz and 1,800MHz bands (spectrum that is present in all markets), this approach accelerates time to market, and maximizes the benefits of a global-scale infrastructure.

Migration to in-band

When the timing is right, GSM spectrum will be refarmed for use by more demanding MBB traffic. Refarming spectrum for use by LTE is a straightforward process, even when NB-IoT carriers exist in the GSM spectrum because refarming does not impact NB-IoT devices, and any NB-IoT carriers in GSM will continue to operate within the LTE carrier after migration. Such a future-proof setup is possible, as the standalone and in-band modes use the same numerology as LTE, and RF requirements are set to match the different deployments, so all devices are guaranteed to support in-band operation at the time of migration.

In-band: best option for LTE

For operators with mainly LTE spectrum available, the LTE in-band option provides the most spectrum- and cost-efficient deployment of NB-IoT. More than anything else, this particular option sets NB-IoT apart from any other LPWA technology.

An NB-IoT carrier is a self-contained network element that uses a single physical resource block (PRB). For in-band deployments with no IoT traffic present, the PRB can be used by LTE for other purposes, as the infrastructure and spectrum usage of LTE and NB-IoT are fully integrated. The base station scheduler multiplexes NB-IoT and LTE traffic onto the same spectrum, which minimizes the total cost of operation for MTC, which essentially scales with the volume of MTC traffic. In terms of capacity, the capability of a single NB-IoT carrier is quite significant – evaluations have shown that a standard deployment can support a deployment density of 200,000 NB-IoT devices within a cell – for an activity level corresponding to common use cases. Naturally, more NB-IoT carriers can be added if more capacity is needed.

Using guard band spectrum

A third alternative is to deploy NB-IoT in a guard band, and here, the focus is on the use of such bands in LTE. To operate in a guard band without causing interference, NB-IoT and LTE need to coexist. In contrast to other LPWA technologies, the physical NB-IoT layers have been designed with the requirements of in-LTE-guard-band coexistence specifically taken into consideration. Again, like LTE, NB-IoT uses OFDMA in the downlink and SC-FDMA in the uplink.

The design of NB-IoT has fully adopted LTE numerology, using 15kHz subcarriers in the uplink and downlink, with an additional option for 3.75kHz subcarriers in the uplink to provide capacity in signal-strength-limited scenarios.

Long range and long battery life

The geographical area for which a mobile network can provide coverage depends on site density and link budget. Compared with GPRS, WCDMA and LTE, the link budget of NB-IoT has a 20dB margin, and use cases tend to operate with lower data rates.

So, not only can NB-IoT reuse the GSM, WCDMA, or LTE grid, the improved link budget enables it to reach IoT devices in signal-challenged locations such as basements, tunnels, and remote rural areas – places that cannot be reached using the network's voice and MBB services.

In technical terms, the coverage target of NB-IoT has a link budget of 164dB, whereas the current GPRS link budget is 144dB (TR 45.820 [2]), and LTE is 142.7 dB** (TR 36.888 [3]). The 20dB improvement corresponds to a sevenfold increase in coverage area for an open environment, or roughly the loss that occurs when a signal penetrates the outer wall of a building. Standardization activities in 3GPP have shown that NB-IoT meets the link budget target of 164dB, while simultaneously meeting the MTC application requirements for data rate, latency, and battery life.

The battery life of an MTC device depends to some extent on the technology used in the physical layer for transmitting and receiving data. However, longevity depends to a greater extent on how efficiently a device can utilize various idle and sleep

** The noise figure assumptions in 3GPP TS 36.888 [3] used in the link budget calculations are more conservative than in the corresponding link budget for GSM in 3GPP TR 45.820. Using the noise figure assumptions from TR 45.820, the LTE link budget becomes 142.7dB.

modes that allow large parts of the device to be powered down for extended periods. The NB-IoT specification addresses both the physical-layer technology and idling aspects of the system.

Like LTE, NB-IoT uses two main RRC protocol states: RRC_idle and RRC_connected. In RRC_idle, devices save power, and resources that would be used to send measurement reports and uplink reference signals are freed up. In RRC_connected, devices can receive or send data directly.

Discontinuous reception (DRX) is the process through which networks and devices negotiate when devices can sleep and can be applied in both RRC_idle and RRC_connected. For RRC_connected, the application of DRX reduces the number of measurement reports devices send and the number of times downlink control channels are monitored, leading to battery savings.

3GPP release 12 supports a maximum DRX cycle of 2.56 seconds, which will be extended to 10.24 seconds in release 13 (eDRX). However, any further lengthening of this period is as yet not feasible, as it would negatively impact a number of RAN functions including mobility and accuracy of the system information. In RRC_idle, devices track area updates and listen to paging messages. To set up a connection with an idle device, the network pages it. Power consumption is much lower for idle devices than for connected ones, as listening for pages does not need to be performed as often as monitoring the downlink control channel.

When PSM was introduced in release 12, it enabled devices in RRC_idle to enter a deep sleep in which pages are not listened for, nor are mobility-related measurements performed. Devices in PSM perform tracking area updates after which they directly listen for pages before sleeping again. PSM and eDRX complement each other and can support battery lifetimes in excess of 10 years for different reachability requirements, transmission frequencies of different applications, and mobility.

The range of solutions designed to extend battery lifetimes need to be balanced against requirements for reachability, transmission frequency of different applications, and mobility. These relations are illustrated in *Figure 3*.

Superior capacity design

To meet capacity requirements, NB-IoT needs to multiplex many devices simultaneously, and provide connectivity in an efficient manner for all of them irrespective of coverage quality. As a result, the design of NB-IoT supports a range of data rates.

The achievable data rate depends on the channel quality (signal to noise ratio), and the quantity of allocated resources (bandwidth). In the downlink, all devices share the same power budget and several may simultaneously receive base-station transmissions. In the uplink, however, each device has its own power budget, and this can be used to advantage by multiplexing the traffic generated by several devices, as their combined power is greater than that of a single device.

In many locations, NB-IoT devices will be limited by signal strength rather than transmission bandwidth. Such devices can concentrate their transmission energy to a narrower bandwidth without loss of performance, which frees up bandwidth for others. The possibility of allocating small amounts of bandwidth to specific devices increases system capacity without loss of performance.

To enable such small bandwidth allocations, NB-IoT uses tones or subcarriers instead of resource blocks. The subcarrier bandwidth for NB-IoT is 15kHz, compared with a resource block, which has an effective bandwidth of 180kHz. Each device is scheduled on one or more subcarriers in the uplink, and devices can be packed even closer together by decreasing the subcarrier spacing to 3.75kHz. Doing so, however, results in differing numerology for LTE and NB-IoT, and some resources will need to be allocated to avoid interference between the 3.75kHz and 15kHz subcarriers instead of utilizing them for traffic, which may lead to performance losses.

For scenarios that include devices in both good and bad coverage areas, it is possible to increase the data rate by adding more bandwidth. In the uplink, data rates can be increased up to 12 times by allocating devices with a multi-tone or multi-subcarrier rather than a single tone, for example. This approach improves capacity for scenarios where many devices have good coverage, as data

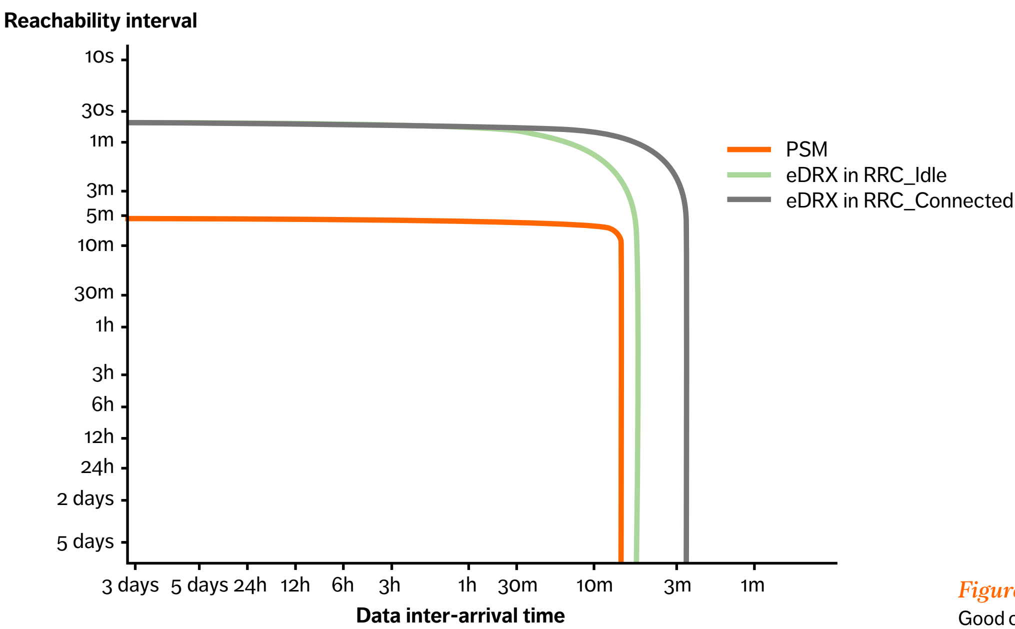

Figure 3
Good coverage

transfer completes quickly. Good coverage is typical when NB-IoT is rolled out on a dense grid and/or when most devices are within the original LTE cell coverage area.

Data rate is a significant factor when trying to achieve the best design for NB-IoT, as it affects both latency and power consumption. *Table 1* shows the uplink latency values for a device to connect and transmit data. The data rates for worst-case coverage (+20dB) are lower than those for MBB at the cell edge (0dB), and latency increases from 1.6 to 7.6 seconds. The uplink data rate is the main cause of this degradation, yet even for worst-case scenarios, NB-IoT uplink latency is still under the 10-second design target. When it comes to power consumption, the dominating factor is the speed at which devices transmit data, which increases in line with accelerating data rates.

NB-IoT has been designed with good multiplexing and adaptable data rates and so it will be able to meet predicted capacity requirements. The capacity requirements target in 3GPP TR 45.820 [1] has been set to 40 devices per household, based on assumptions for London, which correspond to 52,500 devices per cell. Simulations show support for 200,000 devices per cell – four times the set target.

Device aspects

Affordable modems are a key element of large-scale sensor deployment, so that processes such as temperature or water meter reporting can be optimized. At the same time, the data rate and latency requirements of such sensor-heavy applications tend to be relatively modest: a characteristic that can be used to advantage to reduce solution complexity – and cost.

NB-IoT devices support reduced peak physical layer data rates: in the range of 100-200kbps or significantly lower for single-tone devices. To facilitate low-complexity decoding in devices, turbo codes are replaced with convolutional codes for downlink transmissions, and limits are placed on maximum transport block size – which is 680 bits for DL and not greater than 1000 bits for UL.

The performance requirements set for NB-IoT make it possible to employ a single receiver antenna (two are needed for LTE MBB). As a result, the radio and baseband demodulator parts of the device need only a single receiver chain. By operating NB-IoT devices half duplex so that they cannot be scheduled to send and receive data simultaneously, the duplex filter in the device can be replaced by a simple switch, and a only single local oscillator for frequency generation is required. These optimizations reduce cost and power consumption.

At 200kHz, the bandwidth of NB-IoT is substantially narrower than other access technologies. LTE bandwidths, for example, range from 1.4MHz to 20MHz. The benefit of a narrowband technology lies in the reduced complexity of analog-to-digital (A/D) and digital-to-analog (D/A) conversion, buffering, and channel estimation – all of which bring benefits in terms of power consumption.

Table 1: Maximum uplink latency for a device on the MBB cell border (+0dB) and beyond (+10dB and +20dB)

Coverage	Sync	MIB	PRACH	RAmsg2-4	ULgrant	ULdata	Ack	ULdata	TOTAL
+0dB	340	151	324	622	48	39	41	39	**1,604**
+10dB	340	151	688	708	45	553	47	553	**3,085**
+20dB	520	631	1,440	1,060	49	1,923	77	1,923	**7,623**

Duration (ms)

NB-IoT brings about a significant design change in terms of the placement of the device's power amplifier (PA). Integrating this element directly onto the chip, instead of it being an external component, enables single-chip modem implementations – which are cheaper.

Reuse of existing technology

The design of NB-IoT radio access reuses a number of LTE design principles and has the backing of the traditional cellular-network and chipset vendors that made MBB a success. NB-IoT employs the same design principles as LTE (E-UTRA), although it uses a separate new carrier, new channels, and random access procedures to meet the target requirements of IoT use cases – such as improved coverage, lower battery consumption and operation in narrow spectrum. Constructing NB-IoT in this way takes advantage of LTE's well-established global reach, economies of scale, and industry-leading ecosystem.

The NB-IoT downlink is based on OFDMA and maintains the same subcarrier spacing, OFDM symbol duration, slot format, slot duration, and subframe duration as LTE. As a result, NB-IoT can provide both in-band and guard band deployment without causing interference between its carriers and those used by LTE for MBB, making NB-IoT a well integrated IoT solution for LTE-focused operators in addition to Cat-M1.

Use of the same upper layers is yet another similarity between LTE and NB-IoT, with some optimizations to support operation with low-cost devices. For example, as a single technology solution, NB-IoT does not support dual connectivity; and devices do not support switching between access technologies (GSM, WCDMA, or Wi-Fi) in active mode. Support for CS voice services has also been removed. These scope savings result in a much lower requirement for memory capacity for NB-IoT devices compared with even the most rudimentary MBB LTE ones.

NB-IoT: the advantages of being part of 3GPP

- use of the LTE ecosystem, leading to fast development, economies of scale, and global roaming
- can be deployed as a simple addition of new software to existing LTE infrastructure
- a management framework exists, enabling large-scale deployments
- framework includes state-of-the-art security
- future feature growth for MBB and NB-IoT use cases

“DATA RATE IS A SIGNIFICANT FACTOR WHEN TRYING TO ACHIEVE THE BEST DESIGN FOR NB-IOT, AS IT AFFECTS BOTH LATENCY AND POWER CONSUMPTION”

NB-IoT uses an S1-based connection between the radio network and the EPC. The connection to the EPC provides NB-IoT devices with support for roaming and flexible charging, meaning that devices can be installed anywhere and can function globally. The ambition is to enable certain classes of devices – like smoke detectors – to be handled with priority to ensure that emergency-situation data can be prioritized if the network is congested.

Existing 3GPP architecture provides a global, highly automated connectivity management solution that is needed for large-scale IoT deployments. NB-IoT and LTE use the same O&M framework, running as a single network carrying MBB and MTC traffic, which reduces operational costs in areas like provisioning, monitoring, billing, and device management. Similar to present LTE networks, NB-IoT supports state-of-the-art 3GPP security, with authentication, signaling protection, and data encryption.

LTE features that already exist, like cell-ID-based positioning, are straightforward enough for NB-IoT to inherit. By aligning with LTE evolution, NB-IoT could support existing features and future functionality designed for the entire cellular ecosystem, including MBB as well as IoT use cases.

The broadcast feature eMBMS enables a large number of devices to be updated simultaneously, and the device-to-device communication feature that relays transmissions to devices in poor coverage are examples of synergies. In the future, these two features can be specified for NB-IoT using the same concepts and experience that were used to develop them for LTE MBB.

Conclusions

NB-IoT is the 3GPP radio-access technology designed to meet the connectivity requirements for massive MTC applications. In contrast to other MTC standards, NB-IoT enjoys all the benefits of licensed spectrum, the feature richness of EPC, and the overall ecosystem spread of 3GPP. At the same time, NB-IoT has been designed to meet the challenging TCO structure of the IoT market, in terms of device and RAN cost, which scales with transferred data volumes.

The specification for NB-IoT is part of 3GPP release 13 and it includes a number of design targets: device cost under USD 5 per module; a coverage area that is seven times greater than existing 3GPP technologies; device battery life that is longer than 10 years with sustained reachability; and meet a capacity density of 40 devices per household.

As NB-IoT can be deployed in GSM spectrum, within an LTE carrier, or in an LTE or WCDMA guard band, it provides excellent deployment flexibility related to spectrum allocation, which in turn facilitates migration. Operation in licensed spectrum ensures that capacity and coverage performance targets can be guaranteed for the lifetime of a device, in contrast to technologies that use unlicensed spectrum, which run the risk of uncontrolled interference emerging even years after deployment, potentially knocking out large populations of MTC devices.

The first standard development of 5G radio access is currently underway, with system deployment targeted for 2020. In this context, the ability to future-proof additional technologies like NB-IoT is a top priority. In the ongoing discussions in 3GPP surrounding 5G, LTE will continue to be an integral part of radio networks beyond 2020, and so, NB-IoT's resemblance to LTE safeguards the technology from diverging evolution paths.✪

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