Overview of 3GPP Release 14 Enhanced NB-IoT

Andreas Höglund, Xingqin Lin, Olof Liberg, Ali Behravan, Emre A. Yavuz, Martin Van Der Zee, Yutao Sui, Tuomas Tirronen, Antti Ratilainen, and David Eriksson

Abstract

In 3GPP LTE Release 13, Narrowband Internet of Things (NB-IoT) was standardized for providing wide-area connectivity for massive machine-type communications for IoT. In LTE Release 14, NB-IoT was further developed to deliver enhanced user experience in selected areas through the addition of features such as increased positioning accuracy, increased peak data rates, the introduction of a lower device power class, improved non-anchor carrier operation, multicast, and authorization of coverage enhancements. In this article, we provide an overview of these features introduced for NB-IoT in LTE Release 14. An analysis is given on the applicability of these features and their benefits to enhance the NB-IoT radio access technology.

Introduction

The networked society is at our hands, and the Internet of Things (IoT) is the ongoing paradigm shift within communications. In the networked society, everything that benefits from a connection can be and will be connected. The major change lies in that not only people will be connected, but also devices. The connectivity for these devices is referred to as machine-type communication (MTC) [1]. Unlike human generated communication (e.g., surfing or streaming using smartphones or tablets), the key requirement for MTC is the importance of enabling economical wireless connectivity for massive numbers of devices. Examples of different IoT applications are given in Fig. 1. Not only must the cost of the devices be low, the network capacity be sufficient, and the device battery life be long enough to make charging or battery replacement obsolete, but coverage should also be improved to reach devices in challenging locations [1].

To provide affordable solutions for massive numbers of MTC devices, the Third Generation Partnership Project (3GPP) dedicated an immense effort during LTE Release 13 to develop two new cellular technologies: LTE-MTC (LTE-M), where a new user equipment (UE) category, Cat. M1, was introduced, and Narrowband IoT (NB-IoT) where UE category Cat. NB1 was introduced. A Cat. M1 UE, a.k.a. an LTE BL/CE UE,[1] operates in 1.4 MHz bandwidth, and supports a data rate up to 1 Mb/s in both downlink and uplink. It also has support for mobility, that is, handover to neighboring cells, and voice over LTE (VoLTE) service. Therefore, Cat. M1 UEs are suitable for IoT applications such as wearables and asset tracking. A Cat. NB1 UE operates only in 200 kHz bandwidth. These are IoT devices with ultra-low complexity that can be used for services that have no strict requirements for data rate, latency, or mobility, but require massive deployment of low-cost devices (e.g., meters and sensors).

In Fig. 1, we illustrate different IoT use cases that are suitable for the use of LTE-M and/or NB-IoT. It is worth mentioning that in LTE Release 14 [2], a new category of LTE-M UEs, Cat. M2, was introduced that can provide data rates up to 4 Mb/s in downlink and 7 Mb/s in uplink. Cat. M2 UEs are desired for IoT applications that need higher data rate (e.g., video surveillance), but require a lower device cost compared to regular LTE UEs.

MTC is an important component of next (fifth) generation mobile telecommunications (a.k.a. 5G). Both 3GPP and the International Telecommunication Union (ITU) have defined 5G requirements for massive MTC (mMTC). The requirement for mMTC connection density is the same in both cases (i.e., 1,000,000 devices) fulfilling certain quality of service, and should be supported per square kilometer. In addition, 3GPP defines 5G requirements for battery life, latency, and bit rate. Both LTE-M and NB-IoT are candidates for fulfilling these requirements and thus to be considered as 5G technologies [3, 4].

In this article, we provide an overview of the enhancements made for NB-IoT in LTE Release 14. Some of these enhancements may help NB-IoT toward fulfilling the 5G requirements. These features are introduced, described, and analyzed. Before that, the background of Release 13 NB-IoT is given. Finally, we provide discussion and conclusions on the relevance of this in a wider context, related to both the applicability and the relevance for 5G.

3GPP LTE NB-IoT Release 13 Background

To provide massive MTC connectivity, together with LTE-M, NB-IoT was standardized in LTE Release 13. NB-IoT is a cellular radio access technology that provides low-power wide-area (LPWA) IoT connectivity in licensed spectrum, unlike short-range technologies in unlicensed spectrum, including Bluetooth, ZigBee, and so on, and unlike LPWA technologies including SigFox, LoRaWAN, and so on. The 3GPP design targets for Release 13 were those typical for MTC: long device battery life, low device complexity to ensure low cost, support for massive numbers of devices, and coverage enhancements to be able to reach devices in basements and other challenging locations.

It is possible to deploy NB-IoT in a narrow system bandwidth (i.e., 200 kHz). The technology also provides enhanced coverage, up to 164 dB maximum coupling loss (MCL), is energy-efficient to provide long battery life, and is of low com-

The authors are with Ericsson AB, Oy LM Ericsson AB.

[1] BL stands for bandwidth-reduced low-complexity, and CE stands for coverage enhancement.

Digital Object Identifier: 10.1109/MNET.2017.1700082

plexity to enable low-cost devices [5]. NB-IoT has three deployment options and can be deployed either inside an LTE carrier (*in-band*), in the guard band of it (*guard band*), or in its own designated spectrum (*standalone*).

Coverage enhancement is one of the attractive features offered by NB-IoT. NB-IoT can offer up to 20 dB[2] enhanced coverage in all operation modes compared to the general packet radio services (GPRS) system. This coverage enhancement is mostly achieved through repetitions in time, together with power boosting in in-band and guard band operation modes.

NB-IoT reuses the LTE design to a large extent, including numerologies, channel modulation and coding schemes, and higher layer protocols. In the downlink, orthogonal frequency-division multiple access (OFDMA) is used, while the uplink uses single-carrier frequency-division multiple access (SC-FDMA) [6]. This ensures fast development and deployment of NB-IoT products for existing LTE equipment and software vendors.

The major difference between NB-IoT and legacy LTE resides in the uplink design, where a subcarrier spacing of 3.75 kHz is introduced in NB-IoT in addition to the 15 kHz used in legacy LTE systems [6]. In NB-IoT, resource allocations using less than twelve 15-kHz-subcarriers in the uplink are also introduced. For the narrowband physical random access channel (NPRACH), only 3.75 kHz subcarrier spacing is supported. For the narrowband physical uplink shared channel (NPUSCH), both 3.75 kHz and 15 kHz subcarrier spacing are supported by single-tone transmission, whereas only 15 kHz subcarrier spacing is supported for multi-tone transmission. Studies have shown that the introduction of 3.75 kHz subcarrier spacing can have some negative impact on coexistence with the 15 kHz subcarrier spacing, but the impact can be partly compensated by optimizing the scheduling algorithms [7].

To reduce the device cost, NB-IoT only requires a system bandwidth of 200 kHz for both uplink and downlink. Only half-duplex (HD) frequency-division duplex (FDD) is supported, and only one receiving antenna in the device. In addition, many functions have been simplified to further reduce the device costs. In the downlink, only quadrature phase shift keying (QPSK) and convolutional code are used, which is less demanding for the UEs compared to the use of turbo code in LTE. In the uplink, to reduce peak-to-average power ratio (PAPR), single-tone transmissions with $\pi/2$-binary phase shift keying (BPSK) and $\pi/4$-QPSK are adopted [6]. Considering the device complexity, an NB-IoT device is not required to decode the narrowband physical downlink control channel (NPDCCH) and narrowband physical downlink shared channel (NPDSCH) in 1 ms, in contrast to the legacy LTE system. Instead, forward scheduling is introduced; that is, NPDCCH and NPDSCH are transmitted subsequently with at least 4 ms delay in between to guarantee sufficient NPDCCH decoding time at the UE. Only one single adaptive asynchronous hybrid automatic repeat request (HARQ) process is supported for both uplink and downlink. The maximum supported transport block sizes (TBSs) are reduced to 680 bits for downlink and 1000 bits for uplink, respectively [5].

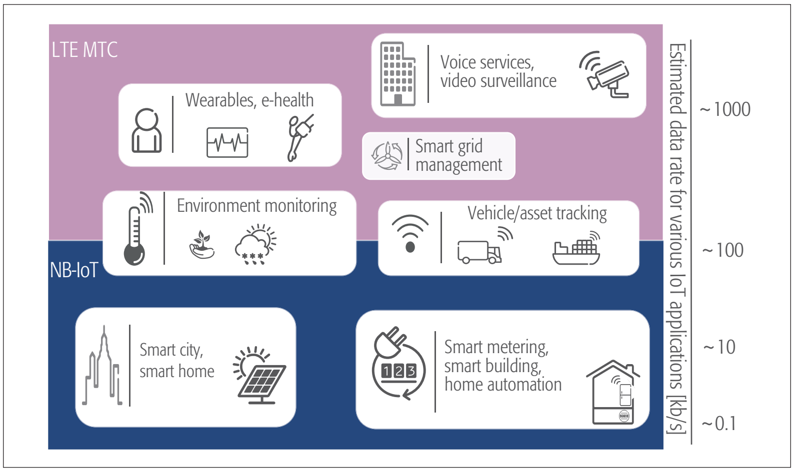

FIGURE 1. Examples of different IoT use cases.

To further reduce the system information (SI) acquisition time and reduce the latency of setting up a connection, several optimizations have been introduced in NB-IoT. Instead of using the system information blocks, the SI value tag and a new access barring indication are broadcasted in the narrowband master information block in NB-IoT. This reduces the efforts for the UE, especially in extended coverage, to verify the SI before accessing the network. Furthermore, new higher-layer optimizations such as data over non-access stratum and radio resource control (RRC) connection resume procedures are introduced to further reduce signaling when accessing the network. These new optimizations significantly reduce the signaling overhead when transmitting small data packets.

Release 13 NB-IoT supports functions to improve battery life, such as extended discontinuous reception (eDRX), power saving mode (PSM), as well as functions to improve capacity (e.g., multi-carrier operations). Detailed descriptions of the NB-IoT Release 13 functionalities and deployment guides are given in [5, 8].

3GPP LTE NB-IoT Release 14 Features

To further improve the user experience as well as cater to more use cases, several enhancements and new functionalities are introduced for NB-IoT in 3GPP LTE Release 14 NB-IoT [9]. The new features include positioning, multicast, and a new UE output power class, whereas the system and UE throughput, non-anchor carrier operation, mobility, and service continuity are further enhanced. In this section, we discuss these new or enhanced features in detail to see how they help NB-IoT provide better mMTC service, and pave the road for NB-IoT to fulfill the 5G MTC requirements. Furthermore, currently the work for LTE Release 15 NB-IoT is ongoing, and new features are introduced to further improve the NB-IoT battery life and latency and improve performance in more use cases [10].

Positioning

Many IoT use cases will require or benefit from location information, making positioning a vital dimension of the IoT. Example use cases include wearables, smart bicycles, asset tracking, and environment monitoring. Release 13 NB-IoT only

[2] The 20 dB coverage enhancement was defined with respect to the weakest channel in GPRS, that is, the uplink packet data traffic channel (PDTCH) coding scheme 1 (CS-1). Interested readers can find the detailed studies and simulation results in [14].

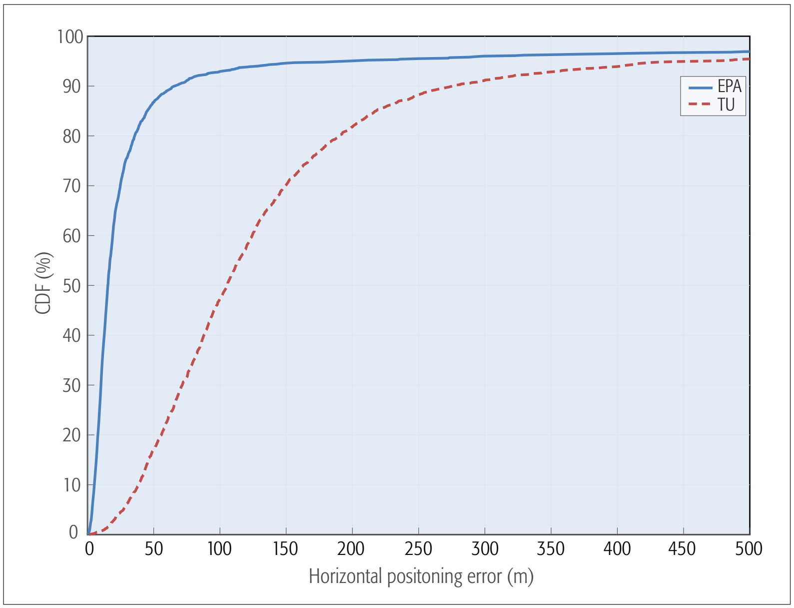

FIGURE 2. NB-IoT OTDOA positioning accuracy.

supports basic positioning features through cell identity (CID), which uses CID information to associate the device to the area covered by the serving cell. Advanced positioning techniques are introduced in Release 14.

The standardization efforts of Release 14 are to:
- Develop support for the feature of observed time difference of arrival (OTDOA) for NB-IoT
- Complete UE measurement requirements for enhanced CID

The measurement requirements of enhanced CID include evolved Node B (eNB) Rx-Tx time difference, and reference signal received power (RSRP) as well as reference signal received quality (RSRQ).

OTDOA is a downlink-based positioning method, where a device measures the times of arrival (TOAs) of positioning reference signals (PRSs) received from multiple transmitting nodes relative to a reference node's PRS transmission to form the reference signal time difference (RSTD) measurements. Each RSTD measurement can be translated into a geographical hyperbola on which the positioned UE can be assumed to reside. By considering multiple RSTD measurements, the UE position can be estimated to be at the crossover point of the corresponding hyperbolas.

A new reference signal was designed for OTDOA in NB-IoT, referred to as the narrowband positioning reference signal (NPRS), which has synergies with LTE PRS such as reusing the PRS waveform definition and basic configuration parameters. Figure 2 presents OTDOA positioning performance for a device with high timing accuracy and two types of radio propagation conditions: typical urban (TU) and extended pedestrian A (EPA). The high delay spread of the TU channel makes it difficult to predict the TOA of the line of sight channel tap, which leads to degraded performance compared to the EPA channel, which is characterized by a low delay spread.

The detailed description of simulation setup and more evaluation results may be found in [11, references therein]. These results are generated based on NPRS, and thus are only applicable to NB-IoT. A maximum number of 10 cells are used in estimating the position, and 100 NPRS transmission subframes are used to achieve the accuracy. We refer interested readers to [12] for more simulation results comparing the OTDOA positioning accuracy of LTE, LTE-M, and NB-IoT.

For NB-IoT, several carriers can be configured in a cell (i.e., one anchor-carrier plus several non-anchor carriers). Hence, the NPRS can be configured per NB-IoT carrier transmitting NPRS. The NPRS mapping to the NB-IoT radio resources is highly flexible and may be indicated with two parts: part A and part B. The network can configure NPRS using part A alone, part B alone, or both. Part A is a subframe bitmap of 10 or 40 bits, and Part B is a configuration mechanism similar to that of LTE PRS. It specifies the periodicity of positioning occasions and the number of consecutive NPRS subframes in a positioning occasion. Parts A and B may be both configured. In this case, a subframe contains NPRS if both parts of the configuration indicate that the subframe contains NPRS.

Multicast

Multicast is group communication, where data is addressed to a group of users in a single transmission. One use case for multicast is firmware upgrade to a group of smart meters. Another one is to reduce latency when addressing large groups of UEs (e.g. turning street lamps on or off). The main motivation is efficiency in terms of energy and resource utilization due to transmitting the data once rather than multiple times separately for each device. In LTE Release 14 NB-IoT, multimedia broadcast multicast services (MBMS) is supported through single-cell point-to-multipoint (SC-PtM). SC-PtM was specified earlier in LTE Release 13, and a general description of MBMS operation including details on SC-PtM can be found in [13, Sec. 15]. The SC-PtM data is carried on the SC-MTCH logical channel, which is mapped to the NPDSCH physical channel similar to unicast traffic, and the scheduling of SC-PtM in NB-IoT follows the same principles. In SC-PtM, the same TBS and coverage enhancement configurations can be used, which leads to similar achievable downlink data rates as in unicast, depending on the network configuration.

In SC-PtM, the single-cell MBMS control channel (SC-MCCH) and single-cell MBMS traffic channel (SC-MTCH) are logical channels that carry control and data traffic, respectively. The SC-MTCH is the traffic channel that carries the multicast data transmissions. Scheduling configuration for SC-MTCH is provided via SC-MCCH for NB-IoT UEs to locate and receive the service of interest. Each SC-PtM service is mapped to one SC-MTCH. A cell may transmit multiple SC-MTCHs, but only a single SC-MCCH is transmitted for informing the UEs about the physical layer scheduling configuration. Both logical channels are mapped to NPDSCH in the physical layer, and scheduled using the downlink control information in NPDCCH, which is transmitted in accordance with the SC-MCCH information.

Information on SC-MCCH scheduling is broadcast in *system information block 20-NB*. The modification and scheduling periodicities for

SC-MCCH are extended compared to LTE due to repetitions required to support enhanced coverage. SC-MCCH message segmentation is supported, and a mechanism similar to SC-MTCH DRX is used to reduce UE power consumption.

SC-MCCH carries the SC-MTCH scheduling information, and the configuration options are similar to the options for SC-MCCH. The ranges for the DRX timers and scheduling periodicity have been extended to accommodate different coverage scenarios. Considering the downlink capacity, in an NB-IoT cell, the maximum number of different supported SC-MTCHs is 64.

Lower Power UE

Release 14 for NB-IoT introduces a new low UE power class, where the objective is to achieve smaller form factor, lower device power consumption, and even lower device cost compared to the 20 dBm devices in NB-IoT Release 13. It has been concluded that the device maximum output power should not exceed 20 dBm to enable a system on chip design with an integrated power amplifier (PA).

In Release 14, a new UE power class with the maximum allowed output power reduced to 14 dBm was introduced to enable using smaller battery form factors for NB-IoT devices. The low power class implies a significantly reduced drain current. As a lower drain current reduces the wasteful voltage drop, calculated as the product of the drain current and the battery internal resistance, a low-power UE will make more efficient use of the available energy provided by a battery. Beyond this effect, it is not expected that low output power will improve the UE power consumption characteristics, since the lower output power must be compensated by increased transmission times to maintain the same energy per bit as a Release 13 UE achieves.

To maintain the coverage of a lower-power device in a wide area network, the reduced uplink power needs to be compensated for by increasing the uplink transmission time to maintain the energy per transmitted bit. This may negatively impact the uplink resource utilization and lead to increased downlink control signaling. To manage this and control the overall system resource utilization, 3GPP agreed that the MCL for low-power devices should be relaxed compared to the Release 13 specification. Here we consider a coverage relaxation of 9 dB, which can be associated with the difference in output power between 23 and 14 dBm power classes. This means that devices experiencing a coupling loss above 164 – (23 –14) = 155 dB to the serving cell are not considered to fulfill the cell suitability criterion and are not allowed to access the system. Figure 3 shows average UL resource utilization for two networks based on 14 dBm devices and 23 dBm devices. The figure shows that the increased resource utilization observed for the 14 dBm case can be controlled by enforcing the mentioned MCL limitation.

The downlink resource utilization may also be impacted if the eNB does not possess accurate knowledge of the used device output power. This is a consequence of the eNB estimating the coupling loss to a connected device based on the received uplink power. The introduction of a 14 dBm power class in addition to the existing Release 13 power classes introduces an ambiguity that called for early indication of the device power class. The NB-IoT connection setup procedure was therefore improved in Release 14 to allow the serving eNB to acquire the device capabilities, including the power class, during the early phases of the connection setup.

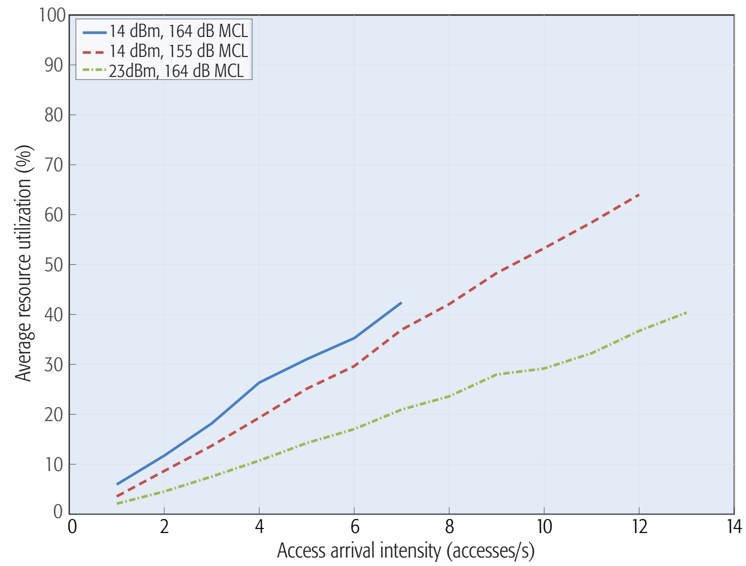

FIGURE 3. Average uplink resource utilization as a function of the user access arrival intensity.

Multi-Carrier Enhancements

The NB-IoT Release 13 design target for capacity largely had the 6 × 10^4 devices/km^2 of the preceding study [14] in mind, whereas from Release 14 the ITU 5G requirement [4] of 6 × 10^6 devices/km^2 is of main interest. The NB-IoT system can be contained in a carrier of 200 kHz bandwidth, and to increase capacity, multiple carriers can be deployed (i.e., multiple cells or systems). However, in this narrow bandwidth the continuous broadcast of system information and synchronization signals will take a quite large part of the downlink resources, above 50 percent for some configurations. Therefore, multi-carrier operation was already introduced in Release 13 in which there is one anchor carrier carrying this always-on broadcast signaling and possible non-anchor carriers for offloading of data traffic and increased capacity.

In Release 13, the non-anchor carriers are restricted to offload devices in active state (RRC connected). That is, all devices will perform RRC idle mode operations, such as monitoring of paging and random access, on the anchor carrier, but the eNB can, after the RRC connection setup or RRC connection, resume messaging to direct a device to a non-anchor carrier for the duration of its connected session.

The obvious drawback is that paging and random access are likely to become capacity bottlenecks. Therefore, a natural enhancement of multi-carrier operation in Release 14 was for devices to be able to both monitor paging and perform random access on non-anchor carriers. Devices will still "camp" on the anchor carrier in

In conditions where repetitions are used, the impact on throughput from the NPDCCH scheduling gaps is limited; instead, it is the actual transmission times that limit the achievable data rates. This also implies that the two HARQ processes feature is mostly useful in good radio conditions.

Carrier	Stand-alone/ Guard-band overhead	In-band overhead
Rel-13 Anchor	40%	59 percent
Rel-14 Anchor	44%	62 percent
Rel-13 Non-anchor	10%	38 percent
Rel-14 Non-anchor	10%	38 percent

TABLE 1. Multi-carrier system overhead.

	NPDSCH	NPUSCH
Category NB 2	79 kb/s	106 kb/s
Category NB 2 with support for 2 HARQ processes (optional)	127 kb/s	158.5 kb/s

TABLE 2. NB-IoT release 14 peak data rates.

the sense that mobility measurements and synchronization are always carried out on the anchor carrier. On non-anchor carriers, the only signals broadcasted are the narrowband reference signals (NRSs), but only when needed for either paging or random access, or when there is a device in RRC connected state.

For the random access procedure, up to three NPRACH resources with a one-to-one mapping to the three possible coverage enhancement levels can be configured for a non-anchor carrier. A device will randomly select an NPRACH resource among all carriers which have NPRACH configured for its coverage enhancement level. Since all Release 13 devices will choose an NPRACH resource on the anchor carrier, a biased NPRACH selection is introduced for Release 14 devices such that a selection weight is used to be able to achieve, say, an uneven load distribution in systems containing both Release 13 and 14 devices. Up to a total of 16 carriers can be configured for random access.

For the monitoring of paging, the paging occasions, and hence the paging load, will be spread over the anchor carrier and the non-anchor carriers configured with paging. Since there can be significant differences between downlink carriers due to differences in deployment modes, load from broadcast, and Release 13 devices, and especially power boosting, uneven paging load distribution can be achieved by configuring a weight per paging carrier. Up to a total of 16 carriers can be configured for paging.

An analysis of the downlink overhead contributed by reference signals, broadcast channels, system information, and the new system information block carrying the non-anchor configurations is provided in Table 1 for all types of carriers. It is seen that the non-anchor gain is an overhead reduction of at least 30 percent-units for stand-alone or guard band carriers and 21 percent-units for in-band carriers. This means that for the stand-alone case, the same downlink capacity increase as achieved by deploying three additional anchor carriers could in fact be achieved by only two additional non-anchor carriers. For Release 14, this capacity increase also applies to NPRACH and paging.

Increased Data Rate

NB-IoT is intended for the ultra-low complexity IoT market segment. A key component to secure low-complexity device design is to limit the requirements on device buffer memory and computational processing power. These limitations result in a downlink peak data rate of ~25 kb/s and the supported uplink peak data rate of ~65 kb/s in NB-IoT Release 13.

To support more diverse traffic scenarios, Release 14 introduces a new NB-IoT device category, Cat. NB 2, supporting 2536 bits TBS in both the uplink and the downlink. Besides increasing the maximum TBS, the optional support for a second HARQ process was also specified. This further increased the peak data rates. Table 2 summarizes the achievable physical layer peak data rates for the new device category taking device processing and NPDCCH scheduling delays into account.

As the larger TBSs are introduced at the expense of an increased code rate, which reduces the robustness of the radio link, it is expected that the higher data rate is mainly intended for devices experiencing favorable radio conditions. The throughput gains achieved by a second HARQ process is mainly due to reducing the overhead from NPDCCH scheduling gaps, which limits the achievable throughput in good radio conditions. In conditions where repetitions are used, the impact on throughput from the NPDCCH scheduling gaps is limited; instead, it is the actual transmission times that limit the achievable data rates. This also implies that the two HARQ processes feature is mostly useful in good radio conditions.

Connected Mode Mobility Enhancement

NB-IoT supports stationary and low-mobility UEs. Handover is not supported in NB-IoT, and when the UE moves out of the coverage area of the serving cell, the UE will experience radio link failure (RLF). A UE that supports NB-IoT supports data transfer via the control plane. Optionally, the UE can also support data transfer via the user plane. When the UE supports data transfer via the user plane, the RRC connection re-establishment procedure is supported, which means that after RLF is detected, the UE tries to find a suitable cell through cell selection.

If the UE finds a suitable cell, the UE will try to re-establish the connection on that cell and resume data transfer. The RRC re-establishment intends to hide the temporary loss of the radio interface to the upper layers. RRC re-establishment for a UE only supporting data transfer via the control plane was added in Release 14 [15].

Release Assistance Indication

NB-IoT is designed to support UEs that have occasional small amounts of data to transmit or receive, according to the traffic model defined in [14, Annex E]. Even though the UE spends most of its time in idle mode in an (extended) DRX to save power, when the UE has data to send and/or receive, it is important that these data transmissions are completed as soon as possible and with the least amount of signaling overhead. After data transmissions have been completed, the eNB releases the connection, and the UE returns to idle mode to save power. The eNB typically releases the connection using a data inactivity timer; that is, the connection is released when no more data is sent or received after some time. Compared to the data transmission times, this is a relatively long inactivity time during which the UE is waiting to be released, especially in normal coverage. In NB-IoT the traffic use cases can be rather predictable, and the UE may have good knowledge when it has finished transmitting and/or receiving data. The release assistance indication procedure allows the UE to send an indication to the eNB when it does not have more data to send or receive. The eNB can use this indication to release the UE more quickly to idle mode.

Restriction on the Use of Coverage Enhancements

To obtain enhanced coverage up to 164 dB MCL, a significant amount of network resources is required (e.g., repetitions). With authorization of the coverage enhancements feature, the network can restrict the use of coverage enhancements to a UE based on subscription information. In Release 14, an NB-IoT UE is required to support this feature. In idle mode, the authorization is enforced by the UE and in connected mode by the eNB. The UE receives authorization information during attachment and tracking area update (TAU) from the network. When the UE is not authorized to use coverage enhancement, the UE shall apply an offset to the measured signal strength of the selected cell in NB-IoT, and the UE shall not use the cell selection criterion for enhanced coverage in MTC. When the signal strength drops below the minimum threshold (i.e., the cell is not suitable for the UE to camp on in idle mode), the UE is required to try to find another suitable cell.

Conclusions

Both new features and enhanced functionalities are introduced in NB-IoT 3GPP LTE Release 14. The new features broaden the use cases that can be offered by NB-IoT, whereas the enhanced functionalities increase the system capacity flexibly, as well as improve the energy efficiency.

NB-IoT systems especially focus on the low-cost device with delay-tolerant services. From the discussion, we can see that NB-IoT in Release 14 is another significant step that paves the road for the NB-IoT technology to fulfill the massive MTC requirements in 5G. Not only can more diversified services be supported by NB-IoT; it also enables the possibility to further reduce the cost of the devices. Furthermore, due to the flexibility of supporting several operation modes, the NB-IoT system is foreseeable to be future-proof in operating and coexisting with the next generation (i.e., 5G) new radio technologies.

> Not only can more diversified services be supported by NB-IoT; it also enables the possibility to further reduce the cost of devices. Furthermore, due to the flexibility of supporting several operation modes, the NB-IoT system is foreseen to be future-proof in operating and coexisting with the next generation (i.e., 5G) new radio technologies.

References

[1] 3GPP TS 22.368, "Service Requirements for Machine-Type Communications (MTC)," v. 13.1.0, Dec. 2014; http://www.3gpp.org, accessed Apr. 30, 2017.

[2] 3GPP RP-161464, "Revised WID for Further Enhanced MTC for LTE," Sept. 2016; http://www.3gpp.org, accessed Apr. 30, 2017.

[3] 3GPP TR 38.913, "Study on Scenarios and Requirements for Next Generation Access Technologies," v. 14.2.0, Mar. 2017, [available: http://www.3gpp.org, accessed Apr. 30, 2017.

[4] ITU Doc. 5D/TEMP/300-E, "Minimum Requirements Related to Technical Performance for IMT-2020 Radio Interface(s)," Feb. 2017; http://www.itu.int/pub/R-REP-M.2134-2008, accessed Apr. 30, 2017.

[5] Y.-P. E. Wang *et al.*, "A Primer on 3GPP Narrowband Internet of Things (NB-IoT)," *IEEE Commun. Mag.*, vol. 55, no. 3, Mar. 2017.

[6] 3GPP TS 36.211, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation," v. 14.3.0, June 2017; http://www.3gpp.org, accessed Aug. 30, 2017.

[7] 3GPP R1-160776, "Discussion on Multiplex of Uplink Signal with Different Subcarrier Spacing," MediaTek Inc, Feb. 2016; http://www.3gpp.org, accessed July 5, 2017.

[8] GSMA, "NB-IoT Deployment Guide to Basic Feature set Requirements," v. 1.0, Aug. 2017; https://www.gsma.com/, accessed Aug. 31, 2017.

[9] 3GPP RP-161901, "Revised Work Item Proposal: Enhancements of NB-IoT," Sept. 2016; http://www.3gpp.org, accessed Apr. 30, 2017.

[10] 3GPP RP-171428, "Revised WID on Further NB-IoT Enhancements," June 2017; http://www.3gpp.org, accessed Aug. 31, 2017.

[11] 3GPP R1-1611118, "OTDOA Performance for NB-IoT," Ericsson, Nov. 2016; http://www.3gpp.org, accessed Apr. 30, 2017.

[12] X. Lin *et al.*, "Positioning for the Internet of Things: A 3GPP Perspective," *IEEE Commun. Mag.*, vol. 55, no. 4, Apr. 2017.

[13] 3GPP TS 36.300, "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall Description; Stage 2," v. 14.3.0, June 2017; http://www.3gpp.org, accessed Aug. 31, 2017.

[14] 3GPP TR 45.820, "Cellular System Support for Ultra-Low Complexity and Low Throughput Internet of Things (CIoT)," v. 13.1.0, Nov. 2015; http://www.3gpp.org, accessed Apr. 30, 2017.

[15] 3GPP R2-1706165, "Introduction of RRC Connection Re-Establishment for NB-IoT Control Plane," Qualcomm Inc., Huawei, HiSilicon, Gemalto N.V., May 2017; http://www.3gpp.org, accessed July 5, 2017.

Biographies

Andreas Höglund (andreas.hoglund@ericsson.com) has a Master of Science in engineering physics (2002) and a Ph.D. in condensed matter physics (2007) from Uppsala University, Sweden. He is currently a senior researcher at Ericsson Research and, since he joined in 2008, has worked on HSPA, LTE, system simulations, 5G research in the METIS project, 3GPP standardization, and more. He has worked on the standardization of LTE MTC (Cat-M1) and NB-IoT from the start in Release 13 and is currently the team leader for the team within Ericsson Research handling the evolution and research of the higher-layer aspects thereof.

Xingqin Lin (xingqin.lin@ericsson.com) received his Ph.D. degree in electrical and computer engineering from the University of Texas at Austin (UT Austin) in 2014. He is currently a research engineer at Ericsson Research Silicon Valley. He held summer internships at Qualcomm CR&D, Nokia Networks, and Alcatel-Lucent Bell Labs. He received the MCD Fellowship from UT Austin and was recognized by Ericsson for outstanding contributions to NB-IoT research and standards. He serves as an Editor of *IEEE Communications Letters*.

Olof Liberg (olof.liberg@ericsson.com) is a master researcher at Ericsson. After studies at Uppsala University, he received a Bachelor's degree in business and economics and a Master's degree in engineering physics. He joined Ericsson in 2008 and has specialized in the design of cellular systems for machine type communications and the Internet of Things. He has, over the years, actively contributed to work in several standardization bodies such as 3GPP, ETSI, and the MulteFire Alliance.

Ali Behravan (ali.behravan@ericsson.com) received his Ph.D. in electrical engineering from Chalmers University of Technology in 2006. He has been with Ericsson Research in Stockholm since 2007, where he is currently working on standardization of 5G. His research interests include physical layer design of mobile broadband communications, machine-to-machine communications, and ultra-reliable and low-latency communications. He received his B.Sc. and M.Sc. degrees, both in electrical engineering, from Ferdowsi University of Mashad, Iran, in 1994 and 1997.

Emre A. Yavuz (emre.yavuz@ericsson.com) received his B.Sc. and M.Sc. degrees in electrical and electronics engineering at METU in Ankara, Turkey, in 1995 and 1998, respectively. He was a software engineer at Alcatel in Toronto developing safety-critical real-time microprocessor firmware for embedded command, control, and communication applications in automated train systems from 1999 to 2001. He received his Ph.D. degree in electrical and computer engineering at the University of British Columbia in Vancouver in 2007. He worked as a technical consultant for a network operator in Vancouver from 2007 to 2009 prior to joining the School of Electrical Engineering at KTH in Stockholm as a postdoctoral fellow. He is now a researcher at Ericsson in Stockholm working on L2/L3 standardization and RAN system design. He is involved in the standardization of machine type communication (MTC/NB-IoT) in new generation cellular networks.

Martin van der Zee (martin.van.der.zee@ericsson.com) has a Master's degree in computer science (1989) and Licentiate degree (1991) in telecommunications from the University of Twente. Between 1991 and 1995 he was a research assistant at the University of Twente. He is currently a researcher at Ericsson Technology & Research. Since he joined Ericsson in 1995, he has worked on protocol simulations, Bluetooth Link Manager, and WCDMA/LTE L2/L3. He has been a Bluetooth standardization delegate, and has been a 3GPP RAN2 delegate since 2007. As a RAN2 delegate, he has been working on WCDMA and NB-IoT (LTE).

Yutao Sui (yutao.sui@ericsson.com) received his Ph.D. degree in communication systems from Chalmers University of Technology, Gothenburg, Sweden. His main research interests are in design and analysis of physical layer algorithms, multiple access, vehicular small cells, and massive machine-type communication. He is currently a standardization researcher at Ericsson, Stockholm, Sweden, with focus on machine-type communication related standardization.

Tuomas Tirronen (tuomas.tirronen@ericsson.com) is a senior researcher at Ericsson Research, which he joined in 2012. He received his M.Sc. in teletraffic theory in 2006 from Helsinki University of Technology and D.Sc. in communications engineering in 2010 from Aalto University. He is currently working on developing concepts and standards for 4G and 5G wireless technologies with focus on machine-type communications and the Internet of Things, performance evaluation, and energy efficiency. He is also currently a 3GPP RAN2 delegate with focus on MTC and NB-IoT. He has (co-) authored several conference and journal papers, and is involved in innovation work and patenting.

Antti Ratilainen (antti.ratilainen@ericsson.com) is an experienced researcher at Ericsson Research, which he joined in 2014. He received his Master of Science in communications engineering in 2014 from Aalto University, carrying out his Master's thesis work at Ericsson Research studying dual connectivity in LTE networks. Currently he is involved in developing and evaluating L2/L3 concepts and contributing to standardization of 4G and 5G cellular networks with focus on machine-type communications.

David Eriksson (david.a.eriksson@ericsson.com) has a Master of Science in engineering physics (2001) from Umeå University and a Ph.D. in theoretical high energy physics (2009) from Uppsala University. He joined Ericsson Research in 2011 and is currently a senior researcher. Since he joined he has worked on HSPA, LTE, system simulation, performance evaluations, and, most recently, system aspects of MTC and NB-IoT.