Overview of Narrowband IoT in LTE Rel-13

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***Abstract*—In 3GPP Rel-13, a narrowband system, named Narrowband Internet of Things (NB-IoT), has been introduced to provide low-cost, low-power, wide-area cellular connectivity for the Internet of Things. This system, based on Long Term Evolution (LTE) technology, supports most LTE functionalities albeit with essential simplifications to reduce device complexity. Further optimizations to increase coverage, reduce overhead and reduce power consumption while increasing capacity have been introduced as well. The design objectives of NB-IoT include low-complexity devices, high coverage, long device battery life, and massive capacity. Latency is relaxed although a delay budget of 10 seconds is the target for exception reports. This paper provides an overview of NB-IoT design, including salient features from the physical and higher layers. Illustrative results with respect to performance objectives are also provided. Finally, NB-IoT enhancements in LTE Rel-14 are briefly outlined.**

Keywords—Narrowband IoT; NB-IoT; low power wide area cellular IoT; cellular IoT design and performance.

I. INTRODUCTION

The deployment of Internet of Things (IoT), consisting of devices of various types interconnected for communication, is expected to reach a massive scale in the next few years and wireless connectivity through wide-area networks will be an important component of this future. In 2015, an estimated 0.4 billion IoT devices are connected using cellular networks. This number will grow to 1.5 billion in 2021, equivalent to a yearly growth rate of 27% [1]. Several releases of LTE have provided progressively improved support for low-power wide-area IoT connectivity [2]-[5]. In Long Term Evolution (LTE) Rel-12, support for low-cost devices with material cost comparable to General Packet Radio Service (GPRS) devices was introduced [3][6]. In LTE Rel-13, two new features have been introduced to support narrowband machine type communications (MTC). For the first feature, called enhanced MTC (eMTC), a new UE category with reduced radio frequency (RF) bandwidth of 1.4 MHz is introduced [7]. The system operates in-band as part of the wideband LTE carrier. Coverage enhancement, providing improved indoor support, is also introduced in eMTC.

The second feature is called narrowband IoT (NB-IoT) [9]. In contrast to eMTC, NB-IoT is a new system built from existing LTE functionalities. NB-IoT has been designed with the following performance objectives [9] –

- Ultra-low complexity devices to support IoT applications.
- Improved indoor coverage of 20 dB compared to legacy GPRS, corresponding to a Maximum Coupling Loss (MCL) of 164 dB while supporting a data rate of at least 160 bps at the application layer.
- Support of massive number of low-throughput devices – at least 52547 devices within a cell-site sector.
- Improved power efficiency – battery life of ten years with battery capacity of 5 Wh.
- Exception report latency of 10 seconds or less is the requirement for 99% of the devices.

In addition to the performance objectives, a compatibility objective also requires that NB-IoT system should avoid negative impacts to legacy 3GPP cellular systems that are deployed in the same frequency band and should adhere to regulatory requirements.

NB-IoT can be deployed in three operation modes – in-band, guard-band, and stand-alone. In in-band operation mode, one or more LTE Physical Resource Blocks (PRBs) are reserved for NB-IoT. The total eNB (i.e. base-station in 3GPP terminology) power is shared between LTE and NB-IoT with the possibility to use power spectral density (PSD) boosting for NB-IoT. Sharing of PRBs between NB-IoT and LTE allows for more efficient use of the spectrum. In addition, although they are two separate systems, they can be supported using the same eNB hardware. In guard-band operation, NB-IoT will be deployed within the guard-band of an LTE carrier. In stand-alone operation, NB-IoT can be used as a replacement of one or more GSM carriers.

NB-IoT design is based on LTE. It therefore supports most LTE functionalities with many simplifications and some optimizations to support low-cost, low-power, and low data-rate IoT services. Reusing LTE design where possible has been vital in achieving rapid specification of NB-IoT in Rel-13. Yet another advantage is the minimization of development effort, which reduces time-to-market.

In this paper, we provide an overview of the physical and higher layer design for NB-IoT. The paper describes the techniques that have been specified and provides illustrative performance results against the objectives. In Section II, a brief description of NB-IoT and techniques to satisfy the objectives is provided. In Section III, the physical layer design is described. Higher layer design is discussed in Section IV. Section V presents performance results. Enhancements being considered for LTE Rel-14 are briefly described in Section VI. Finally, conclusions are drawn in Section VII.

II. NB-IOT DESIGN OVERVIEW

NB-IoT is a new radio access system built from existing LTE functionalities with essential simplifications and optimizations. At the physical layer, NB-IoT occupies 180 kHz of spectrum, which is substantially smaller than LTE bandwidths of 1.4–20 MHz. In the downlink, NB-IoT fully inherits downlink numerology from LTE. The subcarrier spacing is 15 kHz and 12 subcarriers make up the 180 kHz channel. In the uplink, NB-IoT supports the same LTE numerology, but the User Equipment (UE) may be assigned 1, 3, 6 or 12 tones. A 3.75 kHz subcarrier spacing is also supported, with a NB-IoT carrier spanning over 48 subcarriers and occupying 180 kHz as well. For this numerology, four times expansion on the time domain applies to remain compatible with the LTE numerology and the UE is always assigned a single tone. Furthermore, in Rel-13 support is limited only to frequency division duplex (FDD) operation.

In the higher layers, simplified LTE network functions are supported. They include idle mode mobility, extended discontinuous reception, power saving mode, paging, positioning based on the existing location services architecture, and access control. In addition, two optimizations for small data transmission have been specified. The first one is the ability to transmit small amount of data in the control plane via Signaling Radio Bearer (SRB). The second one is the ability to suspend and resume Radio Resource Control (RRC) connection, thus eliminating the need to establish new a connection at each reporting instance.

With respect to the performance objectives, the techniques that are used to satisfy each of the performance objectives are summarized below:

Ultra-low-complexity devices: narrowband transmission, having only 1 receiver chain (i.e. 1 receive antenna) at the device, half-duplex operation only, using Convolutional coding instead of Turbo coding on the downlink, reduced peak data rates by limiting the maximum transport block sizes, supporting only one Hybrid Automatic Repeat reQuest (HARQ) process, relaxed processing time, and supporting only BPSK/QPSK modulation.

Improve indoor coverage by 20 dB: repetitions, PSD boosting, and using single-tone transmission with phase rotation modulations to reduce peak-to-average power ratio in the uplink.

Support of massive number of devices: single-tone/multi-tone transmission, RRC connection suspend/resume, data transmission via control plane, multi-carrier operation, and access control to prevent system overloading.

Improved power efficiency: power saving mode, extended discontinuous transmission/reception, using phase rotated modulations to reduce peak to average power ratio in the uplink, RRC connection suspend/resume, and data transmission via control plane.

Exception report latency of 10 seconds or less: RRC connection suspend/resume, and data transmission via control plane.

III. Physical Layer Design

Table I lists downlink (DL) and uplink (UL) NB-IoT channels and signals. These channels are based on existing LTE channels with necessary modifications to fit into the narrow bandwidth used by NB-IoT. A brief summary of each channel and signal is provided in this section.

TABLE I. NB-IoT Channels and Signals

Channel		Usage
DL	Narrowband Physical Downlink Control Channel (NPDCCH)	Uplink and downlink scheduling information
	Narrowband Physical Downlink Shared Channel (NPDSCH)	Downlink dedicated and common data
	Narrowband Physical Broadcast Channel (NPBCH)	Master information for system access
	Narrowband Synchronization Signal (NPSS/NSSS)	Time and frequency synchronization
UL	Narrowband Physical Uplink Shared Channel (NPUSCH)	Uplink dedicated data
	Narrowband Physical Random Access Channel (NPRACH)	Random access

A. NPSS/NSSS

For the in-band mode, since a NB-IoT PRB cannot be located inside the innermost PRBs zone, there is a frequency offset between the DC carrier and the center of the NB-IoT carrier that shall be kept within the ±7.5 kHz range to ensure efficient cell search. Consequently, only a subset of the available LTE PRB locations is suitable to transmit the NPSS/NSSS signals; a similar constraint applies for the guard-band mode. NPSS is transmitted every 10 ms, NSSS every 20 ms, as illustrated in Fig. 1.

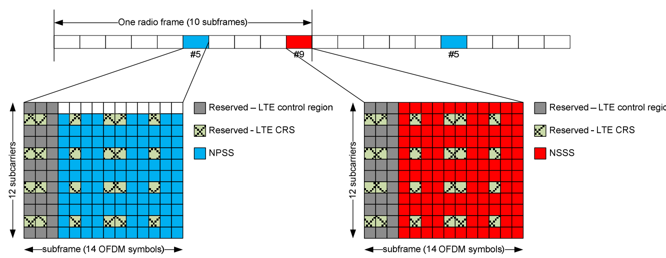

Fig. 1. NPSS and NSSS transmission.

As for LTE, both signals are based upon Zadoff-Chu sequences, of length 11 for the NPSS and of length 131 and scrambled with a Hadamard sequence for the NSSS. For the NSSS, the physical cell identification is indicated by a combination of the Zadoff-Chu sequence root index and the Hadamard sequence index, while the 80-ms boundary is indicated by a time-domain cyclic shift.

B. NPBCH

The NPBCH transmits the Narrowband Master Information Block (MIB-NB) over a 80-ms block, repeated 8 times to cope with extreme coverage conditions; the MIB-NB content remains therefore unchanged for 640 ms. Fig. 2 illustrates NPBCH transmission and shows the narrowband reference signal (NRS) locations. QPSK modulation is used.

The MIB-NB size is 50 bits, including spare bits and a 16-bit CRC; Tail-Biting Convolutional Coding (TBCC) is used for channel coding. As in LTE, the MIB provides the UE with essential information such as system frame number (SFN). The MIB-NB also provides NB-IoT specific information such as the operation mode, and depending of the operation mode, the channel raster and LTE cell-specific reference signal (CRS) information, as well as System Information Block (SIB) scheduling. The Cyclic Redundancy Check (CRC) mask indicates the number of narrowband reference signal ports.

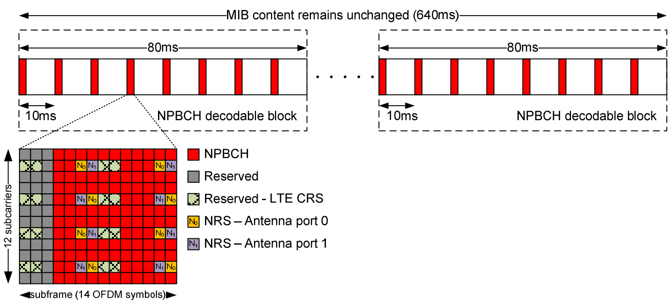

Fig. 2. NPBCH transmission.

C. NPDCCH

Similar to the LTE physical downlink control channel (PDCCH), the NPDCCH consists of control channel elements (CCEs). Within a single PRB pair, two CCEs are defined, corresponding to the upper six and lower six subcarriers. Fig. 3 illustrates this CCE allocation. The maximum aggregation level (AL), i.e., the number of CCEs to which the downlink control information (DCI) is mapped, is two. Repetition of NPDCCH transmission is applied only for an AL of two.

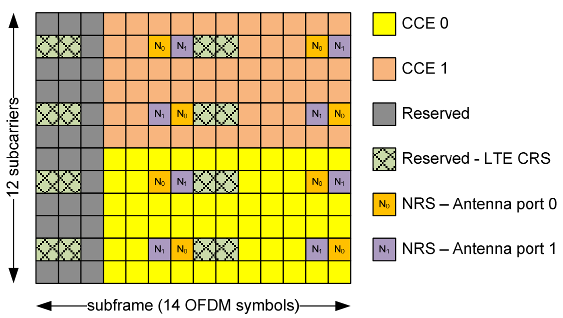

Fig. 3. CCE allocation in the NPDCCH (in-band operation mode).

The search space defines the subframes in which the UE should look for an NPDCCH transmission. In NB-IoT, repetition of transmissions is an important means of achieving coverage enhancement. The maximum number of repetitions of the NPDCCH transmission configured for the UE, R_{max}, depends on its coverage level and is chosen from {1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048}. The UE performs blind decoding within the search space based on the monitoring sets that are defined (separately for the common search space and the UE-specific search space) for the configured R_{max}. The actual number of repetitions used in the transmission is also indicated in the DCI, which allows the UE to determine the end of the NPDCCH transmissions when it is able to successfully decode the NPDCCH even before the last repetition.

The starting subframe of the search space is described by

$$(10n_f + \text{floor}(n_s/2)) \bmod T = \text{floor}(\alpha_{\text{offset}}T)$$

where n_f is the system frame number, n_s is the slot index, T is the period at which the search space repeats, $\alpha_{\text{offset}} \in \{0, 1/8, 1/4, 3/8\}$ is an offset parameter. The period is given by

$$T = R_{max} \cdot G$$

where $G \in \{1.5, 2, 4, 8, 16, 32, 48, 64\}$ determines how the search space interval is related to R_{max}. The values are configured such that $T \geq 4$ ms.

Three new DCI formats are defined: format N0 is used for NPUSCH scheduling, format N1 is used for NPDSCH scheduling and NPDCCH order, and format N2 is used for paging and direct indication (where the DCI directly includes system information update and other fields).

D. NPDSCH

The NPDSCH is scheduled by the NPDCCH but is transmitted after a certain time delay (indicated in the NPDCCH) to allow the low-complexity NB-IoT UE enough time to decode the NPDCCH: a minimum of 4 ms is introduced between the end of the NPDCCH and the beginning of the NPDSCH.

Unlike the NPDCCH, the NPDSCH always occupies the entire downlink bandwidth of 12 subcarriers. A single codeword may be mapped to multiple subframes from the set {1, 2, 3, 4, 5, 6, 8, 10}. The maximum transport block size (TBS) that can be transmitted on the NPDSCH is limited to 680 bits. Only QPSK modulation is supported and TBCC is employed. Redundancy versions are not supported, while error detection is supported through 24-bit CRC.

Two downlink transmission schemes are defined in all operations modes: transmission with single antenna port (port 0), and transmission with two antenna ports (ports 0 and 1) using space-frequency block coding (SFBC). The number of repetitions of the allocated subframes for NPDSCH that can be transmitted is selected from {1, 2, 4, 8, 16, 32, 64, 128, 192, 256, 384, 512, 768, 1024, 1536, 2048}. Only a single HARQ process is supported on the downlink. The HARQ is adaptive and asynchronous. On the downlink, the instantaneous peak data rate is 170 kbps for in-band operation while the corresponding sustained peak data rate is about 26.2 kbps.

E. NPRACH

The NPRACH is based on single-tone transmission with frequency hopping as shown in Fig. 4 for a single user. It uses subcarrier spacing of 3.75 kHz (i.e., symbol length of 266.7 us) and two cyclic prefix lengths are provided to support different cell sizes: 66.7 µs (10 km) and 266.7 µs (35 km). Hopping is between groups of symbols, where each group comprises five symbols and the cyclic prefix, with pseudo-random hopping between repetitions of groups.

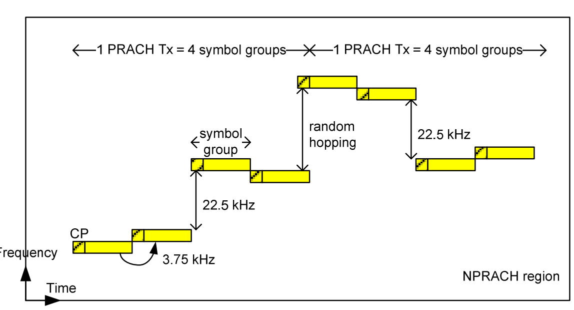

Fig. 4. NPRACH channel.

Up to three NPRACH resource configurations can be configured in a cell with each configuration corresponding to a different coverage level. A resource configuration is given by – periodicity, number of repetitions, starting time, frequency location, and number of subcarriers. In each NPRACH occurrence, {12, 24, 36, 48} subcarriers can be supported. In addition, the transmission can be repeated up to {1, 2, 4, 8, 16, 32, 64, 128} times to enhance coverage.

F. NPUSCH

The NPUSCH is designed to provide extended coverage, massive capacity, and long battery life. Specifically, it supports the following features –

- Single-tone transmission with either 3.75 kHz or 15 kHz subcarrier spacing.
- Multi-tone transmissions (3, 6, 12 tones) using 15 kHz subcarrier spacing.
- Low peak-to-average-power ratio (PAPR) modulation schemes (π/2-BPSK and π/4-QPSK modulation) for single-tone transmission to support efficient power amplifier operation.
- Larger transport block that can be mapped to up to 10 resource units.
- Time-domain repetition. This improves coverage for UEs in extended coverage and helps with channel estimation.

The definition of a resource unit, defined as the smallest amount of time frequency resource, is given in Table II.

TABLE II. NPUSCH RESOURCE UNIT DEFINITION

Subcarrier spacing	No of tones	No of SC-FDMA symbols	Transmission time interval
15 kHz	12	14	1 ms
	6	28	2 ms
	3	56	4 ms
	1	112	8 ms
3.75 kHz	1	112	32 ms

An illustration of NPUSCH multiplexing for different resource units with 15 kHz subcarrier spacing is shown in Fig. 5.

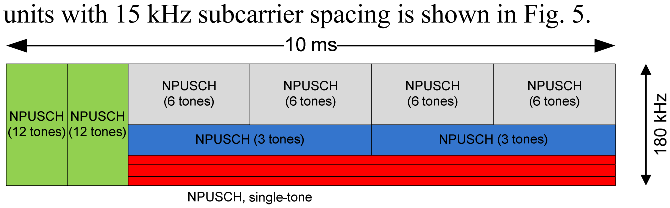

Fig. 5. NPUSCH multiplexing for resource units.

For the NPUSCH, one transport can be mapped to {1, 2, 3, 4, 5, 6, 8, 10} resource units in time. In addition, each transmission can be repeated up to {1, 2, 4, 8, 16, 32, 64, 128} times to improve coverage. The maximum TBS is 1000 bits. The instantaneous peak uplink data rate is 250 kbps. However, the sustained peak data rate is only 62.5 kbps once scheduling delay and other timing constraints are taken into account. Turbo coding is used with incremental redundancy. Only one HARQ process is supported and retransmission uses adaptive asynchronous HARQ.

IV. HIGHER LAYER DESIGN

NB-IoT functionality is specified in the LTE technical specifications. LTE functionality and especially eMTC optimizations are re-used for NB-IoT with simplifications and optimizations [10][11]. Only essential features for small data transmission are supported in Rel-13. The following features are not supported [7]: Inter-RAT mobility, handover, measurement reports, public warning functions, GBR, CSG, HeNBs, relaying, carrier aggregation, dual connectivity, NAICS, MBMS, real-time services, interference avoidance for in-device coexistence, RAN assisted WLAN interworking, sidelink communication/discovery, MDT, emergency call and CS fallback.

Two optimizations for small data transmission have been specified — RRC connection suspend/resume and data transmission using control plane signaling. In addition, multi-carrier operation is also supported. They are briefly described as follows.

RRC connection suspend/resume A RRC connection may be suspended at RRC connection release, and then resumed later. Resume ID is provided to the UE. Both UE and eNB store the Access Stratum (AS) context together with Resume ID upon connection suspension. RRC connection is established using a RRC connection resume procedure. The UE provides the stored Resume ID to be used by the eNB to access the stored information required to resume the RRC connection. Data radio bearer is supported (one by default and optionally up to two). Security is continued and there is no need for the Service Request procedure to establish AS context if the RRC connection is suspended. A diagram to illustrate data transmission using RRC resume operation is shown in Fig. 6.

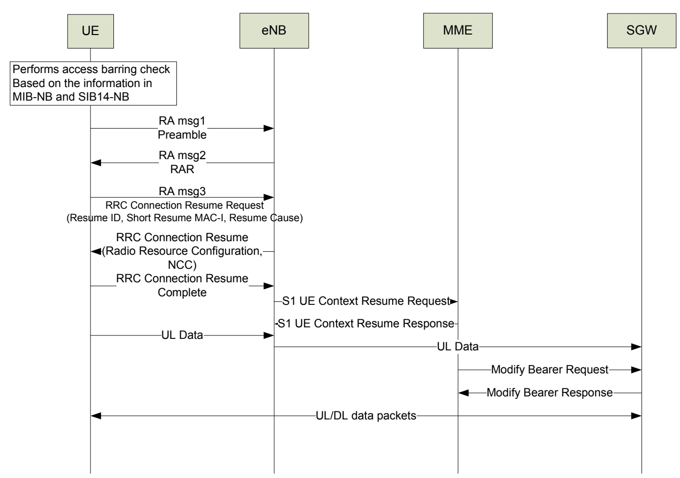

Fig. 6. Data transmission using RRC resume operation.

Data transmission via control plane: User plane data is encapsulated in the Control Plane messages and is transmitted via Signaling Radio Bearer (SRB). An uplink Non-Access Stratum (NAS) signaling message or uplink NAS message carrying data can be transmitted in an uplink RRC container message. A downlink NAS signaling or downlink NAS data can be transmitted in a downlink RRC container message. AS security is not utilized. There is no differentiation between the different data types (i.e. IP, non-IP or SMS) in the AS.

Table III summarizes the signaling comparison among the three methods available for NB-IoT — legacy service request based on LTE, RRC connection suspend/resume, and data transmission via control plane.

TABLE III. SIGNALING COMPARISON AMONG DIFFERENT METHODS

Direction	Legacy Service Request Procedure	RRC Connection Resume	Control Plane Data Transmission
UL	Preamble		
DL	Random Access Response		
UL	RRC Connection Request	RRC Connection Resume Request	RRC Connection Request
DL	RRC Connection Setup	RRC Connection Resume	RRC Connection Setup
UL	RRC Connection Setup Complete	RRC Connection Resume Complete	RRC Connection Setup Complete
DL	Security Mode Command	—	—
UL	Security Mode Complete	—	—
DL	RRC Connection Reconfiguration	—	—
UL	RRC Connection Reconfiguration Complete	—	—
Total number of messages	**9**	**5**	**5**

Multi-Carrier operation: Multiple carriers or PRBs can be supported in NB-IoT to provide more capacity. However, there is only anchor carrier in which UE will access the network. The UE in RRC_CONNECTED state can be configured with dedicated RRC signaling to move to a non-anchor carrier. A non-anchor carrier is not able to broadcast NPSS/NSSS, NPBCH and SIB-NB transmissions, which are always received by the UE from the anchor carrier.

NB-IoT also supports the following functions.

System Information: The MIB-NB contains new parameters to support the special capability requirement for NB-IoT, e.g., the SIB1-NB scheduling index, the deployment configuration, systemInfoValueTag, SFN, hyper SFN (H-SFN) and whether access barring is enabled.

The narrowband SIB 1 (SIB1-NB) contains the necessary information for UE to camp in the cell, such as cell access information as well as the common radio resource configuration. It also provides the frequency/time domain scheduling information for other System Information (SI) messages, and its content is kept unchanged for 40.96 s. SIB1-NB is transmitted in a fixed schedule with a periodicity of 2560 ms and transmission occurs in subframe #4 of every other frame in 16 continuous frames. The TBS and the repetitions within the 2560-ms period are indicated by the MIB-NB.

A reduced set of SIB messages are defined for NB-IoT with the similar functionality but different contents. Each SI message is transmitted periodically within an associated SI-window, but the detailed time/frequency domain scheduling information is provided in SIB1-NB, e.g. the SI-window length, SI-periodicity, TBS and repetition pattern, etc.

System Information update: In RRC_CONNECTED, NB-IoT UE does not detect SI change, while in RRC_IDLE the NB-IoT UE checks both MIB-NB Value tag and SI Value tag in SIB1-NB for SI change. Besides, paging is also used for SI change notification. UE will read different indications in paging message for SI changes and acquire the updated SI messages from different specific radio frames depending on how the Discontinuous Reception (DRX) cycle and the BCCH modification period are configured.

Access control: eNB is able to control different type of access classes and attempt types via system information. Access barring check is supported for the mobile originating exception data, mobile originating data and mobile originating signaling. Network sharing is also supported in the access barring check.

Random Access: NB-IoT supports only contention-based random access, and PDCCH order in case of DL data arrival. NB-IoT reuses the eMTC PRACH resource classification according to coverage levels. A set of PRACH resources is provided for each coverage level configured by SI. The UE selects PRACH resources based on coverage level decided by a UE downlink measurement, e.g., reference signal received power (RSRP). UE will reattempt preamble transmission from the PRACH resource at a higher coverage level if it does not receive a random access response (RAR) even after the allowed number of attempts of a certain level.

Due to the specific uplink transmission scheme in NB-IoT, additional tone information is included in the RAR message and the formula for deriving Random Access Radio Network Temporary Identifier (RA-RNTI) is newly defined. To support the transmission repetitions, the corresponding parameters, including the RAR window size and the medium access control (MAC) contention resolution timer, are extended.

eDRX: Extended DRX (eDRX) is required for NB-IoT UE to save power consumption. With eDRX, the DRX cycle is extended beyond 10.24 s with a maximum value of 10485.76 s for NB-IoT. The H-SFN increments by one when the SFN wraps around. It is broadcast by the cell with 8 bits in SIB1-NB and 2 bits in MIB-NB. Paging Hyperframe (PH) refers to the H-SFN in which the UE starts monitoring paging DRX during a paging timing window (PTW). It is determined based on a formula that is known by the Mobility Management Entity (MME), UE, and eNB as a function of eDRX cycle and UE identity. During the PTW, the UE monitors paging for the duration of the PTW or until a paging message is received, whichever is earlier.

Mobility: Network-controlled mobility including measurement reporting and handover is not supported. The UE stays in the connected mode on the same cell until Radio Link Failure (RLF) occurs or until the eNB releases the connection. Upon RLF the UE transmitting data via control plane optimization goes to RRC_IDLE state and upon RLF the UE transmitting data via user plane optimization performs RRC Connection Re-establishment. Idle-mode mobility is supported. Intra-frequency reselection is based on the ranking of the cells. Inter-frequency reselection is based on the ranking of the frequencies. Blind redirection without measurement results via RRC Connection Release is supported for load balancing.

Paging: eMTC paging solution is reused for NB-IoT, i.e. repetitions are applied for paging transmission (NPDCCH and NPDSCH). The NPDCCH repetitions start from the Paging Occasion (PO), which is determined by the legacy LTE PO-table but also considering the valid DL subframe of NB-IoT.

The coverage level for deciding the repetitions is forward to the MME by eNB when the UE leaves RRC_CONNECTED state, and the MME can provide the coverage level information of the UE, the paging attempt number, and last known Cell ID to eNB in the S1 paging message later.

V. PERFORMANCE RESULTS

Performance results are summarized in this section including coverage, capacity, latency, and battery life. Due to space limitation, only results for in-band operation mode will be shown. Performance for this mode can be considered the limiting factor since eNB power is shared between LTE and NB-IoT and also a portion of the NB-IoT downlink subframe is reserved for transmission of legacy LTE control channels. Additional performance results may be found in [12][13].

A. Coverage

The target is to enhance cell coverage by 20 dB, corresponding to the target MCL of 164 dB [9]. Table IV (at the end of the paper) shows the link budget for NB-IoT in in-band operation mode with 10 MHz broadband LTE carrier. In the downlink, 46 dBm of power is available at the eNB for both LTE and NB-IoT. Out of this total power, 35 dBm is used for NB-IoT (corresponding to 6-dB power boosting of the baseline). The UE has 23 dBm of total power. Single-tone transmission is assumed for uplink data channels. Repetitions are assumed along with transmission of a data transport block over multiple resource units defined in NB-IoT.

From Table IV, it is seen that the target MCL of 164 dB can be achieved for the channels considered through the use of Rel-13 features for NB-IoT outlined in this paper. At this MCL, a physical layer data rate of 0.40 kbps in the downlink and 0.27 kbps in the uplink can be supported. Note that, for the NPUSCH, coverage is approximately the same for 15 kHz and 3.75 kHz subcarrier spacing. This shows that using 3.75 kHz subcarrier spacing does not necessarily increase coverage despite the four times reduction in effective noise power. This is because the symbol length for the 3.75 kHz subcarrier spacing is four times longer and therefore the number of symbols available for a given transmission time is four times less than for 15 kHz subcarrier spacing.

B. Capacity

Capacity results are determined using system simulations. The macro-cell system simulation scenario is of a traditional 19-site, 57-cell system setup with wrap-around. Detailed system simulation parameters are described in [9]. The traffic model is based on Mobile Autonomous Reporting (MAR) described in [9]. In this model, devices wake up periodically to transmit a report, then go back to sleep. The inter-arrival time is periodic as follows: 1 day (40%), 2 hours (40%), 1 hour (15%), and 30 minutes (5%). The mean inter-arrival time is 10.6 hrs. The application payload size follows a Pareto distribution with shape parameter α=2.5, minimum packet size of 20 bytes and maximum packet size of 200 bytes. The mean packet size is 32.6 bytes. In addition, a total protocol overhead of either 65 bytes (without IP header compression) or 29 bytes (with IP header compression) are added.

For capacity, the target is to support at least 52547 devices within a cell-site sector. System-level simulation results show that at least 250K devices can be supported within a cell site sector per NB-IoT carrier. Additional capacity, if needed, can be acquired through using multiple carriers.

C. Battery Life

For power efficiency objective, the goal is to achieve battery life of more than ten years at maximum coverage level (164 dB MCL) using battery capacity of 5 Wh. The analysis assumes periodic uplink reporting with the transactions during an uplink reporting event described in [14] and UE is assumed to remain on the same cell. The four power states and current consumptions are transmit (543 mW), receive (90 mW), idle (2.4 mW), and power saving (0.015 mW).

Based on these assumptions, the estimated battery lifetime at maximum coverage level are 10.5 years to send a daily report of 200 bytes and 16.8 years to send a daily report of 50 bytes. This shows that the 10-year battery life target can be met or exceeded for daily reporting. This long battery life is possible due mostly to the following features –

- Long eDRX which allows UE to sleep for up to 10485.76 seconds while waking up periodically to check for paging.
- Power saving mode where the UE remains registered to but not reachable by the network. The UE is in the power-off or sleep mode, and will wake up only when there is data to send or after timer expiration.

D. Exception Report Latency

Exception report latency of 10 seconds or less is required for 99% of the devices. Latency is evaluated at the maximum coverage level with an exception report consisting of 20 bytes application report, 65 bytes upper layer protocol header, and 15 bytes of SNDCP/LLC/RLC/MAC/CRC overhead [9]. The following times are used in calculating the latency – synchronization, master information block acquisition, random access (including wait time), uplink scheduling grant, and data transmission targeting 99% confidence level.

Analysis shows that an exception report can be successfully transmitted in approximately 9.9 seconds with 99% confidence. This time can be reduced since the eNB can discriminate between normal and exception reports and provides higher priority to exception reports.

VI. REL-14 ENHANCEMENTS

In 3GPP Rel-14, three major enhancements will be introduced for NB-IoT:

- Positioning enhancements to allow device tracking. Currently, location services based on Enhanced Cell-ID (ECID) is supported but without any defined performance requirements. In Rel-14, core requirements for ECID will be defined. In addition, a more accurate location service, such as Observed Time Difference of Arrival (OTDOA) or Uplink-Time Difference of Arrival (UTDOA), will also be supported.
- Multicast downlink transmission to support, e.g., firmware update or group message delivery, based upon the LTE Rel-13 single-cell point-to-multipoint feature.
- Support of new UE power class(es) (e.g., 14 dBm – 20 dBm and 23 dBm power classes are supported in Rel-13), targeted to small form-factor battery devices.

In addition, miscellaneous enhancements related to mobility/service continuity and multi-carrier operation will be introduced.

VII. CONCLUSION

This paper provides an overview of the emerging 3GPP Rel-13 technology known as NB-IoT. The design objectives are outlined. The various physical channels of the new system are summarized while noting the design constraints. The salient features of the higher layer design are also examined, considering the simplifications and optimizations that are targeted. A short performance analysis is presented, focusing on coverage, capacity, battery life, and latency. The results demonstrate that the system meets the design objectives. Rel-14 will bring further enhancements to make the technology very viable for future IoT applications.

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