NarrowBand-IoT: A Survey on Downlink and Uplink Perspectives

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***Abstract*—NarrowBand-IoT (NB-IoT) is a radio access technology standardized by the 3GPP to support a large set of use cases for massive machine-type communications (mMTC). Compared to human-oriented 4G technologies, NB-IoT has key design features in terms of increased coverage, enhanced power saving, and a reduced set of functionalities. These features allow for connectivity of devices in challenging positions, enabling long battery life and reducing device complexity. This paper provides a detailed overview on NB-IoT. This paper provides a detailed overview on NB-IoT, together with analysis and performance evaluation of the technology. Both uplink direction and downlink are presented including the recent updates on the support of multicast transmissions. The paper summarizes the possible configurations of NB-IoT, discusses the procedures for data transmission and reception and analyzes aspects such as latency and resource occupation. We present a performance evaluation focusing on both uplink and downlink, with the aim to understand the channel occupancy of NB-IoT for different real-life IoT use cases and cell deployments. Further analysis focuses on the impact of various radio access parameters on the capacity of NB-IoT. Finally, results focusing on a new use case for NB-IoT, i.e., firmware update of a group of devices, are presented in form of a comparison between unicast and multicast transmission modes.**

***Index Terms*—NB-IoT, LPWA, IoT, mMTC, C-IoT, NPRACH, SC-PTM.**

I. Introduction

THE effective support of massive machine-type communications (mMTC) [1] is expected to play a key role in the market of Internet of Things (IoT) for the emerging 5G ecosystem [2]. The unique requirements in terms of coverage, battery life, and device complexity of mMTC dictated an ad-hoc design of wireless technologies, usually referred to as Low Power Wide Area (LPWA) networks [3]. One emerging standard is NarrowBand-IoT (NB-IoT).

NB-IoT [4] is an access technology defined by the 3rd Generation Partnership Project (3GPP) for mMTC. NB-IoT implements several mMTC-oriented enhancements compared to other mobile technologies [5], [6], [7], examples are: *(i)* narrow-band transmission and the exploitation of repetitions to reach devices in challenging positions such as basements or underground; *(ii)* differentiation of User Equipment (UE) performance according to coverage areas by tuning parameters of the physical channels and network procedures; *(iii)* enhanced power saving mechanisms to improve the battery life; *(iv)* simplification of network procedures to reduce the UE complexity. In addition, being fully integrated within 3GPP networks, NB-IoT can be enhanced to support services usually delivered in mobile networks, as testified by the introduction of multicast capabilities in the recent updates of the standard [8]. Several works and white papers, e.g., [4], [9], [10], [11], present an overview of the main features of NB-IoT and study performance in terms of coverage extension or random access (RA) capacity. Information on NB-IoT are thus currently spread across several technical documents and publications, and an overall overview of all the different features of NB-IoT is still missing.

The aim of this paper is twofold. Firstly, we provide a detailed overview of NB-IoT summarizing all main features and technical information. Secondly, this paper has the unique feature of presenting NB-IoT from both uplink (UL) and downlink (DL) perspectives, motivated by the growing attention towards remote re-configuration of IoT devices. To this aim, the paper also summarizes the procedures for DL and Single Cell Point-to-Multipoint (SC-PTM) transmissions, in addition to the UL case. We discuss in details the configuration capabilities of NB-IoT for parameters such as number of repetitions, physical channel configurations, timers, etc. We also present a detailed discussion of the main sources of latency in both UL and DL directions. Notably, we analyze how latency might vary according to the NB-IoT cell configuration. Above discussions are supported by a performance evaluation of UL and DL considering real mMTC use cases. We further present an analysis on how capacity and resource utilization of NB-IoT are affected when varying the configuration of several parameters. Finally, another contribution of this paper is the analysis of a new use case, i.e., firmware update of a group of devices, conducted by comparing the performance achieved with DL (i.e., unicast) and SC-PTM transmission schemes.

The paper is structured as follows. Sec. II provides an overview of the main features of NB-IoT, while Sec. III and IV focus in details on DL and UL directions, respectively. Sec. V focuses on the performance evaluation of UL, DL, and SC-PTM. Final remarks are given in Sec. VI.

II. NB-IoT: A technology overview

A. Extended Coverage

NB-IoT targets a coverage improvement of 20dB w.r.t. GSM/GPRS, achieved through the utilization of *narrow-band*

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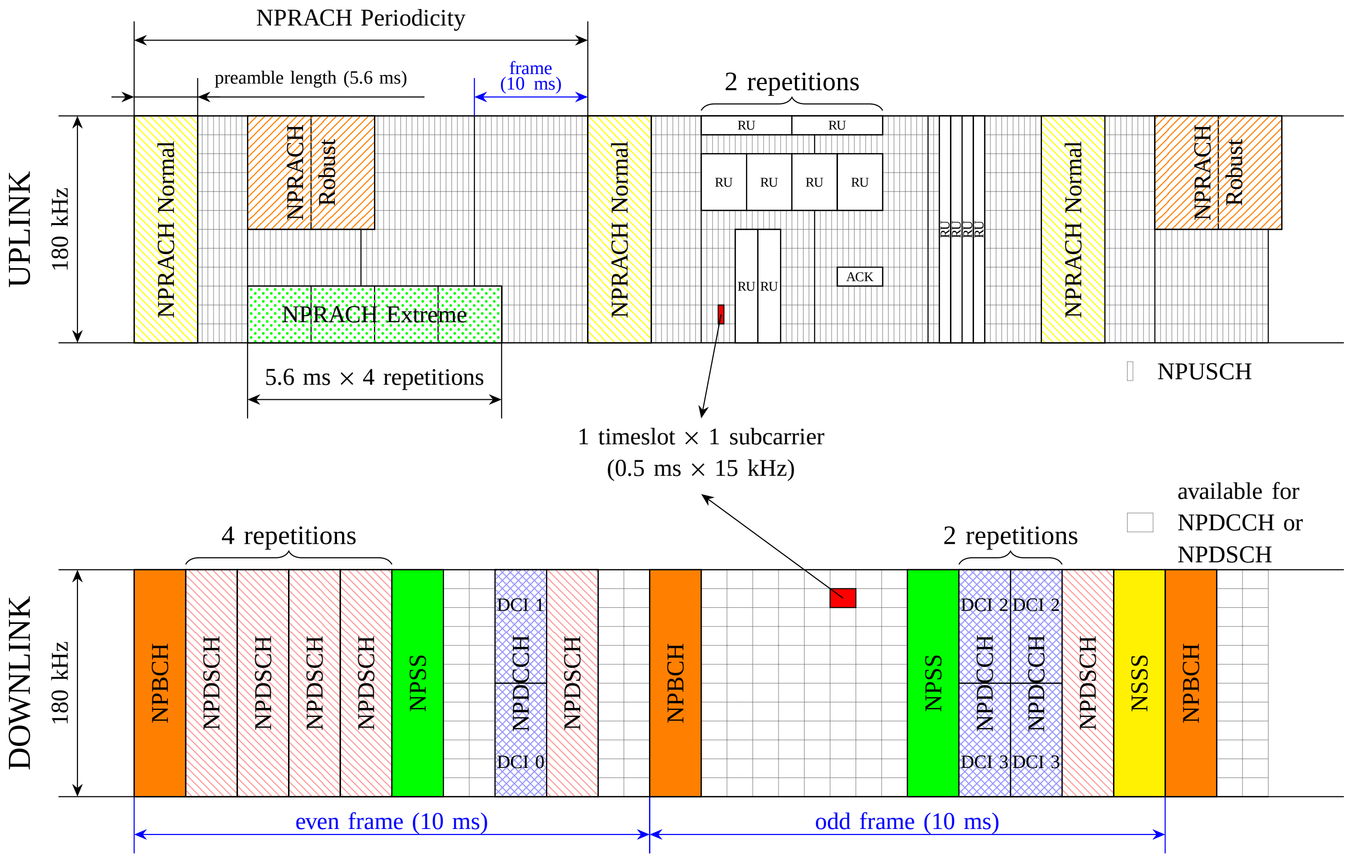

Fig. 1. Representation of NB-IoT UL and DL physical channels, assuming 15 kHz subcarriers in UL, Format 0 preamble and two DCIs in every NPDCCH subframe.

signals and *time diversity*.

A narrow-band signal allows the receiver to filter out more noise, thus improving the Signal to Interference and Noise Ratio (SINR). The standard subcarrier spacing is 15kHz but it can be reduced down to 3.75kHz for higher robustness.

To effectively exploit the time-variation of the radio channel, up to 2048 and 128 *repetitions* are allowed in DL and UL, respectively, to increase the success probability of signal reception. Each replica can be decoded separately, or multiple replicas can be combined to further increase the reception probability.

NB-IoT allows flexibility in the cell configuration by defining three *coverage classes*: *Normal*, *Robust* and *Extreme*. Classes are differentiated through thresholds based on signal strength, defined to introduce three levels of coverage extension w.r.t. GSM/GPRS: 0dB, 10dB, and 20dB for Normal, Robust, and Extreme, respectively. Such thresholds depend on the cell deployment, the propagation environment (i.e., outdoor, indoor, deep-indoor, underground) and the spatial distribution of devices. The number of repetitions and network parameters can be tuned separately for each class, as explained in the remainder of the paper.

B. Deployment and numerology

The channel bandwidth of NB-IoT is 180 kHz, i.e., one LTE Physical Resource Block (PRB). Three deployment options are available: *standalone*, re-using unused 200kHz GSM carriers; *guard-band*, exploiting the guard band of two adjacent LTE carriers; *in-band*, where one LTE PRB is reserved for NB-IoT within a LTE carrier bigger than 1.4MHz.

For the sake of coexistence, NB-IoT numerology is inherited from LTE. In both DL and UL, the channel is divided into 12 subcarriers of 15kHz each. The time domain is divided into *time slots*, each lasting 0.5ms and consisting of 7 OFDM/SC-FDMA symbols. The smallest time-frequency resource, namely Resource Element (RE), is composed of one subcarrier and one symbol. Time slots are grouped as follows: two time slots form one *subframe* (1ms), 10 subframes form one *frame* (10ms). Frames are identified by a system frame number, reset every 1024 frames. This structure is then repeated 1024 times, forming the *hyper frame* lasting ∼3 hours.

To further improve the coverage, a second numerology with 48 subcarriers of 3.75kHz each is introduced. This numerology is used for the preamble transmission of the RA procedure (Sec. IV-A) and optionally for UL transmissions. In this numerology, the time slot lasts 2ms and, for the sake of compatibility, one frame is composed of 5 time slots.

C. Overview of signals and channels

The Narrowband Primary Synchronization Signal (NPSS) is used for initial time-frequency synchronization of the device in the DL and to get partial information regarding the cell identity. The NPSS is always transmitted on subframe #5 of every frame. The Narrowband Secondary Synchronization Signal (NSSS) is used to accomplish full DL synchronization by obtaining the physical Narrowband Cell ID (NCellID). The NSSS is transmitted in subframe #9 of every odd frame.

The Cell-specific Reference Signal (CRS), i.e., the LTE reference signal, is always present for NB-IoT in-band deployments to allow interoperability between the two technologies. NB-IoT uses the Narrowband Reference Signal (NRS) as a reference point for the DL power, where the locations of NRS and CRS are derived from the NCellID. The NRS can be transmitted in either one or two antennas and eight REs per subframe are allocated to each antenna.

NB-IoT defines the following physical channels, depicted in Fig. 1:

- Narrowband Physical Broadcast Channel (NPBCH), used to broadcast information about cell and network configuration;
- Narrowband Physical Downlink Control Channel (NPDCCH), transfers all the control signals from the evolved Node B (eNB) to the UE;
- Narrowband Physical Downlink Shared Channel (NPDSCH), used for data transmission from the eNB to the UE;
- Narrowband Physical Random Access Channel (NPRACH), used to initiate the RA procedure;
- Narrowband Physical Uplink Shared Channel (NPUSCH), used for data transmission from the UE to the eNB.

In all subframes, the first two or three REs are reserved for the LTE PDCCH to allow interoperability for in-band deployments. One single HARQ process is used for NPUSCH and NPDSCH.

D. Power saving techniques

In addition to reducing the maximum transmission power from 23dBm (Class 3) to 14dBm (Class 6), NB-IoT introduces two power saving techniques: the *extended Discontinuous Reception* (eDRX, initially for LTE Cat. M1 in Release 12) and the *Power Saving Mode* (PSM).

In idle state, the UE periodically monitors the paging channel to check for incoming data. This periodicity, i.e., the DRX cycle, has been extended from 2.56s (maximum value in LTE) up to a maximum eDRX of ~175 minutes in NB-IoT.

A UE might also be allowed by the network to switch in PSM. While in PSM, the UE is registered to the network but not reachable (i.e., paging not monitored with further energy savings w.r.t. the idle state). At the expiration of the PSM cycle, the UE performs a Tracking Area Update (TAU).

Two timers are defined for idle and PSM phases: T3324 is the duration of the idle phase (up to ~3 hours); T3412 represents the TAU periodicity and thus determines the duration of the PSM cycle (up to ~413 days) [10], [13]. Fig. 2 shows an example of a complete PSM cycle without any activity followed by an activation to transmit data. The aforementioned timers are also highlighted in Fig. 2 and listed in Table I.

III. Downlink direction

A. Channels and related configurations

Only 15kHz subcarrier spacing is used in DL and QPSK is used in all channels.

The NPBCH always occupies the subframe #0 and carries the Master Information Block (MIB-NB) which delivers information such as system bandwidth, system frame number, number of antennas ports, and the scheduling for the Narrowband System Information Block 1 (SIB1-NB). MIB-NB is split into 8 blocks, each block is consecutively repeated 8 times. The overall transmission period of the MIN-NB is 640ms. Apart from the subframes allocated to NPBCH and NPSS/NSSS (Sec. II-C), the rest of DL subframes are dynamically allocated to either NPDCCH or NPDSCH.

The NPDCCH carries the Downlink Control Information (DCI) for both data reception and transmission with related number of repetitions to be used. NB-IoT has three DCI formats: N0, used for UL grant; N1, used for DL scheduling; N2, used for paging. NB-IoT also defines NPDCCH format 0 and 1. Each NPDCCH subframe can be split in one or two Narrowband Control Channel Elements (NCCEs), each occupying 6 consecutive subcarriers. NPDCCH format 0 uses one NCCE while NPDCCH format 1 can have both NCCEs in the same subframe for more robust transmissions. The possible locations of the NPDCCH are called search spaces and three different types are defined: type-1, used for paging; type-2, used for the RA process; type-3, the user-specific search space where UEs can find DL data or control information such as UL grants. To find out if the NPDCCH carries any data for it, the UE uses the appropriate Radio Network Temporary Identifier (RNTI, specifically P-RNTI for type-1, RA-RNTI for type-2 and C-RNTI for type-3) and looks for it in the NPDDCH's CRC. For user-specific search space, the periodicity of the NPDCCH occasions vary from 4ms to 2.2 minutes [6].

The NPDSCH is scheduled in the NPDCCH and is used for dedicated data transmission towards the UEs, RRC signalling and transmission of System Information Blocks (SIB-NBs), containing other system-related information. Examples of SIB-NBs is the SIB1-NB, which provides information such as the Tracking Area Code (TAC), the PLMN identity and the scheduling information for the rest of the SIB-NBs. Its duration is 2560ms and is transmitted in subframe #4 of 16 consecutive frames. The transmission can be configured with different MCSs (indicated in the MIB-NB) in order to be mapped into 1, 2 or 4 subframes, with 16, 8 or 4 repetitions respectively. Another example of SIB-NBs is the SIB2-NB, which contains the configuration of the paging channel and parameters for the RA procedure. The periodicity of the SIB2-NB is not specified. The NPDSCH supports a maximum transport block size (TBS) of 680 bits. Depending on the TBS, data transmission can span several subframes.

B. System information acquisition, paging and data reception

The first DL procedure performed by the UE is the synchronization and acquisition of *system information*. By decoding the MIB-NB and at least SIB1-NB and SIB2-NB, the UE retrieves cell and access configurations. As analyzed in [12],

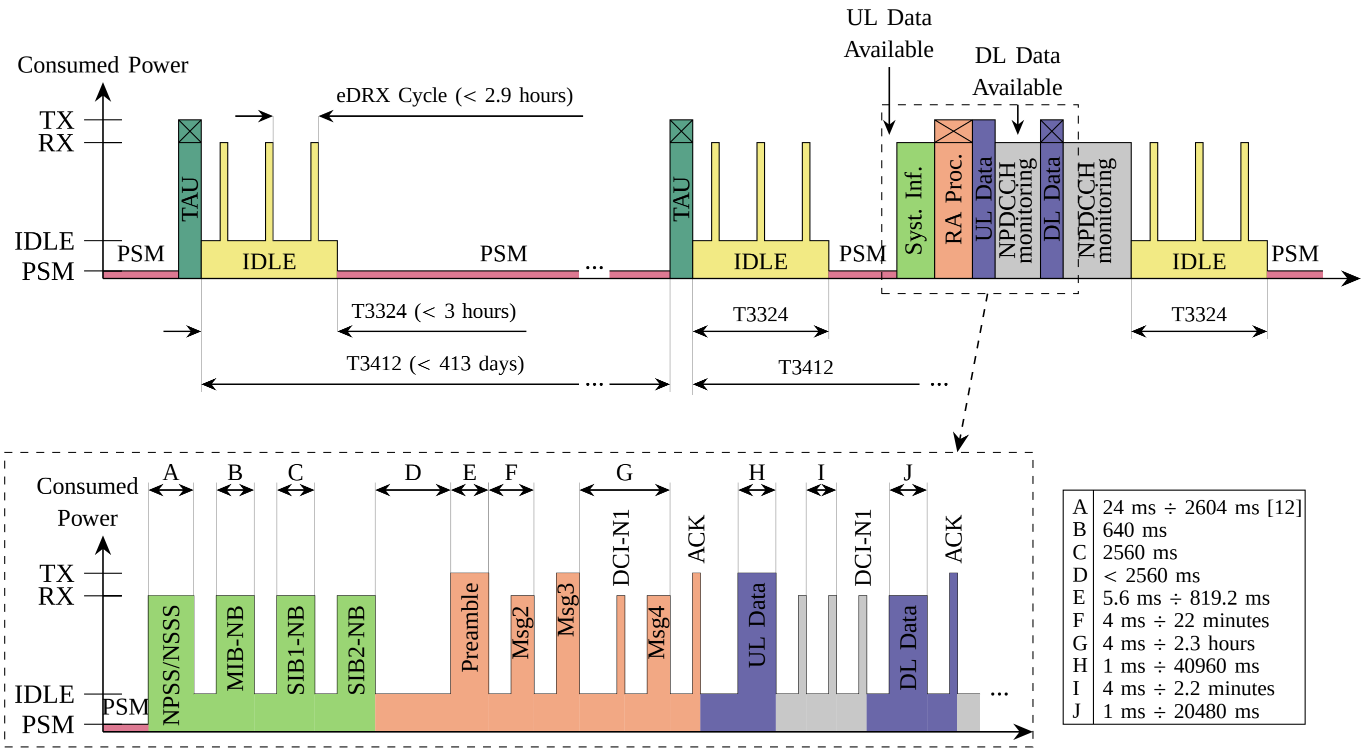

Fig. 2. Life-cycle and related power levels of a NB-IoT UE: TAU, idle state with eDRX, PSM, and data transmission with a detailed insight of the RA procedure. We assume that the UE receives an application acknowledgment before switching to PSM after a UL data transmission.

the time required for the synchronization varies from 24ms to 2604ms for the best and worst propagation conditions, respectively.

To reach a UE in idle state, the network sends a *paging* message to the UE via the NPDSCH with DCI format N2. The paging message also indicates whether the paging is done to initiate a request for an RRC connection (i.e., incoming data) or a change in the system information.

After paging (or if the UE is already connected), the *data reception* can start. The DCI format N1 indicates the resource allocation, the number of subframes the DL transmission spans, the number of repetitions and whether an ACK is being expected. If repetitions are indicated, then identical copies of the data are transmitted by the eNB in consecutive subframes using one subframe inter-leaving. If no repetitions are used, the transmission is mapped in continuous subframes. If the SIB1-NB is also being transmitted in the frame, the data transmission resumes in the subframe after the one used for the SIB1-NB.

The UE uses the NPUSCH Format 2 (please, refer to Sec. IV-A) specified in the DCI to transmit the ACK, if needed. Only a single HARQ process is used, and the maximum number of retransmissions is broadcasted by the eNB using the DL_REPETITION_NUMBER-1 of the SIB1-NB. Fig. 2 depicts the aforementioned procedures.

The support of SC-PTM was introduced for NB-IoT Release 14 to support multicast transmission. Upon subscribing to a service, the UE receives a group Radio Network Temporary Identifier (G-RNTI) for the subscribed service.

The SC-PTM is a mix of the unicast transmissions and the eMBMS framework. Similarly to the eMBMS, the available services for SC-PTM are broadcasted and devices need to subscribe to them in order to receive the content. Upon subscription the device receives a group RNTI (G-RNTI) for the subscribed service. Control information (session start, session stop, resource allocation, etc.) regarding ongoing and upcoming services are carried in the NPDSCH, where such information are transmitted with a periodicity from 320ms to 163.84 seconds [8] and the related location within the NPDSCH is given by the G-RNTI. For data reception, a generic multicast radio bearer (SC-MRB) is established and UEs receive the multicast content in a similar way as for UE-specific unicast transmission using their G-RNTI.

IV. Uplink Direction

A. Channels and related configurations

Only two channels are defined in the UL, the NPRACH and the NPUSCH. The NPRACH is used to trigger the RA procedure. It is composed of a contiguous set of either 12, 24, 36 or 48 subcarriers with 3.75 kHz spacing, which are repeated with a periodicity from 40ms to 2560ms. The RA procedure starts with the transmission of a *preamble*, with a duration of either 5.6ms or 6.4ms (Format 0 and 1, respectively) depending on the size of the cell and can be repeated up to 128 times to improve coverage. A preamble is composed of four symbol groups, each transmitted on a different subcarrier. The first subcarrier is chosen randomly, while the following ones are determined according to a deterministic sequence that depends on the initial subcarrier. Two UEs selecting the same initial

TABLE I
SUMMARY OF THE MAIN SOURCES OF LATENCY.

Source of Latency	Influenced by	Description
eDRX [13]	• DRX cycle periodicity (< 175 minutes)	• The DRX cycle periodicity affects the time for DL reachability
Power Saving Mode [13]	• Idle timer (T3324) < 3 hours • PSM timer (T3412) < 413 days	• T3324 and DRX cycle periodicity define the number of occasions for DL reachability. • T3324 and T3412 define how long the UE will not be reachable.
Initial Synchronization [12]	• Channel Quality • Deployment {inband; standalone}	• Best: 24ms (good channel) • Worst: 2604ms (bad channel, inband)
System Information	• MIB periodicity (640ms) • SIB1 periodicity (2560ms) • SIB2 periodicity (chosen by the operator) • Channel Quality	• MIB and SIBs need to be decoded in sequence, and therefore the latency is at least equal to the sum of the the related periodicities
NPUSCH Transmission	• Payload Size • Subcarrier Spacing (3.75kHz, 15kHz) • Multi-tone capability • RU chosen by the scheduler • Number of repetitions (1, 2, 4, . . ., 128)	• Numerology and UE capabilities determine the duration of each RU [7] • Best: 1ms (15kHz, multi-tone, shortest RU, 1 repetition, 1 RU) • Worst: 40960ms (3.75kHz, 128 repetitions, 10 RUs)
NPRACH occurrence	• NPRACH Periodicity (40, 80, 160, 240, 320, 640, 1280, 2560) ms • Activation Instant	• Average: half of NPRACH periodicity • Upper Bound: NPRACH periodicity
Preamble Transmission	• Preamble Format (Format 0 or 1) • Number of Repetitions (1, 2, 4, . . ., 128)	• The format depends on the cell size and affect the preamble length (Format 0: 5.6ms; Format 1: 6.4ms) • Best: 5.6ms (Format 0, 1 repetition) • Worst: 819.2ms (Format 1, 128 repetitions)
RA Backoff	• Backoff configuration 256×(0, 1, 2, 4, . . ., 2048) ms	• Uniformly distributed between 0 and the configured value • Worst: 524288ms (~9 minutes)
NPDCCH Occasion periodicity	• Number of repetitions • Start offset G (1.5, 2, 4, . . . , 64)	• Computed as $max\{R_{max} \cdot G; 4\}$, where R_{max} is the maximum number of repetitions used in the cell and G a time offset [6] • Best: 4ms • Worst: 2.3 minutes
RAR Reception	• Packet Scheduling • NPDCCH Occasion periodicity • RAR Window Size (2, 3, 4, 5, 6, 7, 8, 10)× NPDCCH Occasion periodicity [8]	• Best: 4ms (processing time at eNB and margin to switch from transmission to reception at UE side) • Worst: 22 minutes
Contention Resolution Window	• Packet Scheduling • NPDCCH Occasion periodicity • Contention Resolution Window Size (1, 2, 3, 4, 8, 16, 32, 64) × NPDCCH Occasion periodicity [8]	• Best: 4ms (processing time at eNB side and margin to switch from transmission to reception at UE side) • Worst: 2.3 hours
NPDSCH/NPDCCH Transmission	• Payload Size • Number of Repetitions (1, 2, 4, . . . , 2048)	• Best: 1ms (1 repetition, 1 subframe) • Worst: 20480ms (2048 repetitions, 10 subframes)
HARQ Retransmission	• TTI (chosen by the operator)	• Only a retransmission per TTI can be triggered by the HARQ process

subcarrier, will thus collide for the entire sequence. Hence, in each NPRACH occurrence there is a number of orthogonal preambles equal to the number of subcarriers allocated to the NPRACH [7].

The number of repetitions, the periodicity and the number of subcarriers are defined for each NPRACH related to a specific coverage class. By choosing an appropriate configuration of the aforementioned parameters and different time offsets it is possible to have a different orthogonal NPRACH, each with its own capacity in terms of accesses per second, for each coverage class. Fig. 1 presents an example of three NPRACHs configured as follows: 48 subcarriers, one repetition, 40ms periodicity for Normal class; 24 subcarriers, 2 repetitions, 80ms periodicity for Robust class; 12 subcarriers, 4 repetitions, 160ms periodicity for Extreme class.

The NPUSCH occupies all the UL resources left available after the allocation of the NPRACH. NPUSCH format 1 is used for UL data while NPUSCH format 2 carries UL control information (UCI), which in Release 13 is a DL HARQ ACK. Only BPSK or QPSK can be used and the code rate is 1/3 for data transmission and 1/16 for DL HARQ ACK. For UL data, a UE can either use a single or multiple subcarriers (single- and multi-tone capability, respectively). To perform a UL transmission, the eNB allocates a certain amount of resources to the UEs. The minimum amount of resources is called Resource Unit (RU), where the possible RU configurations [7] depend on the UE capabilities and the configured numerology, and affect the latency as listed in Table I. In the worst case of 3.75kHz spacing and single-tone capabilities, the only RU that can be used is 32ms long with either BPSK or QPSK. In the best case of multi-tone capabilities and 15kHz spacing, a RU is composed of 12 subcarriers and 2 time slots with QPSK. In Fig. 1 all the possible RU sizes both for Format 1 and Format 2 are show assuming a 15kHz subcarrier spacing. Given the used TBS (up to 1000 bits), the number of required RUs depends on the MCS used to meet a certain success probability target, where the relationship between MCS, TBS and number of required RUs can be found in [6]. From a latency point of view, the overall duration of a transmission on the NPUSCH is thus affected by the number of repetitions, the amount of required RUs and their configuration, as seen in Table I.

B. Procedures for RA and data transmission

The initial procedure in the UL is the RA, which can be triggered as either a response to a paging message or UE-initiated for the purpose of UL data transmission. In order to trigger the RA, the UE needs to be aware of the system configuration. If the UE is in idle state, it already has that information, while if it is in the PSM mode it first has to retrieve the MIB-NB, SIB1-NB, and SIB2-NB (Sec. III-B).

The RA includes four messages and starts with the transmission of a preamble (Msg1) on the first available NPRACH opportunity (Sec. IV-A). If multiple UEs choose the same initial subcarrier the preamble sequence will collide but the eNB is not yet aware of it. After the preamble transmission the UE starts a Random Access Response (RAR) window, which lasts from 2 to 10 times the NPDCCH period (refer to Sec. III-A). During this time, the UE expects to receive the RAR message (i.e., Msg2) through the NPDCCH which indicates the preambles identified by the eNB. The RA-RNTI univocally identifies the preambles and lets the UE identify if the RAR is addressed to it. For each preamble listed in the RAR, the eNB provides a UL grant for the transmission of Msg3 of the RA. The maximum number of preambles that can be addressed for each RAR is a network-specific value, used to moderate the load. The UEs that did not receive the Msg2 within their RAR window will perform a new RA attempt. In this phase, colliding UEs will receive the same RAR without being aware that a collision happened. After Msg2 reception, the UE transmits the Msg3 on the NPUSCH according to the UL grant received in the Msg2. The Msg3 carries information such as the UE identity and the buffer size report (BSR). The UE now starts a Contention Resolution Timer (from 1 to 64 times the NPDCCH period long, refer to Sec. III-A) during which it expects to receive the Msg4 on the NPDSCH. The Msg4 carries the UL grant to be used for data transmission and it is also used to resolve the collisions. The Msg3 and Msg4 are transmitted using HARQ through the NPUSCH and NPDSCH respectively.

If the RA procedure fails in any of the aforementioned phases, the UE performs a new attempt after a backoff time of up to ~9 minutes. If the UE reaches the maximum number of attempts (configured by the network and up to 10), it will keep trying in another coverage class. A maximum total number of attempts can be configured up to 200, after reaching it the UE declares a RA failure. The aforementioned parameters (i.e., RAR window, timers, backoff value, maximum number of attempts) could also be specified for each coverage class separately. Latency components of the RA procedure are summarized in Table I.

Once resources have been granted with the reception of Msg4, the UE starts transmitting its payload on the NPUSCH using HARQ. ACK/NACK for the HARQ are carried within the UL, where the New Data Indicator (NDI) bit is exploited for this purpose. The NDI bit is used to distinguish the request for a new transmission from a request of retransmission of the previous packet. In case of failure, the eNB will send another UL grant where the NDI bit will be exploited as a NACK; the UL grant will inform the UE about the resources assigned for the retransmission. Up to 28 retransmissions are considered for the NPUSCH. The eNB can also instruct a UE to perform each retransmission using different versions of the redundancy bits in order to improve the success probability using the "redundancy version" in the UL [6], [5]. Fig. 2 shows an example of a complete procedure followed by a non-synchronized UE to transmit a data packet (all steps of the RA and data transmission/reception are assumed to be successful).

V. Performance Evaluation

In this Section, we provide an insight on the performance of NB-IoT considering a set of realistic use cases as described in [14], each with different UE density, report periodicity (RP) and Payload Size (PS): water metering, 104 UE/km2, RP 12h, PS 100B; electricity meters, 104 UE/km2, RP 24h, PS 100B; gas meters, 104 UE/km2, RP 30min, PS 100B; vending machines, 150 UE/km2, RP 24h, PS 150B; bike fleet management, 200 UE/km2, RP 30min, PS 150B; pay-as-you-drive, 2250 UE/km2, RP 10min, PS 150B. Each use case has a different percentage of UEs in outdoor, indoor, and deep indoor conditions that determines the percentage of UEs in Normal, Extended and Extreme classes. The total overhead (considering UDP/IP and 3GPP protocol stack) is 65B. UEs randomly wake up considering their RP, decode MIB-NB, SIB1-NB and SIB2-NB, perform the RA procedure to send a UL report, then receive a 30B DL packet (when still connected) representing an application-level acknowledgment.

The deployment scenario considers three-sectorial base stations deployed in an hexagonal grid with an inter-site distance (ISD, dIS) that has been varied considering 500m, 1000m and 1732m. The number of repetitions used is computed considering -100dB and -110dB as received signal power thresholds for the coverage classes definition, their worst case SINR and the results reported in [15].

A. Analysis of realistic use cases

The percentages of Uplink and Downlink channel utilization for each use case and ISD analyzed are reported in Fig. 3, which also shows how UL and DL resources are divided across the different message types. We can observe that the amount of resources used for the NPRACH increases as the

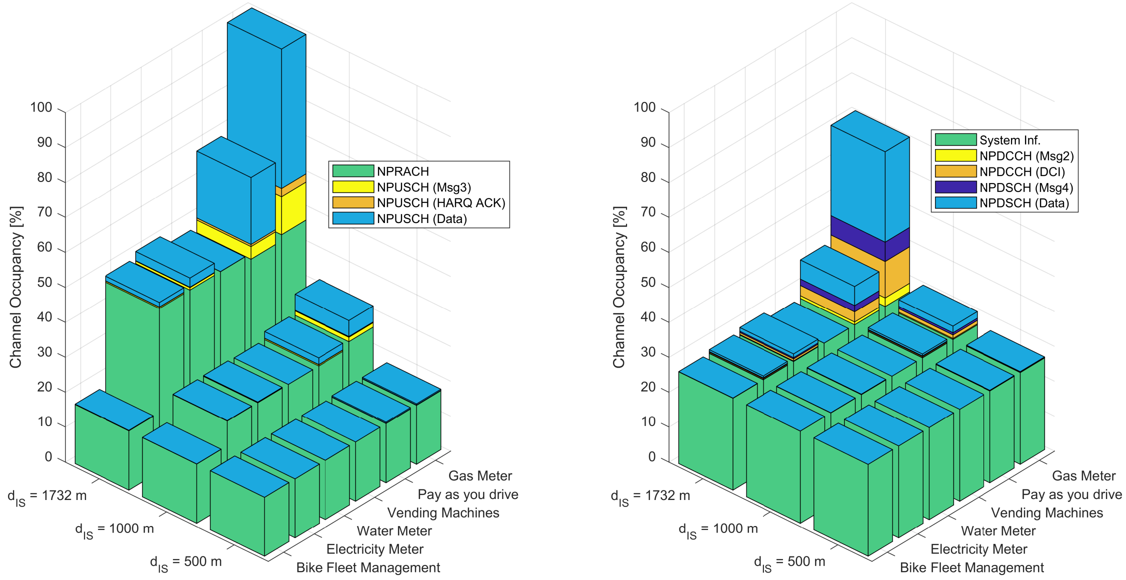

Fig. 3. Channel occupancy in UL (left) and DL (right) directions for different realistic use cases and NPRACH configured with 12 subcarriers and 40, 640, 640 ms periodicity for the three coverage classes.

ISD increases. This is due to the fact that the number of repetitions used in the three coverage classes increases in the same way in order to satisfy the UEs on the edge of the bigger cell. In some cases, such as the Bike Fleet Management, the devices are deployed mostly outdoors so they experience a better channel on average. Therefore the number of repetition can be kept low with a consequent lower occupancy of the radio resources. The amount of resources used for the data transmission through the NPUSCH also increases as the cell becomes larger. This is due to the higher number of repetitions and to the higher number of UEs covered by the bigger cell. Nevertheless, we can observe that in most use cases, a single NB-IoT carrier is sufficient to manage all the traffic, in most cases with a very large margin. However, for Gas Metering with d_{IS} = 1732m the network is almost saturated in the UL. As a first approximation for each data transmission there is a corresponding Msg3 transmission. Although the payload of this message is much smaller with respect to the application data the amount of resources used for both messages are proportional to the traffic. Finally, the resources consumed by the Format 2 ACKs of the DL HARQ processes for Msg4 and data transmission are generally negligible. Around 25% of DL resources are used for the transmission of the NPSS, NSSS, MIB-NB, SIB1-NB and SIB2-NB. The remaining resources are mostly used for DL data and a smaller amount is used for Msg2, Msg4 and the DCIs transmitted in the various phases while the UE is active. As expected, the UL is always more loaded w.r.t. DL, given to the different payload size in the two directions.

B. Impact of NPRACH configuration on the trade-off between network throughput and free resources

In order to investigate the trade-off between the network throughput and the amount of free resources of a NB-IoT network, we conducted an analysis increasing the amount of devices in the cell and varying the configuration of the NPRACH periodicity in order to change the ratio of the radio resources dedicated to NPRACH and NPUSCH. Fig. 4 depicts two possible outcomes of this investigation for Gas Metering use case. The x axis represents the traffic generated by the UEs while the y axis shows the percentage of free resources and the network throughput.

The configuration of the NPRACH period and the number of subcarriers used in each coverage class have an impact on the amount of devices which will succeed the RA procedure and on the amount of resources left available for the NPUSCH.

In Fig. 4 (left) the curves with the circular markers represent a configuration where the NPRACH is big enough to accommodate all the preambles with a very low collision probability. The network saturates at a throughput of 62 kbps (dashed curve) because all the radio resources have been used (solid curve). The curves with the star shaped markers represent a configuration where the NPRACH is significantly smaller. In this case the network saturates to a much lower value, 20 kbps, because only few UEs can complete the RA procedure; in fact approximately 70% of the resources are unused.

It may happen that a large NPRACH, although letting the UEs complete the RA procedure with a high probability, consumes a significant amount of resources. In Fig. 4 (right) a large NPRACH consumes approximately 60% of the resources even with no traffic in the network, leading to a maximum network throughput of 8 kbps. Reducing the NPRACH leads

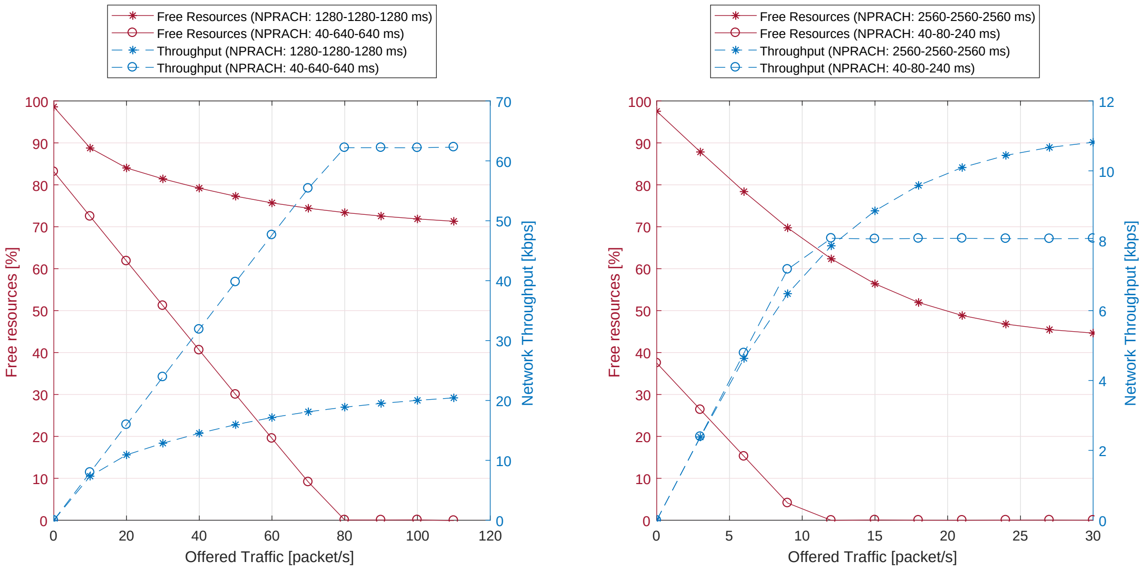

Fig. 4. Analysis of the trade-off between the network throughput and amount of free UL resources varying the NPRACH Periodicity configuration for Gas Metering use case and for 500m ISD (left) and 1000m ISD (right); all NPRACHs use 12 subcarriers.

to a higher maximum throughput, 11 kbps, even though 40% of the resources are unused.

C. Firmware update use-case with unicast and SC-PTM transmissions

We considered a firmware update of 1 MB being transmitted to 50 devices. To transmit the firmware update, we used only the resources remained free after considering the transmission of DL background traffic related to application acknowledgments as described above. We also assumed that each UE receives the update independently from other devices for unicast transmission, while UEs are receiving the firmware simultaneously for the SC-PTM case. We considered pay-as-you-drive and gas meters applications as two examples of use cases with limited and high resource utilization, respectively.

The results reported in Fig. 5 focus on the firmware update delivery time, computed as the time interval from the moment the firmware update is started to be transmitted to the first UE to the moment the last UE receives the update. The analysis shows that the total time required to deliver the update to all of the 50 UEs increases as the ISD increases. When UEs are deployed within a 500m cell, the firmware delivery time does not present significant differences between the different use cases, compared to the differences observed when the ISD is 1732m. This is expected since as devices are placed further away from the cell center they experience greater propagation loss and require more repetitions according to their coverage class. Similarly to the previous results, the Gas Metering use case is the one that requires the longest delivery time, due to the amount of traffic generated, regardless of the ISD tested. In case of SC-PTM, the introduced gains in terms of delivery time are quite obvious w.r.t. unicast, although it is worth mentioning the following. For unicast mode, the delivery time varies from the order of hours and 1 day (i.e., ~24 times higher) when increasing the ISD from 500m to 1732m, while it varies from the order of minutes to 1 hour (i.e., ~60 times higher) for the SC-PTM. This indicates that the effective gains of SC-PTM w.r.t. unicast mode are strictly related to the location of UEs. Nevertheless, it is worth underlining that while the delivery time is affected by the number of UEs for the unicast case, the SC-PTM has a performance that does not vary with the number of UEs to be served. The choice of using either unicast or SC-PTM thus depends on the number of UEs to be served and their coverage class.

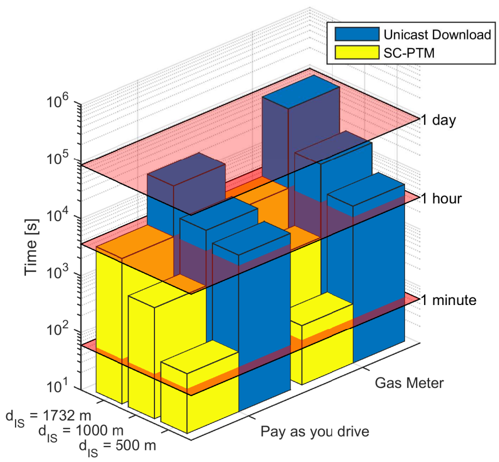

Fig. 5. Firmware update delivery time to 50 devices with unicast and SC-PTM modes for pay-as-you-drive and gas meters use cases.

VI. Conclusion

This article presented a detailed description of the main features of NB-IoT and of the procedures for data transmission and reception with related sources of latency. The paper discussed how the configuration of network parameters affects the latency performance of NB-IoT. We provided an analysis in terms of capacity considering real-life use cases for sensor reporting, also analyzing how NB-IoT might be tuned to improve its capacity. We further analyzed the performance on the downlink direction focusing on a firmware update use case, studying the benefits of the multicast transmission mode recently introduced in Rel. 14.

Further studies are still needed to optimize the resource utilization in both uplink and downlink directions and, especially in downlink, to avoid an excessive drop of performance of the background unicast traffic.

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References

[1] Z. Dawy, W. Saad, A. Ghosh, J. G. Andrews, and E. Yaacoub, "Toward Massive Machine Type Cellular Communications," *IEEE Wireless Communications*, vol. 24, no. 1, pp. 120–128, February 2017.

[2] M. R. Palattella, M. Dohler, A. Grieco, G. Rizzo, J. Torsner, T. Engel, and L. Ladid, "Internet of Things in the 5G Era: Enablers, Architecture, and Business Models," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 3, pp. 510–527, March 2016.

[3] H. Wang and A. O. Fapojuwo, "A Survey of Enabling Technologies of Low Power and Long Range Machine-to-Machine Communications," *IEEE Communications Surveys Tutorials*, vol. 19, no. 4, pp. 2621–2639, Fourthquarter 2017.

[4] Y. P. E. Wang, X. Lin, A. Adhikary, A. Grovlen, Y. Sui, Y. Blankenship, J. Bergman, and H. S. Razaghi, "A Primer on 3GPP Narrowband Internet of Things," *IEEE Communications Magazine*, vol. 55, no. 3, pp. 117–123, March 2017.

[5] 3GPP. (2017) TS 36.321 - Evolved Universal Terrestrial Radio Access (E-UTRA) Medium Access Control (MAC) protocol specification. [Online]. Available: https://portal.3gpp.org

[6] 3GPP. (2017) TS 36.213 - Evolved Universal Terrestrial Radio Access (E-UTRA) Physical layer procedures. [Online]. Available: https://portal.3gpp.org

[7] 3GPP. (2017) TS 36.211 - Evolved Universal Terrestrial Radio Access (E-UTRA) Physical channels and modulation. [Online]. Available: https://portal.3gpp.org

[8] 3GPP. (2017) TS 36.331 - Evolved Universal Terrestrial Radio Access (E-UTRA) Radio Resource Control (RRC) protocol specification. [Online]. Available: https://portal.3gpp.org

[9] J. Schlienz and D. Raddino, "Narrowband Internet of Things," Whitepaper, August 2016.

[10] R. Ratasuk, N. Mangalvedhe, Y. Zhang, M. Robert, and J. P. Koskinen, "Overview of narrowband IoT in LTE Rel-13," in *2016 IEEE Conference on Standards for Communications and Networking (CSCN)*, Oct 2016, pp. 1–7.

[11] N. Mangalvedhe, R. Ratasuk, and A. Ghosh, "NB-IoT deployment study for low power wide area cellular IoT," in *2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Sept 2016, pp. 1–6.

[12] A. Adhikary, X. Lin, and Y. P. E. Wang, "Performance Evaluation of NB-IoT Coverage," in *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*, Sept 2016, pp. 1–5.

[13] GSMA, "3GPP low power wide area technologies, GSMA white paper," Tech. Rep., October 2016.

[14] Ericsson, "Ericsson mobility report," Tech. Rep., November 2016.

[15] Y. D. Beyene, R. Jantti, K. Ruttik, and S. Iraji, "On the Performance of Narrow-Band Internet of Things (NB-IoT)," in *2017 IEEE Wireless Communications and Networking Conference (WCNC)*, March 2017, pp. 1–6.