A Primer on 3GPP Narrowband Internet of Things

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Abstract

Narrowband Internet of Things (NB-IoT) is a new cellular technology introduced in 3GPP Release 13 for providing wide-area coverage for IoT. This article provides an overview of the air interface of NB-IoT. We describe how NB-IoT addresses key IoT requirements such as deployment flexibility, low device complexity, long battery lifetime, support of massive numbers of devices in a cell, and significant coverage extension beyond existing cellular technologies. We also share the various design rationales during the standardization of NB-IoT in Release 13 and point out several open areas for future evolution of NB-IoT.

Introduction

Use cases for machine-type communications (MTC) are developing very rapidly. There has been enormous interest in integrating connectivity solutions with sensors, actuators, meters (water, gas, electric, or parking), cars, appliances, and so on [1, 2]. The Internet of Things (IoT) is thus being created and constantly expanded. IoT consists of a number of networks that may have different design objectives. For example, some networks only intend to cover a local area (e.g. one single home), whereas some networks offer wide-area coverage. The latter case is being addressed in the Third Generation Partnership Project (3GPP). Recognizing the importance of IoT, 3GPP has introduced a number of key features for IoT in its latest release, Release 13 (Rel-13). EC-GSM-IoT [3] and LTE-eMTC [4] aim to enhance existing Global System for Mobile Communications (GSM) [5] and Long Term Evolution (LTE) [6] networks, respectively, for better serving IoT use cases. Coverage extension, user equipment (UE) complexity reduction, long battery lifetime, and backward compatibility are common objectives. A third track, Narrowband IoT (NB-IoT) [7], shares these objectives as well. In addition, NB-IoT aims to offer deployment flexibility, allowing an operator to introduce NB-IoT using a small portion of its existing available spectrum. NB-IoT is designed mainly for targeting ultra-low-end IoT applications.

NB-IoT is a new 3GPP radio access technology in the sense that it is not fully backward compatible with existing 3GPP devices. It is, however, designed to achieve excellent coexistence performance with legacy GSM and LTE technologies. NB-IoT requires 180 kHz minimum system bandwidth for both downlink and uplink, respectively. The choice of minimum system bandwidth enables a number of deployment options. A GSM operator can replace one GSM carrier (200 kHz) with NB-IoT. An LTE operator can deploy NB-IoT inside an LTE carrier by allocating one of the physical resource blocks (PRBs) of 180 kHz to NB-IoT. As will become clear later in this article, the air interface of NB-IoT is optimized to ensure harmonious coexistence with LTE, and thus such an "in-band" deployment of NB-IoT inside an LTE carrier will not compromise the performance of LTE or NB-IoT. An LTE operator also has the option of deploying NB-IoT in the guard-band of the LTE carrier.

NB-IoT reuses the LTE design extensively, including the numerologies, downlink orthogonal frequency-division multiple access (OFDMA), uplink single-carrier frequency-division multiple access (SC-FDMA), channel coding, rate matching, interleaving, and so on. This significantly reduces the time required to develop full specifications. Also, it is expected that the time required for developing NB-IoT products will be significantly reduced for existing LTE equipment and software vendors. The normative phase of the NB-IoT work item in 3GPP started in September 2015 [7] and the core specifications were completed in June 2016. The physical layer specifications of NB-IoT are included in [8–10]. Commercial launch of NB-IoT products and services is expected to be around the beginning of 2017.

In this article, we provide a state-of-the-art overview of the air interface of NB-IoT with a focus on the key aspects where NB-IoT deviates from LTE. In particular, we highlight the NB-IoT features that help achieve the aforementioned design objectives. The remainder of this article is organized as follows. First, transmission schemes and deployment options are given. We then describe the physical channels of NB-IoT. Resource mapping is described, with an emphasis on how orthogonality with LTE is achieved when deploying NB-IoT inside an LTE carrier. Procedures such as cell search, random access, scheduling, and hybrid automatic repeat request (HARQ) are detailed. The article highlights NB-IoT performance, and the final section provides a conclusion.

We describe how NB-IoT addresses key IoT requirements such as deployment flexibility, low device complexity, long battery lifetime, support of massive numbers of devices in a cell, and significant coverage extension beyond existing cellular technologies. We also share the various design rationales during the standardization of NB-IoT in Release 13 and point out several open areas for the future evolution of NB-IoT.

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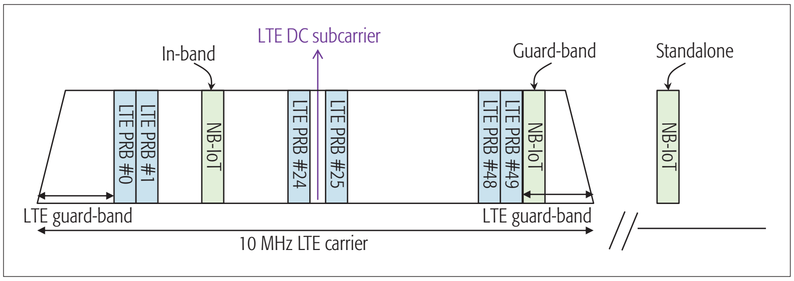

Figure 1. Examples of NB-IoT stand-alone deployment and LTE in-band and guard-band deployments.

Transmission Schemes and Deployment Options

Downlink Transmission Scheme

The downlink transmission scheme of NB-IoT is based on OFDMA with the same 15 kHz subcarrier spacing as LTE [8]. Slot, subframe, and frame durations are 0.5 ms, 1 ms, and 10 ms, respectively, identical to those in LTE. In essence, an NB-IoT carrier uses one LTE PRB in the frequency domain (i.e., 12 15 kHz subcarriers) for a total of 180 kHz. Reusing the same OFDMA numerology as LTE ensures good coexistence performance with LTE in the downlink. For example, when NB-IoT is deployed inside an LTE carrier, the orthogonality between the NB-IoT PRB and all the other LTE PRBs is preserved in the downlink.

Uplink Transmission Scheme

The uplink of NB-IoT supports both multi-tone and single-tone transmissions [8]. Multi-tone transmission is based on single-carrier frequency-division multiple access (SC-FDMA) using the same 15 kHz subcarrier spacing and 0.5 ms slot as LTE. Single-tone transmission supports two numerologies, 15 kHz and 3.75 kHz. The 15 kHz numerology is identical to LTE and thus achieves the best coexistence performance with LTE in the uplink. The 3.75 kHz single-tone numerology uses 2 ms slot duration. Like the downlink, an uplink NB-IoT carrier uses a total system bandwidth of 180 kHz.

Deployment Options

NB-IoT may be deployed as a standalone carrier. It may also be deployed within the LTE spectrum, either inside an LTE carrier or in the guard band. These different deployment scenarios are illustrated in Fig. 1. The deployment scenario, standalone, in-band, or guard-band, however, should be transparent to a user equipment (UE) when it is first turned on and searches for an NB-IoT carrier. Similar to existing LTE UEs, an NB-IoT UE is only required to search for a carrier on a 100 kHz raster. An NB-IoT carrier that is intended for facilitating UE initial synchronization is referred to as an anchor carrier. The 100 kHz UE search raster implies that for in-band deployments, an anchor carrier can only be placed in certain PRBs.

Figure 1 illustrates the deployment options of NB-IoT with a 10 MHz LTE carrier. The PRB right above the DC subcarrier (i.e., PRB #25) is centered at 97.5 kHz. Since the LTE DC subcarrier is placed on the 100 kHz raster, the center of PRB#25 is 2.5 kHz from the nearest 100 kHz grid. Similarly, PRBs #30, #35, #40, and #45 are all centered at 2.5 kHz from the nearest 100 kHz grid. It can be shown that for an LTE carrier of 10 or 20 MHz, there is a set of PRBs that are all centered at 2.5 kHz from the nearest 100 kHz grid, whereas for an LTE carrier of 3, 5, or 15 MHz, the PRBs are centered at least 7.5 kHz away from the 100 kHz raster. A PRB that is no more than 7.5 kHz away from the 100 kHz raster may be used as an NB-IoT anchor carrier. Further, an NB-IoT anchor carrier should not be any of the middle six PRBs of the LTE carrier. This is because LTE synchronization and broadcast channels occupy many resource elements in the middle six PRBs, making it difficult to use these PRBs for NB-IoT.

Similar to the in-band deployment, an NB-IoT anchor carrier in the guard-band deployment needs to have center frequency no more than 7.5 kHz from the 100 kHz raster. NB-IoT cell search and initial acquisition are designed for a UE to be able to synchronize to the network in the presence of a raster offset up to 7.5 kHz.

Multi-carrier operation of NB-IoT is supported. Since it suffices to have one NB-IoT anchor carrier for facilitating initial UE synchronization, the additional carriers do not need to be near the 100 kHz raster grid. These additional carriers are referred to as secondary carriers.

Physical Channels

Downlink

NB-IoT provides the following physical signals and channels in the downlink:

- Narrowband primary synchronization signal (NPSS)
- Narrowband secondary synchronization signal (NSSS)
- Narrowband physical broadcast channel (NPBCH)
- Narrowband reference signal (NRS)
- Narrowband physical downlink control channel (NPDCCH)
- Narrowband physical downlink shared channel (NPDSCH)

Unlike LTE, these NB-IoT physical channels and signals are primarily multiplexed in time. Figure 2 illustrates how the NB-IoT subframes are allocated to different physical channels and signals. Each NB-IoT subframe spans over one PRB in the frequency domain and 1ms in the time domain.

NPSS and NSSS are used by an NB-IoT UE to perform cell search, which includes time and frequency synchronization, and cell identity detection. Since the legacy LTE synchronization sequences occupy six PRBs, they cannot be reused for NB-IoT. A new design is thus introduced.

NPSS is transmitted in subframe #5 in every 10 ms frame using the last 11 OFDM symbols in the subframe. NPSS detection is one of the most computationally demanding operations from a UE's perspective. To allow efficient implementation of NPSS detection, NB-IoT uses a hierarchical sequence. For each of the 11 NPSS OFDM symbols in a subframe, either p or $-p$ is transmitted, where p is the base sequence generated based on a length-11 Zadoff-Chu (ZC) sequence with root index 5 [8]. Each of the length-11 ZC sequences is mapped to the lowest 11 subcarriers within the NB-IoT PRB.

NSSS has 20 ms periodicity and is transmitted in subframe #9, also using the last 11 OFDM sym-

	Subframe number									
	0	1	2	3	4	5	6	7	8	9
Even numbered frame	NPBCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPSS	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NSSS
	Subframe number									
	0	1	2	3	4	5	6	7	8	9
Odd numbered frame	NPBCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPSS	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH

Figure 2. Time multiplexing of NB-IoT downlink physical channels and signals.

bols that consist of 132 resource elements overall. NSSS is a length-132 frequency domain sequence, with each element mapped to a resource element. NSSS is generated by element-wise multiplication between a ZC sequence and a binary scrambling sequence [8]. The root of the ZC sequence and binary scrambling sequence are determined by narrowband physical cell identity (NB-PCID). The cyclic shift of the ZC sequence is further determined by the frame number modulo 8.

NPBCH carries the master information block (MIB) and is transmitted in subframe #0 in every frame. A MIB remains unchanged over the 640 ms transmission time interval (TTI).

NPDCCH carries scheduling information for both downlink and uplink data channels. It further carries the HARQ acknowledgment information for the uplink data channel as well as paging indication and random access response (RAR) scheduling information. NPDSCH carries data from the higher layers as well as paging message, system information, and RAR message. As shown in Fig. 2, there are a number of subframes that can be allocated to carry NPDCCH or NPDSCH. To reduce UE complexity, all the downlink channels use the LTE tail-biting convolutional code (TBCC) [9]. Furthermore, the maximum transport block size of NPDSCH is 680 bits [10]. In comparison, LTE without spatial multiplexing supports a maximum TBS greater than 70,000 bits.

An NRS is used to provide phase reference for the demodulation of the downlink channels. NRSs are time-and-frequency multiplexed with information bearing symbols in subframes carrying NPBCH, NPDCCH, and NPDSCH, using eight resource elements per subframe per antenna port. NB-IoT supports up to two NRS ports.

Uplink

NB-IoT includes the following channels in the uplink:

- Narrowband physical random access channel (NPRACH)
- Narrowband physical uplink shared channel (NPUSCH)

NPRACH is a newly designed channel since the legacy LTE physical random access channel (PRACH) uses a bandwidth of 1.08 MHz, more than NB-IoT uplink bandwidth. One NPRACH preamble consists of four symbol groups, with each symbol group comprising one CP and five symbols [8]. Two CP lengths, 66.67 µs and 266.7 µs, are specified. Each symbol, with fixed symbol value 1, is modulated on a 3.75 kHz

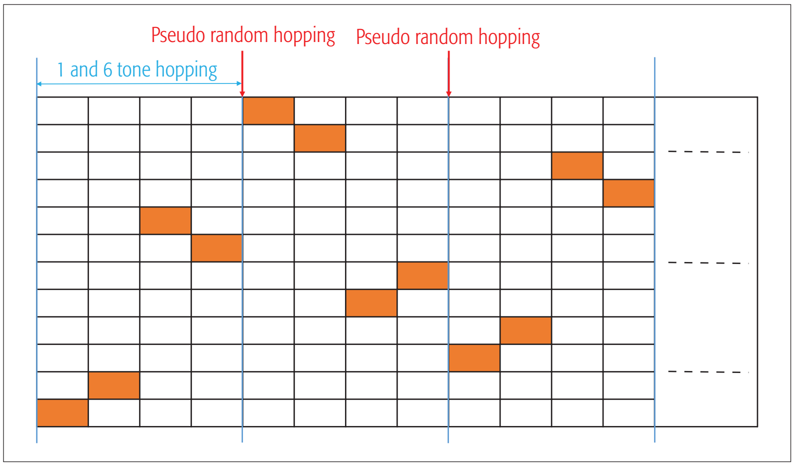

Figure 3. An illustration of NPRACH frequency hopping.

subcarrier. However, the tone frequency index changes from one symbol group to another. The waveform of NPRACH preamble is referred to as single-tone frequency hopping. An example of NPRACH frequency hopping is illustrated in Fig. 3.

NPUSCH has two formats. Format 1 is used for carrying uplink data and uses the same LTE turbo code for error correction. The maximum transport block size of NPUSCH Format 1 is 1000 bits [10], which is much lower than that in LTE. Format 2 is used for signaling HARQ acknowledgment for NPDSCH, and uses a repetition code for error correction. NPUSCH Format 1 supports multi-tone transmission. In this case, the UE can be allocated with 12, 6, or 3 tones. While only the 12-tone format is supported by legacy LTE UEs, the 6-tone and 3-tone formats are introduced for NB-IoT UEs who, due to coverage limitation, cannot benefit from higher UE bandwidth allocation. Moreover, NPUSCH supports single-tone transmission based on either 15 or 3.75 kHz numerology. To reduce peak-to-average power ratio (PAPR), single-tone transmission uses $\pi/2$-binary phase shift keying (BPSK) or $\pi/4$-quadrature phase shift keying (QPSK) with phase continuity between symbols.

NPUSCH Format 1 has 7 OFDM symbols/slot, one of which is the demodulation reference symbol (DMRS). NPUSCH Format 2 also has 7 OFDM symbols/slot, but uses 3 symbols as DMRS. DMRSs are used for channel estimation.

Table 1 summarizes the NB-IoT physical channels and their differences from their LTE counterparts.

Resource Mapping

In this section, we describe how NB-IoT resource mapping is designed to ensure the best coexistence performance with LTE if deployed inside an LTE carrier. In essence, the orthogonality to LTE signals is preserved by avoiding mapping NB-IoT signals to the resource elements already used by the legacy LTE signals. An example is illustrated in Fig. 4, in which each column indicates resource elements in one OFDM symbol. There are 12 resource elements per OFDM symbol corresponding to 12 subcarriers. As shown, for the standalone and guard-band deployments, no LTE resource needs to be protected; thus, NPDCCH, NPDSCH, and NRS can utilize all the resource elements in one PRB pair. However, for in-band deployment, NPDCCH, NPDSCH, and NRS cannot be mapped to the resource elements taken by LTE cell-specific reference symbols (CRS) and LTE physical downlink control channel (PDCCH). NB-IoT is designed to allow a UE to learn the deployment mode (standalone, in-band, or guard-band) as well as the cell identity through initial acquisition. Then the UE can figure out which resource elements are used by LTE. With this information, the UE can map NPDCCH and NPDSCH symbols to available resource elements. On the other hand, NPSS, NSSS, and NPBCH are used for initial synchronization and master system information acquisition. These signals need to be detected without knowing the deployment mode. To facilitate this, NPSS, NSSS, and NPBCH avoid the first three OFDM symbols in every subframe as these resource elements may be used by LTE PDCCH. Furthermore, NPSS and NSSS signals overlapping with resource elements taken by LTE CRS are punctured at the base station. Although the UE is not aware of which resource elements are punctured, NPSS and NSSS can still be detected by correlating the received punctured synchronization signal with the non-punctured signal since the percentage of punctured resource elements is relatively small. NPBCH is rate-matched around LTE CRS. However, this requires the UE to figure out the location of CRS resource elements, which is dependent of LTE physical cell identity (PCID). The relationship of the values of PCID and NB-PCID used by the same cell is such that the UE can use NB-PCID to determine the LTE CRS locations.

	Physical channel	Relationship with LTE
Downlink	NPSS	• New sequence for fitting into one PRB (LTE PSS overlaps with middle six PRBs) • All cells share one NPSS (LTE uses 3 PSSs)
	NSSS	• New sequence for fitting into one PRB (LTE SSS overlaps with middle six PRBs) • NSSS provides the lowest 3 least significant bits of system frame number (LTE SSS does not)
	NPBCH	• 640 ms TTI (LTE uses 40 ms TTI)
	NPDCCH	• May use multiple PRBs in time, i.e. multiple subframes (LTE PDCCH uses multiple PRBs in frequency and 1 subframe in time)
	NPDSCH	• Use TBCC and only one redundancy version (LTE uses Turbo Code with multiple redundancy versions) • Use only QPSK (LTE also uses higher order modulations) • Maximum transport block size (TBS) is 680 bits. (LTE without spatial multiplexing has maximum TBS greater than 70000 bits, see [9]) • Supports only single-layer transmission (LTE can support multiple spatial-multiplexing layers)
Uplink	NPRACH	• New preamble format based on single-tone frequency hopping using 3.75 kHz tone spacing (LTE PRACH occupies 6 PRBs and uses multi-tone transmission format with 1.25 kHz subcarrier spacing)
	NPUSCH Format 1	• Support UE bandwidth allocation smaller than one PRB (LTE has minimum bandwidth allocation of 1 PRB) • Support both 15 kHz and 3.75 kHz numerology for single-tone transmission (LTE only uses 15 kHz numerology) • Use $\pi/2$-BPSK or $\pi/4$-QPSK for single-tone transmission (LTE uses regular QPSK and higher order modulations) • Maximum TBS is 1000 bits. (LTE without spatial multiplexing has maximum TBS greater than 70000 bits, see [9]) • Supports only single-layer transmission (LTE can support multiple spatial-multiplexing layers)
	NPUSCH Format 2	• New coding scheme (repetition code) • Uses only single-tone transmission

Table 1. Summary of NB-IoT physical signals and channels and their relationship with the LTE counterparts.

Cell Search and Initial Acquisition Procedure

When a UE is powered on for the first time, it needs to detect a suitable cell to camp on, and for that cell, obtain the symbol, subframe, and frame timing as well as synchronize to the carrier frequency. In addition, due to the presence of multiple cells, the UE needs to distinguish a particular cell on the basis of an NB-PCID.

NB-IoT is intended to be used for very low-cost UEs and at the same time provide extended coverage for UEs deployed in environments with high penetration losses (e.g., the basement of a building). Such low-cost UEs are equipped with low-cost crystal oscillators that can have an initial carrier frequency offset (CFO) as large as 20 ppm. Deployment in-band and in guard-bands of LTE introduces an additional raster offset (2.5 or 7.5 kHz) as explained earlier, giving rise to an even higher CFO. Despite this large CFO, a UE should also be able to perform accurate synchronization at very low signal-to-noise ratio (SNR).

Synchronization in NB-IoT follows similar principles as the synchronization process in LTE, but with changes to the design of the synchronization sequences in order to resolve the problem of estimating large frequency offset and symbol timing at very low SNR. Synchronization is achieved through the use of NPSS and NSSS. The NPSS is used to obtain the symbol timing and the CFO, and the NSSS is used to obtain the NB-PCID and the timing within an 80 ms block.

For UEs operating at very low SNR, an auto correlation based on a single 10 ms received segment would not be sufficient for detection. As a result, an accumulation procedure over multiple 10 ms segments is necessary. Because of the inherent NPSS design, the accumulation can be performed coherently, providing sufficient signal energy for detection.

After the synchronization procedure is complete, the UE has knowledge of the symbol timing, the CFO, the position within an 80 ms block, and the NB-PCID. The UE then proceeds to the acquisition of the MIB, which is broadcast in subframe #0 of every frame carried by NPBCH. The NPBCH consists of eight self-decodable sub-blocks, and each sub-block is repeated eight times, so each sub-block occupies subframe #0 of eight consecutive frames. Therefore, one NPBCH codeword is distributed over 64 frames (i.e., 640 ms) using subframe 0. The design is intended to enable successful acquisition for UEs in deep coverage.

After the symbol timing is known and the CFO is compensated for, in the in-band and guard-band deployment there is still an additional raster offset which can be as high as 7.5 kHz. The presence of raster offset results in either overcompensation or undercompensation of the carrier frequency. As a result, the symbol timing drifts in either the forward or backward direction depending on whether the carrier frequency was overcompensated or undercompensated. This may cause a severe degradation in the performance of NPBCH detection if the NPBCH is not detected on the first try. For example, an unsuccessful detection of NPBCH in the first attempt introduces a latency of 640 ms before the next NPBCH detection attempt. A 7.5 kHz raster offset leads to a symbol timing drift of 5.33 μs (assuming a carrier frequency of 900 MHz), which is greater than the duration of the cyclic prefix. As a result, the downlink orthogonality of OFDMA is lost. A solution to this problem comes at the expense of a small increase in computational complexity, where the UE can perform "hypothesis testing" over the set of possible raster offsets to improve the detection performance.

Random Access

In NB-IoT, random access serves multiple purposes such as initial access when establishing a radio link and scheduling request. Among others, one main objective of random access is to achieve uplink synchronization, which is important for maintaining uplink orthogonality in NB-IoT.

To serve UEs in different coverage classes that have different ranges of path loss, the network can configure up to three NPRACH resource configurations in a cell. In each configuration, a repetition value is specified for repeating a basic random access preamble. UE measures its downlink received signal power to estimate its coverage level, and transmits a random access preamble in the NPRACH resources configured for its estimated coverage level. To facilitate NB-IoT deployment in different scenarios, NB-IoT allows flexible configuration of NPRACH resources in a time-frequency resource grid with the following parameters:

- Time domain: periodicity of NPRACH resource and starting time of NPRACH resource in a period
- Frequency domain: frequency location (in terms of subcarrier offset) and number of subcarriers

It is possible that in early NB-IoT field trials and deployment, some UE implementations may not support multi-tone transmission. The network should therefore be aware of UE multi-tone transmission capability before scheduling uplink transmission. To support this, the network can partition the NPRACH subcarriers in the frequency domain into two non-overlapping sets. A UE can select

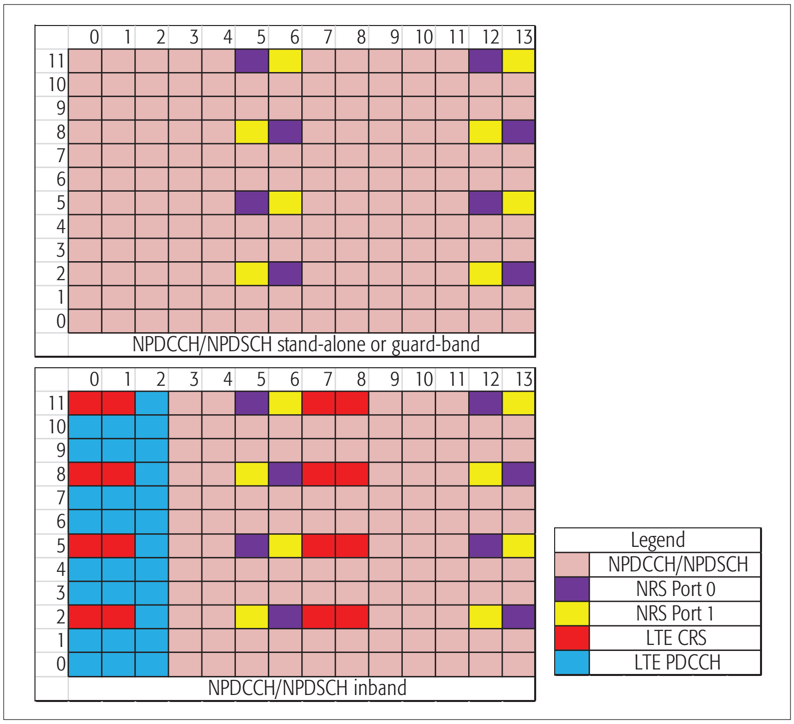

Figure 4. NPDCCH/NPDSCH resource mapping example.

one of the two sets to transmit its random access preamble to signal whether or not it supports multi-tone transmission.

In summary, UE determines its coverage level by measuring downlink received signal power. After reading system information on NPRACH resource configuration, the UE can determine the NPRACH resource configured and the number of repetitions needed for its estimated coverage level and transmit power. Then the UE can transmit repetitions of the basic single-tone random access preamble back to back within one period of the NPRACH resources. The remaining steps in the random access procedure are similar to LTE, and we omit the details here. Additional information about NB-IoT random access can be found in [11].

Scheduling and HARQ Operation

To enable low-complexity UE implementation, NB-IoT allows only one HARQ process in both downlink and uplink, and allows longer UE decoding time for both NPDCCH and NPDSCH. An asynchronous, adaptive HARQ procedure is adopted to support scheduling flexibility. An example is illustrated in Fig. 5. A scheduling command is conveyed through a downlink control indicator (DCI), which is carried by NPDCCH. NPDCCH may use aggregation level (AL) 1 or 2 for transmitting a DCI [8, 10]. With AL-1, two DCIs can be multiplexed in one subframe; otherwise, one subframe only carries one DCI (i.e., AL-2), giving rise to a lower coding rate and improved coverage. Further coverage enhancement can be achieved through repetition. Each repetition occupies one subframe. DCI can be used for scheduling downlink data or uplink data. In the case of downlink data, the exact time offset between NPDCCH and the associated NPDSCH is indicated in the DCI. Since IoT

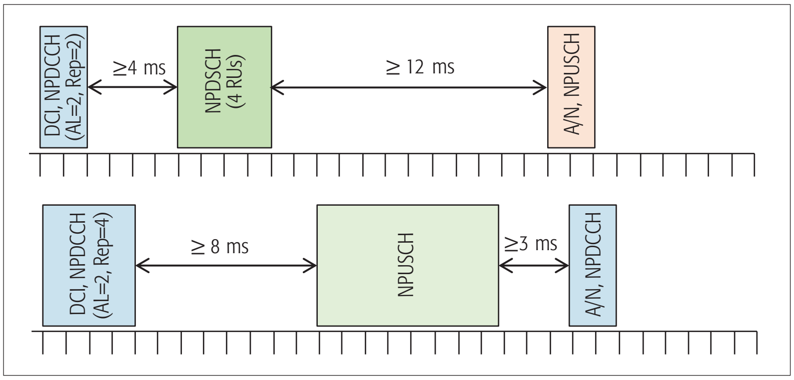

Figure 5. Timing relationship operation (each unit corresponds to one subframe).

devices are expected to have reduced computing capability, the time offset between the end of NPDCCH and the beginning of the associated NPDSCH is at least 4 ms [10]. In comparison, LTE PDCCH schedules PDSCH in the same TTI. After receiving NPDSCH, the UE needs to send back a HARQ acknowledgment using NPUSCH Format 2. The resources of NPUSCH carrying the HARQ acknowledgment are also indicated in DCI [10]. The time offset between the end of NPDSCH and the start of the associated HARQ acknowledgment is at least 12 ms [10]. This allows a UE ample decoding time.

Similarly, uplink scheduling and HARQ operation are also illustrated in Fig. 5. The DCI for an uplink scheduling grant needs to specify which subcarriers a UE is allocated [10]. The time offset between the end of NPDCCH and the beginning of the associated NPUSCH is at least 8 ms [10]. After completing the NPUSCH transmission, the UE monitors NPDCCH to learn whether NPUSCH is received correctly by the base station, or a retransmission is needed.

Performance

IoT use cases are characterized by requirements such as data rate, coverage, device complexity, latency, and battery lifetime. These are thus important performance metrics. Furthermore, according to [12], IoT traffic is forecast to have compounded annual growth rate of 23 percent between 2015 and 2023. It is therefore important to ensure that NB-IoT has good capacity to support such growth in the years to come.

Peak Data Rates

NDSCH peak data rate can be achieved by using the largest TBS of 680 bits and transmitting it over 3 ms [10]. This gives 226.7 kb/s peak layer 1 data rate. NPUSCH peak data rate can be achieved by using the largest TBS of 1000 bits and transmitting it over 4 ms [10]. This gives 250 kb/s peak layer 1 data rate. However, the peak throughputs of both downlink and uplink are lower than the above figures when the time offsets between DCI, NPDSCH/NPUSCH, and HARQ acknowledgment are taken into account.

Coverage

NB-IoT achieves a maximum coupling loss 20 dB higher than LTE Rel-12 [12–14]. Coverage extension is achieved by trading off data rate through increasing the number of repetitions. Coverage enhancement is also ensured by introducing single subcarrier NPUSCH transmission and $\pi/2$-BPSK modulation to maintain close to 0 dB PAPR, thereby reducing the unrealized coverage potential due to power amplifier backoff. NPUSCH with 15 kHz single-tone gives a layer 1 data rate of approximately 20 b/s when configured with the highest repetition factor (i.e., 128) and the most robust modulation and coding scheme (MCS). NPDSCH gives a layer 1 data rate of 35 b/s when configured with repetition factor 512 and the most robust MCS. These configurations support close to 170 dB coupling loss. In comparison, the Rel-12 LTE network is designed for up to approximately 142 dB coupling loss [14].

Device Complexity

NB-IoT enables low-complexity UE implementation by the designs highlighted below:
- Significantly reduced transport block sizes.
- Support only one redundancy version in the downlink.
- Support only single-stream transmissions.
- Only single antenna is required at the UE.
- Support only single HARQ process.
- No need for a turbo decoder at the UE.
- No Connected mode mobility measurement is required. A UE only needs to perform mobility measurement during Idle mode.
- Low sampling rate due to lower UE bandwidth.
- Allow only half-duplex frequency-division duplexing operation.
- No parallel processing is required. All the physical layer procedures occur in a sequential manner.

The coverage objective is achieved with 20 or 23 dBm power amplifier, making it possible to use an integrated power amplifier in the UE.

Latency and Battery Lifetime

NB-IoT targets latency-insensitive applications. However, for applications like sending alarm signals, NB-IoT is designed to allow less than 10 s latency [3]. NB-IoT aims to support long battery life. For a device with 164 dB coupling loss, a 10-year battery life can be reached if the UE transmits 200 bytes of data a day on average [3].

Capacity

NB-IoT supports massive IoT capacity by using only one PRB in both uplink and downlink. Sub-PRB UE scheduled bandwidth is introduced in the uplink, including single-subcarrier NPUSCH. Note that for a coverage limited UE, allocating higher bandwidth is not spectrally efficient as the UE is power limited rather than bandwidth limited. Based on the traffic model in [3], NB-IoT with one PRB supports more than 52,500 UEs per cell [3]. Furthermore, NB-IoT supports multiple carrier operation. Thus, more IoT capacity can be added by adding more NB-IoT carriers.

Conclusion

In this article, a description of NB-IoT radio access is given. We emphasize how radio access is designed differently compared to LTE, and how it is designed to fulfill the performance requirements of IoT such as significant coverage extension, low device complexity, long battery lifetime, and supporting a massive number of IoT devices. Further enhancements of NB-IoT in the next 3GPP Release are ongoing in 3GPP, including, for example, introducing low-complexity multicast functionality, for rolling out firmware updates and enhancing positioning accuracy, which is important to many IoT applications. NB-IoT is a step toward building the fifth generation (5G) radio access technology intended for enabling new use cases like machine type communications. NB-IoT devices, after deployment, are expected to remain in the network for many years, likely beyond network migration toward 5G. It is thus important to design 5G radio access technology to coexist well with NB-IoT and its evolutions. It is also important to ensure that NB-IoT continues to evolve toward meeting all 5G requirements for IoT, minimizing any need to introduce a new 5G IoT technology, which may cause market fragmentation and reduce the benefit of economy of scale. NB-IoT ushers in ultra-low-cost devices and has enough capacity to support a massive number of these devices in a cell. This is also a step toward the fog network [15] as these devices, although individually simple and low-cost, collectively form significant capability in terms of sensing, intelligence, storage, and computing.

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