CHAPTER 6

Internet of Things (NB-IoT and Massive MTC)

Internet of Things (IoT) is an interconnected network of physical objects (devices) that interact with humans or other physical objects and systems, where communications among machines can be performed without human interaction or supervision. The IoT is considered a driving force behind recent improvements in wireless communications technologies such as 3GPP LTE and NR in order to satisfy the stringent requirements of massive machine-type communication (mMTC) diverse applications. The IoT use cases have been divided into two main categories: massive IoT and mission-critical IoT. The massive IoT aims to connect a very large number of devices, for example, remote indoor or outdoor sensors, to the cloud-based control and monitoring systems, where the main requirements are low cost, low power consumption, good coverage, and architectural scalability. In contrast, mission-critical IoT applications, for example, remote healthcare, remote traffic monitoring/control, and industrial control, require very high availability and reliability as well as very low latency.

Narrowband IoT (NB-IoT) is an LTE-based cellular radio access technology that provides low-power wide-area (LPWA) connectivity in licensed spectrum. There are several short-range technologies in unlicensed spectrum, including Bluetooth,[1] ZigBee,[2] etc., and other LPWA technologies, including SigFox,[3] LoRaWAN,[4] etc., which have been developed to address vertically different use cases of industrial IoT. The 3GPP design targets for Rel-13 were long device battery life, low device complexity to ensure low cost, support for massive number of devices, and coverage enhancements to be able to reach devices in basements and other inaccessible locations. The NB-IoT is optimized for machine-type traffic. It was designed to be as simple as possible in order to reduce device complexity and to minimize power consumption. Indoor penetration and rural coverage are among the key requirements for the IoT applications, and support of operation in sub-1 GHz bands is considered as crucial for IoT deployments. The NB-IoT further supports improved battery life through

[1] Bluetooth Special Interest Group, https://www.bluetooth.com/.
[2] Zigbee Alliance, http://www.zigbee.org/.
[3] Sigfox, https://www.sigfox.com/.
[4] LoRa Alliance, https://www.lora-alliance.org/.

5G NR. DOI: https://doi.org/10.1016/B978-0-08-102267-2.00006-3

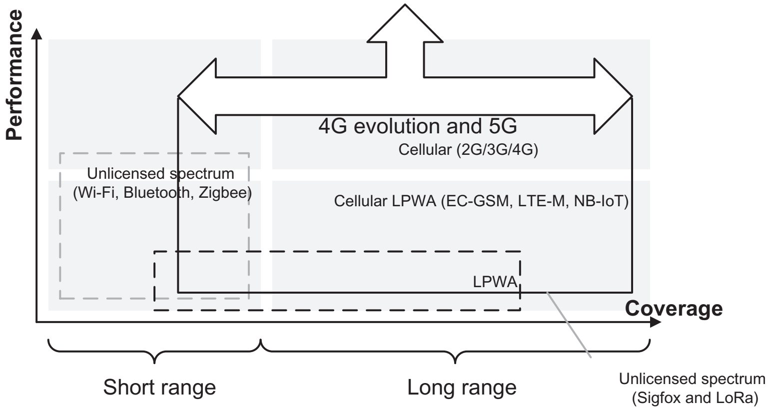


Figure 6.1
Scope and use cases of various wireless access technologies in the IoT domain [10,16].

extended discontinuous reception (eDRX) and power-saving mode, and improved capacity via multi-carrier operation [22].

The NB-IoT specifications have continued to evolve beyond Rel-13, with support for multi-casting and positioning, and are considered the main technology platform to satisfy 5G mMTC applications in Rel-15 and beyond. In 3GPP LTE Rel-13, NB-IoT was standardized for providing LPWA connectivity for mMTC applications. In LTE Rel-14, NB-IoT was further enhanced to provide additional features such as increased positioning accuracy, higher peak data rates, a lower device power class, improved non-anchor carrier operation, multicast, and authorization of the coverage enhancements. To achieve enhanced coverage up to 164 dB maximum coupling loss (MCL),[5] a significant amount of network resources is required due to excessive code repetitions. With authorization of the coverage enhancements feature, the network can restrict the use of coverage enhancements to a UE based on its subscription information. Fig. 6.1 shows the scope and applicability of different wireless technologies when considering the coverage and throughput requirements. While 3GPP and non-3GPP wireless access technologies may equally find application in certain deployment scenarios, 3GPP wireless technologies can provide better integration with the existing and forthcoming cellular access and core networks.

In March 2018, 3GPP decided that no NR-based solution will be studied or specified for the LPWA use cases and those use cases would be exclusively addressed by the evolving 3GPP

[5] Maximum coupling loss is a measure of the attenuation of the radio signal between the transmitter and receiver. Maximum coupling loss is the largest attenuation that the system can support with a defined level of service. This can also be used to define the coverage of the service.

LTE-M and NB-IoT standards. This important decision was motivated by operators' and major vendors' implementation and deployment plans for LTE-M and NB-IoT in 2018 + . In essence, the operators and vendors did not want an NR-based solution for mMTC use cases to distract the market and jeopardize their ongoing developments plans around the world. It was further decided that the enhancements (if any) to coexistence between NR and LTE-M/NB-IoT beyond what is supported in 3GPP Rel-15 can be studied as part of 3GPP Rel-16 [9]. Considering the 3GPP decision, LTE-based NB-IoT solution will be the 3GPP technology to address LPWA applications, and thus we will study the theoretical and practical aspects of this technology in this chapter.

6.1 General Aspects and Use Cases

The IoT market is expected to cover several industry segments and a wide range of applications with different quality of service (QoS) requirements. Fig. 6.2 shows the partitioning of IoT applications into two broad segments namely massive IoT (mMTC) and mission-critical

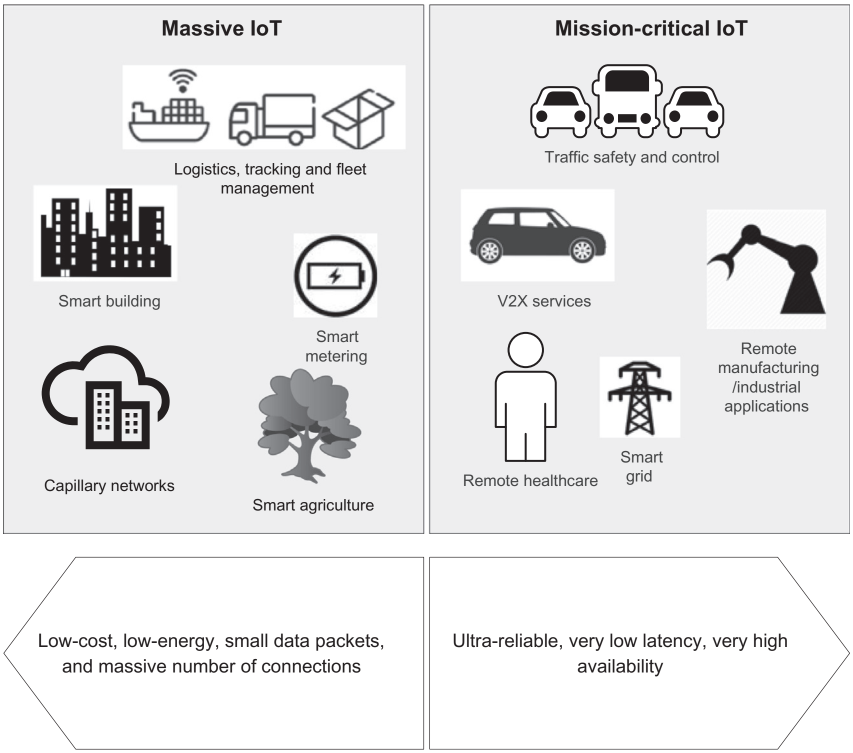


Figure 6.2
Differing requirements for massive and mission-critical IoT applications [10].

IoT (URLLC), in order to underline their distinct requirements. Massive IoT comprises applications involving exchange of small and infrequent data packets to/from numerous standalone devices. Hence, for economic viability, such devices must be implemented with low-cost and low-power consumption without stringent latency requirement. Consequently, the network technology providing connectivity to such devices must satisfy these requirements and support high capacity. On the other hand, mission-critical IoT category consists of time-sensitive applications, with latency requirements in the order of fraction of a millisecond, such as remote surgery and vehicle-to-vehicle communications. These applications demand high reliability, availability, and very low latency.

Server/cloud-based big data analytics and machine learning are central to the majority of IoT business models. IoT uses MTC to harvest data and route control messages between widely distributed things (e.g., sensors or actuators) and cloud-based intelligence. Many topologies include gateway nodes as aggregation points between IoT devices and the cloud. NB-IoT uses a narrow channel bandwidth which can be deployed either in-band with LTE, in the LTE guard-bands, or in reused GSM spectrum. The enhancements to LTE baseline have been selected such that NB-IoT can be deployed via software upgrades to the existing LTE or GSM infrastructure. The NB-IoT requirements include 10-year battery life, very low device implementation cost and complexity, and a network capacity of more than 50,000 devices per cell. The NB-IoT is designed to allow less than 10 seconds latency and aims to support long battery life. For a device with 164 dB coupling loss (i.e., the measure of coverage of a wireless access technology), a 10-year battery life can be reached, if the UE data transmissions are limited to 200 bytes on average per day. The LPWA networks provide connectivity to mMTC applications and require radio access technologies that can deliver extensive coverage, capacity, and low power consumption.

6.2 Network Architecture and Protocol Aspects

6.2.1 Network Architecture

In order to exchange data between a NB-IoT device and an application server via NB-IoT access network, 3GPP has specified two optimizations for the cellular IoT (CIoT) in the evolved packet system (EPS): user-plane CIoT EPS and control-plane CIoT EPS optimizations, as shown in Fig. 6.3. These optimizations are not limited to NB-IoT devices. The control-plane CIoT EPS optimization enables support of efficient transport of user data [Internet protocol (IP), non-IP, or SMS packets] over control plane via the mobility management entity (MME) without triggering data radio bearer establishment in order to reduce the latency. An NB-IoT terminal that only supports control-plane CIoT EPS optimization is a UE that does not support user-plane CIoT EPS optimization and S1-U data transfer, but may support other CIoT EPS optimizations. The user-plane CIoT EPS optimization enables

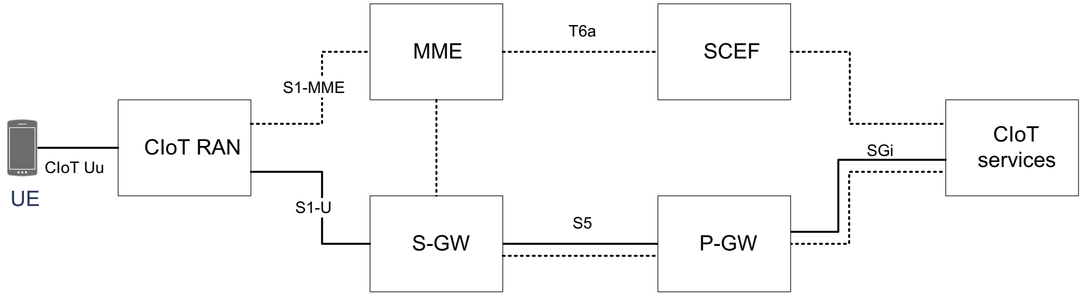


Figure 6.3
NB-IoT network architecture [11,19].

support for transition from EMM-IDLE mode to EMM-CONNECTED mode without invoking the service request procedure [6].

In other words, user-plane CIoT EPS optimization allows radio resource control (RRC) connections to be suspended and resumed. In LTE, a new RRC context must be established when the UE moves from idle mode to connected mode. Reestablishing the context only takes about a 100 ms, but for IoT devices that only send a few bytes, it is a very significant overhead. Therefore, a method has been specified to preserve the context of an RRC connection and suspend it on the mobile device and network side rather than releasing it. In LTE, the control plane is used for management tasks such as authentication and connection establishment, while data is transmitted over the user plane. For high-data-rate transmissions, the overhead of setting up a connection on the control plane may be negligible. But, when dealing with extremely small data packets, setting up the connection for a short transmission has a significant impact on the overall connection time and power consumption. To reduce this overhead, control-plane CIoT EPS optimization specifies a mechanism to include user data packets within signaling messages. By including the payload in the signaling message, the overhead is significantly reduced [11].

As shown in Fig. 6.3, in the control-plane CIoT EPS optimization, the uplink data is transferred from the eNB (CIoT RAN) to the MME. At that point, the data may either be transferred via the S-GW to the P-GW, or to the service capability exposure function (SCEF). The latter is only possible for non-IP data packets. From these nodes, the data is ultimately forwarded to the application server (CIoT services). The downlink data is transmitted over the same route in the reverse direction. However, there is no data radio bearer setup and data packets are instead sent on the signaling radio bearer (SRB). This solution is suitable for transmission of infrequent and small data packets. The SCEF is a new network entity introduced to enable machine-type communications. It is used for delivery of non-IP data over control plane and provides an abstract interface for the network services; that is, authentication and authorization, discovery and access network capabilities. With the user-plane CIoT EPS optimization, the data is transferred in the same way as the conventional data traffic; that is, over radio bearers via the S-GW and the P-GW to the application server. Therefore, it introduces some overhead upon setting up the connection; however, it facilitates the transmission of a sequence of data packets. This solution supports both IP and non-IP data transfer [11]. The access network architecture for NB-IoT is similar to that of LTE. The eNBs are connected to the MME and S-GW via S1 interface, with the difference of carrying the NB-IoT messages and data packets. Even though there is no handover defined, there is still an X2 interface between two eNBs, which enables a fast resume after the UE transitions to the idle state.

In the control-plane CIoT EPS optimization, the data exchange between the NB-IoT terminal and the eNB is performed at RRC level. In the downlink and uplink, the data packets may be piggybacked in the *RRCConnectionSetup* and *RRCConnectionSetupComplete* messages, respectively. For larger payloads, data transfer may continue using *DLInformationTransfer* and *ULInformationTransfer* messages. In all of these messages, there is a byte array containing non-access stratum (NAS) information, which in this case corresponds to the NB-IoT data packets. As a result, this procedure is transparent to the eNB, and the UE's RRC sublayer forwards the content of the received *DLInformationTransfer* directly to its upper layer. The *dedicatedInfoNAS* message is exchanged between the eNB and the MME via the S1-MME interface. For this data transfer mechanism, security on access stratum (AS) level is not applied. Since there is no RRC connection reconfiguration, it may immediately start after or during the RRC connection setup or resume procedure. The RRC connection has to be terminated afterwards with the RRC connection release. In the user-plane CIoT EPS optimization, data is transferred over the conventional user plane through the network; that is, the eNB forwards the data to the S-GW or receives it from this node. In order to minimize the UE complexity, only one or two dedicated radio bearers may be simultaneously configured. One needs to distinguish between two cases:

1. If the previous RRC connection was released with a possible resume operation indicated, the connection may be requested as a resume procedure. If the resume procedure is successful, then the security is established with updated keys and the radio bearer is set up similar to the previous connection.
2. If there was no previous RRC connection release with a resume indication, or if the resume request was not accepted by the eNB, the security and radio bearer have to be reestablished.

6.2.2 Modes of Operation

NB-IoT may be deployed as a standalone system using any available spectrum exceeding 180 kHz. It may also be deployed within an LTE spectrum allocation, either inside an LTE channel or in the guard-band. These different deployment scenarios are illustrated in Fig. 6.4. The deployment scenario, standalone, in-band, or guard-band should be transparent to a UE when it is first turned on and scans 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 access and 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 physical resource blocks (PRBs). For example, in a 10 MHz LTE carrier, the indices of the PRBs that are best aligned with the 100 kHz grid and can be used as an NB-IoT anchor carrier are 4, 9, 14, 19, 30, 35, 40, and 45. The PRB indexing starts from index 0 for the PRB occupying the lowest frequency within the LTE channel bandwidth. In the in-band operation, the assignment of resources between LTE and NB-IoT is not fixed. However, not all frequencies; that is, resource blocks (RBs) within the LTE carrier are allowed to be used for cell connection, rather they are restricted to the values shown in Table 6.1.

Fig. 6.5 illustrates the deployment options of NB-IoT in conjunction with a 10 MHz LTE system. The PRB immediately after the DC subcarrier, that is, PRB_25, is centered at 97.5 kHz; that is, at a distance of 6.5 subcarriers from the center of the band. 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. The spacing between the centers of two neighboring PRBs above the

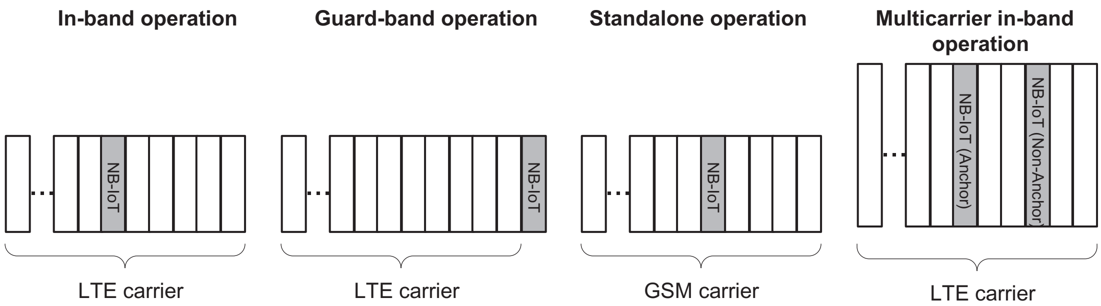


Figure 6.4
Operation modes for NB-IoT [11–15].

Table 6.1: Permissible LTE PRB indices for NB-IoT in-band operation [1].

LTE System Bandwidth (MHz)	3	5	10	15	20
Permissible LTE PRB indices for NB-IoT in-band operation	2, 12	2, 7, 17, 22	4, 9, 14, 19, 30, 35, 40, 45	2, 7, 12, 17, 22, 27, 32, 42, 47, 52, 57, 62, 67, 72	4, 9, 14, 19, 24, 29, 34, 39, 44, 55, 60, 65, 70, 75, 80, 85, 90, 95

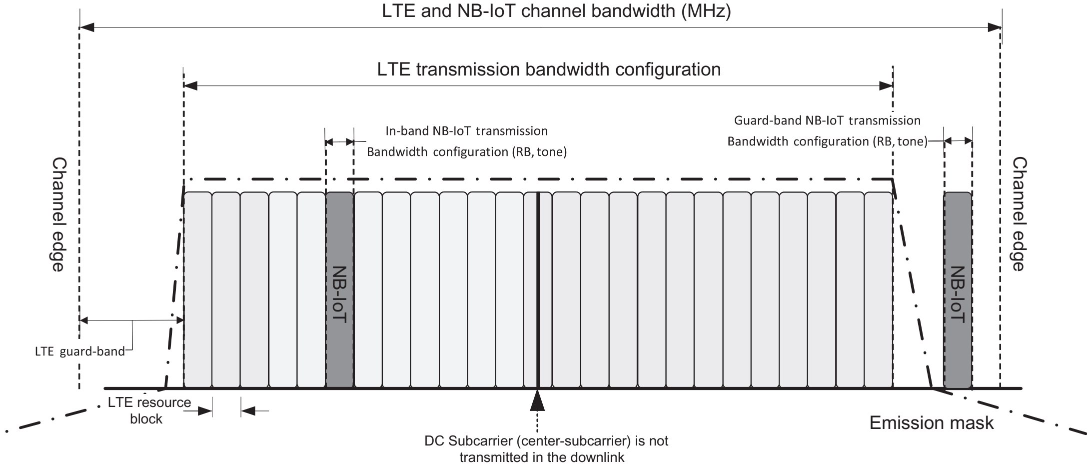


Figure 6.5
Definition of channel bandwidth and transmission bandwidth configuration for in-band/guard-band NB-IoT operation [1].

DC subcarrier is 180 kHz. As a result, the PRB indices 30, 35, 40, and 45 are all centered at 2.5 kHz from the nearest 100 kHz grid. It can be shown that for LTE carriers of 10 and 20 MHz, there exists a set of PRB indices that are all centered at 2.5 kHz from the nearest 100 kHz grid, whereas for LTE carriers of 3, 5, and 15 MHz bandwidth, the PRB indices are centered approximately 7.5 kHz away from the 100 kHz raster. It must be noted that none of the middle six PRBs of the LTE carrier can be assigned as an NB-IoT anchor carrier (e.g., PRB_25 of 10 MHz LTE, despite the fact that its center is 2.5 kHz away from the nearest 100 kHz raster). This is due to the fact that LTE synchronization and broadcast channels occupy the resource elements in the middle six PRBs. Similar to the in-band deployment, an NB-IoT anchor carrier in the guard-band is required to have center frequency no more than 7.5 kHz distant from the 100 kHz raster. The 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 also supported. Since one NB-IoT anchor carrier is necessary to enable UE initial access/synchronization, the additional carriers do not need to be near the 100 kHz raster grid. These additional carriers are referred to as secondary carriers. As we mentioned earlier, NB-IoT carrier occupies 180 kHz of bandwidth, which corresponds to one PRB in an LTE system [2]. With this selection, the following operation modes are possible (see Fig. 6.4):

- *Standalone*: A scenario where currently used GSM frequencies with 200 kHz bandwidth can be utilized for NB-IoT deployment.
- *Guard-band*: A deployment scenario which utilizes the unused RBs within an existing LTE carrier's guard-band.
- *In-band*: A scenario where PRBs within an existing LTE channel bandwidth are utilized for NB-IoT deployment.

In the in-band operation, the assignment of resources between LTE and NB-IoT is not fixed. However, as we mentioned earlier, some of the physical LTE RBs cannot be used for NB-IoT deployment.

The NB-IoT system is designed to operate in the following LTE operating bands: 1, 2, 3, 4, 5, 8, 11, 12, 13, 14, 17, 18, 19, 20, 21, 25, 26, 28, 31, 66, 70, 71, 72, 73, and 74 [1]. 3GPP specifications do not specify how to allocate the RBs between LTE and NB-IoT. However, downlink synchronization and paging can only be established on certain RBs. The RBs located at the center of the band cannot be used due to LTE transmission of the downlink synchronization signals and broadcast channel. Owing to capacity limitations, NB-IoT is not designed for 1.4 MHz channel bandwidth. The RBs allocated for a cell connection are referred to as anchor carriers. For the actual exchange of data (in the connected state), other RBs (non-anchor carriers) can be assigned.

For an LTE service provider, the in-band option provides the most efficient NB-IoT deployment scenario because if there is no IoT traffic, the PRB(s), available for an NB-IoT carrier, may be allocated to LTE services. Note that NB-IoT can be fully integrated with the existing LTE infrastructure. This allows the base station scheduler to multiplex LTE and NB-IoT traffic in the same spectrum. Fig. 6.6 shows the results of a coexistence study where the impact of NB-IoT uplink transmission in in-band and guard-band modes on an LTE [victim] system throughput is given in terms of cumulative distribution function (CDF) of throughput. The results suggest that there is a negligible impact on LTE operation as a result of NB-IoT deployment [17].

6.2.3 Protocol Structure

The NB-IoT protocol stack is a functionally reduced version of the LTE protocols. The NB-IoT further uses a different bearer structure. SRBs are partly reused from LTE; that is, the SRB0 is used for RRC messages transmitted over the common control channel, and the SRB1 is used for transport of RRC and NAS messages using the dedicated control channel. However, there is no SRB2 defined for NB-IoT. In addition, a new SRB, the SRB1bis is defined, which is implicitly configured with SRB1 using the same configuration, rather without the packet data convergence protocol entity. This bearer type plays the role of the SRB1 until the security architecture is activated, after that SRB1bis is not used anymore. This also implies that for the control-plane CIoT EPS optimization, only SRB1bis is used, because there is no security activation in this mode. The NB-IoT user-plane and control-plane protocol stack are the same as those of LTE with functionalities optimized for NB-IoT sustainable operation (see Fig. 6.7).

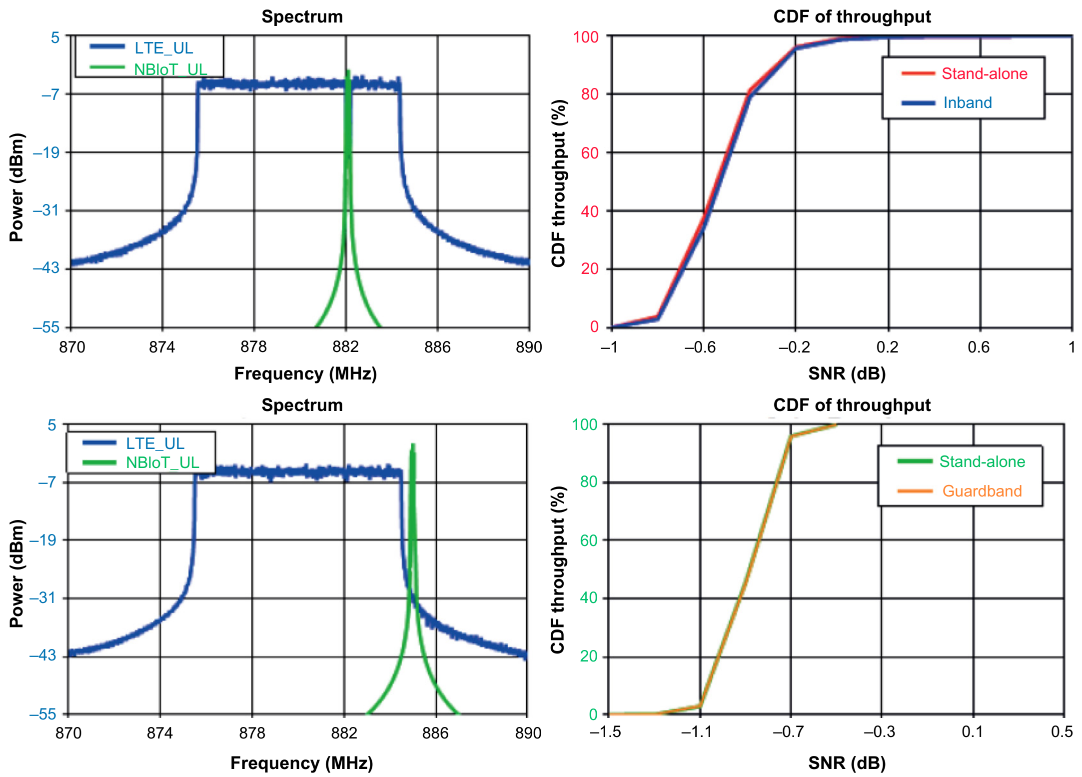


Figure 6.6

Example of in-band/guard-band NB-IoT operation and uplink coexistence analysis (10 MHz victim LTE system and aggressor NB-IoT device). A total of 1000 LTE subframes were used to derive CDF of the throughput [16,17].

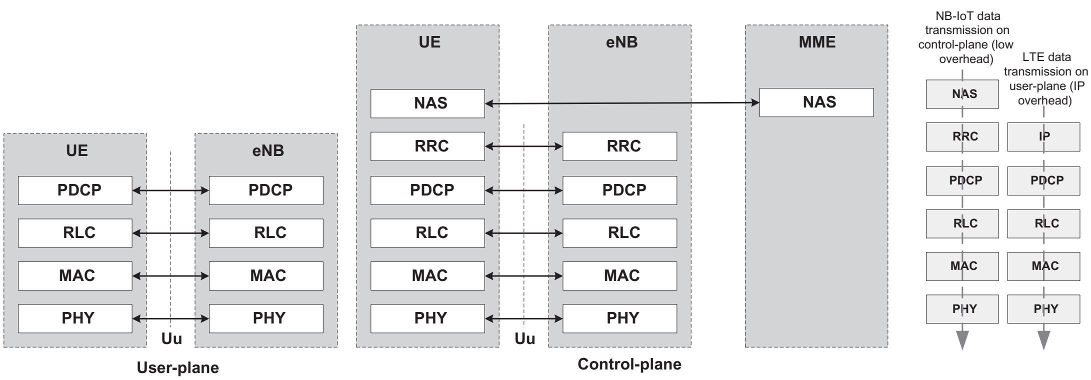


Figure 6.7

NB-IoT user-plane and control-plane protocol structure [6].

6.3 Physical Layer Aspects

6.3.1 Frame Structure

The downlink multiple access scheme of NB-IoT is based on orthogonal frequency division multiple access with the same 15 kHz subcarrier spacing as LTE with the slot, subframe, and frame durations configured as 0.5, 1, and 10 ms, respectively. Furthermore, the slot format in terms of cyclic prefix length and number of OFDM symbols per slot are also identical to those in LTE. In principle, an NB-IoT carrier can occupy one LTE PRB in the frequency domain. Reusing the same OFDM numerology as LTE ensures coexistence with LTE in the downlink. The uplink of NB-IoT supports both multi-tone and single-tone transmissions. Multi-tone transmission is based on single-carrier frequency division multiple access (SC-FDMA) with the same 15 kHz subcarrier spacing, slot, and subframe length as LTE. Single-tone transmission supports two numerologies: 15 and 3.75 kHz. The 15 kHz subcarrier spacing is identical to that of LTE, ensuring coexistence with LTE in the uplink. The 3.75 kHz single-tone numerology uses 2 ms slot duration. Similar to the downlink, an uplink NB-IoT carrier uses a total system bandwidth of 180 kHz [2,11]. In addition to the system frames, the concept of hyper frames is further defined, which counts the number of system frame periods; that is, it is incremented each time the system frame number (SFN) wraps. Similar to the SFN, the hyper frame number (HFN) is a 10-bit counter; thus the hyper frame period spans 1024 system frame periods, corresponding to a time interval of approximately 3 hours. Because NB-IoT only uses a single PRB in the downlink, the physical channels are only multiplexed in the time domain, as shown in Fig. 6.8.

6.3.2 Narrowband Primary Synchronization Signal

Unlike LTE, the NB-IoT physical channels and signals are primarily multiplexed across time. Fig. 6.8 illustrates how NB-IoT subframes are allocated to different physical channels and signals. The first three OFDM symbols are not used for NB-IoT, because they carry the

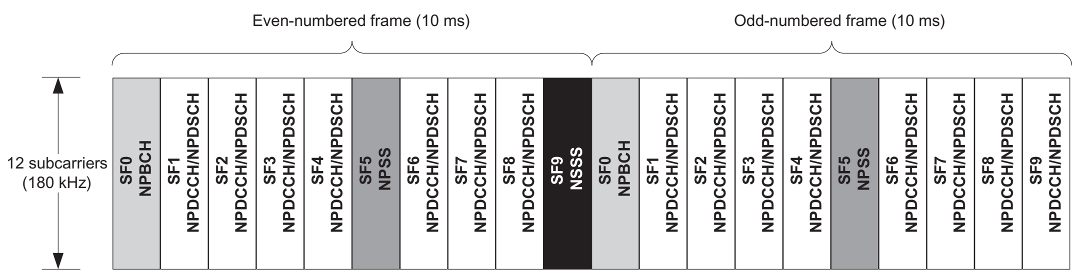


Figure 6.8
NB-IoT frame structure [14,25].

physical control format indicator channel (PCFICH) and physical downlink control channel (PDCCH) in LTE when NB-IoT is operated in the in-band mode. Note that during the time when the UE synchronizes to the narrowband primary synchronization signal (NPSS) and narrowband secondary synchronization signal (NSSS), it may not know the operation mode; consequently, this guard time applies to all modes. In addition, both synchronization signals are punctured by the LTE cell-specific reference signals. It is not specified which of the antenna ports is used for the synchronization signals; this may even change between any two subframes. Each NB-IoT subframe spans over one PRB (i.e., 12 subcarriers) in the frequency domain and 1 ms in the time domain. The 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 could not be reused for NB-IoT, thus a new design was introduced. The NPSS is transmitted in the fifth subframe of every 10 ms frame, using the last 11 OFDM symbols in the subframe. The NPSS detection is one of the most computationally intensive operations from a UE perspective. To allow efficient implementation of NPSS detection, NB-IoT uses a hierarchical sequence. The signal itself consists of a single length-11 Zadoff−Chu (ZC) sequence that is either directly mapped to the 11 lowest subcarriers (the 12th subcarrier is null in the NPSS) or is inverted before the mapping process. After successful detection of the NPSS, an NB-IoT UE is able to determine the frame boundaries of a downlink transmission. For each of the 11 NPSS OFDM symbols in a subframe, either $\mathbf{p}$ or $-\mathbf{p}$ is transmitted, where $\mathbf{p}$ is the base sequence generated based on a length-11 ZC sequence with root index 5. Each of the length-11 ZC sequence is mapped to the lowest 11 subcarriers within the NB-IoT PRB. The sequence $d_l(n)$ used for the NB primary synchronization signal is generated from a frequency domain ZC sequence according to $d_l(n) = S(l)e^{-j\pi un(n+1)/11}; \quad n = 0, 1, \ldots, 10$, where the ZC root sequence index $u = 5$ and $S(l)$ for different symbol indices l is given as $[S(3) \;\; S(4)\ldots S(13)] = [1 \;\; 1 \;\; 1 \;\; 1 \;\; -1 \;\; -1 \;\; 1 \;\; 1 \;\; 1 \;\; -1 \;\; 1]$ for normal cyclic prefix [2]. The structure of NPSS is illustrated in Fig. 6.9.

6.3.3 Narrowband Secondary Synchronization Signal

The NSSS has 20 ms periodicity and is transmitted in the ninth subframe of every other frame and uses the last 11 OFDM symbols. The NSSS spans 132 resource elements and comprises a length-132 frequency domain ZC sequence, with each element mapped to a resource element. The NSSS is generated by element-wise multiplication between a ZC sequence and a binary scrambling sequence. The root of the ZC sequence and binary scrambling sequence is determined by narrowband physical cell identity (NB-PCID). The cyclic shift of the ZC sequence is further determined by the frame number. NB-PCID is an additional input parameter so that it can be derived from the sequence. There are a total of 504 distinct NB-PCID values. The NSSS is transmitted in the last subframe of each

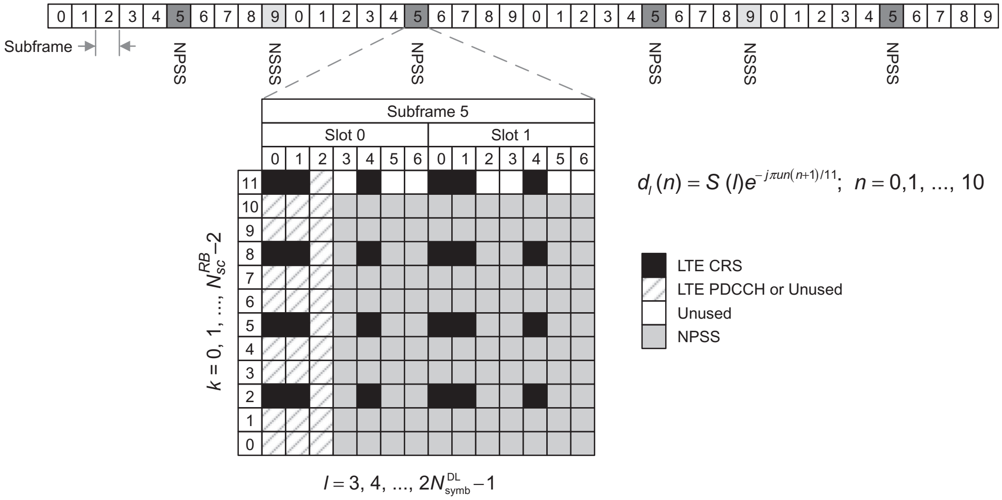


Figure 6.9
Structure of NPSS in time and frequency [2,25].

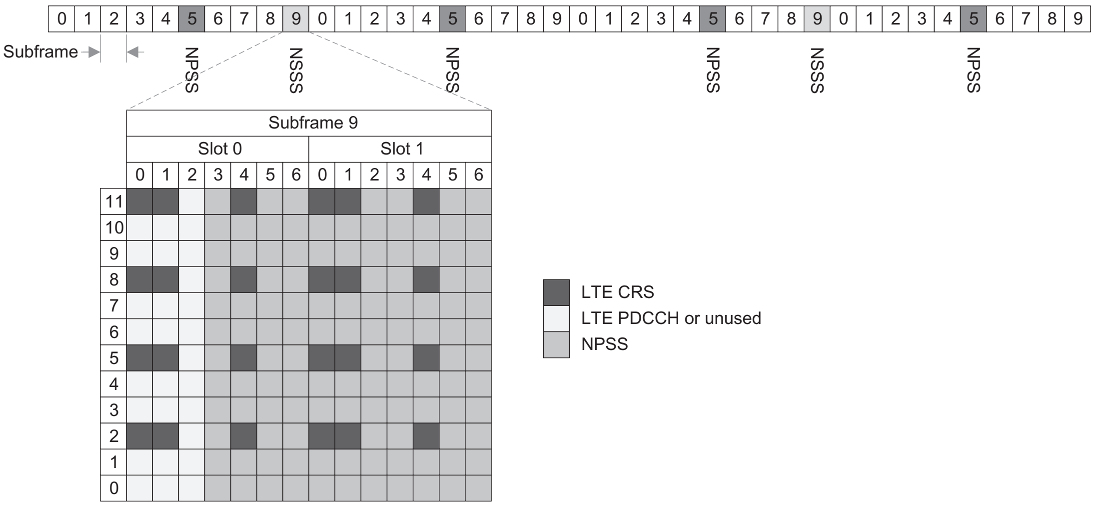


Figure 6.10
Structure of NSSS in time and frequency domains [2,25].

even-numbered radio frame, as shown in Fig. 6.10. The sequence $d(n)$ used for the NSSS is generated from a frequency domain ZC sequence according to the following:

$$d(n) = b_q(m)e^{-j2\pi\theta_f n}e^{-j\pi un'(n'+1)/131} \quad n = 0, 1, \ldots, 131$$

$$n' = n \bmod 131; \quad m = n \bmod 128; \quad u = N_{ID}^{Ncell} \bmod 126 + 3; \quad q = \left\lfloor \frac{N_{ID}^{Ncell}}{126} \right\rfloor$$

The binary sequence $b_q(m)$ is given in [2]. The cyclic shift θ_f in frame number n_f is given by $\theta_f = 33/132\left(n_f/2\right)\text{mod}4$ [2].

6.3.4 Narrowband Reference Signals

The downlink narrowband reference signal (NRS) consists of known reference symbols inserted in the last two OFDM symbols of each slot for NB-IoT antenna ports 0 and 1, except invalid subframes and subframes transmitting NPSS or NSSS. There is one NRS transmitted per downlink NB-IoT antenna port. In addition to NRSs, the physical layer supports narrowband positioning reference signals. Physical layer provides 504 unique cell identities using the NSSS. It will be indicated to the UE whether it may assume that the cell ID is identical for NB-IoT and LTE systems. In the case where the cell IDs are identical, a UE may use the downlink cell-specific reference signals for demodulation and/or measurements when the number of NB-IoT antenna ports is the same as the number of downlink cell-specific reference signals antenna ports [5]. The NRS time−frequency mapping, shown in Fig. 6.11, is additionally cyclically shifted by $N_{ID}^{Ncell}\text{mod}6$ in the frequency domain. When NRS is transmitted on two antenna ports, then the resource elements that are used for NRS on each antenna portare set to zero on the other antenna port. The narrowband physical broadcast channel (NPBCH) is encoded using a tail-biting convolutional code (TBCC) and QPSK modulated.

An important point on the in-band operation concerns N_{ID}^{Ncell} parameter, which may be the same as the PCI for the LTE cell. This is indicated by the *opeartionMode* parameter in narrowband master information block (MIB-NB), which distinguishes between an in-band operation with same PCI as LTE and one whose identities are different. If this parameter is set to true, then N_{ID}^{Ncell} and PCI are the same and the UE may assume that the number of antenna ports is the same as in the LTE cell. The channel may then be inferred from either reference signal set. In that case, LTE cell-specific reference signal (CRS) port 0 is associated with NRS port 0, and CRS port 1 is associated with NRS port 1.

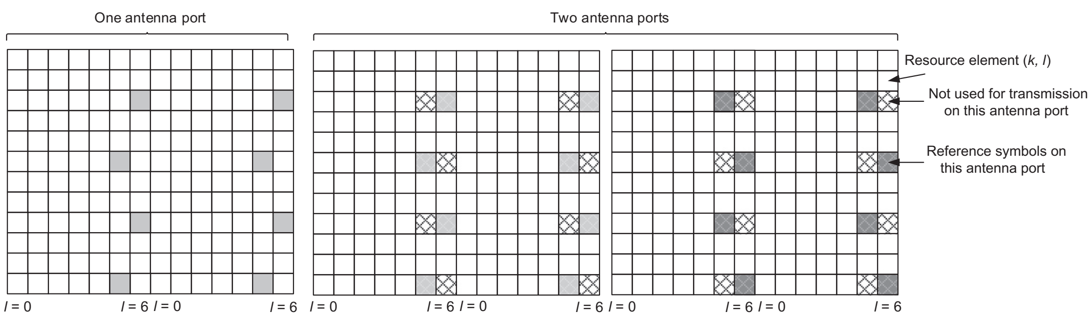


Figure 6.11
NRS subcarrier mapping [2,11,19].

6.3.5 Narrowband Physical Broadcast Channel

The NPBCH carries the MIB-NB. The MIB-NB contains 34 bits and is transmitted over a time period of 640 ms; that is, 64 radio frames, and includes the following information:

- 4 bits indicating the most significant bits of the SFN, the remaining least significant bits (LSBs) are implicitly derived from the MIB-NB starting point.
- 2 bits representing the two LSBs of the HFN.
- 4 bits for the narrowband system information block type 1 (SIB1-NB) scheduling and size.
- 5 bits indicating the system information value tag.
- 1 bit representing whether access class barring is applied.
- 7 bits indicating the operation mode with the mode-specific values.
- 11 reserved bits for future extensions.

Fig. 6.12 shows the mapping of NPBCH to physical resources. After physical layer baseband processing, the resulting MIB-NB is split into eight blocks. The first block is transmitted on the first subframe (SF0) and repeated in SF0 of the next seven consecutive radio frames. In SF0 of the following radio frame, the same procedure is performed for the second block. This process is continued until the entire MIB-NB is transmitted. The use of SF0 for all transmissions ensures collision avoidance of NPBCH with MBSFN transmissions in LTE, if NB-IoT is deployed in in-band operation mode.

The MIB-NB and *SystemInformationBlockType1-NB* use fixed scheduling. The periodicity of MIB-NB is 640 ms in comparison to the periodicity of MIB in LTE, which is 40 ms. The periodicity of SIB1-NB is 2560 ms relative to the periodicity of LTE SIB1 that is 80 ms. The MIB-NB contains the information required to acquire SIB1. SIB1-NB contains the information to acquire other SIBs (see Table 6.2 for a list of NB-IoT SIBs). The broadcast control channel and other logical channels cannot be transmitted in the same subframe. The NB-IoT UE is not required to detect SIB changes in RRC_CONNECTED state. The NPBCH consists of eight independent 80 ms blocks. A block is always transmitted in SF0 of a radio frame and then repeated eight times once per radio frame. The NPBCH is not transmitted in the first three symbols to avoid collision with the LTE control channels. The NPBCH symbols are mapped around the NRS and the LTE CRS resources, where it is always assumed that two antenna ports are defined for NRS and four antenna ports for CRS. This assumption is necessary, because the UE obtains the actual antenna port information only after detecting the MIB-NB. The reference signal location in the frequency domain is given by N_{ID}^{Ncell}, provided by the NSSS. Although the N_{ID}^{Ncell} may be different than PCI in the in-band operation, its range is restricted so that it points to the same frequency locations, thus the CRS cyclic shift in the frequency domain is known to the UE.

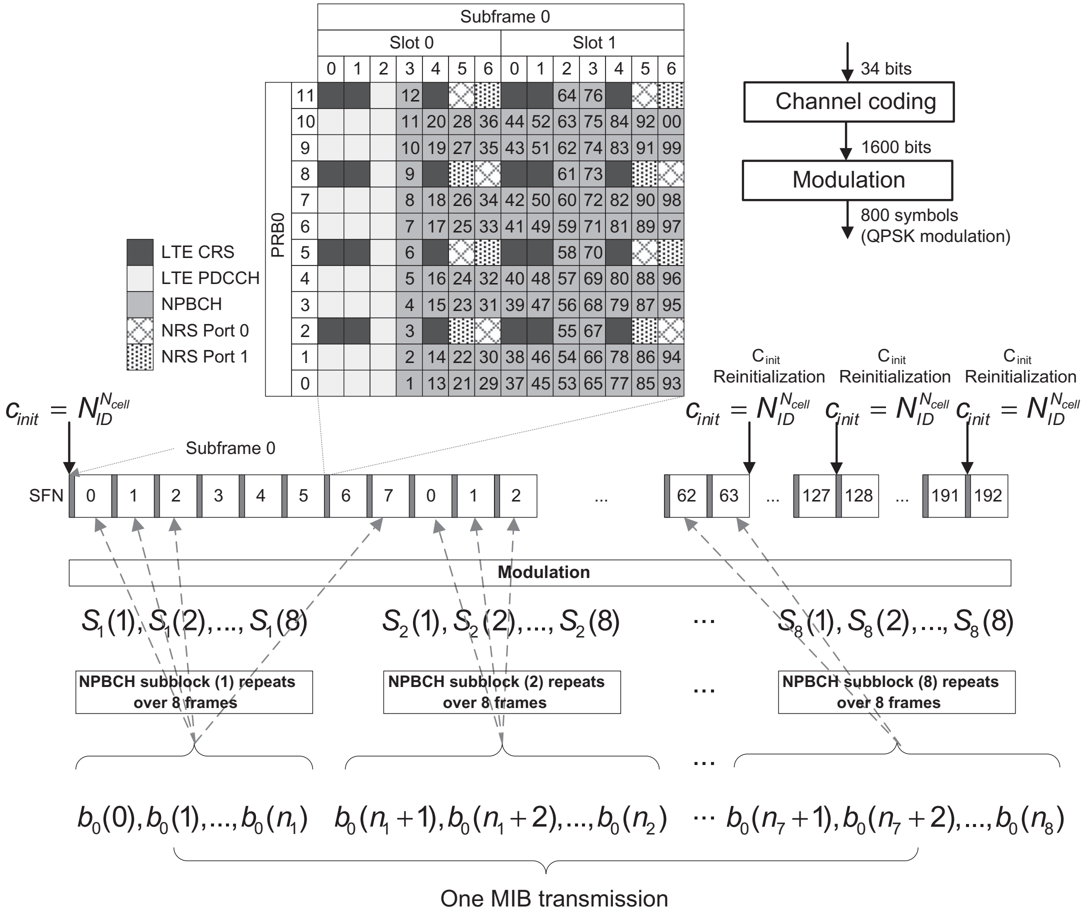


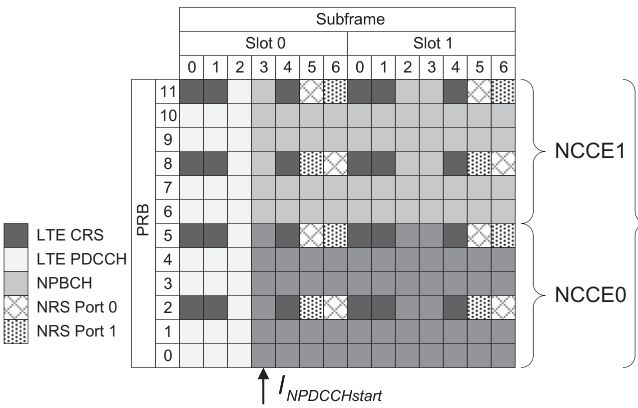
Figure 6.12
Processing and resource mapping of NPBCH [2,3,25].

Table 6.2: MIB and SIB specified for NB-IoT [8].

Message	Content
MIB-NB	Essential information required to receive further system information
SIB1-NB	Cell access and selection, other SIB scheduling
SIB2-NB	Radio resource configuration information
SIB3-NB	Cell reselection information for intra-frequency, inter-frequency
SIB4-NB	Neighbor cell-related information relevant for intra-frequency cell reselection
SIB5-NB	Neighbor cell-related information relevant for inter-frequency cell reselection
SIB14-NB	Access barring parameters
SIB16-NB	Information related to GPS time and coordinated universal time (UTC)

6.3.6 Narrowband Physical Downlink Control Channel

In NB-IoT, the downlink control information (DCI) is carried by the narrowband physical downlink control channel (NPDCCH). The basic resource allocation unit for NPDCCH is defined as narrowband control channel element (NCCE), which is the basic resource unit (RU) allocated for DCI transport. NPDCCH carries scheduling information for downlink and uplink data channels and further carries HARQ ACK/NACK information for the uplink data channel as well as paging indication and random-access response (RAR) scheduling information. There are two different formats for NPDCCH; that is, Format 0 and Format 1. NPDCCH Format 0 occupies only one NCCE, whereas NPDCCH Format 1 occupies two NCCEs. As shown in Fig. 6.13, there are only a few subframes that can be allocated to carry NPDCCH or narrowband physical downlink shared channel (NPDSCH). To reduce UE complexity, all downlink channels use LTE TBCC. Furthermore, the maximum transport block size (TBS) of NPDSCH is limited to 680 bits. The NRS is used to provide phase reference for coherent demodulation of the downlink channels. The NRS resources 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. The NPDCCH structure is depicted in Fig. 6.13. In this example, we show the mapping for an in-band NB-IoT operation assuming a single antenna port in the LTE cell and two antenna ports in NB-IoT. The parameter $l_{NPDCCHstart}$, the LTE control region size signaled by NB-SIB1 [4], indicates the OFDM start symbol, which helps avoid conflict with the LTE control channel in the in-band operation. For the guard-band and standalone operation modes, the control region size is by default zero, which provides more resource elements for the NPDCCH. In order for the UE to find the control information with reasonable amount of decoding complexity, NPDCCH is grouped into the following search spaces:



NPDCCH format	Number of NCCEs
0	1
1	2

Figure 6.13
NPDCCH structure in time and frequency [2,25].

- Type-1/1A common search spaces used for paging
- Type-2/2A common search spaces used for random access
- UE-specific search space

A UE is not required to simultaneously monitor an NPDCCH UE-specific search space and a Type-1 or Type-2 NPDCCH common search space. An NPDCCH search space $NS_k^{(L',R)}$ at aggregation level (AL) $L' \in \{1, 2\}$ and repetition level $R \in \{1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048\}$ is defined by a set of NPDCCH candidates where each candidate is repeated in a set of R consecutive NB-IoT downlink subframes excluding subframes used for transmission of system information messages starting with subframe k [4]. Thus each NPDCCH may be repeated several times with an upper limit configured by the RRC signaling. In addition, Type-2 common search space and UE-specific search space are configured by RRC, whereas the Type-1 common search space is identified by the paging opportunity subframes. The location of NPDCCH (i.e., the subframes used for transmitting NPDCCH) is determined via a process as illustrated in Fig. 6.14. In case of Type-1 NPDCCH common search space, $k = k_0$, which is determined from locations of NB-IoT paging opportunity subframes.

Different radio network temporary identifiers (RNTIs) are assigned to each UE, one for random access (RA-RNTI), one for paging (P-RNTI), and a UE-specific temporary identifier (C-RNTI) provided during the random-access procedure. These identifiers are implicitly indicated (scrambled) in the NPDCCH CRC. Therefore, the UE has to search for a specific

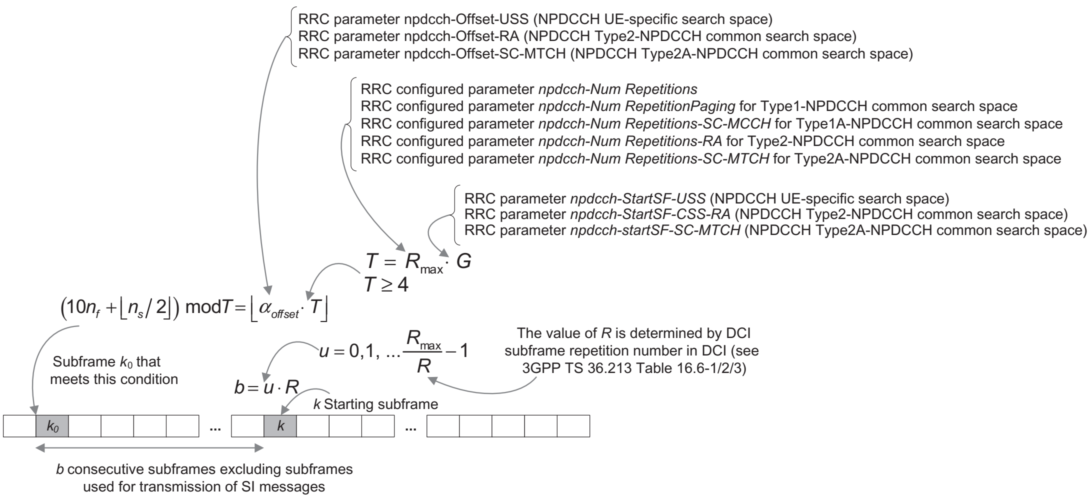


Figure 6.14
Search spaces and determination of NPDCCH location [4,25].

RNTI and, if found, decode the NPDCCH. Three DCI formats have been specified for NB-IoT, namely DCI format N0, N1, and N2.

When an NB-IoT UE receives a NPDCCH, it can distinguish different formats in the following manner. DCI format N2 is implicitly indicated, wherein the CRC is scrambled with the P-RNTI. If the CRC is scrambled with the C-RNTI, then the first bit in the message indicates whether it contains DCI format N0 or N1. For the case that the CRC is scrambled with the RA-RNTI, the content is a restricted DCI format N1 including only those fields required for the random-access response. The scheduling delay is included in DCI formats N0 and N1; that is, the time interval between the end of NPDCCH and the start of NPDSCH or the start of narrowband physical uplink shared channel (NPUSCH). This delay is at least five subframes for the NPDSCH and eight subframes for the NPUSCH. For downlink transmission via DCI format N2, the scheduling delay is fixed and equal to 10 subframes [4] (see Table 6.3).

In order to determine whether there is any data sent through NPDSCH to an NB-IoT UE or to detect any uplink grant for NPUSCH, the UE should monitor and try to decode various regions within downlink subframes. There is no information explicitly sent by the network regarding which regions the UE needs to monitor. The UE should monitor all possible regions that are allowed for NPDCCH and attempt to decode the information; that is, blind decoding. However, the UE does not need to decode every possible combination of resource elements within a subframe. There are a certain set of predefined regions in which a PDCCH could be allocated. The UE monitors only those predefined regions which are called NPDCCH search spaces.

Since an NB-IoT UE does not know in advance when a DCI will be sent to it, it must monitor NPDCCH subframes and attempt to decode them, in order to detect a pending downlink transmission. The NPDCCH configuration for a UE is primarily defined by how often the UE should start to monitor NPDCCH subframes and the maximum number of subframes that it should monitor. These two parameters are denoted by NPDCCH period T and maximum NPDCCH repetitions $R_{\max}$ (Fig. 6.15). In the example shown in Fig. 6.16, the NPDCCH period is assumed to start from a subframe at time $t = 0$. Therefore, the UE starts to monitor

Table 6.3: Various NB-IoT DCI formats [3].

DCI Format	Size (bits)	Content
N0	23	Uplink grant
N1	23	NPDSCH scheduling RACH procedure initiated by NPDCCH order
N2	15	Paging and direct indication

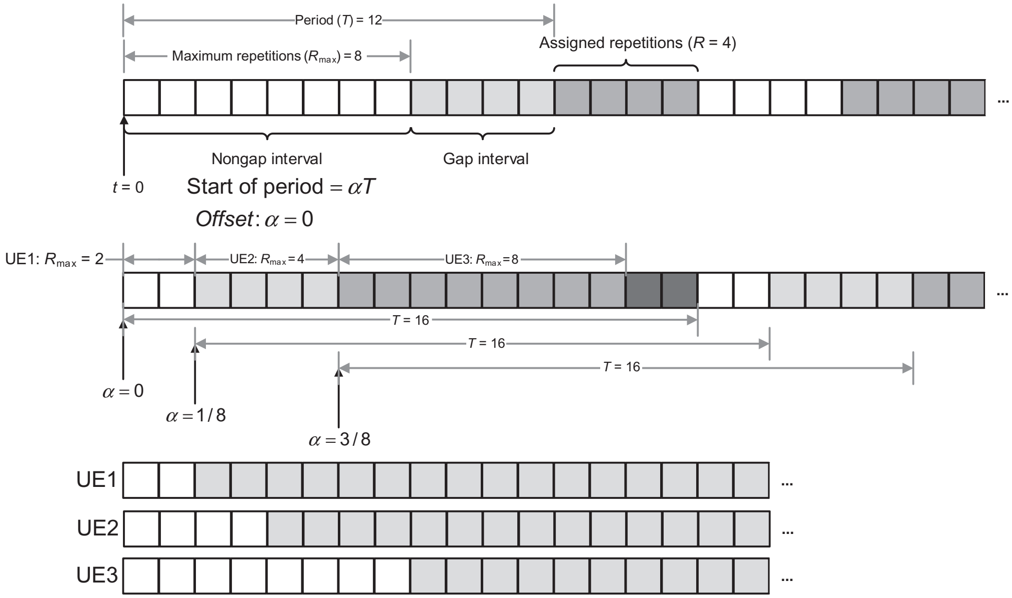
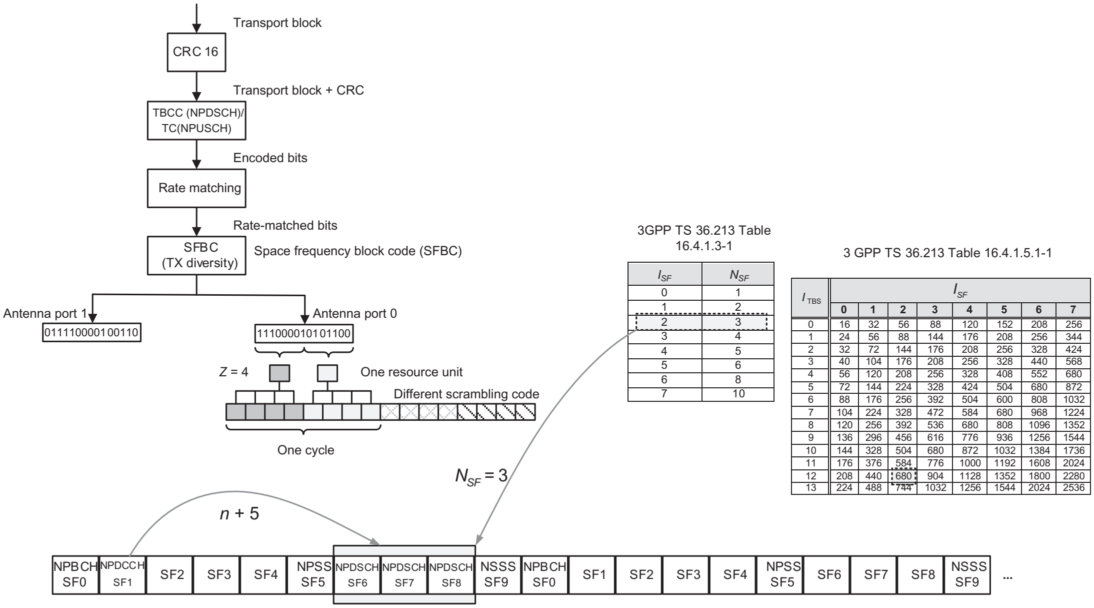


Figure 6.15
Example NPDCCH configuration for an NB-IoT UE and the use of an offset to create non-overlapping NPDCCH configurations [18,19].

NPDCCH subframes at the following time instances $t = 0, T, 2T, \ldots$. While there are T subframes in one period, the UE monitors NPDCCH subframes for a maximum duration equal to $R_{\max}$ subframes, alternatively referred to as the non-gap interval. The duration of the remaining $T - R_{\max}$ subframes are known as gap interval. Fig. 6.16 further shows that at the start of the second period, the UE has received four repetitions of the NPDCCH, which it would then start decoding to check for any relevant control information. The choice of $R_{\max}$, for a given period T, has the following implications. A large $R_{\max}$ implies higher downlink signal-to-interference plus noise ratio (SINR), resulting in better downlink coverage. A large $R_{\max}$ further indicates more opportunities to schedule the UE within period T. In heavy network loading scenarios, this may decrease the waiting time for the UE to be scheduled. The maximum number of scheduling opportunities per second can be represented by $R_{\max}/T$. A trade-off must be made between increasing $R_{\max}$ value and the increased UE energy consumption since the UE receiver needs to be active and monitor NPDCCH subframes for a longer time duration. The beginning of the period may be shifted with respect to $t = 0$ using the offset parameter α. The number of subframes by which the period is shifted is denoted by αT. Fig. 6.15 shows how different α values can be used to create non-overlapping NPDCCH configurations for three UEs having the same value of period $T = 16$. Note that the term non-overlapping means that the non-gap intervals of the UEs do not overlap with each other. As shown in the figure, the NPDCCH periods of UE-2 and UE-3 start two and six subframes



3GPP TS 36.213 Table 16.4.1.3-1

I_{SF}	N_{SF}
0	1
1	2
2	3
3	4
4	5
5	6
6	8
7	10

3 GPP TS 36.213 Table 16.4.1.5.1-1

I_{TBS}	I_{SF}							
	0	1	2	3	4	5	6	7
0	16	32	56	88	120	152	208	256
1	24	56	88	144	176	208	256	344
2	32	72	144	176	208	256	328	424
3	40	104	176	208	256	328	440	568
4	56	120	208	256	328	408	552	680
5	72	144	224	328	424	504	680	872
6	88	176	256	392	504	600	808	1032
7	104	224	328	472	584	680	968	1224
8	120	256	392	536	680	808	1096	1352
9	136	296	456	616	776	936	1256	1544
10	144	328	504	680	872	1032	1384	1736
11	176	376	584	776	1000	1192	1608	2024
12	208	440	680	904	1128	1352	1800	2280
13	224	488	744	1032	1256	1544	2024	2536

Figure 6.16
NPDSCH processing and mapping procedure [25].

later, respectively, compared to that of UE-1. It must be noted that, in an overlapping configuration, if any of the UEs receive one or more NPDCCH subframes, it may partially or fully block the non-gap interval of the remaining UEs, thus blocking the scheduling opportunity of those UEs. Furthermore, the likelihood of this blocking increases with larger $R_{\max}$ values [4].

6.3.7 Narrowband Physical Downlink Shared Channel

The NPDSCH is the traffic channel and carries SIBs, upper layer data, and RAR messages. The NPDSCH subframe has the same structure as the NPDCCH shown in Fig. 6.16. It starts at a configurable OFDM symbol $l_{NPDCCHstart}$ and is mapped around the NRS and LTE CRS during in-band operation, where the value of parameter$l_{NPDCCHstart}$ is provided by RRC signaling for the in-band operation, and is zero otherwise. A maximum TBS of 680 bits is specified for NB-IoT applications. The mapping of a transport block spans N_{SF} subframes. The transport block is repeated providing N_{RP} identical copies using a subframe interleaving mechanism for an optimized reception at the NB-IoT UE, as shown in Fig. 6.16. Both values, N_{SF} and N_{RP}, are signaled via DCI. The resulting subframe sequence is mapped to $N_{SF}N_{RP}$ consecutive subframes defined for NPDSCH (see Fig. 6.16). For the downlink, there is no automatic acknowledgment to a transmission and the eNB indicates this information in DCI. In that case, the UE transmits the acknowledgment using NPUSCH format 2. The associated timing and subcarrier mapping is indicated in this DCI, as well. There is a multi-carrier support for all operation modes, which means that another carrier may be used when the UE is in the connected state. In the idle state, the UE camps on the NB-IoT carrier from which it received the synchronization signals and broadcast information, that is, the anchor carrier. The UE then waits to receive the paging message or to start system access for mobile-originated data or signaling transmission, both by transmitting a preamble on the associated uplink carrier provided in SIB2-NB broadcast message.

The smallest scheduled RU varies depending on the subcarrier spacing and the number of tones. The reliability is obtained through repetitions where in the downlink up to 2048 repetitions are possible and in the uplink up to 128 repetitions are permissible (see Tables 6.4 and 6.5).

The SIB1-NB broadcast message is transmitted over NPDSCH. It has a period of 256 radio frames and is repeated 4, 8, or 16 times. The TBS and the number of repetitions are indicated in the MIB-NB. In general, 4, 8, or 16 repetitions are possible, and four TBSs of 208, 328, 440, and 680 bits are defined, respectively. The radio frame on which the SIB1-NB starts is determined by the number of repetitions and N_{ID}^{Ncell}. The fourth subframe is used for SIB1-NB in all radio frames transmitting SIB1-NB. As the other transmission parameters are fixed, there is no associated indication in the control channel. The SIB1-NB content may only be changed on each modification period, which has a length of 4096 radio frames; that is, every 40.96 seconds. This corresponds to four SFN periods, which is the reason for indication of two LSBs of the HFN in the MIB-NB. If such a modification occurs, it is

Table 6.4: Resource allocation in NB-IoT [2].

Subcarrier Spacing (kHz)	Number of Tones	Link Direction	Resource Unit Size (ms)
15	12	Uplink/Downlink	1
	6	Uplink	2
	3	Uplink	4
	1	Uplink	8
3.75	1	Uplink	32

Table 6.5: Uplink resource allocation in NB-IoT [2,4].

Uplink Data Type	Subcarrier Spacing (kHz)	Subcarriers per RU	Slots per RU	Duration of RU (ms)	Number of Resource Elements per RU
Uplink data	3.75	1	16	32	96
	15	1	16	8	96
		3	8	4	144
		6	4	2	144
		12	2	1	144
Uplink control information (ACK/NACK)	3.75	1	4	8	16
	15	1	4	2	16

indicated in the NPDCCH using DCI format N2. Although sent over the NPDSCH, the SIB1-NB resources are mapped similar to the MIB-NB shown in Fig. 6.12; that is, excluding the first three OFDM symbols, which is necessary because the UE obtains the start of the resource mapping from SIB1-NB.

One of the key features of NB-IoT is coverage enhancement through signal repetition. For typical NB-IoT use cases, the signal-to-noise ratio (SNR) operation point is below 0 dB. Under this operating condition, the channel estimation error is the dominating factor affecting the receiver performance. It can be shown that the effective SNR after combining N_{RP} repetitions is given as follows [18]:

$$SNR_{effective} = \frac{N_{RP}(\sigma^2 + \gamma)}{(\sigma^2 + \gamma + \sigma^2/\gamma)(1 + \sigma^2/2\gamma)}$$

where γ denotes SNR per transmission, σ^2 represents the variance of channel estimation error, and N_{RP} is the number of repetitions.

6.3.8 Narrowband Physical Random-Access Channel

Similar to LTE, the narrowband physical random-access channel (NPRACH) is used by an unsynchronized UE to inform the eNB of its desire to establish a connection. The random-access procedure is a contention-based and collision-prone mechanism in which the UE selects and transmits a random-access preamble to the base station. The NPRACH preamble consists of four symbol groups, with each symbol group comprising one cyclic prefix and five symbols, as shown in Fig. 6.17. The length of the cyclic prefix is 66.67 μs (Format 0) for cell radius up to 10 km and 266.7 μs (Format 1) for cell radius up to 40 km. Each symbol, with fixed symbol value 1, is modulated on a 3.75 kHz tone with symbol duration of 266.67 μs. 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. 6.18. To support coverage

Preamble format	T_{CP}	T_{SEQ}
0	$2048T_s$	$5 \cdot 8192T_s$
1	$8192T_s$	$5 \cdot 8192T_s$

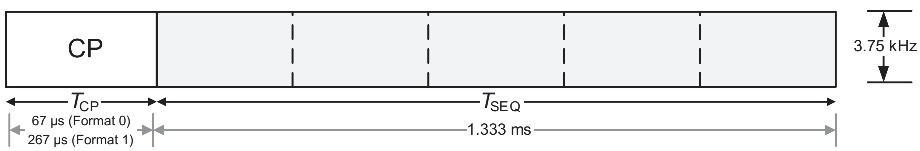


Figure 6.17
Time domain structure of NPRACH [2].

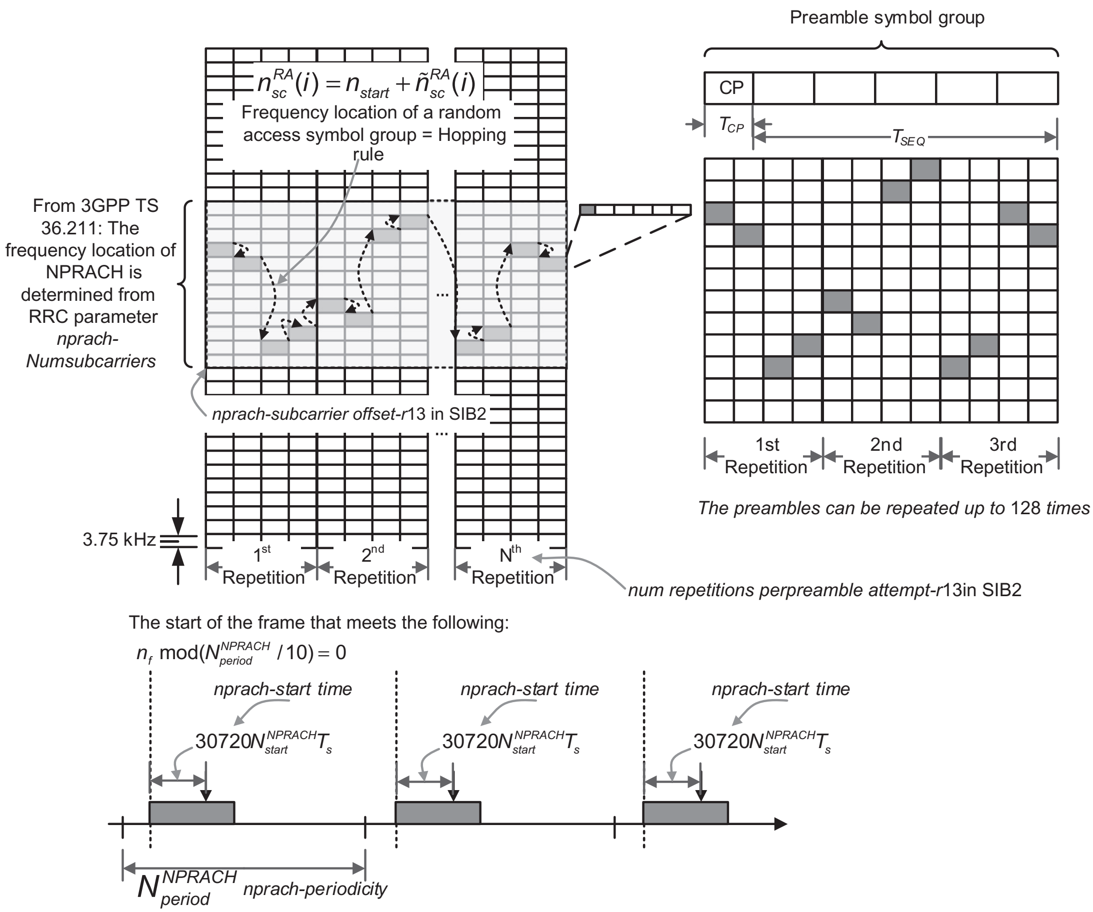


Figure 6.18

Illustration of NPRACH time and frequency domain resource allocation and transmission timing [2,25].

extension, a NPRACH preamble can be repeated up to 128 times. The NPUSCH has two formats. Format 1 is used for carrying uplink data and uses the same LTE turbo code for forward error correction. Depending on the coverage level, the cell may indicate that the NB-IoT UE must repeat the preamble 1, 2, 4, 8, 16, 32, 64, or 128 times, using the same transmission power in each repetition. Each of the four groups is made up of a cyclic prefix and four identical symbols. The NPRACH hops among 12 neighboring subcarriers (see Fig. 6.18). The base station specifies a range for the allowed subcarriers, and communicates both the delay and the permissible range via the SIB to the NB-IoT UE. The UE can choose from 12 subcarriers. If the UE uses a specific range within the designated subcarriers, this would signal to the base station that the UE supports multi-tone transmission format.

The NPRACH resources are separately provided for each coverage enhancement group. They consist of the assignment of time and frequency resources and occur periodically, where an NPRACH periodicity between 40 ms and 2.56 seconds may be configured. Their start time within a period is provided in the system information, whereas the number of repetitions and the preamble format determine their end. In the frequency domain, subcarrier spacing of 3.75 kHz is utilized. The NPRACH resources occupy a contiguous set of 12, 24, 36, or 48 subcarriers and are located on a discrete set of subcarrier ranges. Depending on the cell configuration, the resources may be further partitioned into resources used by UEs supporting multi-tone transmission for msg3 and UEs that do not support it.

The physical random-access preamble is based on single-subcarrier frequency-hopping symbol groups. A symbol group is illustrated in Fig. 6.18, which consists of a cyclic prefix of length T_{CP} and a sequence of five identical symbols with total length T_{SEQ}. The preamble consists of four symbol groups transmitted without gaps and is transmitted N_{RP}^{NPRACH} times. The NPRACH transmission can only start $30720\,N_{start}^{NPRACH}T_s$ time units after the start of a radio frame whose frame number satisfies $n_f \bmod (N_{period}^{NPRACH}/10) = 0$. Following the transmission of $256(T_{CP} + T_{SEQ})$ time units, a gap is inserted [2]. The NPRACH preamble formats, that is, format 0 and format 1, differ in the cyclic prefix length. The five symbols have a duration of $T_{SEQ} = 1.333$ms, appended with a cyclic prefix of $T_{CP} = 67\ \mu s$ for format 0 and $T_{CP} = 267\ \mu s$ for format 1, making a total length of 1.4 and 1.6 ms, respectively. The preamble format to be used is broadcast in the system information.

The NPRACH starting subcarriers which are allocated to UE-initiated random access are divided into two sets of subcarriers, $\{0, 1, \ldots, N_{sc\_cont}^{NPRACH} N_{MSG3}^{NPRACH} - 1\}$ and $\{N_{sc\_cont}^{NPRACH} N_{MSG3}^{NPRACH}, \ldots, N_{sc\_cont}^{NPRACH} - 1\}$, where the second set would indicate the UE support for multi-tone msg3 transmission. The frequency location of the NPRACH transmission is constrained within $N_{sc}^{RA} = 12$ subcarriers. Frequency hopping is used within the 12 subcarriers, where the frequency location of the ith symbol group is given by $n_{sc}^{RA}(i) = n_{start} + \tilde{n}_{sc}^{RA}(i)$ where $n_{start} = N_{sc-offset}^{NPRACH} + \lfloor n_{init}/N_{sc}^{RA} \rfloor N_{sc}^{RA}$ and

$$\tilde{n}_{sc}^{RA}(i) = \begin{cases} \left[\tilde{n}_{sc}^{RA}(0) + f(i/4)\right] \bmod N_{sc}^{RA} & i \bmod 4 = 0 \text{ and } i > 0 \\ \tilde{n}_{sc}^{RA}(i-1) + 1 & i \bmod 4 = 1, 3 \text{ and } \tilde{n}_{sc}^{RA}(i-1) \bmod 2 = 0 \\ \tilde{n}_{sc}^{RA}(i-1) - 1 & i \bmod 4 = 1, 3 \text{ and } \tilde{n}_{sc}^{RA}(i-1) \bmod 2 = 1 \\ \tilde{n}_{sc}^{RA}(i-1) + 6 & i \bmod 4 = 2 \text{ and } \tilde{n}_{sc}^{RA}(i-1) < 6 \\ \tilde{n}_{sc}^{RA}(i-1) - 6 & i \bmod 4 = 2 \text{ and } \tilde{n}_{sc}^{RA}(i-1) \geq 6 \end{cases}$$

$$f(t) = \left(f(t-1) + \left[\sum_{n=10t+1}^{10t+9} c(n) 2^{n-(10t+1)} \right] \bmod \left(N_{sc}^{RA} - 1\right) + 1 \right) \bmod N_{sc}^{RA}$$

$$f(-1) = 0$$

where $\tilde{n}_{sc}^{RA}(0) = n_{init} \mathrm{mod} N_{sc}^{RA}$ and n_{init} denotes the subcarrier selected by the MAC sublayer from $\{0, 1, \ldots, N_{sc}^{NPRACH} - 1\}$, and the pseudo-random sequence $c(n)$ is specified in [2]. Note that the pseudo-random sequence generator is initialized with $c_{init} = N_{ID}^{Ncell}$ [2]. The NPRACH can be transmitted only with a specific timing within a NPRACH period as illustrated in Fig. 6.18, where *nprach-StartTime* and *nprach-Periodicity* parameters are configured by higher layers via SIB2-NB. The RACH procedure for NB-IoT will be described later in layer 2 aspects.

6.3.9 Narrowband Physical Uplink Shared Channel

The NPUSCH transports two types of information: uplink data via NPUSCH format 1 and uplink control information (UCI) via NPUSCH format 2. The latter always uses one subcarrier and is always BPSK modulated. It carries HARQ ACK/NACK corresponding to NPDSCH, whereas NPUSCH format 1 can use one or more subcarriers. For single-tone $\pi/2$-BPSK or $\pi/4$-QPSK modulation is used, while for multi-tone QPSK modulation is used. The NPUSCH can repeat data up to 128 times to improve the link budget. NPUSCH format 1 uses the same LTE turbo code (minimum code rate 1/3) for forward error correction. The maximum TBS of NPUSCH format 1 is 1000 bits, which is much lower than that in LTE. NPUSCH format 2 uses a repetition code for error control (minimum code rate of 1/16). NPUSCH format 1 supports multi-tone transmission based on the same legacy LTE numerology. 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 six-tone and three-tone formats are introduced for NB-IoT UEs, which 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 the peak-to-average power ratio (PAPR), single-tone transmission uses $\pi/2$-BPSK or $\pi/4$-QPSK with phase continuity between symbols. As shown in Fig. 6.19, NPUSCH format 1 uses the same slot structure as LTE PUSCH with seven OFDM symbols per slot and the middle symbol as the demodulation reference signal (DMRS), whereas NPUSCH format 2 consists of seven OFDM symbols per slot, but uses the middle three symbols as DMRS. The DMRS is used for channel estimation and coherent detection. The smallest unit to map a transport block is the resource unit whose definition depends on the NPUSCH format and subcarrier spacing. For NPUSCH format 1 and 3.75 kHz subcarrier spacing, an RU consists of one subcarrier in the frequency domain, and 16 slots in the time domain; that is, an RU has a length of 32 ms. For the 15 kHz subcarrier spacing, there are four options: 1, 3, 6, and 12 subcarriers over 16, 8, 4, and 2 slots, respectively (see Fig. 6.19). For NPUSCH format 2, the RU is always composed of one subcarrier with a length of four slots. As a result, for 3.75 kHz subcarrier spacing, the RU has 8 ms duration and for 15 kHz subcarrier spacing, the RU spans over 2 ms.

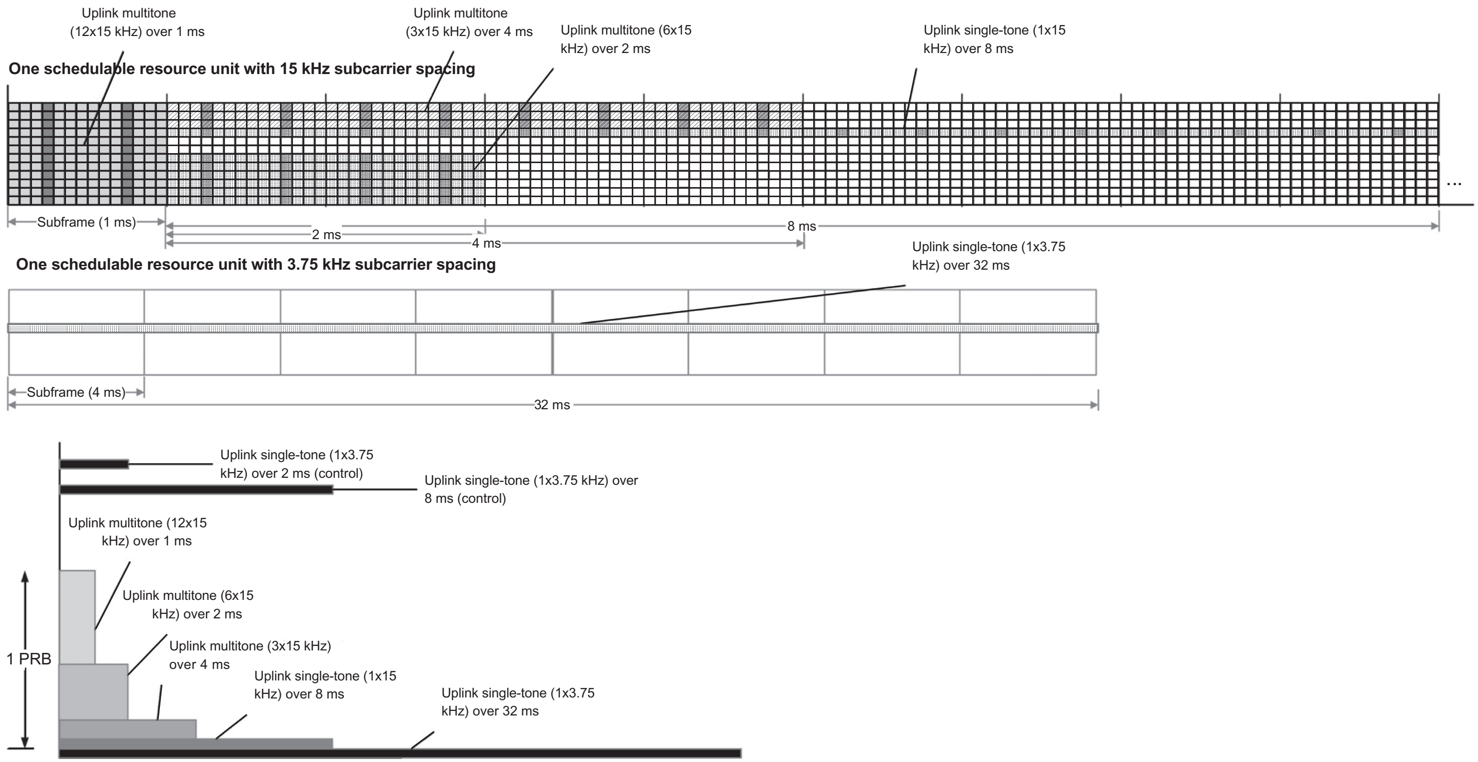


Figure 6.19

NPUSCH time–frequency mapping and uplink slot structure [11,19].

The signal in time domain is generated by applying an IFFT and inserting a cyclic prefix. For 15 kHz subcarrier spacing, the cyclic prefix is similar to that of LTE, while for 3.75 kHz, the cyclic prefix is 256 samples, corresponding to 8.3 μs. For the latter case, a period of 2304 samples (75 μs) at the end of each slot remains empty, which is used as a guard interval. For the in-band operation, this guard interval may be used to transmit sounding reference signals in the LTE system. Unlike downlink transmission, where HARQ ACK/NACK transmission is configurable, there is always HARQ acknowledgment in the associated downlink slot. The random-access signal $s(t)$ for the ith symbol group is defined as follows [2]:

$$s_i(t) = \beta_{NPRACH} \exp\left[j2\pi\left(n_{sc}^{RA}(i) + k_0\Delta f/\Delta f_{RA} + 1/2\right)\Delta f_{RA}(t - T_{CP})\right]$$

where $0 \leq t < T_{SEQ} + T_{CP}$. β_{NPRACH} is an amplitude scaling factor to conform to the transmit power P_{NPRACH}, $k_0 = -N_{sc}^{UL}/2$, $\Delta f_{\mathrm{RA}} = 3.75$ kHz, and the location in the frequency domain controlled by the parameter $n_{sc}^{RA}(i)$. For single-tone NPUSCH carrying uplink shared channel (UL-SCH), the uplink DMRSs are transmitted in the fourth block of the slot for 15 kHz subcarrier spacing, and in the fifth block of the slot for 3.75 kHz subcarrier spacing. For multi-tone NPUSCH carrying UL-SCH, the uplink DMRSs are transmitted in the fourth block of the slot. The length of the uplink DMRS sequence is 16 for single-tone transmission and is equal to the size (number of subcarriers) of the assigned resource for multi-tone transmission. In the uplink, the DMRS is defined and it is multiplexed with the data so that it is only transmitted in the RUs containing data. There is no MIMO transmission mode defined for the uplink; consequently, all transmissions use a single antenna port. Depending on the NPUSCH format, DMRS is transmitted in either one or three SC-FDMA symbols per slot. As shown in Fig. 6.20, the SC-FDMA symbols used for DMRS transmission depend on the subcarrier spacing. The DMRS symbols are constructed from a base sequence multiplied by a phase factor. They have the same modulation as the associated data channel. For

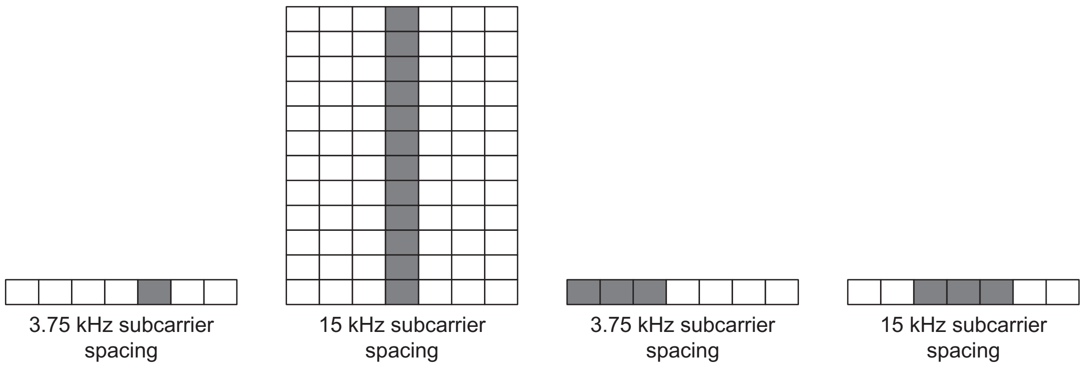


Figure 6.20
Resource elements used for DMRS in NPUSCH format 1 and 2 [2].

NPUSCH format 2, DMRS symbols are spread with the same orthogonal sequence as defined for the LTE PUCCH formats 1, 1a, and 1b.

6.4 Layer 2/3 Aspects

As in physical layer, there has been a number of changes in LTE L2/L3 operation to enable NB-IoT including introduction of new RRC messages and information elements. Some of the baseline LTE functions are not supported in NB-IoT including public safety notifications, inter-RAT mobility, and security activation for transfer of RRC context information, measurement configuration and reporting, and self-configuration and self-optimization as well as measurement logging and reporting for network performance optimization. The UE in RRC_CONNECTED can be configured, via UE-specific RRC signaling, with a non-anchor carrier for all unicast transmissions. The UE in RRC_IDLE, based on broadcast/multicast signaling, can use a non-anchor carrier for single-cell point-to-multipoint reception. The UE in RRC_IDLE can, based on broadcast signaling, use a non-anchor carrier for paging reception. The UE in RRC_IDLE or RRC_CONNECTED, based on broadcast signaling, can use a non-anchor carrier for random access. If the non-anchor carrier is not configured for the UE, all transmissions occur on the anchor carrier.

6.4.1 HARQ Protocol and Scheduling

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. Asynchronous, adaptive HARQ procedure is adopted to support scheduling flexibility. An example is illustrated in Fig. 6.21. The scheduling commands are conveyed through DCI, which is carried by NPDCCH using aggregation-level (AL)-1 or AL-2 for transmission. With AL-1, two DCIs are multiplexed in one subframe, otherwise each subframe carries only one DCI (i.e., AL-2), resulting in 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 NB-IoT 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. In comparison, LTE PDCCH schedules PDSCH in the same subframe. After receiving NPDSCH, the UE needs to send HARQ ACK/NACK using NPUSCH format 2. The resources of NPUSCH carrying HARQ ACK/NACK are also signaled in DCI. Considering the limited computing resources in an NB-IoT device, the time offset between the end of NPDSCH and the start of the associated HARQ ACK/NACK is at least 12 ms. This offset is longer than that between NPDCCH and NPDSCH because the size of the transport block carried in NPDSCH can be as large as 680 bits, which is much

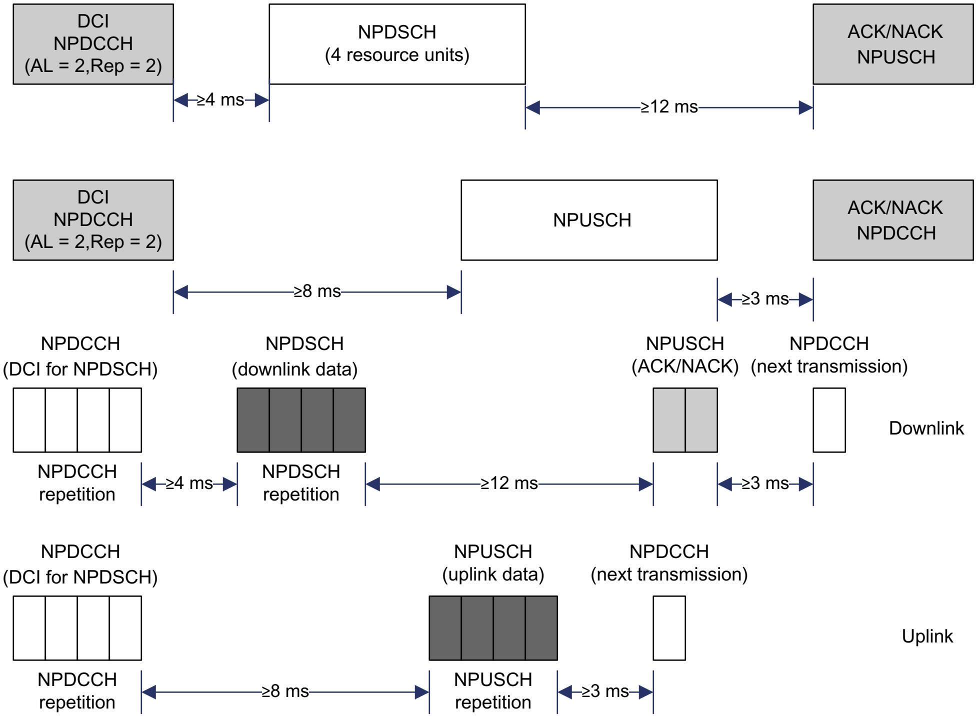


Figure 6.21
Illustration of the NB-IoT HARQ operation [14].

larger than DCI that is only 23 bits long. The DCI for uplink scheduling grant needs to specify which subcarriers are allocated for the UE. The time offset between the end of NPDCCH and the beginning of the associated NPUSCH is at least 8 ms. Upon completion of the transmission of NPUSCH, the UE monitors NPDCCH to check whether NPUSCH was received correctly by the base station, or a retransmission is required [4,14].

6.4.2 Physical, Logical, and Transport Channels

NB-IoT physical, transport, and logical channel structure are similar to LTE, with the exception that there is no physical uplink control channel in NB-IoT and the UCI content is carried in NPUSCH. In the downlink, NB-IoT provides the following physical signals and channels. Unlike LTE, these NB-IoT physical channels and signals are primarily multiplexed in time [6].

- NPSS
- NSSS
- NPBCH

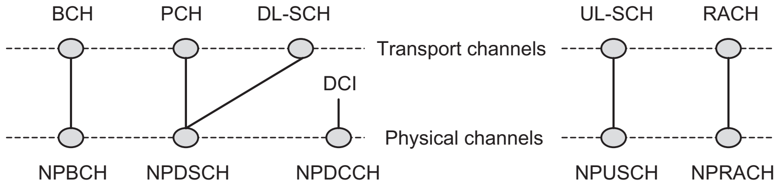


Figure 6.22
NB-IoT channel structure [6].

- NRS
- NPDCCH
- NPDSCH

The NB-IoT includes the following channels in the uplink:

- NPRACH
- NPUSCH

NPRACH is a newly designed channel since LTE PRACH uses a bandwidth of 1.08 MHz, which is more than NB-IoT uplink bandwidth (Fig. 6.22).

6.4.3 Cell Search and Random-Access Procedure

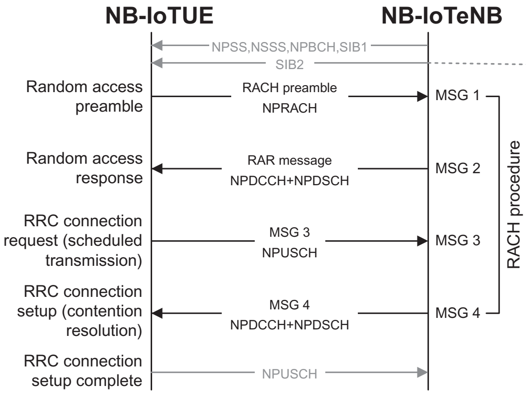
Synchronization is an important aspect in cellular network operation. When a UE is powered on, it needs to find and camp on a suitable cell. For this purpose, the UE must synchronize to downlink symbol, subframe, and frame timing, as well as to the carrier frequency. In order to synchronize with the carrier frequency, the UE needs to correct any frequency offset that is present due to local oscillator inaccuracy, and to perform symbol timing alignment with the frame structure from the base station. In addition, due to the presence of multiple cells, the UE needs to detect a particular cell on the basis of an NB-PCID. As a result, a typical synchronization procedure consists of determining the timing alignment, correcting the frequency offset, obtaining the correct cell identity, and the absolute subframe and frame number reference. The NB-IoT technology is intended to be used for low-cost UEs and at the same time, to provide extended coverage for UEs deployed in environments with high penetration loss. The low-cost UEs inevitably utilize less expensive crystal oscillators that can have carrier frequency offsets (CFOs) as large as 20 ppm. Deployment of NB-IoT in the in-band or guard-band mode introduces an additional raster offset as large as 2.5 or 7.5 kHz, resulting in even higher CFO values. Despite of the large frequency offset, an NB-IoT UE must be able to perform accurate synchronization at low SNR conditions.

Time–frequency synchronization in NB-IoT follows the same principles as in LTE; nevertheless, it incorporates improvements in the design of the synchronization sequences in order to mitigate large frequency offset and symbol timing estimation error issues in low SNR regions. As we mentioned earlier, time−frequency synchronization is achieved through NPSS and NSSS signals. The NPSS is used to obtain the symbol timing and correct the CFO, whereas the NSSS is used to obtain the NB-PCID, and the timing within 80 ms block. For UEs operating at low SNRs, an autocorrelation based on a single 10 ms received segment would not be sufficient for detection, thus for more accurate detection, the UE must coherently accumulate several sequences over multiple 10 ms segments. Due to large initial CFO value, the sampling time at the UE is different from the actual sampling time, the difference being proportional to the CFO. For UEs with limited coverage, more number of accumulations might be required to successfully achieve downlink synchronization.

Following the synchronization procedure, the UE proceeds to the acquisition of the MIB. The NPBCH consists of eight self-decodable subblocks, and each subblock is repeated eight times. The design is intended to provide successful acquisition for coverage-limited UEs. Subsequent to symbol timing detection and CFO compensation, in the in-band and guard-band deployments, there is still an additional raster offset, as high as 7.5 kHz, which needs to be compensated. 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.

During cell selection, the UE measures the received power and quality of the NRS. These values are then compared to cell-specific thresholds provided by the SIB1-NB. If the UE is in coverage of a cell, it will try to camp on it. Depending on the received NRS power, the UE may have to start a cell reselection. The UE compares this power to a reselection threshold, which may be different for the intra-frequency and the inter-frequency scenarios. All required parameters are received from the serving cell; thus there is no need to acquire system information from other cells. Among all cells fulfilling the cell-selection criteria, the UE ranks the cells with respect to the excess power over a threshold. A hysteresis is added in this process in order to prevent frequent cell reselection, and also a cell-specific offset may be applied for the intra-frequency scenarios. In contrast to LTE, there are no priorities for different frequencies. The UE selects the highest ranked cell which is deemed suitable.

In NB-IoT, random-access procedure serves multiple purposes such as initial access when establishing a radio link and scheduling request. Among others, the main objective of random access is to achieve uplink synchronization, which is important for maintaining uplink orthogonality in NB-IoT. As shown in Fig. 6.23, the contention-based random-access procedure in NB-IoT consists of four steps: (1) UE transmits a random-access preamble; (2) the network transmits a RAR message that contains the timing advance command and scheduling of uplink resources for the UE to use in the third step; (3) the UE transmits its identity



SIB2 parameters	
nprach-Periodicity	NPRACH resource periodicity
nprach-SubcarrierOffset	Frequency location of the first subcarrier allocated to NPRACH
nprach-NumSubcarriers	Number of subcarriers allocated to NPRACH
nprach-NumCBRA-StartSubcarriers	Number of starting sub-carriers allocated to contention based NPRACH random access
numRepetitionsPerPreambleAttempt	Number of NPRACH repetitions per attempt
nprach-StartTime	NPRACH starting time
nprach-SubcarrierMSG3-RangeStart	Fraction for calculating starting subcarrier index for the range of NPRACH subcarriers reserved for indication of UE support for multi-tone msg3 transmission

Figure 6.23

NB-IoT RACH procedure (these messages are repeated according to the UE coverage enhancement level) [6].

to the network using the scheduled resources; and (4) the network transmits a contention resolution message to resolve any contention due to multiple UEs transmitting the same random-access preamble in the first step. More specifically, upon transmission of the preamble, the UE first calculates its RA-RNTI from the transmission time. It then looks for a PDCCH with the DCI format N1 scrambled with the expected RA-RNTI, in which the RAR message is signaled. The UE expects this message within the response window, which starts three subframes after the last preamble subframe and has a coverage enhancement dependent length given in SIB2-NB. If the preamble transmission was not successful, that is, the associated RAR message was not received, the UE transmits another RACH preamble. This process is repeated up to a maximum number, which depends on the coverage enhancement level. For the case that this maximum number is reached without success, the UE proceeds to the next coverage enhancement level, if this level is configured. If the total number of access attempts is reached, an associated failure is reported to the RRC sublayer. With the RAR message, the UE receives a temporary C-RNTI and the timing advance command. Consequently, the forthcoming msg3 is already time aligned, which is necessary for transmission over the NPUSCH. Further, the RAR message provides the uplink grant for msg3, containing all relevant data for msg3 transmission. The remaining procedure is performed similar to LTE; that is, the UE sends an identification and upon reception of the contention resolution message, indicating successful completion of the random-access procedure.

The network can configure up to three NPRACH resource configurations in a cell in order to serve UEs in different coverage scenarios (based on the measured path loss). In each configuration, a repetition value is specified to increase the reliability of random-access preamble transmission. The UE measures the downlink received signal strength to estimate its coverage level, and transmits a random-access preamble in the NPRACH resources configured for that coverage level. To facilitate NB-IoT deployment in different scenarios, NB-IoT allows flexible configuration of NPRACH resources in time−frequency resource grid with the following parameters: (1) periodicity of NPRACH resource and starting time of NPRACH resource; (2) subcarrier offset (location in frequency) and number of subcarriers (see Fig. 6.23). The UE should indicate its support of single-tone/multi-tone transmission in the first step of random-access procedure in order to facilitate the network's scheduling of uplink transmission in the third step. The network can partition the NPRACH subcarriers in the frequency domain into two non-overlapping sets. A UE can select one of the two sets to transmit its random-access preamble to signal its supports for multi-tone transmission in the third step of random-access procedure.

As we mentioned earlier, a set of PRACH resources (e.g., time, frequency, and preamble sequences) is provided for each coverage level. The PRACH resources per coverage level are configurable by the system information. The UE selects PRACH resources based on the coverage level estimated using downlink signal measurements, for example, RSRP [5]. The UE MAC will reattempt the process at a higher coverage level RACH preamble set, if it does not receive the RAR message after the anticipated number of attempts at a certain level. If the contention resolution is not successful, the UE will continue to use the same coverage level RACH preamble set [2,21].

6.4.4 Power-Saving Modes

Power-save mode (PSM) is a power conserving mechanism in NB-IoT that allows the devices to skip the periodic paging channel monitoring cycles between active data transmissions, letting the device enter a sleep state. However, the device becomes unreachable when PSM is active; therefore, it is best utilized by device-originated or scheduled applications, where the device initiates communication with the network. Assuming there is no device-terminated data, an NB-IoT device can remain in PSM state for a long time, with the upper limit determined by the maximum value of the tracking area update (TAU) timer. During the PSM active state, the access stratum at the device is turned off, and the device would not monitor paging messages or perform any radio resource management measurements. In addition, the PSM enables more efficient low-power mode entry/exit, as the device remains registered with the network and its NAS state is maintained during the PSM without the need to spend additional cycles to setup registration/connection after each PSM exit event. Examples of applications that can take advantage of PSM include smart meters, sensors, and any IoT devices that periodically send data to the network. When a device initiates PSM with the network, it provides two preferred internal timers (T3324 and T3412), where the PSM time is the difference between these timers. The network may accept these values or set different ones. The network then retains state information and the device remains registered with the network. If a device wakes up and sends data before the expiration of the time interval it

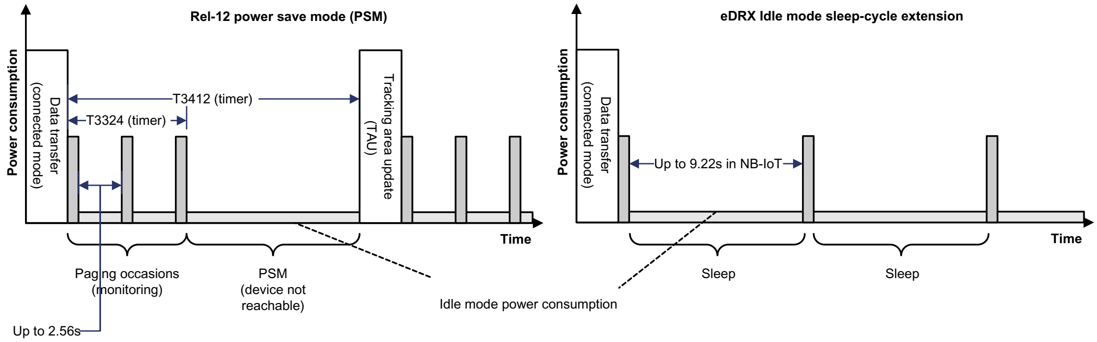


Figure 6.24
Illustration of PSM and eDRX operation [21,24].

agreed with the network, a reattach procedure is not required. However, in a similar manner to a radio module that has been powered off, a radio module in PSM cannot be contacted by the network while it is in sleep mode [7,8,21].

One problem with PSM mechanism is the ability to support device-terminated traffic, as the UE is unreachable when it is in PSM state. The device would become reachable by the network as the TAU timer expires (Fig. 6.24), which can introduce significant latency for device-terminated traffic. While periodic TAU can be configured to occur more frequently to match the UE's delay requirement, such configurations would result in additional signaling overhead from unnecessary periodic TAU procedures and increased device power consumption. To address this shortcoming of PSM, the extended DRX (eDRX) was introduced in 3GPP Rel-13. The eDRX is an extension of LTE DRX feature which can be used with NB-IoT devices to reduce power consumption. The eDRX can be used without PSM or in conjunction with it to obtain additional power savings. It allows the time interval during which a device is not listening to the network to be greatly extended. For an NB-IoT application, it might be acceptable not to be reachable for a few seconds or longer. Although it does not provide the same level of power saving as PSM, for some applications, the eDRX may provide a good compromise between device reachability and power consumption reduction. Fig. 6.24 illustrates the concept and the operation of PSM and eDRX mechanisms. In eDRX, the DRX cycle is extended up to and beyond 10.24 seconds in idle mode, with a maximum value of 2621.44 seconds. For NB-IoT, the maximum value of the DRX cycle is 10,485.76 seconds [7,21].

6.4.5 Paging and Mobility

Paging is used to notify an idle-mode UE of a pending downlink traffic, to establish an RRC connection and to indicate a change in system information. A paging message is sent over the NPDSCH and may contain a list of UEs being paged and the information on whether paging is for connection setup or system information has changed. Each UE which finds its identifier in this list would notify the upper layers in order to initialize the RRC connection setup. If the paging message indicates a change in system information, then the UE acquires SIB1-NB to find out which SIBs have been updated. The UE in the RRC_IDLE state only monitors some of the subframes with respect to paging, the paging occasions (POs) within a subset of radio frames and the paging frames (PFs), as shown in Fig. 6.25. If coverage enhancement repetitions are applied, the PO refers to the first transmission within the repetitions. The PFs and POs are determined from the DRX cycle provided in SIB2-NB, and the international mobile subscriber identity (IMSI) provided by the universal subscriber identity module (USIM) card. The DRX is the discontinuous reception of downlink control channel that is used to save the UE battery life. DRX cycles of 128, 256, 512, and 1024 radio frames are supported, corresponding to a time interval between 1.28 and 10.24 seconds. Since the algorithm for determining the PFs and POs also depends on the IMSI, different UEs have different POs, which are uniformly distributed across time. It is sufficient for the UE to monitor one PO within a DRX cycle, if there are several POs therein, the paging is repeated in every one of them. As we stated earlier, the concept of extended DRX may be applied for NB-IoT, as well. If eDRX is supported, then the time interval in which the UE does not monitor the paging messages may be considerably extended up to almost 3 hours. Correspondingly, the UE must know on which HFN and on which time interval within this HFN, that is, the paging transmission window (PTW), it has to monitor the paging. The PTW is defined by a start and stop SFN. Within a PTW, the determination of the PFs and POs is done in the same way as for the non-eDRX.

The NB-IoT supports stationary and low-mobility UEs as most of the NB-IoT nodes are sensors and devices that hardly move. Handover is not supported in NB-IoT, thus when an

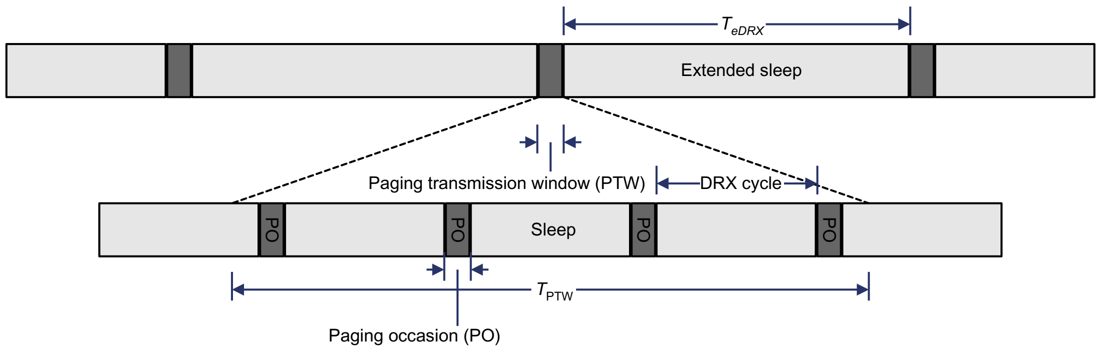


Figure 6.25
Illustration of the correspondence of PO and PTW.

NB-IoT UE moves out of the coverage area of the serving cell, it will experience a radio link failure (RLF). As we mentioned earlier, an NB-IoT UE may support data transport via control plane. The UE may also support data transfer via the user plane, and when it does, the RRC connection reestablishment procedure is supported, which means that after an RLF is detected, the UE attempts to find a suitable cell through cell selection. If the UE finds a suitable cell, it will try to reestablish the connection on that cell and resume the data transfer. The RRC reestablishment intends to hide the temporary loss of the radio interface to the upper layers. The RRC reestablishment for a UE only supporting data transfer via the control plane was added in 3GPP Rel-14 [6,8].

6.5 Implementation and Deployment Considerations

The NB-IoT specifications meet a number of challenging requirements including a greater coverage area, longer device battery life, and lower device cost resulting from the small and intermittent data transmissions. The reduced peak data rate requirements make it possible to employ a simple radio and baseband processing in the receiver chain. With half-duplex operation of the NB-IoT, the duplex filter in a typical LTE device can be replaced by a simple switch in addition to fewer oscillators for frequency synthesis. The use of simplified downlink convolutional coding instead of the LTE turbo code would allow a low-complexity baseband decoding process. The main candidate architectures are the zero-IF and low-IF receivers, which combine analog frontends and digital baseband signal processing on a single chip. However, each of these architectures has some structural issues that must be resolved. In the zero-IF receiver, the desired signal is degraded by time variant DC offset caused by local oscillator leakage and self-mixing. In the low-IF receiver, nonideal hardware results in amplitude and phase mismatches between the I and Q signal paths, which results in degradation of the desired signal with leakage from the interference signal. In the generic low-IF receiver architecture, the incoming RF signal in the antenna is filtered by the band selection filter and amplified by a low-noise amplifier. The quadrature demodulator down-converts the RF signal to the complex low-IF signal, which is represented by in-phase and quadrature components. The IF signals pass through low-pass filters and then sampled by the analog to digital converters (ADCs). After the ADC sampling and conversion, the digitized IF signal is down-converted to the baseband, yielding digital complex signals. Using a moderately low-IF frequency, this architecture can avoid DC offset and $1/f$ noise issues that frequently arise from zero-IF receivers. However, it also reintroduces image issues. Image cancellation can be achieved after the low-noise amplifier, but requires narrowband filtering, thus significantly increasing the complexity and cost of the device. The latter issue can be addressed by complex mixing and subsequently and filtering techniques in the low-IF receiver.

In order to meet the stringent link budget requirements of NB-IoT, low-cost low-complexity single-chip devices have been developed by various vendors [20]. The integration of the power amplifier (PA) and antenna switch simplifies routing by reducing the number of RF components in the frontend. The PA design with a low PAPR is possible with the use of the single-tone transmission technique. This enables the implementation of an RF chip that includes an efficient on-chip PA that may be operated near its saturation point for maximum output power. While there is a trade-off between an integrated on-chip PA and an external PA, one can analyze the effect of PA nonlinearity on error vector magnitude (EVM), and thus on the NB-IoT uplink coverage, using an RF and baseband cross-domain simulation technique. In that case, the baseband LTE signal is generated, which supports both single-tone and multi-tone transmission. The baseband signal is filtered by two digital filters and fed into the modulator to generate a spectrum centered at the carrier frequency. The signal is then amplified using an amplifier with certain characteristics. The linearity of the PA can be modeled by setting the 1 dB compression point to an appropriate value. After the signal is amplified by the PA, it is demodulated by the receiver to determine the EVM. For single-tone transmission, the EVM values are very small, less than 0.08% for a 3.75 kHz subcarrier spacing and less than 0.9% for 15 kHz subcarrier spacing [16,17]. Therefore, we can conclude that the nonlinearity of PA has slight effect on the EVM for single-tone transmission mode. The studies suggest that PAPR is 4.8, 5.7, and 5.6 dB for a signal with 3, 6, and 12 tones, respectively; thus we can conclude that the nonlinearity of PA has unfavorable effects on EVM for multi-tone transmissions. From this study one can conclude that, in case of single-tone transmission, some of the PAPR reduction circuit inside the chip can be removed which significantly reduces chip design complexity. Considering the key aspects of NB-IoT applications, devices that only support single-tone transmission combined with an on-chip nonlinear PA are much more advantageous in ultra-low-power and low-cost applications.

The NPUSCH provides two subcarrier spacing options: 15 and 3.75 kHz. The additional option of using 3.75 kHz provides deeper coverage to reach challenging locations such as inside buildings, where there is limited signal strength. The data subcarriers are modulated using BPSK and QPSK with a phase rotation of $\pi/2$ and $\pi/4$, respectively. Selection of the number of subcarriers for a resource unit can be 1, 3, 6, or 12 to support both single-tone and multitone transmission. The narrowband downlink physical resource block has 12 subcarriers with 15 kHz spacing, providing180 kHz transmission bandwidth (see Fig. 6.26). It only supports a QPSK modulation scheme. To facilitate low-complexity decoding for downlink transmission in devices, the turbo coding was traded off with TBCC .

NB-IoT achieves an MCL 20 dB higher than LTE. Coverage extension is achieved by increasing the reliability of data transmission through increasing the number of repetitions.

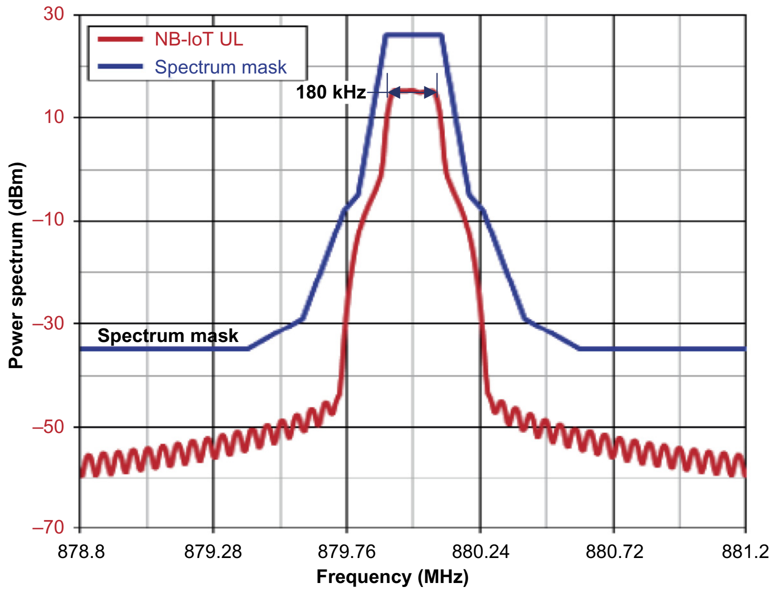


Figure 6.26
Example of NB-IoT NPUSCH transmission spectrum with 15 kHz subcarrier spacing [16,17].

Coverage enhancement is ensured also by introducing single-tone NPUSCH transmission and $\pi/2-$BPSK modulation to maintain close to 0 dB PAPR, thereby reducing the unrealized coverage potential due to PA backoff. The single-tone NPUSCH transmission with 15 kHz subcarrier spacing provides a layer-1 data rate of approximately 20 bps when configured with the highest repetition factor, that is, 128, and the lowest modulation and coding scheme. The NPDSCH can provide a layer-1 data rate of 35 bps when configured with repetition factor 512 and the lowest modulation and coding scheme. These configurations support close to 170 dB coupling loss. In comparison, the LTE network is designed for approximately 142 dB coupling loss.

Fig. 6.27 shows an example of NPUSCH format 1 and 2 signal processing stages in order to achieve 144, 154, and 164 dB MCL in the uplink. The information bits can be mapped to NPUSCH format 1 based on LTE uplink SC-FDMA waveform. Furthermore, it depicts the processing stages for achieving 164 dB MCL based on NPUSCH format 2. In the latter case, following the use of $\pi/2-$BPSK modulation, there are 3840 symbols which are repeated six times, appended with cyclic prefix and guard time to occupy one slot, requiring 3840 slots in total. For every six slots with data symbols, one slot of DMRS is added. As a result, 640 DMRS slots are added. Overall, it requires 4480 slots, that is, 2240 subframes [23].

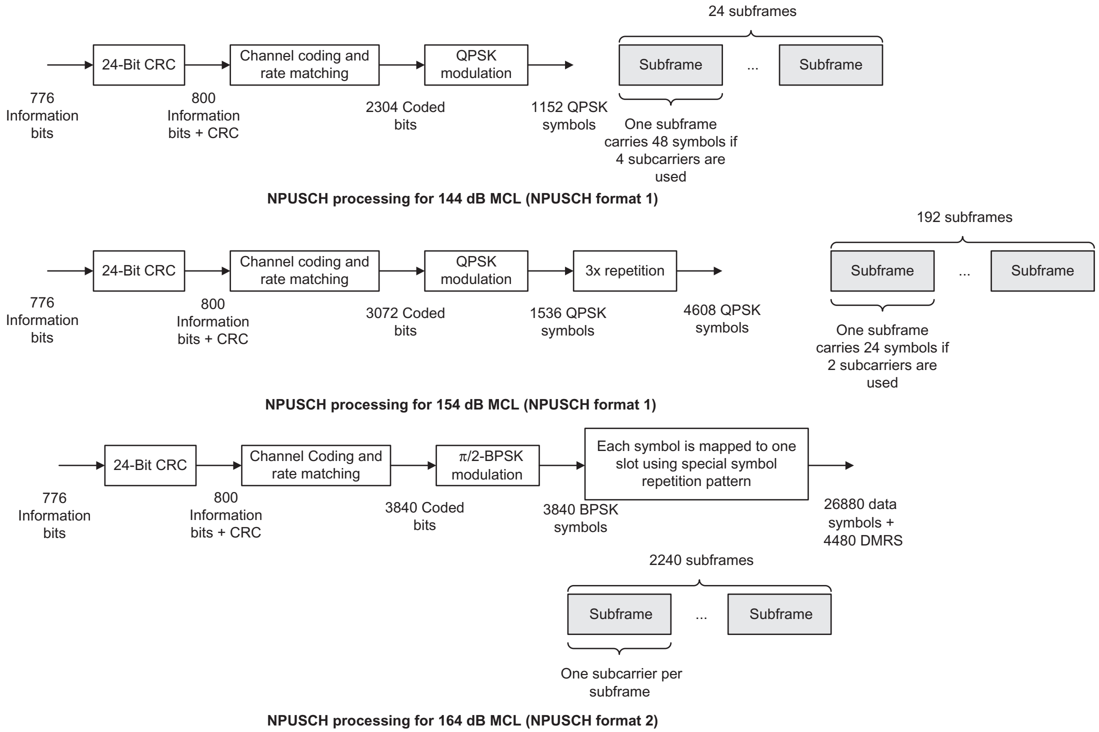


Figure 6.27
Example NB-IoT uplink processing to achieve various MCL values [23].

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