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An introduction to cellular IoT: Signal processing aspects of NB-IoT

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NEON
Network of Competence on Internet of Things
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Outline…

NB-IoT layers

- NB-IoT layer functions: PDCP, RLC, MAC
- Congestion control : ACB and EAB
- Power efficiency: PSM, I-DRX, C-DX

NB-IoT Idle and Connected Mode Procedures

- Idle Mode
- Connected Mode

NB-IoT DL synchronization methods

- System model
- Cell search
- Timing and frequency acquisition

NB-IoT UL synchronization

- NPRACH preamble design
- NPRACH estimation methods 1 and 2

NB-IoT in ISM bands

- Characteristics - Alternatives for NB-IoT

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Physical layer:
UE Idle and connected modes

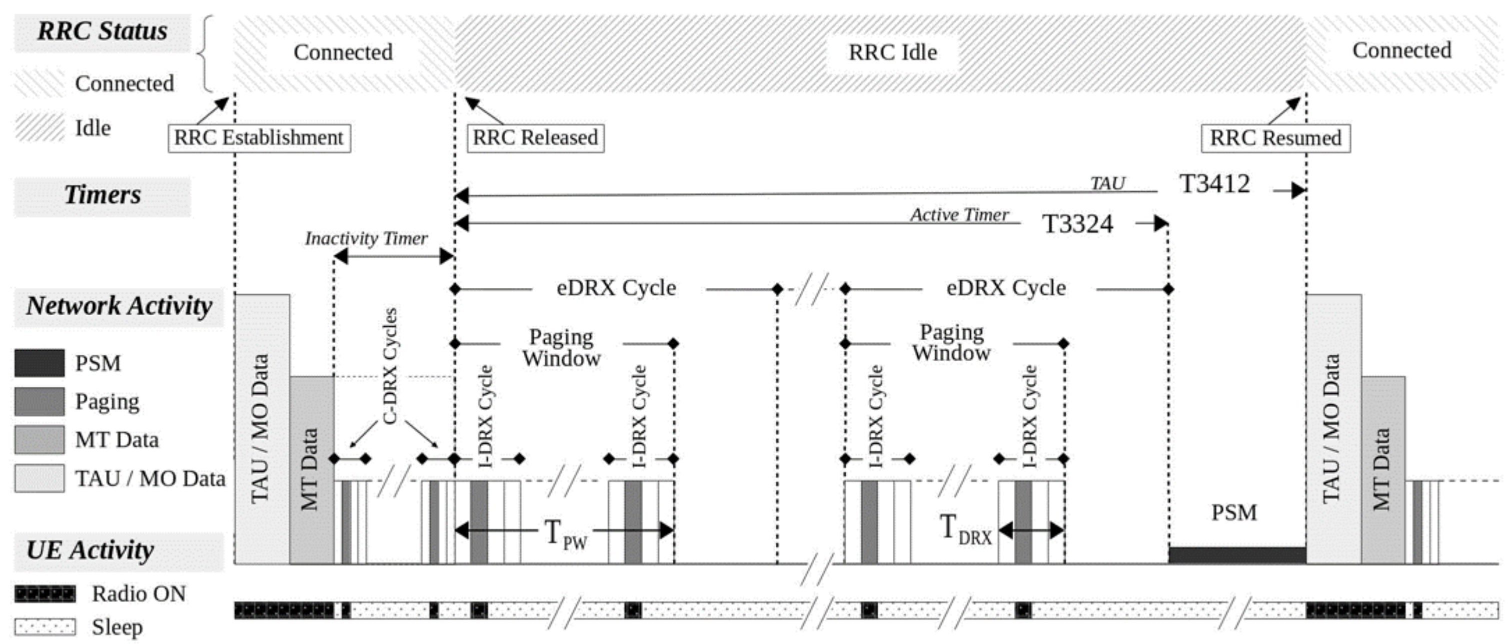

Fig. 2. Summary diagram of UE's behavior in NB-IoT. From top to bottom: (top) state of the RRC connection, (middle) timing involved and (bottom) radio interactivity between the UE and the network, with the associated power consumption depicted schematically.

TAU/MO: tracking area update – mobile originated data (transmitted)
MT: mobile terminated data (received)
DRX: discontinuous receiver mode (idle or connected)
T_PW: timer paging window
T_DRX: timer idle-DRX cycle

Physical layer:
Idle mode procedures

Cell selection

- Time and frequency synchronization
- Physical Cell Identification and Initial Frame Synchronization
- Master Information Block (MIB) Acquisition
- Cell Identity and System Frame Number (SFN) Acquisition

System information acquisition

- System Information Block 1 (SIB1)
- Information Specific to In-Band Mode of Operation
- System Information Blocks 2, 3, 4, 5, 14, 16
- System Information Update

Paging and enhanced discontinuous receive (eDRX) mode
Power Saving Mode (PSM)
Random access procedure
Access control

Physical layer: Idle mode procedures… Cell selection

Objective: is to identify, synchronize to, and determine the suitability of an NB-IoT cell.

Carried out by UE before it possesses any knowledge of the network and before any prior synchronization to the network has taken place.

Selection needed with large CFO because oscillator inaccuracy of the device. Oscillator inaccuracy for a low-cost device module may be as high as 20 ppm. For a 900 MHz band, CFO may be 18 kHz (900E6 x 20E-6).

Also, searching for a cell on the 100 kHz raster grid, there is a raster offset of 2.5 or 7.5 kHz for the in-band and guard-band deployments.

Thus, the magnitude of total initial frequency offset for in-band and guard-band deployments can be as high as 25.5 kHz.

Physical layer: Idle mode procedures… Cell selection

The general steps in the NB-IoT cell selection procedure are as follows:

1. Search for the NPSS to identify the presence of an NB-IoT cell.
2. Synchronize in time and frequency to the NPSS to identify the carrier frequency and the subframe structure within a frame.
3. Identify the PCID (physical cell ID) and the three LSBs of the SFN by using the NSSS.
4. Acquire the MIB to identify the complete SFN as well as the two LSBs of H-SFN, and resolve the frequency raster offset.
5. Acquire the SIB1-NB to identify the complete H-SFN, the PLMN, tracking area, and cell identity and to prepare for verification of the cell suitability.

Physical layer: Idle mode procedures…
Cell selection - Time and frequency synchronization

For low-end IoT devices, it is easier to achieve NPSS time synchronization first, in the presence of CFO, and once achieved, the device can use additional occurrences of NPSS for CFO estimation.

NPSS is transmitted in subframe 5 in every frame, and by time synchronizing to NPSS the device detects subframe 5 and consequently all the subframe numbering within a frame.

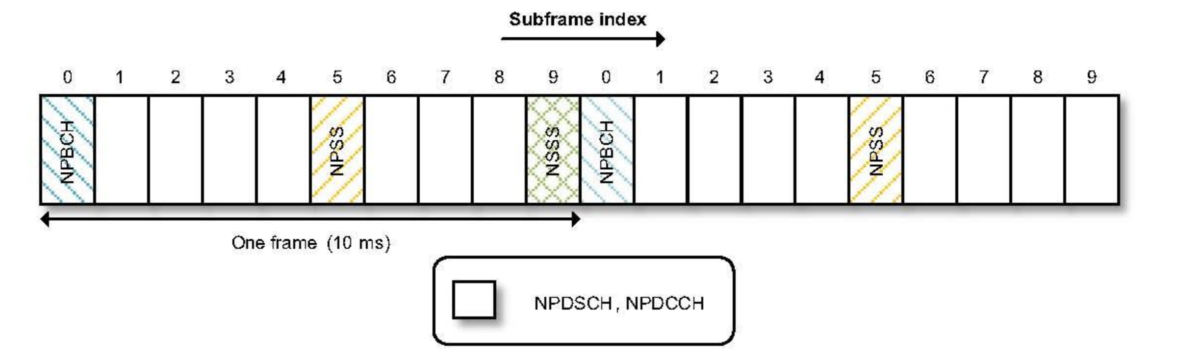

FIGURE 7.11
Time-multiplexing of downlink physical channels on an NB-IoT anchor carrier.

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Physical layer: Idle mode procedures…
Cell selection - Time and frequency synchronization

For in-band and guard-band deployments, there is an offset referred to the frequency separation of 100 kHz raster grid (basis of device searching for an NB-IoT carrier, and the actual center frequency of an NB-IoT anchor carrier).
The frequency raster offset is unknown to the device before the initial cell selection.

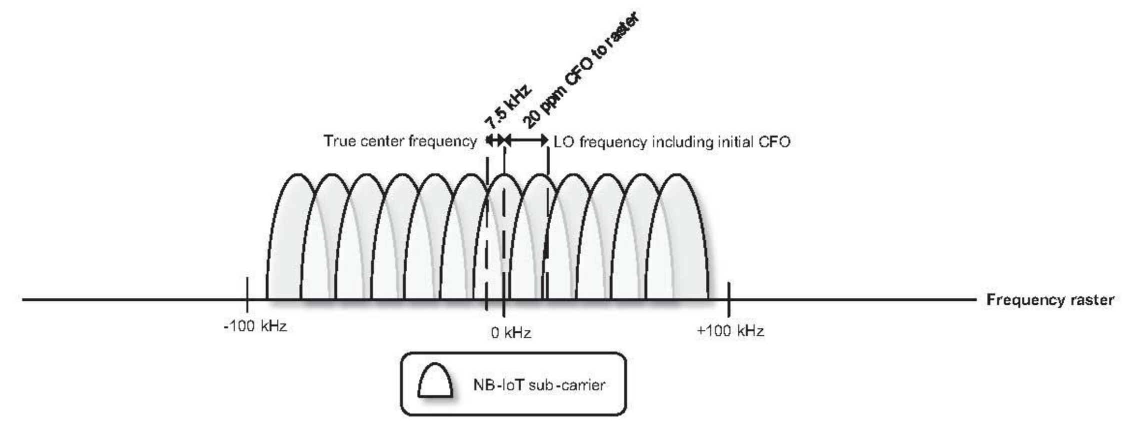

FIGURE 7.35
Illustration of over-CFO estimation due to the raster offset in the in-band and guard-band deployments.

This may result in a needed correction of the local oscillator exceeding the oscillator induced CFO (2.5 or 7.5 kHz).

Physical layer: Idle mode procedures…
Cell Identification and Initial Frame Synchronization

The NSSS transmissions are mapped to subframe 9 in even-numbered radio frames. After NPSS synchronization, the device knows where subframe 9 is, but does not know whether a frame is even- or odd-numbered.

NSSS waveforms depend on the PCID (mapped in 8 frames). A straightforward NSSS detection algorithm is therefore to form 504 x 8 = 4032 hypotheses, where 504 is the number of PCIDs used in a NB-IoT network.

Correlating the received signal with the NSSS based on each of these hypotheses allows the device to detect the PCID and the 80 ms framing structure.

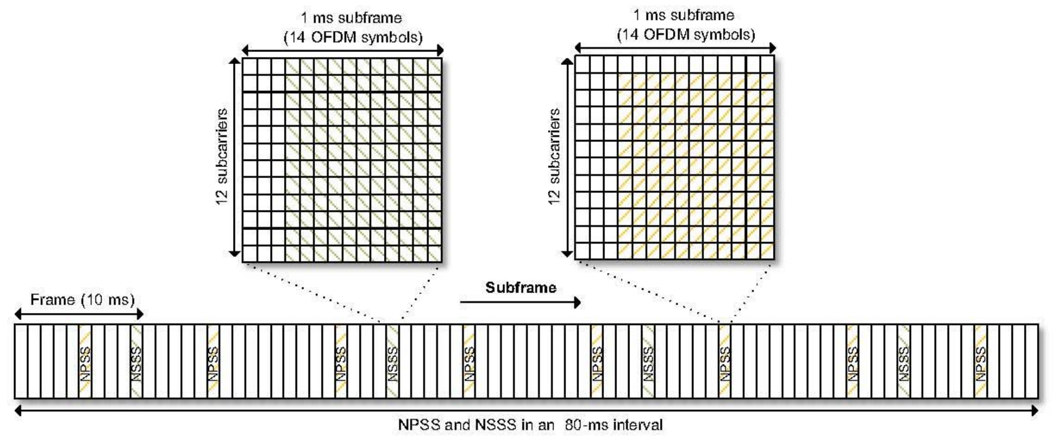

FIGURE 7.13

NPSS and NSSS transmissions within an 80-ms repetition interval.

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Physical layer: Idle mode procedures…
Master Information Block (MIB) acquisition

With PCID, the device knows NRS placement within a resource block. It can thus demodulate and decode NPBCH, which carries the NB-IoT MIB.

A MIB is encoded to an NPBCH code block, consisting of 8 CSBs. A CSB is repeated in 8 consecutive NPBCH subframes. Thus, by knowing the 80 ms frame block structure, the device knows which NPBCH subframes carry identical CSB.

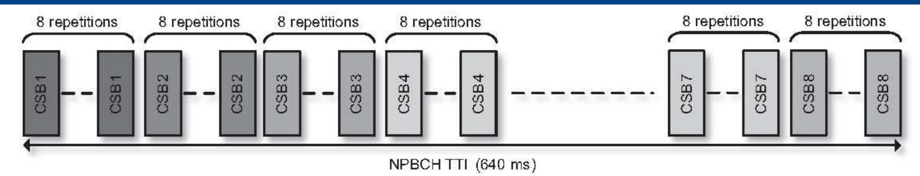

FIGURE 7.18

Transmission of NPBCH CSBs.

CSB: code sub-block

However, the device does not know which CSB is transmitted in a specific 80 ms interval. Therefore, the device needs to form 8 hypotheses to decode a MIB during the cell selection process.
When the device can successfully decode NPBCH, it acquires the 640 ms NPBCH TTI boundaries.

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Physical layer: Idle mode procedures… MIB acquisition…

From MIB the device also acquires the following information:

- Operation mode (stand-alone, in-band, guard-band).
- In case of in-band and guard-band, the frequency raster offset (2.5, 7.5 kHz).
- Information about SIB1 scheduling.
- System information SI value tag. It is common for all SIBs, except for SIB14 and SIB16.
- Access barring (AB) information which indicates whether AB is enabled, and in that case, the device shall acquire SIB14 before initiating RRC connection establishment or resume.

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Physical layer: Idle mode procedures …
Cell Identity and H-SFN Acquisition

From a cell selection perspective, the SIB1 carries the 8 MSBs of the H-SFN, the PLMN, tracking area, and a 28-bit long cell ID.

With SIB1, the device is able to evaluate the suitability of the cell against a pair of minimum required signal strength and signal quality threshold parameters (RSRP and RSRQ).

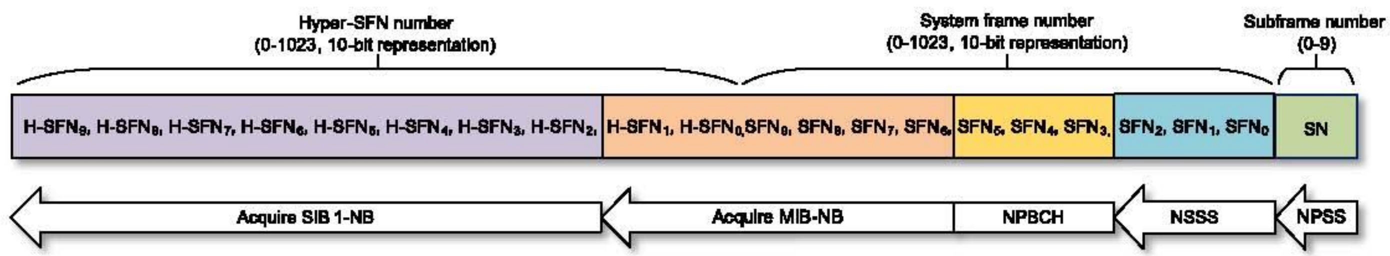

FIGURE 7.36

Illustration of how the device acquires complete timing information during the initial cell selection.

After completing the initial cell selection, the device is expected to have a time-accuracy within a few microseconds and a residual frequency offset within 50 Hz.

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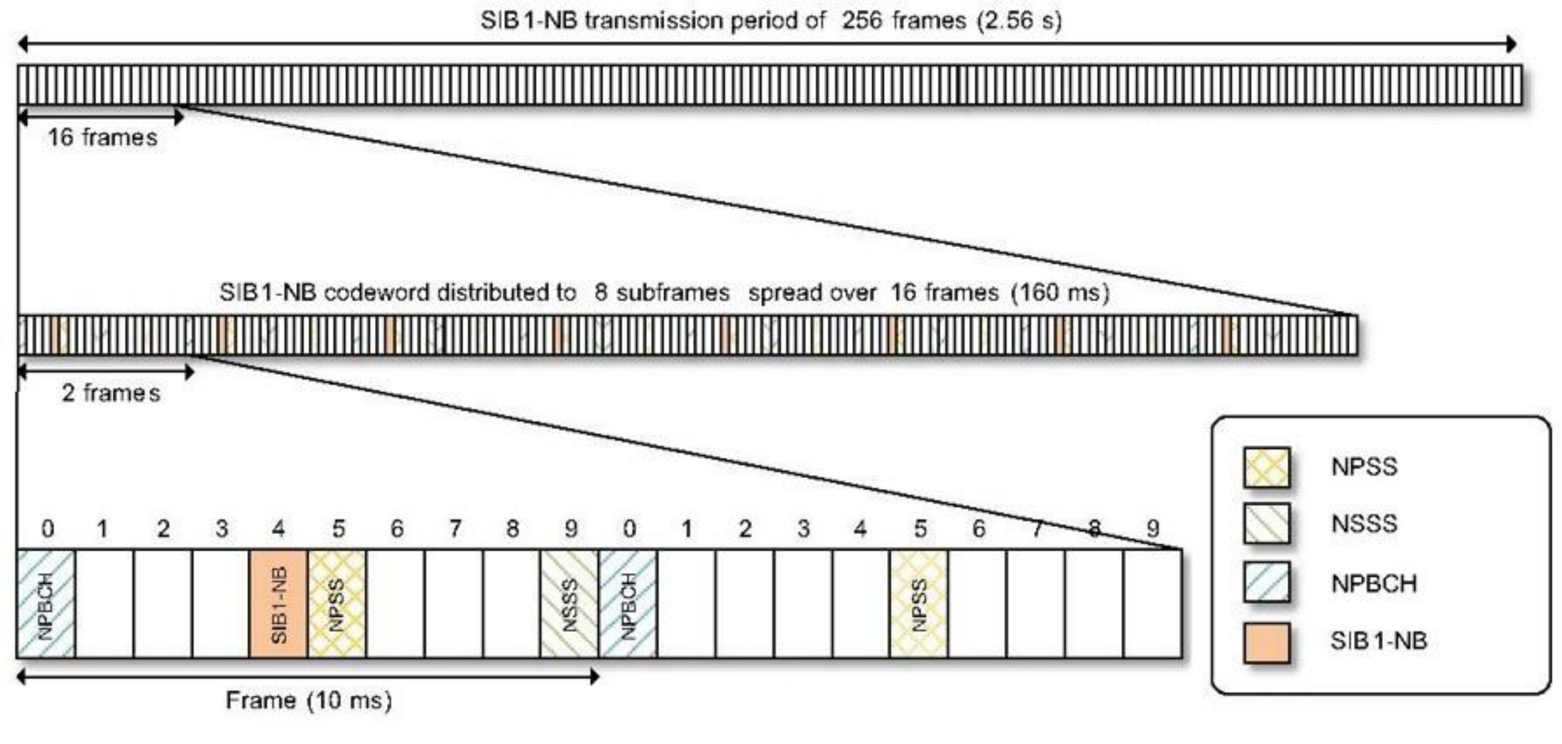
Physical layer: Idle mode procedures…
System Information Acquisition

Hyperframe information, network information such as PLMN, tracking area and cell ID, access barring status, thresholds for evaluating cell suitability, valid subframe bitmap and scheduling information regarding other SIB.



Physical layer: Idle mode procedures…
System Information Acquisition…

Table 7.17 System Information Blocks 2, 3, 4, 5, 14, 16

System Information Block	Content
SIB2-NB	Radio resource configuration (RRC) information for all physical channels that is common for all devices.
SIB3-NB	Cell reselection information that is common for intrafrequency and interfrequency cell reselection. It further provides additional information specific to intrafrequency cell reselection such as cell suitability related information.
SIB4-NB	Neighboring cell-related information, e.g., cell identities, relevant only for intrafrequency cell reselection.
SIB5-NB	Neighboring cell-related information, e.g., cell identities and cell suitability-related information, relevant only for interfrequency cell reselection.
SIB14-NB	Access class barring information per PLMN. Contains a specific flag for barring of a specific access class, It also indicates barring of exception reporting.
SIB16-NB	Information related to GPS time and Coordinated Universal Time (UTC).

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Physical layer: Idle mode procedures… Paging and eDRX

The monitoring of paging during the idle mode has implications on device battery lifetime and the latency of DL data delivery to the device.

A key to determining the impact is how often a device monitors paging. NB-IoT does just as LTE, uses **search spaces** for defining paging transmission opportunities.

The search space concept includes the Type-1 Common Search Space (CSS) implementation used for paging indication.

A device monitors a set of subframes defined by the Type-1 CSS to detect an NPDCCH containing a DCI of format N2 that schedules a subsequent NPDSCH containing a paging message addressed to the device.

The P-RNTI (Paging-Radio Network Temporary Identifier) is the identifier used to address a device for the purpose of paging.

Physical layer: Idle mode procedures…
Paging and eDRX…

Type-1 CSS starting subframe is determined from paging opportunity (PO) subframe, which is determined based on configured DRX cycle.

If the starting subframe is not a valid DL subframe, then the first valid DL subframe after the PO is the starting subframe of the NPDCCH repetitions.

A search space contains NPDCCH candidates defined for repetition levels R up to a configured maximum NPDCCH repetition level Rmax.

Rmax is typically configured to secure that all devices in a cell can be reached by the paging mechanism.

Table 7.18 NPDCCH Type-1 common search space candidates

R_{max}	R
1	1
2	1, 2
4	1, 2, 4
8	1, 2, 4, 8
16	1, 2, 4, 8, 16
32	1, 2, 4, 8, 16, 32
64	1, 2, 4, 8, 16, 32, 64
128	1, 2, 4, 8, 16, 32, 64, 128
256	1, 4, 8, 16, 32, 64, 128, 256
512	1, 4, 16, 32, 64, 128, 256, 512
1024	1, 8, 32, 64, 128, 256, 512, 1024
2048	1, 8, 64, 128, 256, 512, 1024, 2048

Physical layer: Idle mode procedures… Paging and eDRX…

Example of possible paging configurations in NB-IoT:

- Either DRX or eDRX can be used.
- For DRX the paging occasions occur with a periodicity of at most 10.24 s.
- For eDRX, the longest period is 2 h, 54 min, and 46 s, i.e. one hyperframe cycle.

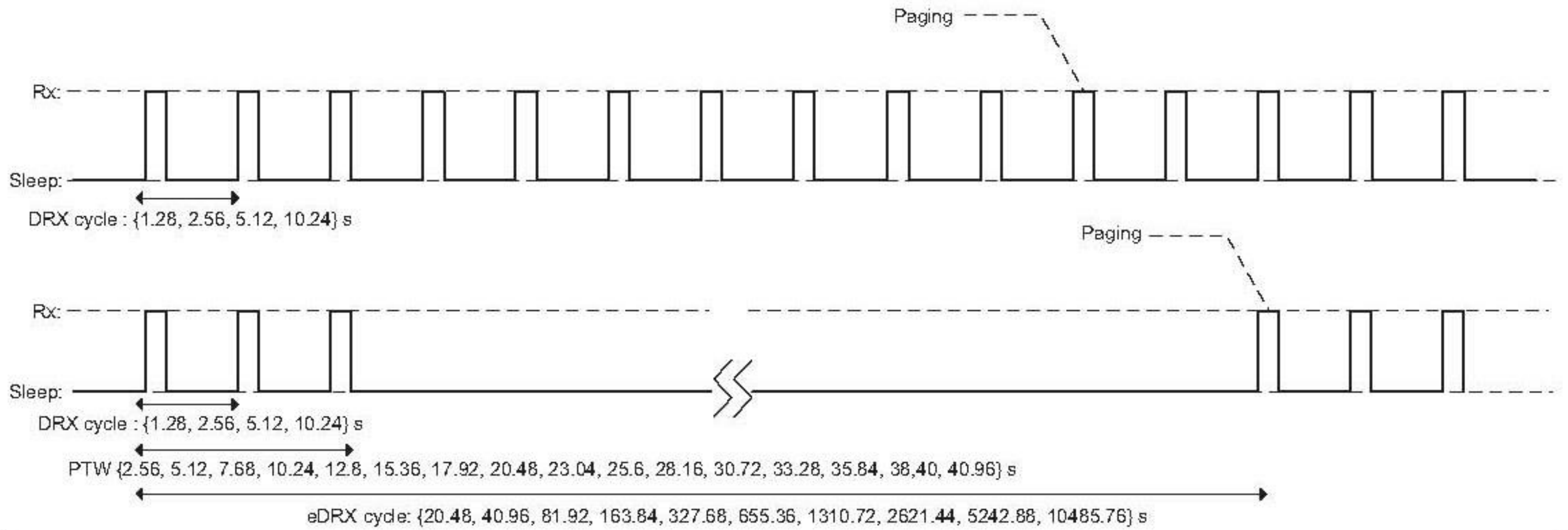

Illustration of possible Discontinuous Reception (DRX) and extended DRX (eDRX) paging configuration

PTW: paging time window

Physical layer: Idle mode procedures…
Power saving mode (PSM)

Some applications have very relaxed requirements on mobile terminated reachability (e.g. longer than a day) and then power consumption can be further reduced compared with using eDRX (close to 3 h).

After monitoring paging, the device can enter the PSM, during which it uses the smallest possible amount of energy, essentially only needing to leave its Real Time Clock running for keeping track of time and scheduled events.

The device aborts all idle mode operations in PSM and will not transmit or monitor paging during PSM and need not keep an up-to-date synchronization to the network.

The duration of PSM is configurable (even > a year).

Physical layer: Idle mode procedures…
Power saving mode (PSM)

The device exits the PSM once it has UL data to transmit or is mandated to send a tracking area update (TAU or RAU: Routing Area Update).

After its UL transmission, the device may enter DRX mode for a short period of time, configured by the active timer, for monitoring paging to enable mobile terminated reachability.

After such a short duration in which the device monitors paging, the device enters the next PSM period.

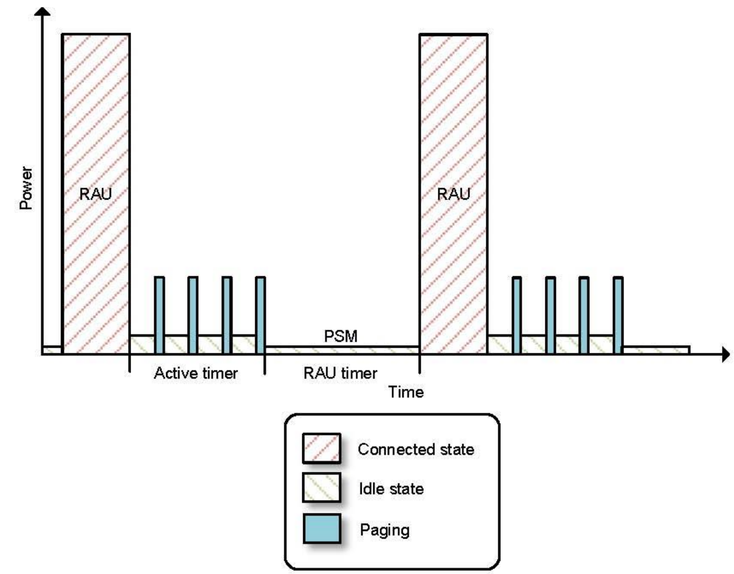

FIGURE 2.3

Illustration of operation in PSM including periodic RAUs.

Physical layer: Idle mode procedures…
Random access procedure

After synchronizing to the network and confirming that access is not barred, the device sends a random access preamble using NPRACH.

The device needs to determine an appropriate NPRACH configuration according to its coverage class estimation. SIB2 carries RRC information. One of the RRC information elements is the NPRACH configuration.

The cell can configure up to two RSRP thresholds that are used by the device to select the NPRACH configuration appropriate for its coverage class.

Physical layer: Idle mode procedures…
Random access procedure…

Example: two reference signal received power (RSRP) thresholds are configured and therefore there are three NPRACH configurations for three CE levels, respectively.

The network uses these RSRP thresholds to configure the MCLs (Maximum Coupling Loss) of the different CE levels.

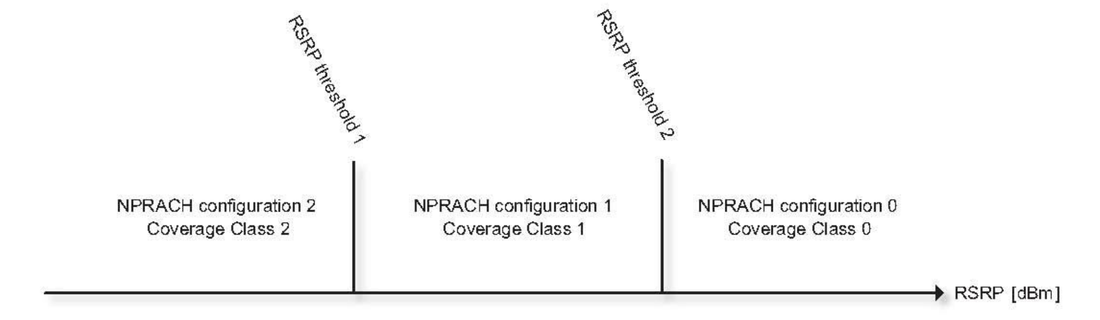

FIGURE 7.42

NPRACH configurations and RSRP thresholds.

If the network does not configure any RSRP threshold, the cell supports only a single NPRACH configuration used by all devices regardless of their actual path loss to the serving base station.

Physical layer: Idle mode procedures…
Random access procedure…

The SIB2 NPRACH configuration information for each CE level includes the time – frequency resource allocation.

The resource allocation in the frequency domain is a set of starting preambles. Each starting preamble is equivalent to the first NPRACH symbol group and associated with a specific 3.75 kHz tone. The set of starting preambles is determined by a subcarrier offset and a number of spanned subcarriers.

The time-domain allocation is defined by a periodicity, a starting time with the period, and the number of repetitions associated with the NPRACH resource.

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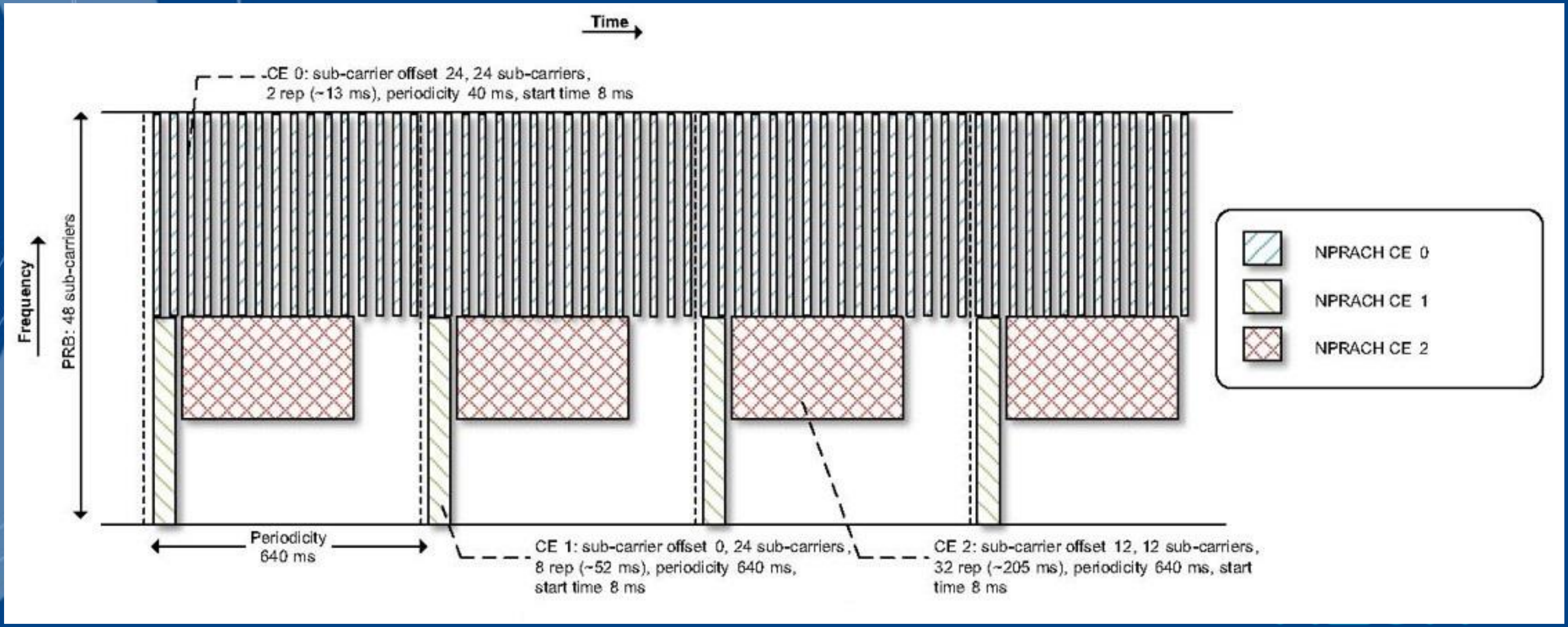
Physical layer: Idle mode procedures…
Random access procedure…

Example: An NPRACH configuration intended to support a high access load.

This set of starting preambles may further be partitioned into two subsets: the first subset is used by devices that do not support multitone NPUSCH transmissions, whereas the second subset is used by devices with multitone capability.



Physical layer: Idle mode procedures… Random access procedure…

If the base station detects an NPRACH preamble, it sends back a random access response (RAR) Message 2.

The RAR further contains scheduling information pointing to the radio resources that the device can use to transmit a request to connect, Message 3.

At this point, eNodeB knows the device multitone transmission capability, and thus resource allocation for Message 3 will account for the device multitone transmission capability.

In Message 3, the device will include its Identity, a scheduling request, its buffer status and power headroom (to facilitate eNodeB scheduling and power allocation decision for subsequent UL transmissions).

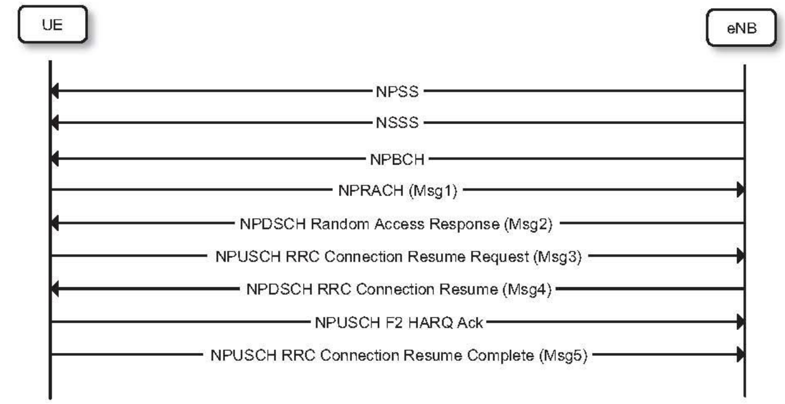


FIGURE 7.41

NB-IoT random access procedure, using the Radio Resource Control (RRC) resume procedure.

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Physical layer: Idle mode procedures…
Random access procedure…

In Message 4, the network resolves any contention because of multiple devices transmitting the same random access preamble in the first step and transmits a connection setup or resume message.

The device finally replies with an RRC connection setup, or resume, complete message to complete the transition to connected state.

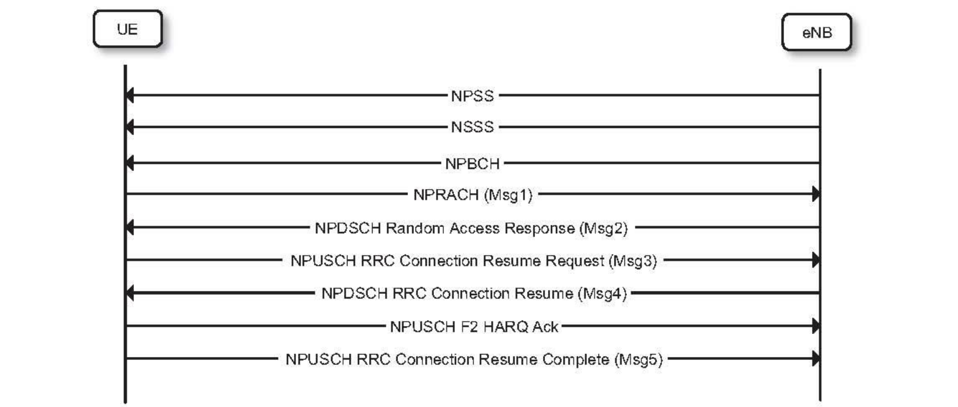

FIGURE 7.41
NB-IoT random access procedure, using the Radio Resource Control (RRC) resume procedure.

Physical layer: Idle mode procedures… Access control

Access Barring (AB) is an access control mechanism adopted in NB-IoT; it closely follows the Access Class Barring functionality described for LTE and allows PLMN-specific barring across 10 normal and 5 special access classes.

An AB flag is provided in MIB. If it is set false, then all devices are allowed to access the network. If the AB flag is set true, then the device must read SIB14 before it attempts to access the network, which provides the just introduced access class-specific barring information.

In case the device is barred, it should back off and then reattempt access at a later point in time.

Physical layer: Connected mode procedures

- **NPDCCH search spaces**

- **Scheduling**
  - Uplink scheduling
  - Downlink scheduling

- **Power control**

Physical layer: Connected mode procedures

NPDCCH signal

The NPDCCH is used to carry Downlink Control Information (DCI). A device needs to monitor NPDCCH for three types of information:

- UL grant information (DCI format N0)
- DL scheduling information (DCI format N1)
- Indicator of paging or system information update (DCI format N2)

An NPDCCH subframe is divided into two narrowband control channel elements (NCCE).

NCCE0 takes the lowest six subcarriers and NCCE1 take the highest six subcarriers.

The number of REs available for one NCCE depends on NB-IoT deployment modes and the number of logical antenna ports.

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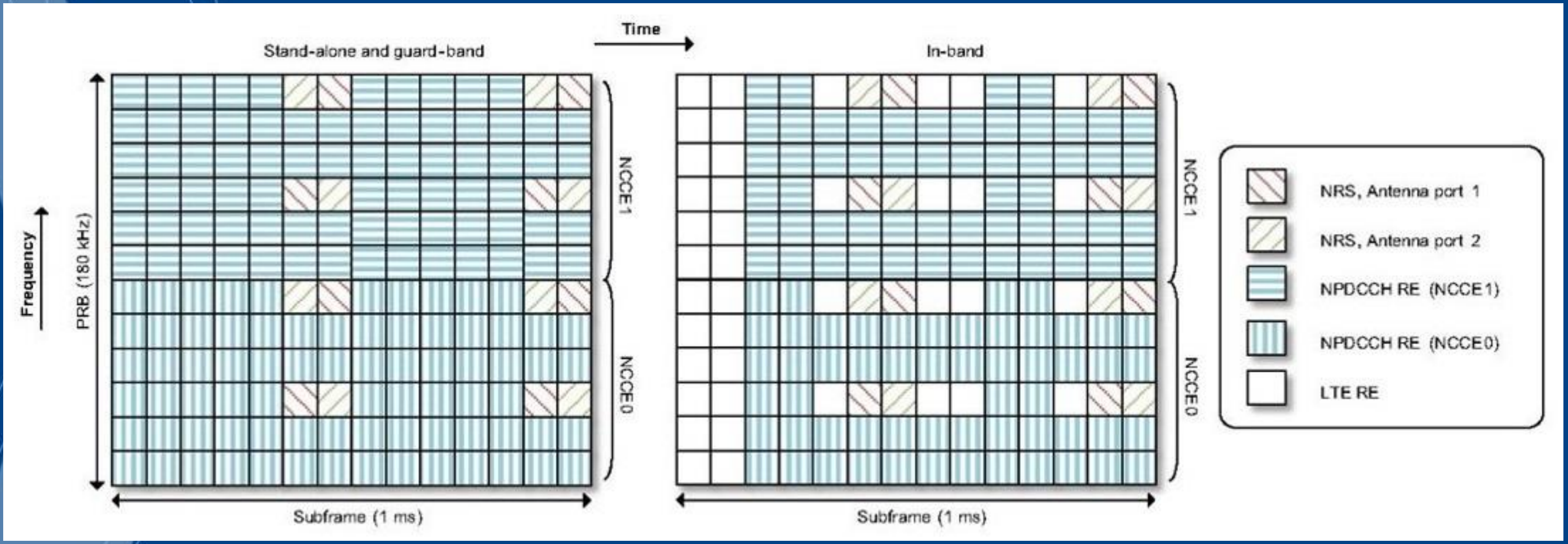
Physical layer: Connected mode procedures
NPDCCH signal…

Examples



Stand-alone and guard-band deployments with 2 NRS ports

In-band deployment with 2 NRS ports, 4 CRS ports and 2 OFDM symbols for LTE DL control region.

Physical layer: Connected mode procedures
NPDCCH signal…

A DCI can be mapped to one NCCE (Aggregation Level, AL 1), or both NCCEs in the same subframe (AL 2).

A DCI is attached with 16-bit CRC, which is masked with a sequence determined by a RNTI.

After the CRC attachment and RNTI masking, TBCC encoding and rate-matching is used to generate a code word with a length matched to the number of encoded bits available.

QPSK modulation is used for NPDCCH, and thus the code word length ranges from 100 to 160 for AL 1, or from 200 to 320 for AL 2.

NPDCCH AL 2 is used for increasing the coverage of NPDCCH.

More REs used for transmitting a DCI message give rise to a higher energy level per information bit. Further coverage enhancements can be provided by subframe-level repetitions.

Physical layer: Connected mode procedures
NPDCCH search space

A key concept related to connected mode scheduling as well as idle mode paging is the NPDCCH search space.

To detect whether there is data (NPDSCH) sent for it or detect any UL Grant for NPUSCH, the UE should monitor (try to decode) various regions within DL subframes.

UE needs to monitor all the possible regions that are allowed for NPDCCH and decode the information in try-and-error based.

However, UE does not try to decode every possible combinations of resource elements within a subframe. There are a certain set of predefined regions in which a NPDCCH can be allocated. UE monitor only those predefined regions.

These predefined set of regions are called NPDCCH search space.

Physical layer: Connected mode procedures
NPDCCH search spaces…

A search space consists of one or more subframes in which a device may search for DCI addressed to the device.

There are three types of search spaces defined:

- **Type-1 CSS (common search space)**, used for monitoring paging.
- **Type-2 CSS**, used for monitoring RAR (random access response), Message 3 (HARQ retransmissions) and Message 4 (radio resource assignments).
- **UE-specific search space (USS)**, used for monitoring DL or UL scheduling information.

The device is not required to simultaneously monitor more than one type of search space.

Physical layer: Connected mode procedures
NPDCCH search spaces…

Key parameters for defining NPDCCH search spaces for Type-2 CSS and USS are:

- *Rmax*: Maximum repetition factor of NPDCCH
- α_{offset}: Offset of the starting subframe in a search period
- *G*: Parameter that is used to determine the search period (scheduling periodicity)

Then, the search space period is *T* = *Rmax G* (number of subframes)

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Physical layer: Connected mode procedures
NPDCCH search spaces…

For Type-2 CSS, the parameters *Rmax*, α_{offset} , and *G* are signaled in SIB2, whereas for USS these parameters are signaled through device-specific RRC signaling.

For Type-2 CSS, *Rmax* should be adapted according to the NPRACH coverage class it is associated to.

For USS, *Rmax* can be optimized to serve the coverage of the connected device. There is a restriction that a search period must be $T > 4$.

Within a search period, the number of subframes that UE needs to monitor is *Rmax* and the number of search space candidates defined is also based on *Rmax*.

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Physical layer: Connected mode procedures
NPDCCH search spaces…

Search space USS concept example:

A device in coverage conditions requiring the NPDCCH to be transmitted with up to *Rmax=2* repetitions. It is assumed that the scheduling periodicity is configured to be 8 times longer than the maximum repetition interval, i.e., *G = 8*. Finally, an offset α_{offset} = *1/8* is selected.

Then, the search period is *T = Rmax G = 16* subframes.

The starting subframes are the ones satisfying (SFN x 10 + SN) mod T = 0, when the offset value is set to 0.

The offset value is set to 1/8 of the search period, i.e., the starting subframe is shifted by 2 subframes.

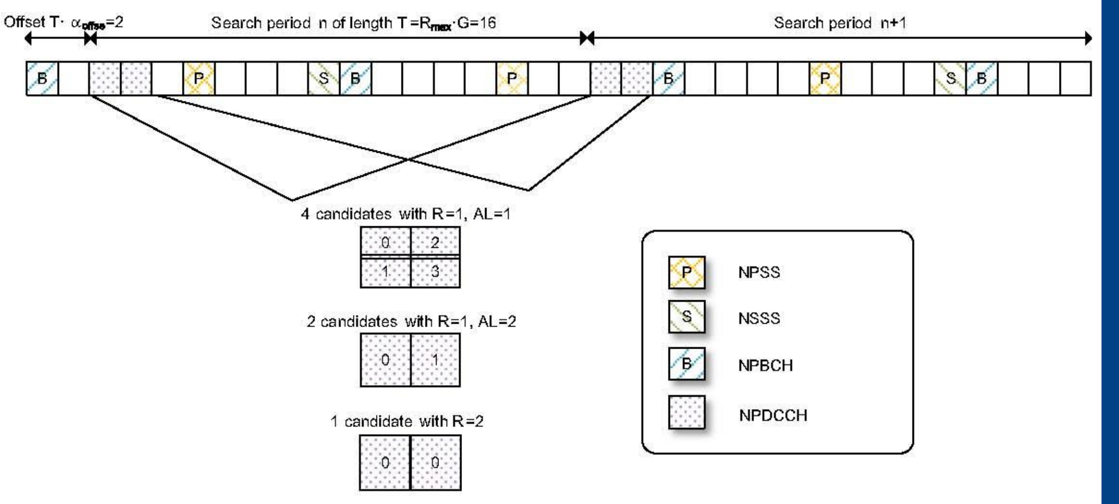

FIGURE 7.44

An example of User Equipment-specific search space (USS) configuration.

SFN: System frame number
SN: Subframe number
AL: aggregated level

Physical layer: Connected mode procedures
NPDCCH search spaces…

With Rmax = 2, the search space may have NPDCCH repetition factor of R = 1 or 2. Furthermore, for the case of R = 1, AL 1 may be used and thus both NCCE0 and NCCE1 are individually a search space candidate.

For AL 2, NCCE0 and NCCE1 are used jointly as a search space candidate.

All the search space candidates are, including the following set of seven candidates within a search period:
• Four candidates with R = 1 and AL = 1,
• Two candidates with R = 1 and AL = 2, and
• One candidate with R = 2.

Table 7.19 NPDCCH UE-specific search space candidates

R_{max}	R	NCCE Indices of Monitored NPDCCH Candidates AL = 1	AL = 2
1	1	{0},{1}	{0,1}
2	1	{0},{1}	{0,1}
	2	–	{0,1}
4	1	–	{0,1}
	2	–	{0,1}
	4	–	{0,1}
≥8	$\frac{R_{max}}{8}$	–	{0,1}
	$\frac{R_{max}}{4}$	–	{0,1}
	$\frac{R_{max}}{2}$	–	{0,1}
	R_{max}	–	{0,1}

NCCE: Narrowband control channel element
AL: Aggregated level

Physical layer: Connected mode procedures
NPDCCH search spaces…

It should be noted that the device needs to monitor a set of search space subframes that are not taken by NPBCH (subframe 0), NPSS (subframe 5), NSSS (subframe 9, in even-numbered SFN), and SI.

The search space candidates shown in previous Table also applies to Type-2 CSS, with the only exception that Type-2 CSS candidates are only based on AL = 2.

Furthermore, Type-2 CSS and USS share the same set of values for G, {1.5, 2, 4, 8, 16, 32, 48, 64} .

Considering the maximum repetition factor of NPDCCH is 2048, the values of search period for Type-2 CSS and USS are $4 < T < 131072$.

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Physical layer: Connected mode procedures
Scheduling

When the network needs to schedule a UE, it sends a DCI addressed to the device during one of the search space candidates that the device monitors.

The NPDCCH carries a DCI that includes resource allocation (in both time and frequency domains), modulation and coding scheme (MCS), and information needed for supporting the HARQ operation.

Among others, NB-IoT adopts the following scheduling principles:

- A device only needs to support one HARQ process in the DL and one in the UL not simultaneously.

- Cross-subframe scheduling (i.e., DCI and the scheduled data transmission do not occur in the same subframe) with relaxed processing time requirements.

- Half-duplex operation at the device (i.e., no simultaneous transmit and receive at the device) allows time for the device to switch between transmission and reception modes.

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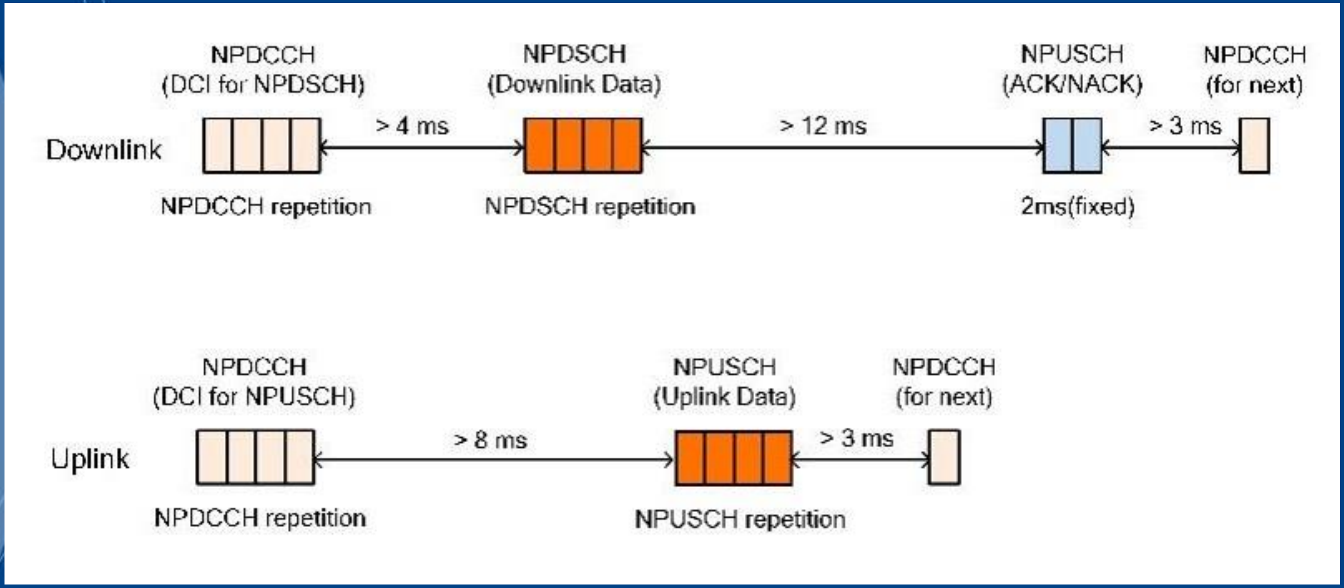
Physical layer: Connected mode procedures
Scheduling

Example of minimum delays



Physical layer: Connected mode procedures
UL Scheduling

UL scheduling uses DCI Format N0.

Information carried in DCI Format N0 is the following:

Table 7.20 DCI Format N0 used for scheduling NPUSCH Format 1

Information	Size [bits]	Possible Settings
Flag for format N0/N1	1	DCI N0 or DCI N1
Subcarrier indication	6	Allocation based on subcarrier index
		3.75 kHz spacing: {0}, {1}, …, or {47}
		15 KHz spacing: 1-tone allocation: {0}, {1}, …, or {11} 3-tone allocation: {0, 1, 2}, {3, 4, 5}, {6, 7, 8}, {9, 10, 11} 6-tone allocation: {0, 1,…,5} or {6, 7,…,11} 12-tone allocation: {0, 1,…,11}
NPUSCH scheduling delay	2	8, 16, 32, or 64
DCI subframe repetition number	2	The *R* values in Table 7.19
Number of RUs	3	1, 2, 3, 4, 5, 6, 8, or 10
Number of NPUSCH repetition	3	1, 2, 4, 8, 16, 32, 64, or 128
MCS	4	0, 1,…, or 12, for indexing the row of the NPUSCH TBS
Redundancy version	1	Redundancy version 0 or 2
New data indicator (NDI)	1	NDI toggles for new TB or does not toggle for same TB

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Physical layer: Connected mode procedures
UL Scheduling example

We use the same USS search space configuration than previously.

For UL at least an 8 ms time gap between the last DCI subframe and the first scheduled NPUSCH subframe is required: *scheduling delay* . This time gap allows the device to decode the DCI, switch from the reception mode to the transmission mode, and prepare the UL transmission.

After the device completes its NPUSCH transmission, there is at least a 3-ms gap to allow the device to switch from transmission mode to reception mode and be ready for monitoring the next NPDCCH search space candidate.

This means that according to this example the network cannot use the second search period to send the next DCI.

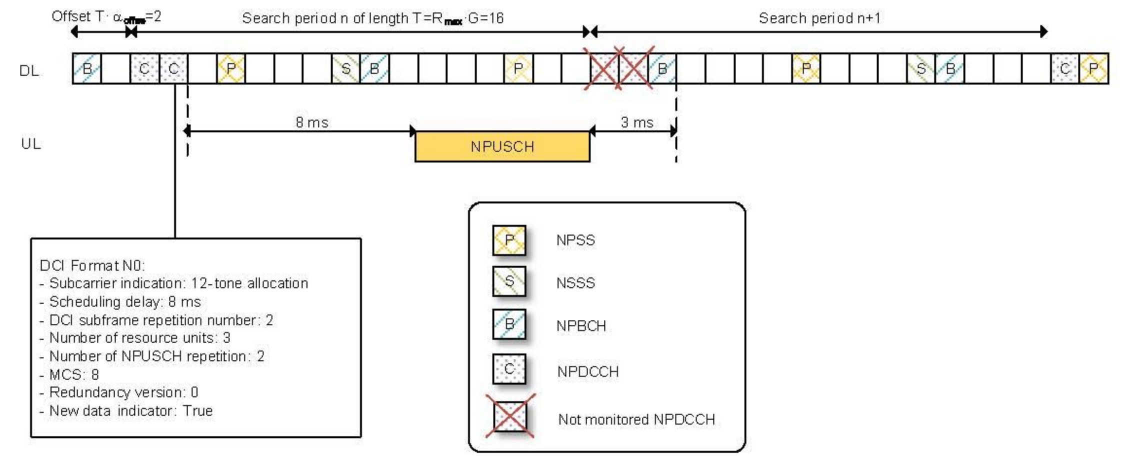

FIGURE 7.45

An uplink scheduling example.

Physical layer: Connected mode procedures
UL Scheduling example…

DCI Format N0 provides the information about:

- starting subframe,
- total number of subframes of the scheduled NPUSCH resources,
- scheduling delay (time gap between the last NPDCCH subframe carrying the DCI and the first scheduled NPUSCH slot is indicated in the DCI).

The total number of scheduled NPUSCH slots is determined by the number of RUs per repetition, the number of repetitions, and the length of an RU. The length of an RU is inferred from the number of subcarriers used for NPUSCH Format 1.

According to the example, 12 subcarriers are used, and one RU for 12-tone NPUSCH Format 1 is 1 ms. Thus, with 2 repetitions and 3 RUs per repetition the total scheduled duration is 6.

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Physical layer: Connected mode procedures
UL Scheduling example…

Modulation format is determined based on the MCS index, and the coding scheme is determined jointly based on the MCS index, number of RUs, and the redundancy version.

According to the current example, the MCS index according to the DCI is 8.

The MCS index is converted to a TBS index. Thus, MCS index 9 is mapped to TBS index 9, which, together with the information that each repetition uses three RUs, is used to determine TBS as 456.

The number of data symbols per RU is 144 symbols in this case. With QPSK and three RUs per repetition, there are overall 864 coded bits available.

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Physical layer: Connected mode procedures
DL Scheduling

Scheduling of NPDSCH is signaled using DCI Format N1 that includes the following information

Table 7.22 DCI Format N1 for scheduling NPDSCH

Information	Size [bits]	Possible Settings
Flag for format N0/N1	1	DCI N0 or DCI N1
NPDCCH order indication	1	Whether the DCI is used for NPDSCH scheduling or for NPDCCH order
Additional time offset for NPDSCH (in addition to a minimal 4-ms gap)	3	$R_{max} < 128$: 0, 4, 8, 12, 16, 32, 64, or 128 (ms) $R_{max} \geq 128$: 0, 16, 32, 64, 128, 256, 512, or 1024 (ms)
DCI subframe repetition number	2	The R values in Table 7.19
Number of NPDSCH subframes per repetition	3	1, 2, 3, 4, 5, 6, 8, or 10
Number of NPDSCH repetition	4	1, 2, 4, 8, 16, 32, 64, 128, 192, 256, 384, 512, 768, 1024, 1536, or 2048
MCS	4	0, 1,..., or 12, for indexing the row of the NPDSCH TBS
NDI	1	NDI toggles for new TB or does not toggle for same TB
HARQ-ACK resource	4	15 kHz subcarrier spacing: • Time offset value: 13, 15, 17, or 18 • Subcarrier index: 0, 1, 2, or 3 3.75 kHz subcarrier spacing: • Time offset value: 13 or 17 • Subcarrier index: 38, 39, 40, 41, 42, 43, 44, or 45

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Physical layer: Connected mode procedures
DL Scheduling…

Most of the general aspects of DL scheduling are similar to those used for UL scheduling, although the exact parameter values are different.

For example, cross-subframe scheduling is also used for DL scheduling, but the minimum time gap between the last DCI subframe and the first scheduled NPDSCH subframe is 4 ms (for UL cross-subframe scheduling this gap is at least 8 ms).

A smaller minimum gap in the DL case reflects that there is no need for the device to switch from receiving to transmitting between finishing receiving the DCI and starting NPDSCH reception.

Physical layer: Connected mode procedures

DL Scheduling…

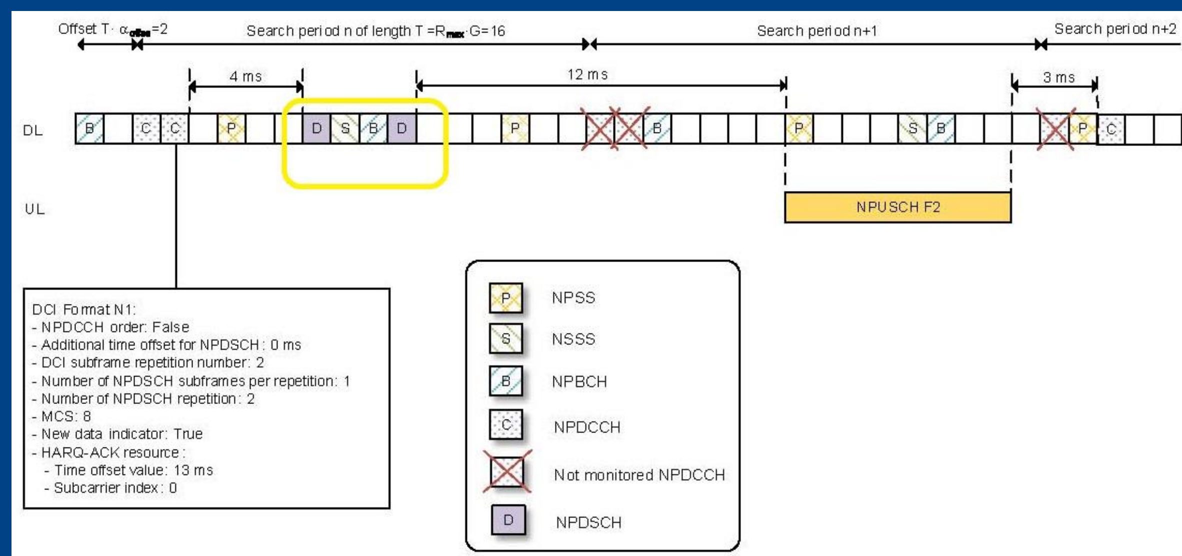
Example: NPDSCH scheduling, again based on the same NPDCCH USS configuration example.

First, DCI indicates that there is no additional scheduling delay, and thus the scheduled NPDSCH starts after a minimum 4 ms gap following the last subframe carrying the DCI.

DCI also indicates that 1 subframe is used per repetition of NPDSCH and there are 2 repetitions. Then, the device knows that there are 2 subframes scheduled for its NPDSCH reception.

These 2 subframes are the 1st two available subframes from the scheduled starting point of NPDSCH (the ones not used by NPBCH, NPSS NSSS, SI or invalid subframes).

The 1st subframe after the scheduled NPDSCH starting point is available, but the next 2 subframes need to be skipped.



A DL scheduling example.

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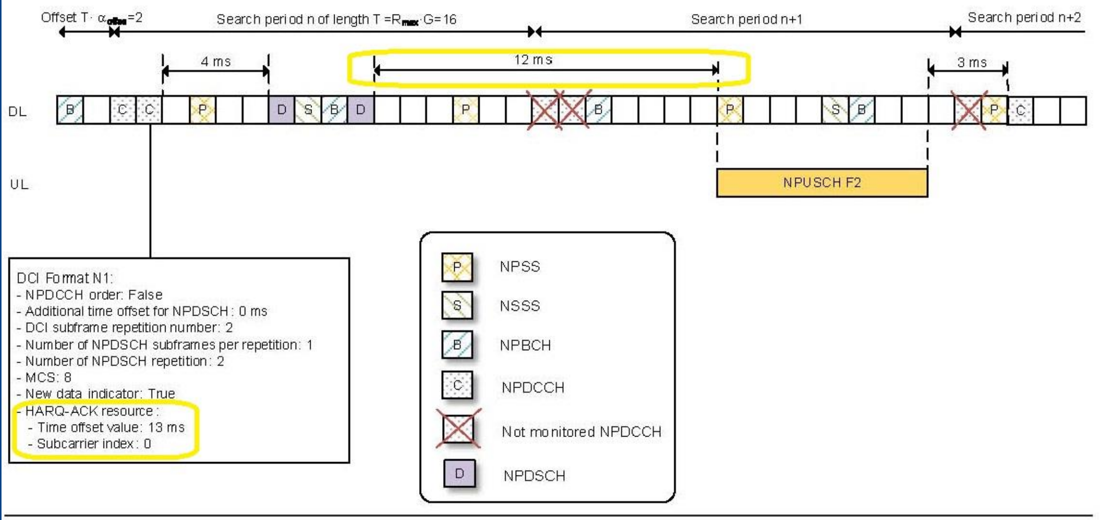
Physical layer: Connected mode procedures
DL Scheduling example…

A major difference between DL and UL scheduling is that in the DL case, the scheduler also needs to schedule NPUSCH Format 2 resources for the signaling of HARQ feedback. This information is provided in the DCI in the format of a subcarrier index and a time offset.

The time offset is defined between the ending subframe of scheduled NPDSCH and the starting slot of NPUSCH Format 2.

NB-IoT requires such a time offset to be at least 13 ms, giving a gap of at least 12 ms between the end of NPDSCH and the start of NPUSCH Format 2.

This gap is to allow sufficient NPDSCH decoding time at the device, time for switching from reception to transmission, and time for preparing the NPUSCH Format 2 transmission.



A DL scheduling example.

Physical layer: Connected mode procedures
DL Scheduling example…

NPUSCH Format 2 uses single-tone transmissions, either with 15 or with 3.75 kHz numerology.

The RU for NPUSCH Format 2 is 2 ms for 15 kHz subcarrier numerology or 8 ms for 3.75 kHz numerology.

Whether the device uses 15 or 3.75 kHz numerology is configured through RRC signaling.

For the example the device is configured to use four repetitions for NPUSCH Format 2 (assuming 15 kHz subcarrier numerology).

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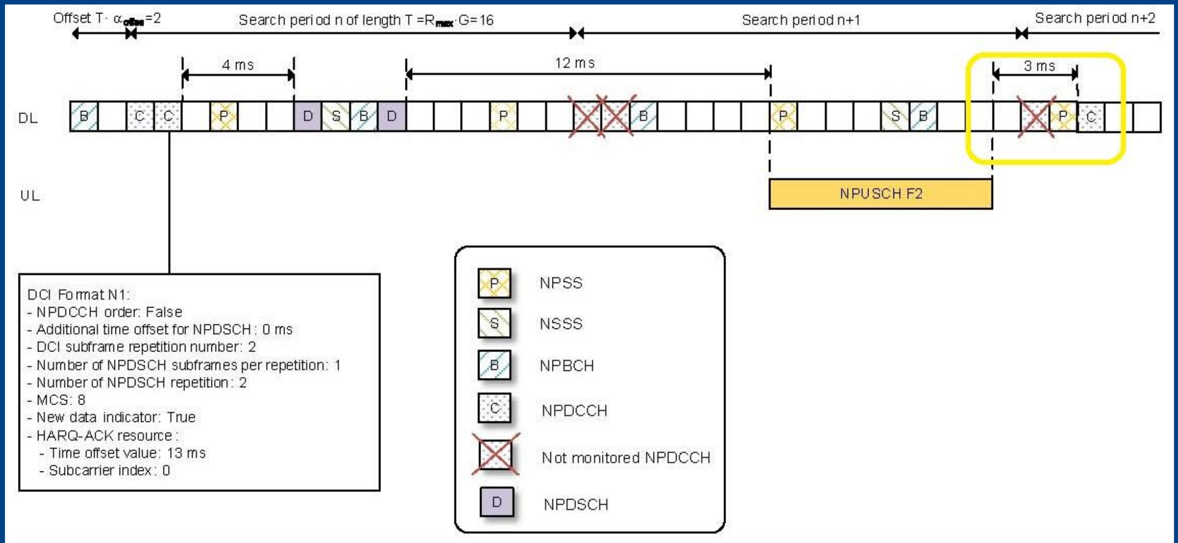
Physical layer: Connected mode procedures
DL Scheduling example…

After the device completes its NPUSCH Format 2 transmission, it is not required to monitor NPDCCH search space for 3 ms. This is to allow the device to switch from the transmission mode to getting ready for receiving the NPDCCH again.

According to the Figure, the first subframe of search period *n + 2* is within the 3-ms gap and thus cannot be used for signaling a DCI to the device.

The subframe immediately after the NPSS subframe is another NPDCCH search space candidate and is not within the 3-ms gap.

Therefore, a DCI may be sent using this subframe.



A DL scheduling example.

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Physical layer: Connected mode procedures
Power control

NB-IoT supports open-loop power control.

The decision to not allow closed-loop power control was based on the following considerations:

- A data session for many IoT use cases is very short and thus not a good match for a closed-loop control mechanism, which takes time to converge.
- Closed-loop power control requires constant feedback and measurements, which are not desirable from device energy efficiency point of view.
- For devices in extreme coverage extension situations, the quality of channel quality measurements and reliability of power control command might be very poor.

Physical layer: Connected mode procedures

Power control…

Instead, NB-IoT uses open-loop power control based on a set of very simple rules.

For NPUSCH, Format 1 and Format 2, if the number of repetitions is greater than 2, the transmit power is the maximum configured device power, P_{max}. The maximum configured device power is set by the serving cell, P_{max} < 23 *dBm*.

If the number of NPUSCH repetitions is 1 or 2, the transmit power is determined by

$$P_{NPUSCH} = \max\{P_{max}, 10\log_{10}(M) + P_{target} + \alpha L\}\ \text{(dBm)}$$

where P_{target} is the target received power level at the base station, *L* is the estimated path loss, α is a path loss adjustment factor, and *M* is a parameter related to the bandwidth of NPUSCH waveform.

The bandwidth-related adjustment is used to relate the target received power level to target received SNR.

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Physical layer: Connected mode procedures
Power control…

The device uses the value of *M* according to its NPUSCH transmission configuration.

M for different NPUSCH configurations are the following

Table 7.23 Bandwidth adjustment factors used in open-loop power control

NPUSCH Configuration	NPUSCH Bandwidth [kHz]	*M*
Single-tone, 3.75 kHz subcarrier spacing	3.75	1/4
Single-tone, 15 kHz subcarrier spacing	15	1
3-tone, 15 kHz subcarrier spacing	45	3
6-tone, 15 kHz subcarrier spacing	90	6
12-tone, 15 kHz subcarrier spacing	180	12

The values of P_{max}, P_{target}, and α are provided by higher-layer configuration signaling.

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Physical layer: Connected mode procedures
Power control…

Power control for NPRACH follows the same general principles. There may be multiple NPRACH configurations for supporting different coverage levels.

For NPRACH preambles not having the lowest repetition level, the maximum configured device power, P_{max}, is used in all transmissions.

For NPRACH preambles having the lowest repetition level, the transmit power is determined based on the expression below.

$$P_{NPRACH} = \max\{P_{max}, P_{target} + \alpha L\} \text{ (dBm)}$$

where P_{target} is the target NPRACH received power level, which is indicated by the higher layers.

If the device does not get a response and has not used the maximum configured device power, it can increase its transmit power in its subsequent RA attempts until it reaches the maximum configured device power. This is referred to as *power ramping*.

Physical layer: Multicarrier operation

To support a massive number of devices, NB-IoT also includes a multicarrier feature. In addition to the anchor carrier, which carries synchronization and broadcast channels, one or more non anchor carriers can be provided.

As nonanchor carrier does not carry NPBCH, NPSS, NSSS, and SI, a device in idle mode camps on the anchor carrier, monitoring the paging messages on the anchor.

When the device needs to switch from the idle to connected mode, the NPRACH procedure also takes place on the anchor carrier. The network can use RRC configuration to point the device to a nonanchor carrier. Essential information about the nonanchor carrier will be provided to the device using dedicated signaling.

During the remaining duration of the connected mode, USS monitoring and NPDSCH and NPUSCH activities all take place on the assigned nonanchor carrier.

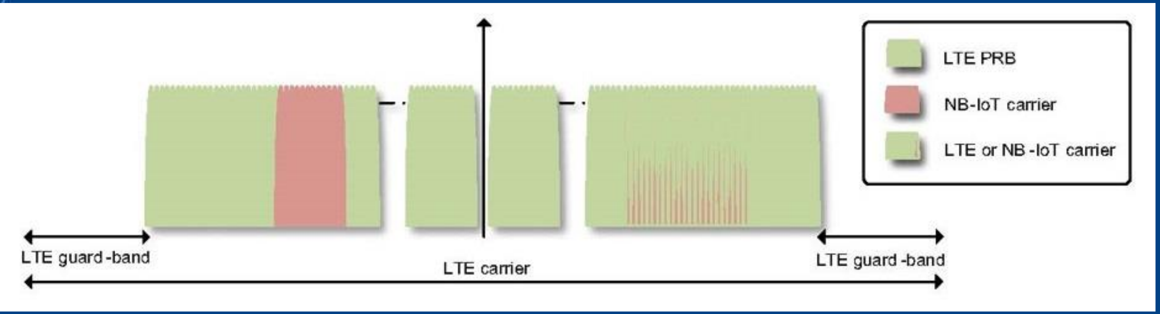
After the device completes the data session, it comes back to camp on the anchor carrier during the idle mode.

Physical layer: Multicarrier operation…

The nonanchor carriers can be allocated adapting to the traffic load of NB-IoT. Many IoT use cases generate highly delay-tolerant traffic. Such traffic can be delivered during off-peak hours in the network.

The multicarrier feature allows the radio resources normally reserved for serving broadband or voice to be allocated for NB-IoT when the load of broadband and voice traffic is low.

For example, during the middle of the night many of the LTE PRBs may be allocated as nonanchor NB-IoT carriers serving the IoT traffic. The network can, as an example, take advantage of the multicarrier feature to push firmware upgrades to a massive number of devices during the middle of the night.



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Conclusions

- Physical layer working description can be divided in: idle mode and connected mode procedures.
- Cell selection (using MIB and SIB), paging, DRX and PSM random access and access control are the basic functions in idle mode.
- On the other hand, connected mode procedures are related to NPDCCH and the search space concept. Also, DL, and UL scheduling, power control and multicarrier operation are discussed as part of the connected mode procedures.