CHAPTER

LTE FOR MASSIVE MTC APPLICATIONS

20

20.1 INTRODUCTION

Applications such as mobile telephony, mobile broadband, and media delivery are fundamentally about information being communicated to and/or from human beings. However, wireless communication is increasingly also being used to provide end-to-end connectivity between nonhumans—that is, different types of "things" or "machines." In 3GPP this is referred to as *machine-type communications* (MTC). The term *internet of things* (IoT) is also often used in this context.

Although MTC applications span a very wide range of different applications, on a high level one is often talking about two main categories, *massive-MTC* applications and *critical-MTC* applications.

Massive-MTC applications are applications typically associated with a very large, or *massive*, number of connected devices, such as different types of sensors, actuators, and similar devices. Massive-MTC devices typically have to be of very low cost and have very low average energy consumption enabling very long battery life. At the same time, the amount of data generated by each device is typically small and the data-rate and latency requirements are often relatively relaxed.

For some massive-MTC applications it is important that one can provide connectivity also in locations such as deep within the basement of buildings and in very rural or even deserted areas with very sparse network deployments. A radio-access technology supporting such massive-MTC applications must therefore be able to operate properly with very high path loss between base stations and devices.

Critical-MTC applications, on the other hand, are applications typically associated with requirements on extremely high reliability and extremely high availability within the area where the application is to be supported. Examples of critical-MTC applications include traffic safety, control of critical infra-structure, and wireless connectivity for industrial processes. Many of these applications also have requirements on very low and predictable latency. At the same time, very low device cost and very low device energy consumption is typically less important for these kinds of applications.

4G, LTE-Advanced Pro and The Road to 5G. http://dx.doi.org/10.1016/B978-0-12-804575-6.00020-0

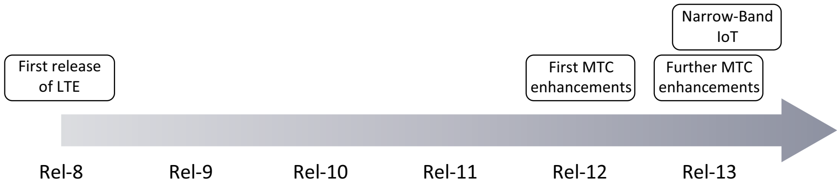

FIGURE 20.1

Steps in the LTE evolution targeting enhanced support for massive-MTC applications.

Many MTC applications can be well supported already with the first releases of LTE. However, recently there have been updates as part of the evolution of LTE specifically targeting enhanced support for massive-MTC applications.

As outlined in Figure 20.1, the first step in this evolution was taken in 3GPP release 12. This was then followed by additional steps in release 13. The different updates to the LTE specifications addressing massive-MTC applications in releases 12 and 13 are discussed in more detail in Section 20.2 and 20.3, respectively.

In addition to this more direct evolution of LTE toward enhanced support for massive-MTC applications, there is an ongoing parallel 3GPP activity referred to as *narrow-band IoT* (NB-IoT). NB-IoT started as a 3GPP technology track separated from the evolution of LTE. However, recently the NB-IoT technology has been aligned with LTE and it can now be seen as part of the overall LTE evolution. NB-IoT is further discussed in Section 20.4

20.2 MTC ENHANCEMENTS FOR LTE RELEASE 12

As mentioned earlier, the first step to enhance the support for MTC applications, specifically targeting lower device cost and reduced device energy consumption, was taken as part of LTE release 12. This included a new UE category with reduced data-rate capability, modified half-duplex operation, and possibility for devices with only one receive antenna. It also included a new *power-saving mode* targeting reduced device energy consumption.

20.2.1 DATA-RATE CAPABILITY AND UE CATEGORY 0

As described in Chapter 3, LTE defines different UE categories, where each category is associated with a maximum supported data rate.

To enable lower-cost devices for MTC applications, LTE release 12 introduced a new, lower-rate UE category. The new UE category was labeled *Category 0* (zero) in line with the typical association of higher-numbered UE categories with more extensive capabilities.[1]

[1]Strictly speaking, there are, from release 12, different categories for downlink and uplink.

The data-rate limitations of different UE categories are in the LTE specifications expressed as upper limits for the size of a transport block. For UE category 0, this limit was set to 1000 bits for both uplink and downlink. In combination with a TTI of 1 ms, this leads to a maximum supported data rate of 1 Mbit/s for category 0 devices assuming full-duplex FDD operation. It can be noted that the 1 Mbit/s data-rate limitation corresponds to the transport-channel data rate, including overhead added on higher layers (MAC and above). The maximum data rate from an application point of view is thus somewhat lower.

It should also be pointed out that that the 1000-bit limit for the transport-block size is only valid for user-data transmission. In order to be able to support category 0 devices without more extensive updates on the network side, these devices must still be able to receive system information, paging messages, and random-access responses with a transport-block size of 2216 bits which is the maximum size of SIB1.

Similar to category 1, category 0 does not include support for spatial multiplexing. Furthermore, uplink modulation is limited to QPSK and 16QAM.

It should be pointed out that category 0 devices still have to support the full carrier bandwidth, that is, up to 20 MHz. As is seen in Section 20.3, this requirement was relaxed as part of the further MTC enhancements in LTE release 13.

20.2.2 TYPE-B HALF-DUPLEX OPERATION

Already from its first release, the LTE specifications have allowed for terminals only capable of half-duplex FDD operation. As described in Chapter 5, half-duplex operation implies that there is no simultaneous transmission and reception on the device side. This allows for relaxed duplex-filter requirements, enabling lower-cost devices.

Due to timing advance, the transmission of an uplink subframe will start before the end of the previous downlink subframe. As described in Chapter 5, when uplink transmission follows directly upon downlink reception, a device only capable of half-duplex operation is therefore "allowed" to skip reception of the last OFDM symbol(s) of the downlink subframe.

To allow for further complexity/cost reduction, LTE release 12 introduced a new half-duplex mode, *half-duplex type B*, specifically targeting category 0 devices. Half-duplex type B allows for a much larger idle time between downlink reception and uplink transmission by specifying that a device is not expected to receive the last downlink subframe before an uplink subframe nor the first downlink subframe *after* an uplink subframe, see Figure 20.2.

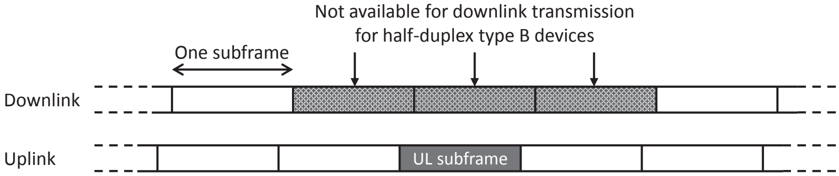

FIGURE 20.2

Scheduling restrictions for half-duplex type B.

By providing such a large idle time when switching between transmission and reception, half-duplex type B allows for more reuse of RF functionality—for example, in terms of oscillators—between the transmitter and the receiver, thereby further reducing the complexity of category 0 devices.

20.2.3 POSSIBILITY FOR DEVICES WITH A SINGLE RECEIVE ANTENNA

The LTE technical specifications do not explicitly mandate any specific receiver implementation such as the number of receive antennas to be used at the device side. However, already since the first release, the LTE performance requirements have been such that, implicitly, two-antenna reception has been mandatory for all UE categories.

To enable further complexity reduction for devices targeting massive-MTC applications, this requirement was relaxed for UE category 0. Rather, the performance requirements for category 0 devices are such that they can be fulfilled with only a single receive antenna at the device side.

20.2.4 POWER-SAVING MODE

In addition to the above-mentioned steps to enable lower-cost devices, LTE release 12 also included a new *power-saving mode* (PSM) to enable reduced energy consumption and corresponding extended battery life for massive-MTC devices.

Entering PSM is from a device point of view similar to powering off. The difference is that the device remains registered in the network and does not need to reattach or reestablish PDN (packet data network) connections.

As a consequence, a device that has entered PSM cannot be reached by the network and reestablishing connectivity must be initiated by the device. PSM is therefore mainly relevant for "monitoring" devices for which the need for data transfer is typically triggered by events on the device side.

To enable network-originating data transfer, devices using PSM must regularly reconnect to the network and stay awake for a brief period to allow the network to make paging attempts to the UE. Such reconnection should be infrequent in order to retain the energy-saving benefits of PSM, implying that PSM is primarily beneficial for infrequent network-originating data traffic that is not latency critical.

20.3 MTC ENHANCEMENTS FOR LTE RELEASE 13: eMTC

As part of LTE release 13, additional steps were taken to further enhance the LTE support for massive-MTC applications, an activity referred to as *enhanced MTC* (eMTC). The main targets for this activity were to

- Enable further device cost reduction beyond what was achieved with release 12 UE Category 0.

- Extend the coverage for low-rate massive-MTC devices with a target to enable operation with at least 15 dB higher coupling loss, compared to pre-release 13 devices.

On a high level, the main new features of eMTC were the possibility for

- more narrow RF bandwidth on the device side, enabling further reduction in device complexity and corresponding cost;
- extensive repetition for both downlink and uplink, enabling extended coverage for low-rate services;
- extended DRX.

Devices that are limited to narrow RF bandwidth are, in the LTE specification referred to as *bandwidth-reduced low-complexity* (BL) UEs. However, we will use the term eMTC rather than BL in the following.

It should also be pointed out that the limitation to narrow RF bandwidth and the support for coverage extension by means of repetition are actually independent properties in the sense that the coverage extension may be used also for devices not limited to narrow RF bandwidth.

In Sections 20.3.1 and 20.3.2 some higher-level aspects of narrowband operation and coverage extension by means of repetition are discussed. The following sections (Sections 20.3.3–20.3.7) then describe how these features impact, in more detail, different aspects of the LTE radio interface. Finally, Section 20.3.8 gives an overview of extended DRX.

Similar to release 12 category 0 devices, a limit on the transport-block size to 1000 bits, no support for spatial multiplexing, half-duplex type B operation, and the possibility for single-antenna reception at the device side, is valid also for release 13 eMTC. For eMTC devices, modulation is limited to QPSK and 16QAM for both uplink and downlink.

It should be pointed out that, for eMTC devices, the 1000-bit limit on the transport-block size is valid for *all* transmissions, including system information, paging message, and random-access responses. Due to the narrowband characteristics of eMTC devices there was anyway a need to redesign the mechanisms for delivering system information and therefore no need to retain the release 12 requirement that devices must be able to receive the maximum SIB1 transport-block size of 2216 bits.

It should also be pointed out that, due to an increase in HARQ round-trip time, see Section 20.3.3.4, the maximum sustainable downlink data rate for full-duplex eMTC devices is limited to 800 kbps.

20.3.1 NARROW–BAND OPERATION

From its first release, the LTE specifications have required that all devices should support all LTE carrier bandwidths, that is, up to 20 MHz. The reason for this requirement was to simplify specification and network operation by ensuring that all devices accessing the network were able to transmit and receive over the full network carrier bandwidth.

Taking into account the overall complexity of a device, including high-resolution screens and application processors, the RF complexity associated with having to support all carrier bandwidths is not critical for typical mobile-broadband devices, However, the situation is

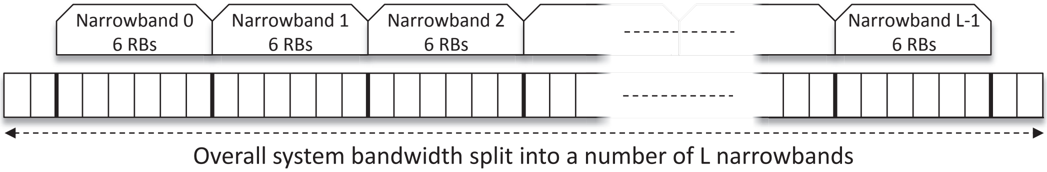

FIGURE 20.3

Overall carrier bandwidth split into *L* narrowbands of size six resource blocks.

different for low-cost MTC devices for which the radio part contributes a much larger fraction of the overall device complexity and associated cost. Support for a wide bandwidth also impacts the energy consumption, and thus the battery life, of the device. For these reason it was decided that release-13 eMTC devices were only required to support transmission and reception over an instantaneous bandwidth corresponding to the minimum LTE carrier bandwidth, that is, about 1.4 MHz.

To allow for such narrowband eMTC devices to access a more wideband LTE carrier, the concept of *narrowbands* was introduced in LTE release 13. As outlined in Figure 20.3, the overall wideband carrier is split into a number of narrowbands, each consisting of six resource blocks in the frequency domain. As the overall carrier bandwidth measured in number of resource blocks may not always be a multiple of six, there may be one or two resource blocks not part of any narrowband at each edge of the carrier. Also, the center resource block of the carrier will not be part of any narrowbands in case of an odd number of resource blocks within the overall carrier bandwidth.

At a given time instant, an eMTC device can only transmit over a bandwidth corresponding to a single narrowband, that is, six consecutive resource blocks. Similarly, at a given time instant, an eMTC device can only receive over a bandwidth corresponding to a single narrowband. Consequently, physical channels inherently spanning more than one narrowband, that is, more than six consecutive resource blocks, cannot be received by an eMTC device. This is, for example, the case for the PDCCH, PCFICH, and PHICH. The functions of these channels thus have to be provided by other means for eMTC devices.

Although an eMTC device can only transmit/receive a single narrowband, the device should be able to switch narrowband between subframes. Assuming that the device has an RF front end with a bandwidth corresponding to the bandwidth of a single narrowband, switching between different narrowbands will require retuning of the RF front end, something that may take as long time as 150 μs or up to two OFDM symbols. How such a retuning time is made available depends on if the retuning is to be done between subframes used for downlink reception or between subframes used for uplink transmission. In short one can say that

- receiver retuning between downlink subframes is assumed to take place during the control region at the start of the subframe;
- time for transmitter retuning between uplink subframes is made available by not transmitting the last symbol(s) just before retuning and/or the first symbols(s) just after retuning, see also Section 20.3.4.

20.3.2 COVERAGE ENHANCEMENTS BY MEANS OF REPETITION

The second aim of the 3GPP eMTC activities was to enable significantly extended coverage for low-rate MTC applications. The explicit target in the design of eMTC was to enable operation with at least 15 dB higher coupling loss compared to pre-release 13 devices.

It is important to understand that the aim of eMTC was not to extend coverage for a given data rate. Rather, coverage is extended by reducing the data rate. The key task was then to ensure that

- the lower data rates could be provided with sufficient efficiency;
- there is sufficient coverage for the different control channels and signals needed to establish and retain connectivity.

The following should be noted:

- For RF-complexity reasons, there is an assumption that eMTC devices may have a maximum output power limited to 20 dBm—that is, 3 dB lower than the typical maximum output power of LTE devices. To allow for at least 15 dB higher coupling loss, the uplink link budget for eMTC devices thus needs to be improved by at least 18 dB.
- Use of single-antenna reception implies a loss in downlink link performance, a loss which also has to be compensated for by the downlink coverage enhancements.
- The different LTE channels and signals are not fully balanced in the sense that they do not have exactly the same coverage. This means that coverage does not necessarily need to be improved the same amount for all signals and channels to reach an overall network coverage gain of 15 dB.
- Certain signals and channels, such as the PSS/SSS and the PBCH, are transmitted over only a fraction of the carrier bandwidth and are normally assumed to share the overall base-station power with other, parallel transmissions. The coverage of such signals/channels can partly be extended by *power boosting*—that is, by assigning them a larger fraction of the overall base-station power at the expense of other, parallel transmissions.

The main tool to extend the coverage of eMTC devices is the use of *multi-subframe repetition*. This means that a single transport block is transmitted over multiple, in some cases a very large number of, subframes (N_{rep} subframes), thereby providing higher transmit energy per information bit for a given transmit power.

The LTE specifications distinguish between two *modes* of coverage enhancements for eMTC

- *Coverage enhancement mode A (CE mode A)* targeting relatively modest coverage enhancement;
- *CE mode B* targeting more extensive coverage enhancement.

The two modes differ, for example, in the number of repetitions supported, where CE mode B supports much more extensive repetition compared to CE mode A.

To some extent one can see the aim of CE mode A to compensate for the lower (−3 dB) eMTC device output power and the degraded receiver performance due to single-antenna

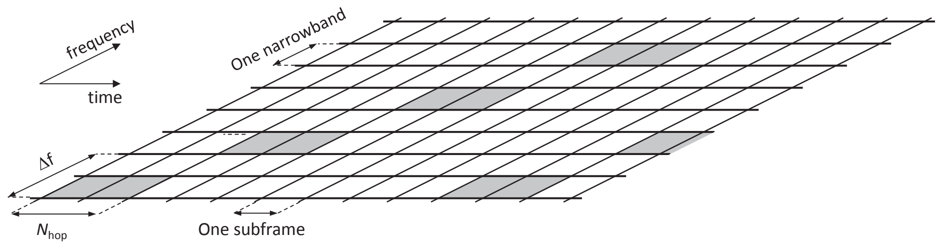

FIGURE 20.4 Frequency hopping for eMTC.

The figure assumes frequency hopping between four different narrowbands (possible only for downlink) with a frequency-hopping block length $N_{hop} = 2$.

reception of eMTC devices. From that point of view, the aim of CE mode A is, at least partly, to ensure the same coverage for low-complexity eMTC devices as for non-eMTC devices. CE mode B then provides the full coverage extension up to at least the targeted 15 dB higher maximum coupling loss.

Each eMTC device is individually configured by the network to operate in either CE mode A or CE mode B.

Repetitions will, by default, take place in consecutive subframes.[2] However, the network can explicitly configure certain subframes as not being available for repetition ("invalid subframes") by means of a bitmap provided as part of the eMTC-specific system information. In case of FDD, the set of invalid subframes are independently configured for downlink and uplink.

If the set of invalid subframes is not explicitly configured by the network, the device can assume that all uplink subframes are valid subframes. Furthermore, the device can assume that all downlink subframes are valid subframes except subframes configured as MBSFN subframes.

In case of an invalid subframe, repetition is postponed until the next valid subframe. Thus, the presence of invalid subframes does not reduce the number of repetitions but simply prolong the time over which the overall set of repetitions is carried out.

The concept of valid and invalid subframes is also applicable for the first transmission in a sequence of repetitions. On the other hand, in case of no repetitions ($N_{rep} = 1$), the transmission is carried out even if the corresponding subframe is configured as an invalid subframe.

In case of repetition over multiple subframes, *inter-subframe frequency hopping* can optionally be applied on both uplink and downlink. As illustrated in Figure 20.4, frequency hopping is carried out between different narrowbands and in blocks of N_{hop} subframes, where N_{hop} can be configured from $N_{hop} = 1$ (frequency hopping between every subframe) to $N_{hop} = 8$ (frequency hopping between every eight subframe) for CE mode A and from

[2]In case of TDD, consecutive downlink and uplink subframes for downlink and uplink transmission, respectively.

$N_{hop} = 2$ to $N_{hop} = 16$ for CE mode B.[3] The reason to allow for frequency hopping on a multi-subframe basis ($N_{hop} > 1$), rather than to hop every subframe, is to allow for inter-subframe channel estimation.

In order to align the frequency hopping between different transmissions and ensure that all devices "hop" at the same time instant, the hopping instants are not UE specific. Rather, the hopping instants are common for all frequency-hopping eMTC devices within the cell and depend on the absolute subframe number counted from the first subframe in the frame with frame number (SFN) equal to 0. In other words, if one labels the first subframe of the frame with SFN equal to 0 as subframe number 0, hopping takes place between subframe $k \cdot N_{hop} - 1$ and subframe $k \cdot N_{hop}$ for all frequency-hopping transmissions regardless of the start of the transmission. This also means that the subframe counter in case of frequency hopping takes into account also invalid subframes.

The frequency-hopping block length N_{hop} and the hopping offset Δf are cell-specific parameters that are separately configured for downlink and uplink and also separately configured for CE mode A and CE mode B. In case of uplink frequency hopping, hopping is carried out between just two different narrowbands. For the downlink, frequency hopping can be configured to be carried out over two narrowbands or four equally spaced narrowbands.

20.3.3 DOWNLINK TRANSMISSION: PDSCH AND MPDCCH

As described in Chapter 6, conventional (non-eMTC) downlink data transmission is carried out on the PDSCH with the associated control signaling (downlink control information, DCI) provided by means of the PDCCH. The PDCCH is transmitted in the *control region* of the subframe, consisting of the up to three first OFDM symbols of each subframe.[4] The size of the control region, or equivalently, the start of the *data region* in which PDSCH is transmitted, is dynamically signaled on the PCFICH.

As also described in Chapter 6, DCI can alternatively be provided by means of the EPDCCH which is confined to a limited set of resource blocks.

Both the PDCCH and PCFICH are inherently wideband and can thus not be received by a narrowband eMTC device. DCI for eMTC devices is therefore provided by means of a new physical control channel, the *MPDCCH*. The MPDCCH can be seen as an EPDCCH extended to support narrowband operation and coverage extension by means of repetition. This also includes the introduction of new eMTC-specific DCI formats for downlink scheduling assignments and uplink scheduling grants.

Even if the PDCCH is not used for eMTC devices, there will typically still be PDCCH transmissions targeting other (non-eMTC) devices within the cell. Thus, there will still be a control region within each subframe, and even though an eMTC device does not need to read the different control channels transmitted within the control region, it still needs to know the

[3]This is true for FDD. For TDD the possible values for N_{rep} are {1,5,10,20} for CE mode A and {5,10,20,40} for CE mode B.
[4]Or up to four OFDM symbols in case of 1.4 MHz carrier bandwidth.

starting point for the data region, that is, the starting point for PDSCH/MPDCCH transmissions. This information is provided to eMTC devices as part of the eMTC-specific system information.[5] In contrast to non-eMTC devices, for eMTC devices the starting point for PDSCH/MPDCCH transmissions is thus semi-static and assumed to change only on a very slow basis.

Note that the semi-static configuration of the PDSCH/MPDCCH starting point for eMTC devices does not prevent dynamic variations of the size of the control/data regions for other devices. The only constraint is that, in subframes with downlink eMTC transmissions (PDSCH or MPDCCH), *these* transmissions must start at the semi-statically configured position. As a consequence, in subframes with downlink eMTC transmissions, the control region of the subframe cannot extend *beyond* this position. However, it may very well be shorter, with a corresponding earlier starting position for PDSCH/EPDCCH transmissions to other, non-eMTC devices scheduled in the same subframe. Furthermore, in subframes with no eMTC downlink transmissions, the size of the control region can be fully flexible.

20.3.3.1 Downlink Transmission Modes

As described in Chapter 6, there are ten different downlink transmission modes defined for LTE. Of these ten modes, transmission modes 1, 2, 6, and 9 are applicable for eMTC devices. As eMTC devices are not assumed to support multi-layer transmission, transmission mode 9 is limited to single-layer precoding in case of eMTC.

In Section 20.3.2 it was described how frequency hopping is carried out in blocks of N_{hop} subframes. This was done in order to enable inter-subframe channel estimation. For the same reason, an eMTC device can assume that the transmission mode 9 precoder does not change over the same block of N_{hop} subframes. Note that the assumption that the precoder is unchanged for a block of N_{hop} subframes is valid even if frequency hopping is disabled.

20.3.3.2 PDSCH/MPDCCH Repetition

Repetition can be applied to the PDSCH with a very wide range of different repetition numbers, ranging from a single transmission ($N_{\mathrm{rep}} = 1$) to 2048 repetitions ($N_{\mathrm{rep}} = 2048$). The number of repetitions to use for a certain PDSCH transmission is a combination of semi-static configuration and dynamic selection on a per-transmission basis.

For each of the two coverage-enhancement modes, the network configures a set of possible number of repetitions on cell level, where each set consists of four and eight different values for CE mode A and CE mode B, respectively. The actual number of repetitions for a specific PDSCH transmission is then dynamically selected by the network from the four/eight values available in the corresponding configured set. The device is informed about the selected number of PDSCH repetitions in the scheduling assignment (two/three bits of signaling indicating one of four/eight values for CE mode A and CE mode B, respectively).

[5]The starting of the data region in subframes in which the corresponding system information is transmitted is predefined to the fifth OFDM symbol for carrier bandwidths equal to 1.4 MHz and the fourth OFDM symbols for carrier bandwidths larger than 1.4 MHz.

Table 20.1 Set of PDSCH Repetition Numbers for CE Mode A and CE Mode B

	CE Mode A	CE Mode B
Set 1	{1,2,4,8}	{4,8,16,32,64,128,256,512}
Set 2	{1,4,8,16}	{1,4,8,16,32,64,128,192}
Set 3	{1,4,16,32}	{4,8,16,32,64,128,192,256}
Set 4	–	{4,16,32,64,128,192,256,384}
Set 5	–	{4,16,64,128,192,256,384,512}
Set 6	–	{8,32,128,192,256,384,512,768}
Set 7	–	{4,8,16,64,128,256,512,1024}
Set 8	–	{4,16,64,256,512,768,1024,1536}
Set 9	–	{4,16,64,128,256,512,1024,2048}

The table is also valid for PUSCH repetition, see Section 20.3.4.

Table 20.1 shows the different sets of repetition numbers that can be configured on cell-level for CE mode A and CE mode B, respectively. Note that the maximum number of repetitions for CE mode A is 32 while the corresponding number of CE mode B is 2048. For CE mode A, the minimum number of transmissions is always one (no repetitions).

Repetition can also be applied to the MPDCCH. Similar to PDSCH transmissions, the number of repetitions to use for a certain MPDCCH transmission is a combination of semi-static configuration and dynamic selection on a per-transmission basis.

On cell level, the network configures the maximum number of MPDCCH repetitions (R_{max}) from the set {1,2,4,8,16,32,64,128,256} and broadcast it as part of the eMTC-specific system information. The network then dynamically selects the actual number of repetitions to use for a specific MPDCCH transmission from the set $\{R_{max}, R_{max}/2, R_{max}/4, R_{max}/8\}$.[6]

Information about the number of repetitions used for a specific MPDCCH transmission is included in the scheduling assignment as a 2-bit parameter indicating one of four different values. In other words, information about the number of MPDCCH repetitions is carried within the MPDCCH itself. An MPDCCH transmission carried out with a certain number of repetitions R can only start at, at most, every R subframe. Consequently, a device that has correctly decoded an MPDCCH transmission with a DCI indicating a certain number of repetitions can, without ambiguity, determine the first subframe, and consequently also the last subframe, in which the MPDCCH was transmitted. As we will see later, in case of DCI carrying downlink scheduling assignments, the device needs to know the last subframe in which the MPDCCH was transmitted in order to be able to determine the starting subframe for the corresponding scheduled PDSCH transmission. Similarly, in case of DCI carrying uplink scheduling grants, the device needs to know the last subframe in which the MPDCCH

[6]If R_{max} is less than eight, the number of repetitions can only be within a subset of the configured values.

was transmitted in order to be able to determine the starting subframe for the corresponding scheduled PUSCH transmission.

20.3.3.3 PDSCH Scheduling

In the normal case, downlink scheduling assignment is *intra-subframe*. This means that a scheduling assignment provided on PDCCH or EPDCCH in a certain subframe relates to a PDSCH transmission *in the same subframe*.

In contrast, scheduling assignments for eMTC devices are *inter-subframe*. More specifically, also taking into account the possibility for repetition on both MPDCCH and PDSCH, a scheduling assignment on MPDCCH ending in subframe n relates to a corresponding PDSCH transmission starting in subframe $n+2$, see Figure 20.5. The delay between the end of the scheduling assignment and the start of the corresponding PDSCH transmission allows for decoding of the scheduling assignment without having to buffer the received signal, thereby enabling lower device complexity.

In order to determine the subframe in which the PDSCH transmission starts, the device must know the last subframe of the corresponding MPDCCH transmission. As mentioned earlier, this is possible due to the inclusion of the number of MPDCCH repetitions in the DCI, in combination with the restriction that an MPDCCH transmission carried out with a certain number of repetitions R can only start at, at most, every R subframe.

In general, DCI for eMTC devices is provided by means of a set of new DCI formats carried on EPDCCH. Among these, *DCI format 6-1A* and *DCI format 6-1B* are used for scheduling assignments for PDSCH transmissions. The content of these DCI formats are shown in Table 20.2 where the values in the right column indicates the number of bits used for the specific parameter.

DCI format 6-1A is used for scheduling assignments for devices operating in CE Mode A. It contains similar information as the DCI formats used for normal (non-eMTC) scheduling assignments, but extended with information related to PDSCH and MPDCCH repetition as well as a frequency-hopping flag to dynamically enable/disable PDSCH frequency hopping (see later). DCI format 6-1B is a more compact format used for scheduling assignments for devices operating in CE Mode B.

The resource assignment included in DCI format 6-1A and 6-1B is split into two parts. A *narrowband indicator* specifies the narrowband in which the downlink PDSCH is located. A

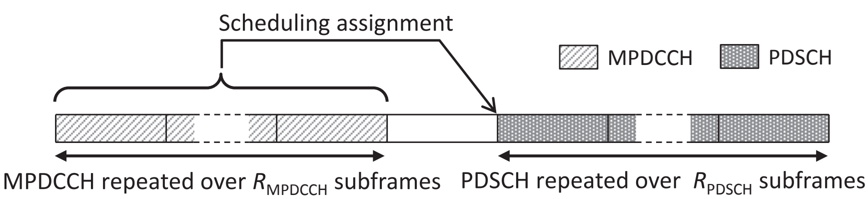

FIGURE 20.5

Timing relation between scheduling assignment on MPDCCH and corresponding PDSCH transmission.

Table 20.2 DCI Formats 6-1A and 6-1B

Field	6-1A	6-1B
Frequency-hopping flag	1	–
Resource information (resource assignment)		
Narrowband indicator	Var[a]	Var[a]
Resource-block indicator	5	1
Number of PDSCH repetitions	2	3
HARQ process number	3/4[b]	1
MCS	4	4
RV	2	–
New data indicator	1	1
PMI confirmation	1	–
Precoding information	1/2[c]	–
DM-RS scrambling/antenna ports	2	–
Downlink assignment index	2	–
PUCCH power control	2	–
SRS request	0/1	–
Ack/Nack offset	2	2
Number of MPDCCH repetitions	2	2
Flag for 6-0/6-1 differentiation	1	1

[a] *Number of bits depends on the system bandwidth.*
[b] *3 bits for FDD; 4 bits for TDD.*
[c] *Number of bits depends on number of antenna ports.*

resource-block indicator then specifies the exact set of resource blocks used for the PDSCH transmission given the narrowband specified by the narrowband indicator.

For DCI format 6-1A, that is, for CE mode A, the resource-block indicator consists of 5 bits, thus being able to point at any set of consecutive resource blocks within the six resource blocks of the narrowband.[7] Note that this is essentially the same as downlink resource-allocation type 2 used for normal (non-eMTC) scheduling assignments, see Chapter 6, where the bandwidth of the carrier has been replaced by the "bandwidth" of a single narrowband, that is, six resource blocks.

For DCI format 6-1B, used for CE mode B, the resource-block indicator consists of a single bit indicating two sets of consecutive resource blocks:

- all six resource blocks within the narrowband;
- resource block 0–3, that is, four consecutive resource blocks.

In case of frequency hopping, the resource assignment provides the narrowband of the first transmission. Narrowbands for subsequent repetitions are then given by cell-specific offsets

[7] There are a total of $1+2+3+4+5+6=21$ such combinations.

relative to the first transmission. The set of resource blocks within the narrowband is the same for each hop. For the downlink, frequency hopping can take place between either two or four narrowbands.

The hopping period, the hopping offset, and the number of hopping frequencies are configured on a cell level.

Even if frequency hopping for PDSCH is configured, for CE mode A frequency hopping can be dynamically disabled on a per-transmission basis by means of a *frequency-hopping flag* in the scheduling assignment, see Table 20.2. It is not possible to dynamically disable frequency hopping for CE mode B and, consequently, there is no frequency-hopping flag in DCI format 6-1B.

The "6-0/6-1 differentiation" flag indicates if the DCI is of format 6-1A/6-1B (downlink scheduling assignment) or 6-0A/6-0B (uplink scheduling grant, see Section 20.3.4.1). A device configured in CE mode A only has to receive DCI formats 6-0A and 6-1A. Likewise, a device configured in CE mode B only has to receive DCI formats 6-0B and 6-1B. To reduce the number of blind decoding when detecting MPDCCH, DCI formats 6-0A and 6-1A are of the same size; likewise, DCI formats 6-0B and 6-1B are of same size. Once an MPDCCH of the expected size has been decoded, the device can, from the 6-0/6-1 differentiation flag, determine if the DCI corresponds to a downlink scheduling assignment ("6-1" format) or an uplink scheduling grant ("6-0" format).

20.3.3.4 Downlink Hybrid ARQ

Downlink HARQ for eMTC is asynchronous and adaptive as in pre-release-13. This means that the network can make a retransmission at any time and using a different frequency resource compared to the prior transmission.

The two-subframe shift between scheduling assignment on MPDCCH and the corresponding PDSCH transmission, as outlined in Figure 20.5, implies a two-subframe increase in the HARQ round-trip time. Thus, even without any repetitions the eMTC downlink HARQ round-trip will be ten subframes, compared to the eight-subframe round-trip time for normal (non-eMTC) transmission. As eMTC devices still only need to support eight HARQ processes, the maximum duty cycle for transmission to a specific device is 80% for full-duplex devices. This will reduce the maximum sustainable data rate to 800 kbit/s, compared to 1 Mbit/s for UE category 0 devices.

20.3.4 UPLINK TRANSMISSION: PUSCH AND PUCCH

As described in Chapter 7, conventional (non-eMTC) uplink data transmission is carried out on the PUSCH physical channel while uplink control signaling (uplink control information, UCI) is provided by means of the PUCCH physical channel.

PUSCH and PUCCH are used also for eMTC in essentially the same way as for non-eMTC devices, with the following extensions/modifications:

- Possibility for repetition for extended coverage for both PUSCH and PUCCH.
- Modified hybrid ARQ with adaptive and asynchronous retransmissions, see Section 20.3.4.2.

Repetitions for PUSCH follows a similar approach as for downlink PDSCH, see Section 20.3.3.2. On a cell level the network configures a set of possible repetition numbers where each set consists of four and eight different repetition numbers for CE mode A and CE mode B, respectively. The actual number of repetitions to be used for the uplink PUSCH transmission, from the four/eight values of the configured set, is then dynamically selected by the network and provided to the device as part of the scheduling grant.

In case of retuning between subframes used for uplink transmission, the time for retuning is made available by not transmitting two symbols of the uplink transmissions before and/or after the retuning. Exactly what symbols are used for retuning depends on what is being transmitted in the subframes before and after the retuning. In general, symbols are, if possible, taken from subframes with PUSCH transmission, rather than PUCCH transmission. Thus, if PUSCH is transmitted in the last subframe before retuning and/or in the first subframe after retuning, two symbols of the PUSCH subframe are used for retuning.[8] In case of PUCCH transmission in both the last subframe before retuning and the first subframe after retuning, one OFDM symbol of each subframe is used for retuning.

20.3.4.1 PUSCH Scheduling

Similar to downlink scheduling assignments, uplink scheduling grants for eMTC devices are carried on the MPDCCH using two new DCI formats, see Table 20.3.

DCI format 6-0A is used for scheduling grants for devices operating in CE Mode A. It contains similar information as DCI format 0 (see Chapter 6) but extended with information related to PUSCH and MPDCCH repetition:

- A frequency flag allowing for dynamic enabling/disabling of PUSCH frequency hopping.
- A HARQ process number needed for asynchronous uplink HARQ, see Section 20.3.4.2.
- The number of repetitions for the scheduled PUSCH.
- The number of repetitions for the MPDCCH transmission.

DCI format 6-0B is a more compact DCI format used for scheduling grants for devices operating in CE Mode B.

Similar to downlink scheduling assignments, the resource assignment included in DCI formats 6-0A and 6-0B is split into two parts. A *narrowband indicator* specifies the narrowband in which the uplink resource to be used for the PUSCH transmission is located. A *resource-block indicator* then specifies the exact set of resource blocks to use for the PUSCH transmission given the narrowband specified by the narrowband indicator.

For DCI format 6-0A, used for CE mode A, the resource-block indicator consists of 5 bits, thus being able to point at any combination of consecutive resource blocks within the six

[8]If PUSCH is transmitted in both the last subframe before the retuning and in the first subframe before the retuning, one symbol from each subframe is used for retuning.

Table 20.3 DCI Format 6-0A and 6-0B

Field	6-0A	6-0B
Frequency-hopping flag	1	–
Resource information (resource assignment)		
Narrowband indicator	Var[a]	Var[a]
Resource-block indicator	5	3
Number of PUSCH repetitions	2	3
HARQ process number	3	1
MCS	4	4
RV	2	–
New data indicator	1	1
CSI request	1	–
SRS request	0/1	–
Downlink assignment index/uplink index	2	–
PUSCH power control	2	–
Number of MPDCCH repetitions	2	2
Flag for 6-0/6-1 differentiation	1	1

[a]*Number of bits depends on the system bandwidth.*

resource blocks of the narrowband. Note that this is essentially the same as uplink resource-allocation type 0 used for normal (non-eMTC) uplink grants, see Chapter 6, where the bandwidth of the carrier has been replaced by the "bandwidth" of a single narrowband, that is, six resource blocks.

For DCI format 6-0B, used for CE mode B, the resource-block indicator consists of 3 bits indicating eight sets of consecutive resource block. Thus, there are some restrictions in what resource-block combinations that can be assigned. This is similar to downlink scheduling assignments for CE mode B (DCI format 6-1B), although the restrictions are less for DCI format 6-0B (eight different combinations) compared to DCI format 6-1B (only two combinations).

The timing for uplink scheduling grants is the same as for other (non-eMTC) PUSCH. In other words, a scheduling grant *ending* in downlink subframe n is valid for an uplink PUSCH transmission starting in uplink subframe $n+4$. Note that, due to repetition, the eMTC scheduling grant may be transmitted over several downlink subframes. Similarly, the scheduled PUSCH transmission may extend over several uplink subframes.

Similar to the downlink, in case of frequency hopping the resource grant provides the narrowband of the first transmission. Narrowbands for subsequent repetitions are then given by cell-specific offsets relative to the first transmission. For the uplink, frequency hopping, if configured, always takes place between only two narrowbands.

Also similar to the downlink, in case of CE mode A, frequency hopping can be dynamically disabled by means of a frequency-hopping flag in the scheduling grant.

20.3.4.2 Uplink Hybrid ARQ

As described in Chapter 8, the baseline LTE uplink hybrid ARQ is *synchronous* and *non-adaptive*. More specifically,

- a single-bit hybrid-ARQ acknowledgment transmitted on the downlink PHICH physical channel is provided at a specific time instant relative to the uplink PUSCH transmission to be acknowledged;
- depending on the detected hybrid-ARQ acknowledgment, there is a well-defined retransmission carried out at a specific relative time instant, more exactly eight subframes after the prior transmission;
- the retransmission is carried out on the same frequency resource as the original transmission.

As the PHICH is a wideband transmission spanning the entire carrier bandwidth, it cannot be received by an narrowband eMTC device. Thus, the pre-release 13 uplink HARQ procedure cannot be applied to eMTC devices.

As also described in Chapter 8, there is, in general, a possibility to override the PHICH by explicitly scheduling a retransmission using a scheduling grant on PDCCH or EPDCCH. This allows for *adaptive* retransmissions—that is, the retransmission can be scheduled on a different frequency resource, compared to the prior transmission. However, the retransmission will still occur at a specific time instant, that is, retransmissions are still synchronous.

For eMTC devices uplink retransmissions are *always* explicitly scheduled, that is, eMTC device are not assumed to receive HARQ acknowledgments on the PHICH. As there is no PHICH to which the explicit retransmission requests have to be time aligned, eMTC uplink retransmissions are also *asynchronous*, that is, there is no strict relation between the timing of the initial transmissions and the timing of the requested retransmission.

As shown in Table 6.7 in Chapter 6, DCI format 0 and 4, providing scheduling grants for uplink non-eMTC transmissions, include a new data indicator (NDI) to support the explicit scheduling of uplink retransmissions. Due to the asynchronous HARQ, the scheduling grant for eMTC devices (DCI format 6-0A and 6-0B, see earlier) also includes a HARQ process indicator. For CE mode A, there are a total of eight HARQ processes, (corresponding to a 3-bit HARQ-process indicator) while CE mode B is limited to two HARQ processes (1-bit HARQ-process indicator).

20.3.4.3 PUCCH

As described in Chapter 7, UCI, including CSI reports, scheduling requests and hybrid-ARQ acknowledgments, are carried on the PUCCH physical channel. Each PUCCH transmission covers one subframe and is frequency-wise located at the edge of the carrier with frequency hopping on slot level. There are several different PUCCH formats associated with different payload sizes and, in practice, addressing different types of UCI.

UCI is needed also for eMTC. However, due to the limited set of supported transmission modes, as well as other limitations, not all PUCCH formats need to be supported for eMTC.

More specifically, only PUCCH formats 1, 1A, and 2 are supported in case of FDD while, for TDD, also PUCCH format 2A is supported.

The structure of each PUCCH transmission is also somewhat different, compared to the conventional (non-eMTC) PUCCH transmission.

Similar to other physical channels, repetition can be applied to PUCCH transmission, where the number of repetitions is configured by the network:

- For CE mode A, the number of repetitions can be 1 (no repetitions), 2, 4, and 8.
- For CE mode B, the number of repetitions can be 4, 8, 16, and 32.

In contrast to PDSCH, MPDCCH, and PUSCH, it is thus not possible to dynamically vary the number of repetitions for PUCCH.

PUCCH frequency hopping in case of eMTC PUCCH is carried out in blocks of N_{hop} subframes, rather than on slot level which is used for PUCCH for non-eMTC devices. This means that, in case the number of repetitions is configured to be smaller or equal to the frequency hopping-block length N_{hop}, there may be no PUCCH frequency hopping for eMTC. Especially, in case of no repetitions ($N_{\mathrm{rep}} = 1$), there is no frequency hopping for eMTC devices.

20.3.4.4 Uplink Power Control

Uplink power control (PUSCH and PUCCH) for eMTC devices differs depending on if the device is configured for coverage extension mode A or coverage extension mode B.

In case of coverage extension mode A, uplink power control is essentially the same as for non-eMTC devices as described in Chapter 7 where, in case of eMTC devices, power control commands are provided within DCI format 6-0A (uplink scheduling grants) and 6-1A (downlink scheduling assignments). eMTC devices can also receive the power-control-specific DCI formats 3 and 3A. In case of repetition, the transmit power is unchanged for the set of subframes over which the repetition is carried out.

In case of coverage extension mode B, which is assumed to be used in the most severe propagation conditions, the transmit power is always set to the maximum per-carrier transmission power for both PUCCH and PUSCH transmissions. For this reason there are also no power-control commands included in DCI formats 6-0B and 6-1B.

20.3.5 SYNCHRONIZATION SIGNALS AND BCH

The LTE synchronization signals (PSS/SSS) and the PBCH are confined within the 72 center subcarriers of a carrier. Thus they can be received also by eMTC devices having an RF front end with a bandwidth limited to 1.4 MHz, despite that they are not necessarily confined within a single narrowband.

The synchronization signals are used unchanged for eMTC devices. As these signals do not vary in time, extended coverage can be achieved by having devices accumulating the received signal for longer time when searching for PSS/SSS. This may result in longer search

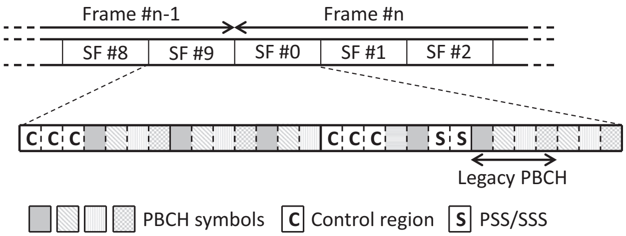

FIGURE 20.6

PBCH mapping for eMTC (FDD).

time, both at initial access and for mobility. However, as latency is not considered a critical parameter for massive-MTC applications, and the devices can be assumed to be stationary or of low mobility at least in case of the massive-MTC applications for which a large amount of coverage extension is important, this has been considered acceptable.

As described in Chapter 11, the coded BCH transport block is mapped to the first subframe of four consecutive frames. In each of these subframes, the PBCH is transmitted within the first four OFDM symbols of the second slot. Each BCH transport block is thus transmitted over a total of 16 OFDM symbols (four subframes and four OFDM symbols in each subframe).

To extend coverage, the PBCH is repeated a factor 5, that is, each BCH transport block is transmitted over a total of 80 OFDM symbols. Exactly how this is done differs somewhat between FDD and TDD.

For FDD, the four OFDM symbols of subframe 0 are repeated in five additional symbols in subframe 0 and eleven symbols in subframe 9 of the preceding frame, see Figure 20.6. Each symbol is thus repeated four times. For TDD, PBCH is likewise transmitted in subframes 0 and 5.[9]

If the five times repetition does not provide sufficient coverage, additional power boosting can be used to further extend the coverage of the PBCH.

The mapping of the repeated PBCH symbols is done such that a modulation symbol is repeated on the same subcarrier as the original symbol. This allows for the PBCH to be used for frequency tracking by the device, without having to decode the PBCH.

Note that the PBCH structure described above is not a new physical channel. Rather, the pre-release-13 PBCH is extended in a backward compatible way to support extended coverage. Legacy devices can still detect the PBCH and thus acquire the master information block (MIB), by just receiving the four pre-release 13 OFDM symbols in the second slot.

This also means that the MIB transmitted on the BCH still contains all the legacy information expected by pre-release 13 devices. Additional eMTC-specific information on the MIB

[9]This is true for the case of normal cyclic prefix. In case of an extended cyclic prefix, each symbol is repeated only three times and in somewhat different symbols, compared to normal cyclic prefix.

is provided by using 5 of the original 10 "spare bits" of the BCH, see Chapter 11. These 5 bits are used to convey information about the scheduling of SIB1-BR, see the following section.

20.3.6 SYSTEM-INFORMATION BLOCKS

As discussed in Chapter 11, the MIB only includes a very minor amount of system information, while the main part of the system information is included in different system-information blocks (SIBs) transmitted using the normal data-delivery mechanisms (DL-SCH marked with SI-RNTI). The scheduling of SIB1 is fixed in the specification while information about the time-domain scheduling of the remaining SIBs is included in SIB1.

As the legacy SIB1 may have a bandwidth exceeding six resource blocks and may consist of up to 2216 bits, it cannot be received by eMTC devices which are limited to a 1.4 MHz bandwidth and a maximum transport-block size of 1000 bits. Thus, for eMTC, a new SIB1, referred to as SIB1 *bandwidth-reduced* (SIB1-BR) was introduced.

SIB1-BR is transmitted over six resource blocks (one narrowband) and repeated a number of times per 80 ms interval. Although SIB1-BR is formally transmitted on PDSCH, repetition is done in a different way compared to other PDSCH transmissions. As described in earlier sections, in normal case PDSCH repetitions are carried out over contiguous valid subframes. However, for SIB1-BR the repetitions are equally spaced in time during the 80 ms period:

- For a repetition factor of 4, SIB1-BR is transmitted in one subframe every second frame.
- For a repetition factor of 8, SIB1-BR is transmitted in one subframe every frame.
- For a repetition factor of 16, SIB1-BR is transmitted in two subframes every frame.

The exact set of frames/subframes in which SIB1-BR is transmitted is provided in Table 20.4.

Information about the SIB1-BR repetition factor (4, 8, or 16) and transport block size (six different sizes) are included in the MIB, using 5 of the original 10 spare bits.

SIB1-BR then includes scheduling information for the remaining SIBs relevant for eMTC devices.

Table 20.4 Set of Subframes in Which SIB1-BR is Transmitted

		FDD		TDD	
Repetition Factor	**PCID**	**SFN**	**Subframe**	**SFN**	**Subframe**
4	Even	Even	4	odd	5
	Odd	Odd	4	odd	0
8	Even	Any	4	any	5
	Odd	Any	9	any	0
16	Even	Any	4 and 9	any	0 and 5
	Odd	Any	0 and 9	any	0 and 5

20.3.7 RANDOM ACCESS

As described in Chapter 11, the LTE random-access procedure consists of four steps:

Step 1: Uplink preamble transmission.
Step 2: Downlink random-access response providing timing-advance command and uplink resource for step 3.
Step 3: Uplink transmission of mobile-terminal identity.
Step 4: Downlink transmission of contention-resolution message.

As also described in Chapter 11, steps 2–4 use the same physical-layer functionality as normal uplink and downlink data transmission. They can thus directly rely on the repetition for PDSCH, MPDCCH, PUCCH, and PUSCH for CE described earlier.

To provide CE for the entire random-access procedure, repetition can also be applied to the preamble transmission.

As described in Chapter 11, the random-access (preamble) resource consists of a frequency block with a bandwidth corresponding to six resource blocks occurring in a set of subframes. In each cell there is one PRACH configuration defining

- the preamble format;
- the exact frequency resource used for PRACH transmissions;
- the exact set of subframes in which PRACH can be transmitted.

For the preamble transmission, the device selects a preamble from the set of available preambles and transmits it with the specified power. If a random-access response (step 2) is detected within the configured time window, the random-access procedure continues with steps 3 and 4. If no random-access response is detected, the procedure will be repeated, possibly with an increased transmission power.

For eMTC devices, up to four different random-access *CE levels* can be defined, each associated with its own PRACH configuration and corresponding PRACH resource.[10] Especially, the different CE levels can be associated with different frequency resources. A device selects the CE level based on its estimated path loss. In this way, random-access attempts from devices that are in very different coverage situations within a cell can be kept separate and not interfere with each other.

Each CE level is also associated with a specific repetition number indicating the number of repetitions to be used for the preamble transmission. The device selects a corresponding CE level, carries out a sequence of consecutive preamble transmissions according to the indicated number of repetitions and waits for a random-access response in the same way as for non-eMTC devices. If a random-access response in detected within the configured window, the random-access procedure continues with steps 3 and 4. If no random-access response is detected, the procedure is repeated a specified number of times. If no random-access response

[10]Note that the up to four CE levels are different from the two CE modes discussed earlier.

is detected within the specified number of attempts, the device moves the next higher CE level and repeats the procedure.

As discussed earlier, each active eMTC device is configured with a CE mode, limiting, for example, how many repetitions are carried out and determining, for example, what DCI formats are valid.

During random access, a device is not yet in RRC_CONNECTED state and has thus not been configured with a specific CE mode. Still, the different messages transmitted during steps 2−4 of random-access procedure are carried using the normal CE mechanisms for PDSCH, MPDCCH, PUCCH, and PUSCH assuming a certain CE mode. More specifically, for steps 2−4 of the random-access procedure, the device should assume.

- CE mode A if the latest PRACH (preamble) transmission used the resources associated with CE level 0 or 1.
- CE mode B if the latest PRACH transmission used the resources associated with CE level 2 or 3.

20.3.8 EXTENDED DRX

To reduce energy consumption and extend battery life, a device can enter DRX as described in Chapter 9. In DRX, a device monitors downlink control signaling in one subframe per *DRX cycle* and can be asleep during the remaining time of the cycle. A device can be in DRX in both connected and idle state, where DRX in idle state corresponds to a device being asleep and only waking up to check for paging messages, see Chapter 13.

From the first release of LTE, the DRX cycle has been limited 256 frames or 2.56 s. This has been sufficient for conventional mobile broadband devices for which longer time for access is typically anyway not acceptable. However, for some massive MTC applications for which very long battery life is a requirements and which, at the same time, can accept very long latency when accessing the network, the possibility for longer DRX/sleep cycles would be desirable.

As described in Section 20.1, LTE release 12 introduced PSM for reduced energy consumption and corresponding extended battery life. PSM is an excellent mechanism for applications characterized by device-triggered communication. However, it is not suitable for applications where the network needs to initiate communication as a device that has entered PSM cannot be paged by the network.

To further reduce device energy consumption for applications characterized by network-initiated traffic that is not latency critical, *extended DRX* was introduced as part of LTE release 13.

In extended DRX, the DRX cycle can be extended to 1024 frames corresponding to 10.24 s for devices in connected state and up 262144 frames corresponding to 2621.44 s or close to 44 min for devices in idle state.

To handle such very long DRX cycles that exceed the range of the SFN, a new 10-bit hyper-SFN (HSFN) has been defined. In contrast to the SFN, which is provided on the MIB, the HSFN is provided within SIB1.

20.4 NARROW-BAND INTERNET OF THINGS

20.4.1 BACKGROUND

In parallel to the release 12/13 activities discussed earlier to enhance the LTE support for massive-MTC applications, a separate activity related to low-cost MTC devices was initiated within the 3GPP GERAN group—that is, the 3GPP group responsible for the GSM technical specifications. Even today, GSM is by far the most dominating cellular technology for truly low-cost MTC applications, and the aim of the GERAN activities was to develop a technology that could eventually replace GSM for these applications. For reasons explained in the following, this activity was referred to as NB-IoT.

A key requirement for NB-IoT was that it should be truly narrowband, with an RF bandwidth in the order of 200 kHz or less, in order to be able to replace GSM carriers with NB-IoT carriers on a carrier-by-carrier basis. It should also be possible to deploy an NB-IoT carrier within the guard bands of LTE carriers, see Figure 20.7.

Several different technologies were considered as part of the NB-IoT work in GERAN, most of which were very different from LTE. However, late in the process it was decided to move the NB-IoT activities from GERAN to 3GPP RAN—that is, the 3GPP group responsible for the LTE technical specifications. At the same time an additional NB-IoT requirement was introduced, namely that, in addition to being able to be deployed in LTE guard bands, an NB-IoT carrier should also be able to efficiently coexist *within* an LTE carrier, see Figure 20.8.

While deployment in LTE guard bands essentially just requires a sufficiently narrowband carrier, the later requirement puts much stronger constraints on the NB-IoT physical-layer design. As a consequence, it was concluded that at least the NB-IoT downlink should have a physical-layer structure aligned with LTE, that is, OFDM with a subcarrier spacing of

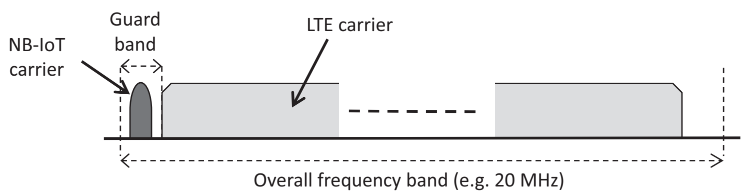

FIGURE 20.7

NB-IoT deployed in LTE guard band.

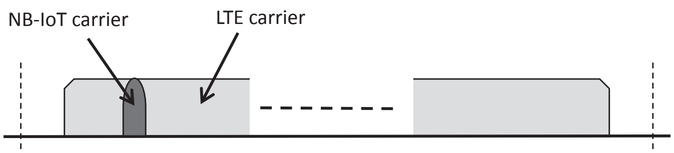

FIGURE 20.8

NB-IoT deployed within an LTE carrier.

15 kHz. This turned the NB-IoT activity from being a completely separate technology track to becoming much more integrated with the main stream evolution of LTE.

The rest of this section provides an overview of the current technical status of NB-IoT. It should be pointed out though that the work on NB-IoT is at the time of this writing still ongoing in 3GPP and details may still be changed/updated.

20.4.2 NB-IOT DEPLOYMENT MODES

As discussed earlier, there are three different deployment modes for NB-IoT:

- Deployment in spectrum of its own, for example, in spectrum refarmed from GSM. This is referred to as *stand-alone deployment*.
- Deployment within the guard band of an LTE carrier, referred to as *guard-band deployment*.
- Deployment within an LTE carrier, referred to as *inband deployment*.

It should be pointed out that, even in case of inband deployment, NB-IoT should be seen as a carrier of its own, separate from the LTE carrier.

20.4.3 DOWNLINK DATA TRANSMISSION

On the downlink, NB-IoT is based on OFDM transmission fully aligned with LTE, that is, with a subcarrier spacing of 15 kHz and the same basic time-domain structure as LTE.

Each NB-IoT carrier consists of 12 subcarriers. In other words, each NB-IoT carrier corresponds to a single LTE resource block in the frequency domain.

In case of stand-alone and guard-band deployment the entire resource block is available for NB-IoT transmissions.[11] On the other hand, in case of inband deployment NB-IoT transmissions will avoid the control region of the LTE carrier within which the NB-IoT carrier is deployed. This is done by not transmitting during the few first OFDM symbols of the subframe. The exact number of symbols to avoid is provided as part of the NB-IoT system information, see Section 20.4.5. Transmissions on an inband NB-IoT carrier will also avoid the resource elements corresponding to CRS transmission on the LTE carrier within which the NB-IoT carrier is deployed.

NB-IoT downlink data transmission is based on two physical channels:

- The *narrowband PDCCH* (NPDCCH) carrying scheduling information, that is, scheduling assignments/grants for downlink and uplink transport-channel transmission.
- The *narrowband PDSCH* (NPDSCH) carrying the actual downlink transport-channel data.

Within a resource block, either NDPCCH or NDPSCH is transmitted. In addition, NB-IoT reference signals (NRS) corresponding to up to two antenna ports are included in the last two OFDM symbols of each slot, see Figure 20.9.

[11] Not true for subframes carrying the NPBCH physical channel, see Section 20.4.5.

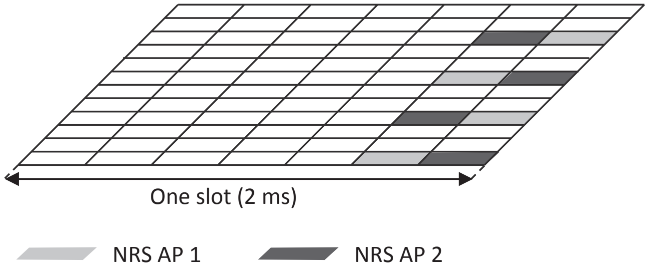

FIGURE 20.9

NRS structure.

Up to two NDPCCH can be frequency multiplexed within a subframe. Downlink scheduling assignment for NB-IoT is inter-subframe, that is, a scheduling assignment on NPDCCH ending in subframe n relates to a corresponding NPDSCH transmission starting in subframe $n + \Delta$. This is similar to eMTC, see Section 20.3.3.3. However, while for eMTC the time offset between the end of the NPDCCH transmission and the start of the corresponding NPDSCH transmission is fixed to two subframes, in case of NB-IoT the time offset Δ can vary dynamically with information about the time offset provided as part of the scheduling assignment. The possibility for different time offset allows for the transmission of scheduling assignments to two different devices in the same subframe even though their corresponding NPDSCH transmissions have to occur in different subframes.[12]

Channel coding for downlink data (the DL-SCH transport channel) is based on the same tail-biting convolutional code as used for downlink control signaling in LTE, see Chapter 6. The main reason for using tail-biting convolutional coding, rather than Turbo coding as is used for DL-SCH in LTE, is to reduce the channel-decoding complexity at the device side. NB-IoT downlink modulation is limited to QPSK.

In terms of multi-antenna transmission, NB-IoT supports transmission from one antenna port or two antenna ports. In case of two antenna ports transmission is based on space-frequency block codes (SFBC) as is also used for LTE transmission mode 2, see Chapter 6.

20.4.4 UPLINK TRANSMISSION

In contrast to the downlink there are two different modes with different numerologies for the NB-IoT uplink:

- one mode based on a 15 kHz subcarrier spacing;
- one mode based on 3.75 kHz subcarrier spacing.

The numerology of the 15-kHz mode is fully aligned with LTE. However, in contrast to LTE, uplink transmissions from a device can be carried out over only a subset of the

[12]There can only be one NPDSCH transmission per subframe within an NB-IoT carrier.

subcarriers of a resource block. More specifically, uplink transmission can be carried out over one, three, six, or twelve subcarriers, where transmission over twelve subcarriers corresponds to the full NB-IoT carrier bandwidth. The reason for allowing for transmission over only a fraction of the total NB-IoT carrier bandwidth is that, in extreme coverage situations, a device may not be able to transmit with a data rate that justifies the use of such large bandwidths. By transmitting over only a fraction of the subcarriers, that is, over only a fraction of the NB-IoT carrier bandwidth, multiple devices can be frequency multiplexed within one uplink carrier, thereby allowing for more efficient resource utilization.

In case of transmission over 12 subcarriers, the minimum scheduling granularity in the time domain is 1 ms (one subframe or two slots). For smaller assigned bandwidths, the scheduling granularity is increased to 2 ms (two subframes), 4 ms (four subframes), and 8 ms (eight subframes) for transmission over six, three, and one subcarrier, respectively.

In case of 3.75 kHz subcarrier spacing, there can be up to 48 subcarriers within the NB-IoT uplink bandwidth. However, each uplink transmission only consists of *a single subcarrier*. As a consequence, the 3.75-kHz uplink mode only supports very low uplink data rates.

The time-domain structure of the 3.75-kHz uplink mode is outlined in Figure 20.10. As can be seen, the time-domain structure is not a direct factor-of-four scaling of the LTE numerology. Especially, even though the cyclic prefix for the 3.75-kHz mode is longer than the cyclic prefix of the 15-kHz mode, it is not four times longer. As a consequence, there is an idle time at the end of each subframe. In case of inband deployment, this idle time could, for example, be used to reduce interference to SRS transmissions on the uplink LTE carrier.

For the 3.75-kHz uplink mode the time-domain scheduling granularity is 16 slots or 32 ms.

Scheduling grants for uplink transmissions are provided on the NDPCCH. Similar to the downlink, the time offset between the NDPCCH transmission and the start of the corresponding uplink transmission can vary dynamically with the exact offset provided as part of scheduling grant.

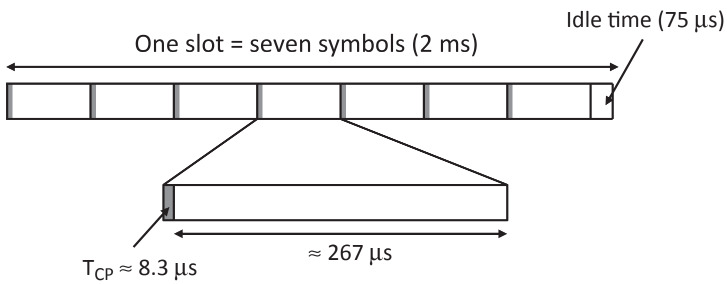

FIGURE 20.10

Time-domain structure of 3.75-kHz uplink mode.

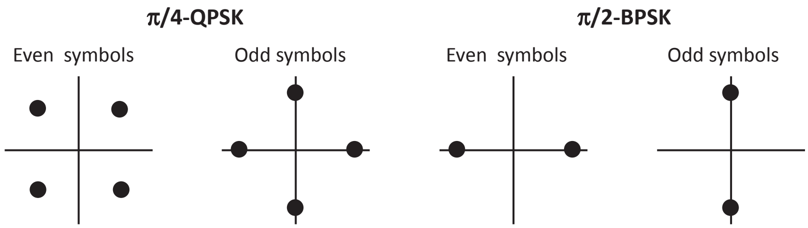

FIGURE 20.11

Constellations for π/4-QPSK and π/2-BPSK modulation.

Channel coding for UL-SCH is, for NB-IoT, based on the same Turbo coding as for LTE. Although decoding of Turbo codes is relatively complex, thus the use of tail-biting convolutional coding for the NB-IoT downlink, encoding for Turbo codes is of low complexity.

In case of transmission over multiple subcarriers, uplink modulation is based on conventional QPSK. However, in case of single-subcarrier transmission (both 15 kHz and 3.75 kHz), modulation is based on π/4-QPSK or π/2-BPSK. As shown in Figure 20.11, π/4-QPSK is the same as QPSK but where the entire constellation is shifted an angle of π/4 for odd-numbered symbols. Likewise, π/2-BPSK is the same as BPSK with the constellation shifted an angle of π/2 for odd-numbered symbols. The error performance of π/4-QPSK and π/2-BPSK is identical to that of QPSK and BPSK. However, the phase shift between consecutive symbols leads to a further reduced cubic metric, thereby enabling higher power-amplifier efficiency.

After modulation, DFT-precoding is applied in the same way as for the LTE uplink. Note that in case of transmission using a single subcarrier the DFT precoding has no effect.

20.4.5 NB-IOT SYSTEM INFORMATION

Similar to LTE, NB-IoT system information consists of two parts:

- A MIB transmitted on a special physical channel (NPBCH).
- SIBs transmitted in, essentially, the same way as any other downlink data. Information about the scheduling of SIB1 is provided in the MIB while the scheduling of the remaining SIBs is provided on SIB1.

As illustrated in Figure 20.12, the NPBCH is transmitted in subframe 0 in every frame with each transport block transmitted over a total of 64 subframes (640 ms). The TTI of the NPBCH (strictly speaking, the TTI of the BCH transport channel transmitted on the NPBCH) is thus 640 ms.

The transmission of NPBCH always “assumes” inband deployment in the sense that the NPBCH transmissions:

- avoid the first three symbols of the subframe;
- avoid the possible location of LTE CRS.

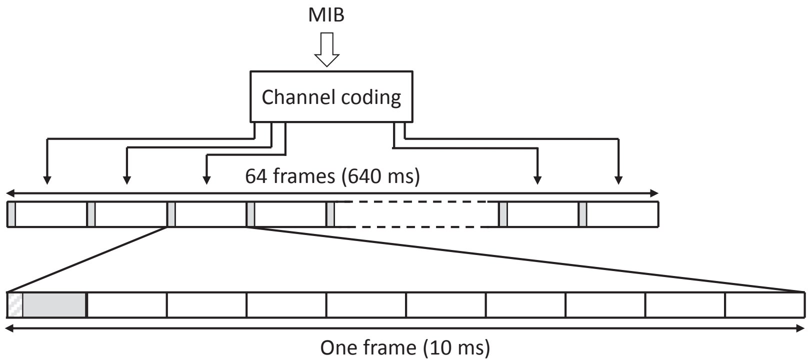

FIGURE 20.12

NB-IoT system information.

This makes it possible for a device to detect and decode the corresponding system information, without knowing if the NB-IoT carrier is deployed inband or not. Information about the deployment mode is then provided as part of the system information on SIB1.