CHAPTER

5

LTE-M

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Abstract

In this chapter, we describe the *Long-Term Evolution for Machine-Type Communications* (LTE-M) technology with an emphasis on how it is designed to fulfill the objectives that LTE-M targets, namely achieving low device cost, deep coverage and long battery lifetime while maintaining capacity for a large number of devices per cell, with performance and functionality suitable for both low-end and mid-range applications for the Internet of Things.

Section 5.1 describes the background behind the introduction of LTE-M in the Third Generation Partnership Project (3GPP) specifications and the design principles of the technology. Section 5.2 focuses on the physical channels with an emphasis on how these channels were designed to fulfill the objectives that LTE-M was intended to achieve. Section 5.3 covers LTE-M procedures in idle and connected mode, including all activities from initial cell selection to completing a data transfer. The idle mode procedures include the initial cell selection, which is the procedure that a device has to go through when it is first switched on or is attempting to select a new cell to camp on. Idle mode activities also include acquisition of system information, paging, random access, and multicast. Descriptions of some fundamental connected mode procedures include scheduling, power control, mobility, and positioning. Both the fundamental functionality introduced in 3GPP Release 13 and the improvements introduced in Release 14 and Release 15 are covered. Finally, coexistence between LTE-M and *Fifth Generation* (5G) *New Radio* (NR) is presented in Section 5.4. The performance of LTE-M including its fulfillment of 5G mMTC requirements is covered in Chapter 6.

5.1 Background

In this section we describe the introduction of *Long-Term Evolution for Machine-Type Communications* (LTE-M) into the 3GPP specifications and the design principles. The design principles were adopted in order to achieve the required low device complexity and cost, coverage enhancement, long device battery lifetime and support of massive number of devices for the massive Internet of Things (IoT) segment. In addition, the design was required to support adequate peak rates and mobility support to be able to address more demanding applications such as voice services, and ensuring high deployment flexibility and coexistence with ordinary LTE.

5.1.1 3GPP standardization

LTE-M extends LTE with features for improved support for *Machine-Type Communications* (MTC) and IoT. These extensions have their origin in the 3GPP study item *Study on provision of low-cost MTC User Equipments based on LTE* [1], in this book referred to as the *LTE-M study item*.

Since the conclusion of the LTE-M study item, a number of related 3GPP work items have been completed, starting with an initial Release 12 work item that can be seen as a precursor for the more ambitious Release 13 work item:

- Release 12 work item *Low cost and enhanced coverage MTC UE for LTE* [2], sometimes referred to as the *MTC work item*, which introduced LTE device category 0 (Cat-0)
- Release 13 work item *Further LTE Physical Layer Enhancements for MTC* [3], sometimes referred to as the *eMTC work item*, which introduced the Coverage Enhancement (CE) modes A and B as well as LTE device category M1 (Cat-M1)

In this book we use the term LTE-M when we refer to the Cat-M device category series, the CE modes, and all functionality that can be supported by the Cat-M devices or the CE modes, such as the power consumption reduction techniques *Power Saving Mode* (PSM) and *Extended Discontinuous Reception* (eDRX). According to this definition, all LTE devices (including Cat-0 devices) that implement CE mode support are considered LTE-M devices, but if they do not implement CE mode support then they are not considered LTE-M devices. Cat-M devices have mandatory support for CE mode A and are always considered LTE-M devices.

Already, many LTE-M networks have been deployed and a device ecosystem has been established. The GSM Association (GSMA), which is an organization that represents the interests of mobile network operators worldwide, tracks the status of commercial launches of LTE-M. Since the completion of Release 13 LTE-M in March 2016, there had been more than 30 LTE-M launches in over 25 markets as of June 2019, according to GSM Association [4]. On the device side, the Global Mobile Suppliers Association (GSA) published a research report in 2018 [5] stating that as of August 2018, there were 101 modules supporting LTE-M, 48 of which also support NB-IoT.

Release 13 laid the foundation for LTE-M in the form of low-cost devices and coverage enhancements, but the LTE-M standard has been further evolved in Releases 14 and 15:

- Release 14 work item *Further Enhanced MTC for LTE* [6], sometimes referred to as the *feMTC work item*, which introduced various improvements for support of higher data rates, improved VoLTE support, improved positioning, multicast support, as well as the new LTE device category M2 (Cat-M2)
- Release 15 work item *Even Further Enhanced MTC for LTE* [7], sometimes referred to as the *efeMTC work item*, which introduced further improvements for reduced latency and power consumption, improved spectral efficiency, new use cases, and more

TABLE 5.1 New LTE-M features introduced in 3GPP Releases 14 and 15.

Release 14 (2017)	Section	Release 15 (2018)	Section
Support for higher data rates		**Support for new use cases**	
• New device category M2	5.2.3	• Support for higher device velocity	5.3.2.5
• Higher uplink peak rate for Cat-M1	5.2.3	• Lower device power class	5.1.2.1
• Wider bandwidth in CE mode	5.2.2.3		
• More downlink HARQ processes in FDD	5.3.2.1.1	**Reduced latency**	
• ACK/NACK bundling in HD-FDD	5.3.2.1.1	• Resynchronization signal	5.2.4.2.2
• Faster frequency retuning	5.2.4.1	• Improved MIB/SIB performance	5.3.1.2.1
		• System info update indication	5.3.1.2.3
VoLTE enhancements			
• New PUSCH repetition factors	5.2.5.4	**Reduced power consumption**	
• Modulation scheme restriction	5.2.5.4	• Wake-up signals	5.2.4.5
• Dynamic ACK/NACK delays	5.3.2.1.1	• Early data transmission	5.3.1.7.3
		• ACK/NACK feedback for uplink data	5.3.2.1.2
Coverage improvements		• Relaxed monitoring for cell reselection	5.3.2.5
• SRS coverage enhancement	5.2.5.3.2		
• Larger PUCCH repetition factors	5.2.5.5	**Increased spectral efficiency**	
• Uplink transmit antenna selection	5.2.5.4	• Downlink 64QAM support	5.2.4.7
		• CQI table with large range	5.3.2.2
Multicast support	5.3.1.9	• Uplink sub-PRB allocation	5.2.5.4
Improved positioning	5.3.2.6	• Flexible starting PRB	5.3.2.1
Mobility enhancements	5.3.2.5	• CRS muting	5.2.4.3.1
		Improved access control	5.3.1.8

Table 5.1 provides a summary of the LTE-M enhancements introduced in 3GPP Releases 14 and 15, with references to the relevant book sections. All the Releases 14 and 15 features can be enabled through a software upgrade of the existing LTE network equipment. In many cases it may also be possible to upgrade the software/firmware in existing devices to support the new features.

In Release 15, 3GPP evaluated LTE-M against a set of agreed *Fifth Generation* (5G) performance requirements defined for the *massive machine-type communications* (mMTC) use case [8]. As shown in Chapter 6, LTE-M meets these requirements with margins and does in all relevant aspects qualify as a 5G mMTC technology. As we will see in Section 5.4, LTE-M is also able to coexist efficiently with the 5G New Radio (NR) air interface introduced in Release 15.

5.1.2 Radio Access Design Principles

5.1.2.1 Low device complexity and cost

During the LTE-M study item [1], various device cost reduction techniques were studied, with the objective to bring down the LTE device cost substantially to make LTE attractive for low-end MTC applications that have so far been adequately handled by GSM/GPRS. It was estimated that this would correspond to a device modem manufacturing cost in the order of 1/3 of that of the simplest LTE modem, which at that time was a single-band LTE device Cat-1 modem.

The study identified the following cost reduction techniques as most promising:

- Reduced peak rate
- Single receive antenna
- Half-duplex operation
- Reduced bandwidth
- Reduced maximum transmit power.

A first step was taken in Release 12 with the introduction of LTE device Cat-0 that supported a reduced peak rate for user data of 1 Mbps in downlink and uplink (instead of at least 10 Mbps in downlink and 5 Mbps in uplink for Cat-1 and higher categories), a single receive antenna (instead of at least two), and optionally *half-duplex frequency-division duplex* (HD-FDD) operation.

The next step was taken in Release 13 with LTE device Cat-M1 that includes all the cost reduction techniques of Cat-0, plus a reduced bandwidth of 1.4 MHz (instead of 20 MHz), and optionally a lower device power class with a maximum transmit power of 20 dBm (instead of 23 dBm). Release 15 introduces an even lower 14-dBm power class to enable implementation of devices with low power consumption and small form factor, see Section 5.2.3.

With the cost reduction techniques introduced in Release 13, the *Bill of Material* cost for the Cat-M1 modem was estimated to reach that of an Enhanced GPRS modem. For further information on LTE-M cost estimates, refer to Section 6.7.

5.1.2.2 *Coverage enhancement*

The LTE-M study item [1] also studied coverage enhancement (CE) techniques, with the objective to improve coverage of LTE networks at that time by 20 dB to provide coverage for devices with challenging coverage conditions, for example stationary utility metering devices located in basements.

The study identified various forms of prolonged transmission time as the most promising coverage enhancement techniques. The fact that many of the IoT applications of interest have very relaxed requirements on data rates and latency can be exploited to enhance the coverage through repetition or retransmission techniques. The study concluded that 20 dB coverage enhancement can be achieved using the identified techniques.

Release 13 standardized two *CE modes*: CE mode A, supporting up to 32 repetitions for the data channels, and CE mode B, supporting up to 2048 repetitions. Recent evaluations show that the initial coverage target of 20 dB can be reached using the repetitions available in CE mode B. For further information on LTE-M coverage and data rate estimates, refer to Sections 6.2 and 6.3.

In this book we refer to LTE devices with CE mode support as *LTE-M devices*. These devices may be low-cost *Cat-M devices*, or they may be higher LTE device categories configured in a CE mode. For more information on the CE modes refer to Section 5.2.2.3.

5.1.2.3 Long device battery lifetime

Support for a device battery lifetime of many years, potentially decades, has been introduced in a first step in the form of the PSM in Release 12 and in a second step in the form of the eDRX in Release 13. These features are supported for LTE-M devices and also for other 3GPP radio access technologies.

These techniques reduce the power consumption primarily by minimizing any unnecessary "on" time for the receiver and the transmitter in the device. Compared to ordinary LTE devices, LTE-M devices can have a further reduced power consumption during their "on" time mainly thanks to the reduced transmit and receive bandwidths.

PSM and eDRX are described in Sections 2.2.3, 5.3.1.4, and 5.3.1.5, and the battery lifetime for LTE-M is evaluated in Section 6.5.

5.1.2.4 Support of massive number of devices

The handling of massive numbers of devices in LTE was improved already in Releases 10 and 11, for example in the form of access class barring (ACB) and overload control, as discussed in Section 2.2.1. Further improvements have been introduced later on, for example in the form of the *Radio Resource Control (RRC) Suspend/Resume* mechanism described in Section 2.2.2, which helps reduce the required signaling when resuming an RRC connection after a period of inactivity as long as the device has not left the cell in the meanwhile.

For more information on LTE-M capacity estimates, refer to Section 6.6.

5.1.2.5 Deployment flexibility

LTE-M can be deployed in a wide range of frequency bands, as can be seen from the list of supported bands in Table 5.2. Both paired bands for frequency-division duplex (FDD) operation and unpaired bands for time-division duplex (TDD) operation are supported, and new bands have been added in every release. Even though the simplest LTE-M devices (i.e. the Cat-M devices) only support a reduced bandwidth, LTE-M supports the same system bandwidths at the network side as LTE (1.4, 3, 5, 10, 15, and 20 MHz).

5.1.2.6 Coexistence with LTE

LTE-M extends the LTE physical layer with features for improved support for MTC. The LTE-M design therefore builds on the solutions already available in LTE.

The fundamental downlink and uplink transmission schemes are the same as in LTE, meaning *Orthogonal Frequency-Division Multiplexing* (OFDM) in downlink and *Single-Carrier Frequency-Division Multiple-Access* (SC-FDMA) in uplink, with the same numerologies (channel raster, subcarrier spacing, cyclic prefix (CP) lengths, resource grid, frame structure, etc.). This means that LTE-M transmissions and LTE transmissions related to, for example, smartphones and mobile broadband modems can coexist in the same LTE cell on the same LTE carrier and the resources can be shared dynamically between LTE-M users and ordinary LTE users.

If an operator has a large spectrum allocation for LTE, then there is also a large bandwidth available for LTE-M traffic. The downlink and uplink resources on an LTE carrier can serve as a resource pool that can be fully dynamically shared between LTE traffic and LTE-M traffic. It may furthermore be possible to schedule delay-tolerant LTE-M traffic during periods when the ordinary LTE users are less active, thereby minimizing the performance impact from the LTE-M traffic on the LTE traffic.

TABLE 5.2 Frequency bands defined for Cat-M1/M2 as of Release 15 [9].

Band	Duplex mode	Uplink [MHz]	Downlink [MHz]
1	FDD	1920–1980	2110–2170
2	FDD	1850–1910	1930–1990
3	FDD	1710–1785	1805–1880
4	FDD	1710–1755	2110–2155
5	FDD	824–849	869–894
7	FDD	2500–2570	2620–2690
8	FDD	880–915	925–960
11	FDD	1427.9–1447.9	1475.9–1495.9
12	FDD	699–716	729–746
13	FDD	777–787	746–756
14	FDD	788–798	758–768
18	FDD	815–830	860–875
19	FDD	830–845	875–890
20	FDD	832–862	791–821
21	FDD	1447.9–1462.9	1495.9–1510.9
25	FDD	1850–1915	1930–1995
26	FDD	814–849	859–894
27	FDD	807–824	852–869
28	FDD	703–748	758–803
31	FDD	452.5–457.5	462.5–467.5
39	TDD	1880–1920	1880–1920
40	TDD	2300–2400	2300–2400
41	TDD	2496–2690	2496–2690
66	FDD	1710–1780	2110–2200
71	FDD	636–698	617–652
72	FDD	451–456	461–466
73	FDD	450–455	460–465
74	FDD	1427–1470	1475–1518
85	FDD	698–716	728–746

5.2 Physical layer

In this section, we describe the LTE-M physical layer design with an emphasis on how these physical signals and channels are designed to fulfill the objectives that LTE-M targets, namely low device cost, deep coverage, and long battery lifetime, while maintaining capacity for a large number of devices per cell, with performance and functionality suitable for both low-end and mid-range applications for the IoT.

5.2.1 Physical resources

5.2.1.1 Channel raster

LTE-M supports many frequency bands (see Table 5.2 for a list of supported bands) and the same system bandwidths as ordinary LTE (1.4, 3, 5, 10, 15, and 20 MHz). A *channel raster* defines the allowed carrier frequencies.

LTE-M is reusing LTE's *Primary Synchronization Signal* (PSS), *Secondary Synchronization Signal* (SSS), and the core part of the *Physical Broadcast Channel* (PBCH) carrying the *Master Information Block* (MIB). These physical signals are located in the center of the LTE system bandwidth and this center frequency is aligned with a channel raster of 100 kHz. The absolute frequency that the LTE and LTE-M system is centered around can be deduced from the *E-UTRA Absolute Radio Frequency Channel Number* (EARFCN). For more details on synchronization signals and procedures, see Sections 5.2.4.2 and 5.3.1.1.

When an LTE-M device is operating in a so-called *narrowband* or *wideband*, its center frequency is not necessarily aligned with the 100-kHz channel raster of LTE. For more information on narrowband and wideband operation, see Section 5.2.2.2.

5.2.1.2 Frame structure

The overall time frame structure on the access stratum for LTE and LTE-M is illustrated in Fig. 5.1. On the highest level one hyperframe cycle has 1024 hyperframes that each consists of 1024 frames. One frame consists of 10 subframes, each dividable into two slots of 0.5 ms as shown in the figure. Each slot is divided into 7 OFDM symbols in case of *normal CP* length and 6 OFDM symbols in case of *extended CP* length. The normal CP length is designed to support propagation conditions with a delay spread up to 4.7 μs, while the extended CP is intended to support deployments where the delay spread is up to 16.7 μs. All illustrations in this book assume the normal CP length because it is much more commonly used than the extended CP length.

Each subframe can be uniquely identified by a *hyper system frame number* (H-SFN), a *system frame number* (SFN), and *subframe number*. The ranges of H-SFN, SFN, and subframe number are 0–1024, 0–1024, and 0–9, respectively.

5.2.1.3 Resource grid

One *physical resource block* (PRB) spans 12 subcarriers, which with the 15-kHz subcarrier spacing correspond to 180 kHz. When full-PRB transmission is used, the smallest time-frequency resource that can be scheduled to a device is one PRB pair mapped over two slots,

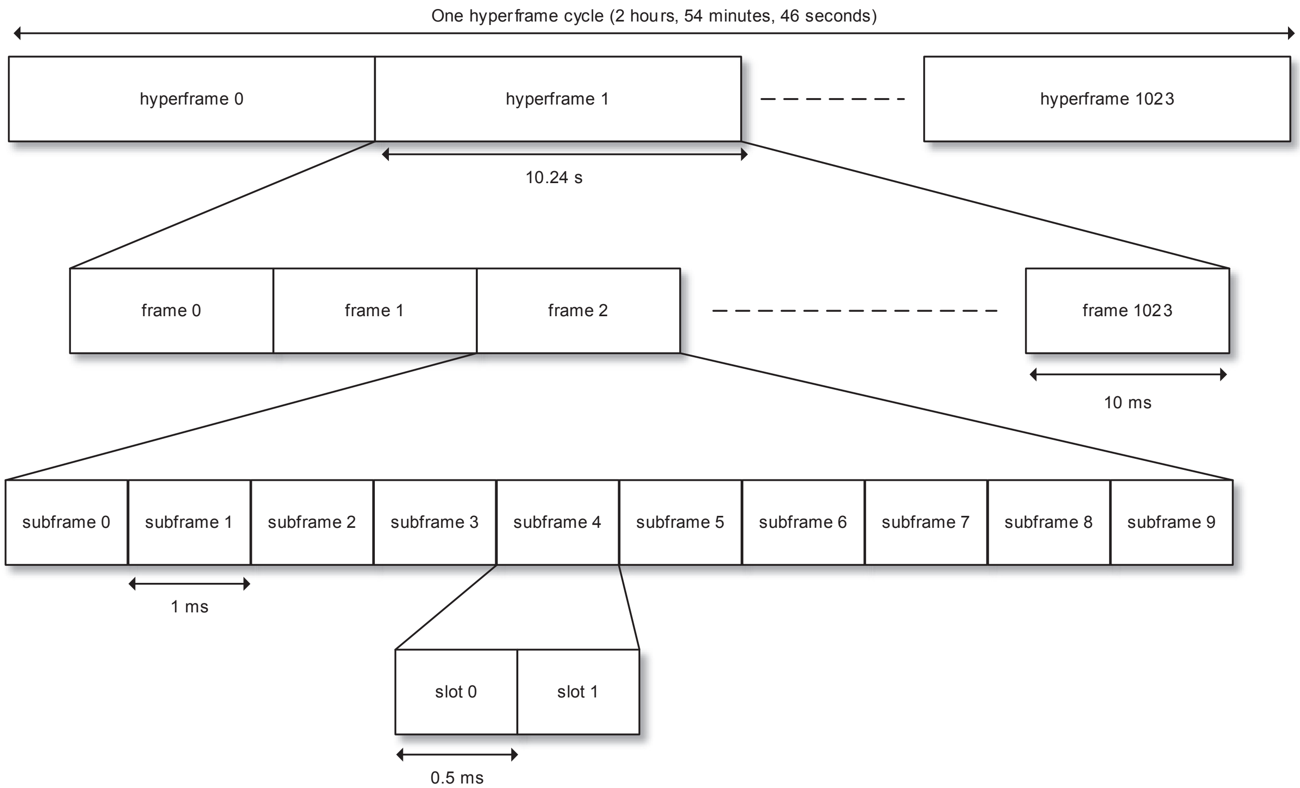

FIG. 5.1 Frame structure for LTE and LTE-M.

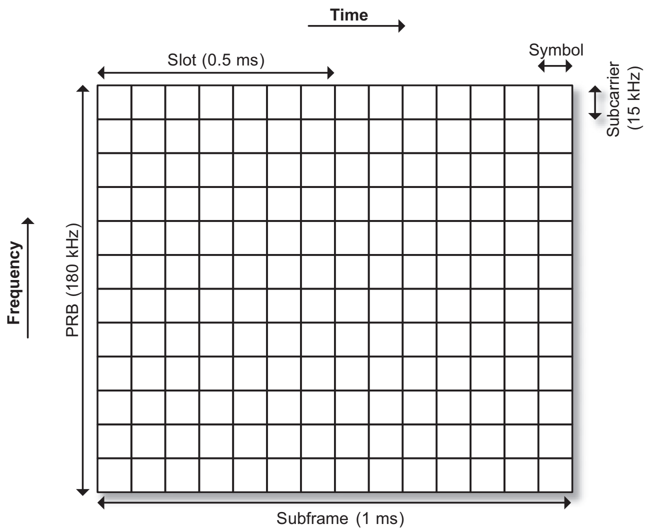

FIG. 5.2 Physical resource block (PRB) pair in LTE and LTE-M.

which for the normal CP length case (with 7 OFDM symbols per slot) corresponds to 12 subcarriers over 14 OFDM symbols as illustrated in Fig. 5.2.

Release 15 introduces sub-PRB transmission in uplink, with *resource unit* (RU) definitions according to Table 5.16 in Section 5.2.5.4.

An even smaller time-frequency resource used in the physical layer specifications is the *resource element* (RE) that refers to one subcarrier in one OFDM symbol.

5.2.2 Transmission schemes

The fundamental downlink and uplink transmission schemes are the same as in LTE. This means that the downlink uses OFDM and the uplink uses SC-FDMA, with 15 kHz subcarrier spacing in both downlink and uplink [10]. In the downlink, a *direct current (DC) subcarrier* is reserved at the center of the system bandwidth. Both normal and extended CP lengths are supported. Downlink *transmission modes* supporting beamforming from up to four antenna ports are supported (see Section 5.2.4.7 for more information on the downlink TM).

5.2.2.1 Duplex modes

LTE-M supports both *frequency-division duplex* (FDD) operation and *time-division duplex* (TDD) operation. In FDD operation, two different carrier frequencies are used for downlink and uplink. If the device supports *full-duplex FDD* (FD-FDD) operation, it can perform reception and transmission at the same time, whereas if the device only supports *half-duplex FDD* (HD-FDD) operation, it has to switch back and forth between reception and transmission. According to the basic LTE behavior for HD-FDD devices that is referred to as *HD-FDD operation type A*, a device that only supports HD-FDD is only expected to be able to do downlink reception in subframes where it does not perform uplink transmission. In

HD-FDD operation type A, the switching back and forth between reception and transmission is fast but relies on the existence of two separate local oscillators for downlink and uplink carrier frequency generation. However, to facilitate implementation of low-cost devices employing just a single local oscillator for carrier frequency generation for both downlink and uplink, *HD-FDD operation type B* was introduced [5,6], and it is HD-FDD operation type B that is used for LTE-M devices (and also for LTE device Cat-0). In HD-FDD operation type B, a guard subframe is inserted at every switch from downlink to uplink and from uplink to downlink, giving the device time to retune its carrier frequency.

In TDD operation, where the same carrier frequency is used for downlink and uplink transmission, the division of so-called *normal subframes* within a frame into downlink and uplink subframes depends on the cell-specific *UL—DL configuration* as indicated in Table 5.3. The switching from downlink to uplink takes place during a guard period within a so-called *special subframe*, indicated by "S" in the table. The symbols before the guard period are used for downlink transmission and the symbols after the guard period are used for uplink transmission. The location and length of the guard period within the special subframe is given by a cell-specific *special subframe configuration*. Interested readers can refer to Ref. [10] for more details.

LTE-M devices can be implemented with support for FD-FDD, HD-FDD operation type B, TDD, or any combination of these duplex modes. This means that LTE-M can be deployed both in paired FDD bands and unpaired TDD bands (see Table 5.2 for a list of supported bands), and that both full-duplex and half-duplex device implementations are possible, allowing for trade-off between device complexity and performance.

5.2.2.2 Narrowband and wideband operation

The supported LTE system bandwidths are {1.4, 3, 5, 10, 15, 20} MHz including guard bands. Discounting the guard bands, the maximum bandwidth that can be scheduled in the largest system bandwidth (20 MHz) is 100 PRBs or 18 MHz. Ordinary LTE devices support transmission and reception spanning the full system bandwidth.

TABLE 5.3 UL—DL configurations for TDD operation in LTE and LTE-M.

	Subframe number									
UL—DL configuration	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	DL	S	UL	UL	UL	DL	S	UL	UL	UL
1	DL	S	UL	UL	DL	DL	S	UL	UL	DL
2	DL	S	UL	DL	DL	DL	S	UL	DL	DL
3	DL	S	UL	UL	UL	DL	DL	DL	DL	DL
4	DL	S	UL	UL	DL	DL	DL	DL	DL	DL
5	DL	S	UL	DL	DL	DL	DL	DL	DL	DL
6	DL	S	UL	UL	UL	DL	S	UL	UL	DL

LTE-M introduces low-cost devices that are only required to support a reduced bandwidth for transmission and reception. These low-cost devices are sometimes referred to as *Bandwidth-reduced Low-complexity* (BL) devices in the standard specifications. The simplest LTE-M device was introduced in Release 13 and it supports a maximum channel bandwidth of 6 PRBs [11]. In many cases, the transmissions to or from LTE-M devices are restricted to take place within one out of a number of nonoverlapping *narrowbands* of size 6 PRBs as illustrated in Fig. 5.3 for the 15-MHz system bandwidth case.

For all system bandwidths except for the smallest one, the system bandwidth cannot be evenly divided into narrowbands which means that there are some PRBs that are not part of any narrowband. For the system bandwidths which have an odd total number of PRBs, the PRB at the center is not included in any narrowband, and if there are any remaining PRBs not included in any narrowband, they are evenly distributed at the edges of the system bandwidth, i.e., with the lowest and highest PRB indices, respectively [10]. The number of narrowbands and the PRBs not belonging to any narrowband are listed in Table 5.4.

In Release 13, the PRBs not belonging to any narrowband cannot be used for LTE-M related transmissions on the physical channels *MTC Physical Downlink Control Channel* (MPDCCH), *Physical Downlink Shared Channel* (PDSCH), and *Physical Uplink Shared Channel* (PUSCH) but can be used for LTE-M related transmissions on other physical channels/signals and for any ordinary LTE transmissions in the cell.

In Release 14, support for *larger data channel bandwidths* than 6 PRBs is introduced in order to allow transmission of larger *transport block size* (TBS) for the data channels PDSCH and PUSCH (see Section 5.2.2.3), which motivates the definition of nonoverlapping *widebands*, each one composed of up to 4 adjacent nonoverlapping narrowbands. For small system bandwidths (1.4, 3, 5 MHz) the wideband contains the whole system bandwidth. In odd system bandwidths (3, 5, 15 MHz) the central wideband contains the center PRB as well. The number of widebands for each system bandwidth are listed in the rightmost column in Table 5.4.

In Release 15, the scheduling flexibility in the frequency domain is improved also for devices configured with a maximum channel bandwidth of 6 PRBs through the introduction of a more *flexible starting PRB* for the data channels PDSCH and PUSCH. The main benefit with this increased flexibility is that it allows LTE-M data transmissions to be more

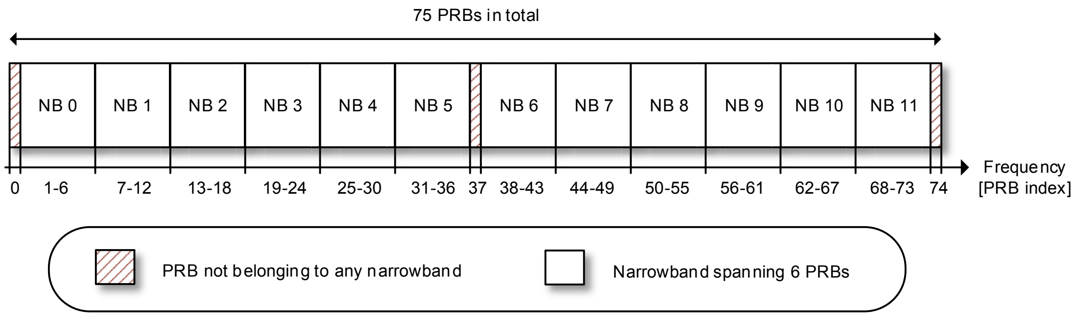

FIG. 5.3 LTE-M narrowbands in 15 MHz LTE system bandwidth.

TABLE 5.4 LTE-M narrowbands and widebands.

LTE system bandwidth including guard bands (MHz)	Total number of PRBs in system bandwidth	Number of narrowbands	PRBs not belonging to any narrowband	Number of widebands (introduced in release 14)
1.4	6	1	None	1
3	15	2	3 (1 on each edge + 1 at the center)	1
5	25	4	1 (at the center)	1
10	50	8	2 (1 on each edge)	2
15	75	12	3 (1 on each edge + 1 at the center)	3
20	100	16	4 (2 on each edge)	4

efficiently multiplexed with other LTE and LTE-M transmissions (see Section 5.3.2.1 for more detailed information). This means that resource allocations can contain almost any contiguous 6 PRBs rather than being confined within a single narrowband. So, while the control channel MPDCCH is still confined within a narrowband, the data channels are now less tied to the narrowbands than they used to be in Release 13.

The center frequency of a narrowband or wideband is not necessarily aligned with the 100-kHz channel raster of LTE (and as already mentioned, the center frequency of an LTE-M device is not necessarily aligned with the center frequency of a narrowband or wideband). However, as explained in Section 5.2.1, the signals and channels essential for cell search and basic system information (SI) acquisition, i.e., PSS, SSS, and PBCH (see Section 5.2.4), are common with LTE, and therefore still located at the center of the LTE system bandwidth (around the DC subcarrier) and aligned with the 100-kHz channel raster [9].

To ensure good frequency diversity even for devices with reduced bandwidth, frequency hopping is supported for many of the physical signals and channels (see Section 5.3.3.2 for more information on frequency hopping).

5.2.2.3 *Coverage enhancement modes*

LTE-M implements a number of coverage enhancement (CE) techniques, the most significant one being the support of repetition of most physical signals and channels. The motivation for the coverage enhancement is twofold.

First, low-cost LTE-M devices may implement various simplifications to drive down the device complexity, for example, a single-antenna receiver and a lower maximum transmission power. These simplifications are associated with some performance degradation that would result in a coverage loss compared to LTE unless it is compensated for through some coverage enhancement techniques.

Second, it is expected that some LTE-M devices will experience very challenging coverage conditions. Stationary utility metering devices mounted in basements serve as an illustrative example. This means that it may not be sufficient that LTE-M provides the same coverage as LTE, but in fact the LTE-M coverage needs to be substantially improved compared to LTE.

To address these aspects, LTE-M introduces two CE modes. *CE mode A* provides sufficient coverage enhancement to compensate for all the simplifications that can be implemented by low-cost LTE-M devices and then some additional coverage enhancement beyond normal LTE coverage. *CE mode B* goes a step further and provides the deep coverage that may be needed in more challenging coverage conditions. CE mode A is optimized for moderate coverage enhancement achieved through a small amount of repetition, whereas CE mode B is optimized for substantial coverage enhancement achieved through a large amount of repetition. If a device supports CE mode B, then it also supports CE mode A.

The low-cost LTE-M device categories (Cat-M1 and Cat-M2) have mandatory support for CE mode A and can optionally also support CE mode B. These low-cost devices always operate in one of the two CE modes. The CE modes support efficient operation of low-cost LTE-M devices, which, for example, means that resource allocation in CE mode is based on the narrowbands and widebands introduced in Section 5.2.2.2.

Higher LTE device categories (Cat-0, Cat-1, and so on) can optionally support the CE modes—either just CE mode A or both CE mode A and B. These more capable devices will typically only operate in CE mode if this is needed in order to stay in coverage, i.e., when they are outside the normal LTE coverage. When these devices are in normal LTE coverage, they will typically use normal LTE operation rather than CE mode and enjoy the higher performance available in normal LTE operation in terms of, e.g., data rates and latency.

The maximum data channel bandwidths supported by the CE modes have been increased above 6 PRBs in Release 14 as shown in Table 5.5. This helps to increase the achievable data rates which enables LTE-M to address use cases with more demanding throughput requirements. As can be seen from the table, the new LTE-M device category M2 has a maximum data channel bandwidth of 5 MHz (see Section 5.2.3), and ordinary LTE devices that support CE mode can be configured with a maximum data channel bandwidth of up to 20 MHz. In CE mode B, the maximum uplink channel bandwidth is limited to 1.4 MHz, as shown in

TABLE 5.5 Maximum channel bandwidths for LTE-M in Release 14.

CE mode data channel bandwidth capability (MHz)	Introduced in	Associated Cat-M device	CE mode A		CE mode B	
			Downlink (MHz)	Uplink (MHz)	Downlink (MHz)	Uplink (MHz)
1.4	Release 13	Cat-M1	1.4	1.4	1.4	1.4
5	Release 14	Cat-M2	5	5	5	1.4
20	Release 14	–	20	5	20	1.4

Table 5.5, since devices configured with CE mode B are expected to be so power limited that they cannot exploit a larger uplink bandwidth.

As already mentioned, an ordinary LTE device can indicate support for CE mode A, or A and B. Furthermore, the device can since Release 14 indicate support for a maximum data channel bandwidth (1.4, 5, 20 MHz) in CE mode. A device indicating support for a particular bandwidth must also support bandwidths smaller than the indicated bandwidth.

The base station decides what maximum data channel bandwidth to configure for a device. Typically, an ordinary LTE device would only be configured in CE mode if it needs the coverage enhancement provided by the CE modes. However, even for a device in good coverage, it may be beneficial to be configured in CE mode with a relatively small bandwidth to save power. Therefore, Release 14 introduces assistance signaling that allows the device to indicate to the base station that the device would prefer to be configured in CE mode with a particular maximum bandwidth, and then the base station may choose to take this information into account when configuring the device.

5.2.3 Device categories and capabilities

LTE-M defines two low-cost device categories, *Category M1* (Cat-M1) and *M2* (Cat-M2). Cat-M1 was introduced in Release 13 and Cat-M2 was introduced in Release 14. They are differentiated by the parameters listed in Table 5.6 [11]. Furthermore, note that the whole range of ordinary LTE device categories can implement support for CE mode A or B if desired (see Section 5.2.2.3).

LTE-M device category Cat-M1 is suitable for MTC applications with low data rate requirements. Many utility metering applications would fall into this category. For these applications, the data rates supported by GSM/GPRS are fully adequate, and the design goal for Cat-M1 was to achieve similar device complexity and cost as an Enhanced GPRS (EGPRS) device. Cat-M1 devices have instantaneous physical layer peak rates in downlink

TABLE 5.6 Cat-M1 and Cat-M2 physical layer parameters.

Device category	**Cat-M1**	**Cat-M1 with extra-large uplink TBS**	**Cat-M2**
Introduced in	Release 13	Release 14	Release 14
Maximum channel bandwidth [MHz]	1.4	1.4	5
Maximum uplink transport block size [bits]	1000	2984	6968
Maximum downlink transport block size [bits]	1000	1000	4008
Total number of soft channel bits for decoding	25344	25344	73152
Total layer 2 buffer sizes [bits]	20000	40000	100000
Half-duplex FDD operation type (see Section 5.2.2.1)	Type B	Type B	Type B

and uplink of 1 Mbps. In Release 13, taking MAC-layer scheduling delays into account, Cat-M1 devices supporting FD-FDD have MAC-layer peak rates of 800 kbps in downlink and 1 Mbps in uplink, and Cat-M1 devices supporting HD-FDD have MAC-layer peak rates of 300 kbps in downlink and 375 kbps in uplink. In Release 14, various data rate improvements are introduced, including scheduling improvements that can increase the downlink MAC-layer peak rate for Cat-M1 to 1 Mbps in FD-FDD and to 588 kbps in HD-FDD (see Section 5.3.2.1.1).

Table 5.6 also contains a column for *Cat-M1 with extra-large uplink TBS*. In downlink-heavy TDD configurations, support of a larger TBS in uplink than in downlink will help balance the downlink and uplink peak rates, and it may be possible to do this without increasing the device complexity significantly. For this reason, Release 14 introduces the possibility to support a larger maximum uplink TBS of 2984 bits instead of 1000 bits for Cat-M1. The larger uplink TBS is an optional device capability that can be supported in any duplex mode. If the new maximum TBS is used in FD-FDD, it gives Cat-M1 an uplink MAC-layer peak rate of around 3 Mbps instead of 1 Mbps.

There is a range of IoT applications with requirements on low device cost and long battery lifetime where LTE-M would be an attractive solution if the supported data rates would be even higher, closer to that of 3G devices or LTE Cat-1 devices. An important class of such applications is wearables such as smart watches. For this reason, a new LTE-M device category (Cat-M2) was introduced in Release 14, with 5 MHz transmit and receive bandwidths instead of the 1.4 MHz supported by Cat-M1. The larger bandwidth allows data transmission in downlink (on PDSCH) and uplink (on PUSCH) with a maximum channel bandwidth of 24 PRBs (a wideband) instead of just 6 PRBs (a narrowband).

A maximum TBS of 4008 bits in downlink and 6968 bits in uplink gives Cat-M2 instantaneous physical layer peak rates of ∼4 Mbps in downlink and ∼7 Mbps in uplink. Again, the reason for the larger maximum TBS in uplink compared to downlink is that it helps balance the downlink and uplink peak rates in some downlink-heavy TDD configurations (see e.g., UL−DL configuration #2 in Table 5.3). As mentioned earlier, increasing the uplink TBS typically has a relatively small impact on the device complexity compared to increasing the downlink TBS. Furthermore, the decoder complexity increase (in terms of number of *soft channel bits* that need to be stored) caused by the larger downlink TBS is rather moderate thanks to the use of *Limited Buffer Rate Matching* [12].

The maximum channel bandwidth for control channels (MPDCCH, SIBs, etc.) is still 6 PRBs, because there is no strong need to increase the data rates for the control channels. This means that the implementation efforts required to upgrade existing LTE-M networks to support the higher data rates of Cat-M2 will be small because most physical channels and procedures are the same as in Release 13. Note that a Cat-M2 device can operate as a Cat-M1 device in an LTE-M network that has not been upgraded because Cat-M2 is fully backward compatible with Cat-M1, and a Cat-M2 device only activates the advanced features when configured to do so by a base station.

An LTE-M device (Cat-M1, Cat-M2, or an ordinary LTE device supporting CE mode) can indicate the support of various *device capabilities* [11]. A selection of these device capabilities is listed in Table 5.7 (note that this is a simplified view, i.e. the actual RRC signaling does

TABLE 5.7 Some important LTE-M device capabilities (simplified view).

Release	Device capability	Parameter value	Section
13/14	Device power class [dBm]	14, 20, or 23	5.1.2.1
13	Coverage enhancement mode A support (mandatory for device categories M1 and M2)	YES or NO	5.2.2.3
13	Coverage enhancement mode B support	YES or NO	5.2.2.3
13	Support for downlink transmission mode 6 in CE mode A	YES or NO	5.2.4.7
13	Support for downlink transmission mode 9 in CE mode A	YES or NO	5.2.4.7
13	Support for downlink transmission mode 9 in CE mode B	YES or NO	5.2.4.7
13	Support for frequency hopping for unicast transmission	YES or NO	5.3.3.2
13	Support for basic OTDOA positioning	YES or NO	5.3.2.6
14	Support for enhanced OTDOA positioning	YES or NO	5.3.2.6
14	Support for multicast transmission of 1.4 MHz or 5 MHz	Not indicated	5.3.1.9
14	Support for extra-large uplink TBS for Cat-M1	YES or NO	5.2.3
14	Max data channel bandwidth in CE mode [MHz]	1.4, 5, or 20	5.2.2.3
14	Support for 10 downlink HARQ processes in FDD	YES or NO	5.3.2.1.1
14	Support for HARQ-ACK bundling in HD-FDD	YES or NO	5.3.2.1.1
14	Support for faster frequency retuning (number of symbols)	0, 1, or 2	5.2.4.1
14	Support for additional PUSCH repetition factors and PUSCH/PDSCH modulation scheme restriction	YES or NO	5.2.5.4
14	Support for dynamic HARQ-ACK delays	YES or NO	5.3.2.1.1
14	Support for SRS repetition	YES or NO	5.2.5.3.2
14	Support for additional PUCCH repetition factors	YES or NO	5.2.5.5
14	Support for closed-loop transmit antenna selection	YES or NO	5.2.5.4
15	Support for resynchronization signal	Not indicated	5.2.4.2.2
15	Support for wake-up signal	YES or NO	5.2.4.5
15	Minimum gap for wake-up signal in eDRX [ms]	40, 240, 1000, or 2000	5.2.4.5
15	Support for mobile-originated early data transmission	YES or NO	5.3.1.7.3
15	Support for relaxed cell reselection monitoring	YES or NO	5.3.2.5
15	Support for CRS muting	YES or NO	5.2.4.3.1
15	Support for downlink 64QAM transmission	YES or NO	5.2.4.7
15	Support for alternative CQI table	YES or NO	5.3.2.2
15	Support for HARQ feedback for uplink data	YES or NO	5.3.2.1.2
15	Support for PUSCH sub-PRB allocation	YES or NO	5.2.5.4
15	Support for flexible starting PDSCH PRB in CE mode A	YES or NO	5.3.2.1.1
15	Support for flexible starting PDSCH PRB in CE mode B	YES or NO	5.3.2.1.1
15	Support for flexible starting PUSCH PRB in CE mode A	YES or NO	5.3.2.1.2
15	Support for flexible starting PUSCH PRB in CE mode B	YES or NO	5.3.2.1.2

not necessarily look like in the table). In most cases it is optional for LTE-M devices and LTE-M networks to support these new features. If a device supports a feature, it indicates its capability to the network, and then it is up to the network whether and how to take the capability into account when configuring the device. Most of the Release 14 and 15 features listed in Table 5.1 have signaling support for capability indication (from the device to the network) as well as configuration parameters (from the network to the device).

5.2.4 Downlink physical channels and signals

LTE-M supports the set of downlink channels and signals depicted in Fig. 5.4. The physical layer provides data transport services to higher layers through the use of *transport channels* via the *Medium Access Control* (MAC) layer [13]. The *Downlink Control Information* (DCI) is not a transport channel, which is indicated by the dashed line. The MAC layer in turn provides data transport services through the use of *logical channels* that are also shown in the figure for completeness [14]. For more information on the higher layers, refer to Section 5.3.

In this section we focus on the downlink physical channels and signals. PSS, SSS, and PBCH are transmitted periodically in the center of the LTE carrier. MPDCCH and PDSCH are transmitted in a narrowband (see Section 5.2.2.2). Downlink *Reference Signals* (RS) are transmitted in all PRBs.

5.2.4.1 Downlink subframes

A cell-specific *subframe bitmap* can be broadcasted in the SI (see Section 5.3.1.2) to indicate which downlink subframes are valid for LTE-M transmission. The bitmap length is 10 or 40 bits corresponding to the subframes within 1 or 4 frames. A network can, for example, choose to indicate subframes that are used as *Positioning Reference Signal* (PRS) or *Multimedia Broadcast Multicast Service (MBMS) Single Frequency Network* (MBSFN) subframes as invalid for LTE-M, but this is up to the network implementation.

Fig. 5.5 shows an example with a 10-bit LTE-M subframe bitmap indicating that subframes #5 and #7 are invalid. Assume that the downlink (MPDCCH or PDSCH)

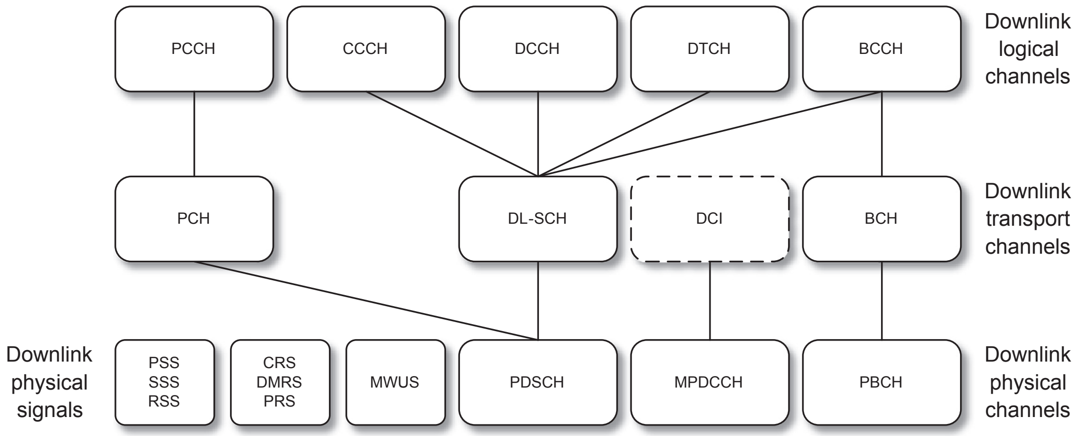

FIG. 5.4 Downlink channels and signals used in LTE-M.

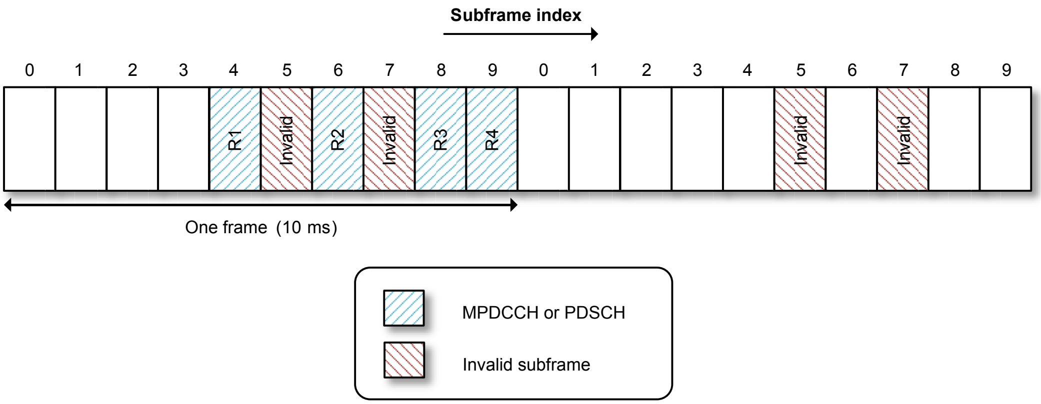

FIG. 5.5 LTE-M subframe bitmap example.

transmission that starts in subframe #4 in the first frame should use subframe repetition factor 4. If all subframes were valid, the repetitions denoted R1, R2, R3, and R4 in the figure would be mapped to subframes #4, #5, #6, and #7, respectively, but due to the invalid subframes, the repetitions are instead mapped to valid subframes #4, #6, #8, and #9, respectively.

The downlink subframe structure in LTE-M only uses a part of the downlink subframe REs in LTE. As shown in Fig. 5.6, the downlink subframe structure in LTE consists of an *LTE control region* and an *LTE data region*. The LTE control region consists of one or more OFDM symbols in the beginning of the subframe and the LTE data region consists of the remaining OFDM symbols in the subframe. In LTE, data transmissions on PDSCH are mapped to the LTE data region, whereas a number of control channels (*Physical Control Format Indicator Channel*, *Physical Downlink Control Channel* (PDCCH), and *Physical Hybrid Automatic Repeat Request (HARQ) Indicator Channel* (PHICH)) are mapped to the LTE control region. These control channels are all wideband channels spanning almost the whole LTE system bandwidth, which can be up to 20 MHz.

Because LTE-M devices can be implemented with a reception bandwidth as small as one narrowband, the mentioned wideband LTE control channels are not used for LTE-M. Instead, a new narrowband control channel (MPDCCH) is used for LTE-M devices and it is mapped to the LTE data region rather than the LTE control region to avoid collisions between the LTE control channels and the new LTE-M control channel. This means that in LTE-M, both the control channel (MPDCCH) and the data channel (PDSCH) are mapped to the LTE data region. (The MPDCCH shares this property with the *Enhanced Physical Downlink Control Channel* (EPDCCH) channel that was introduced in LTE Release 11, and as we will see in Section 5.2.4.6, the MPDCCH design is in fact based on the EPDCCH design).

The LTE-M *starting symbol* for MPDCCH/PDSCH transmissions is cell-specific and broadcasted in the SI (see Section 5.3.1.2). An early LTE-M starting symbol can be configured if the LTE control channel load is not expected to require an LTE control region longer than one symbol. If a larger LTE control region is deemed necessary, then a later LTE-M starting symbol should be configured to avoid collisions between LTE and LTE-M transmissions. The possible LTE-M starting symbols are the second, third, and fourth symbol in the subframe,

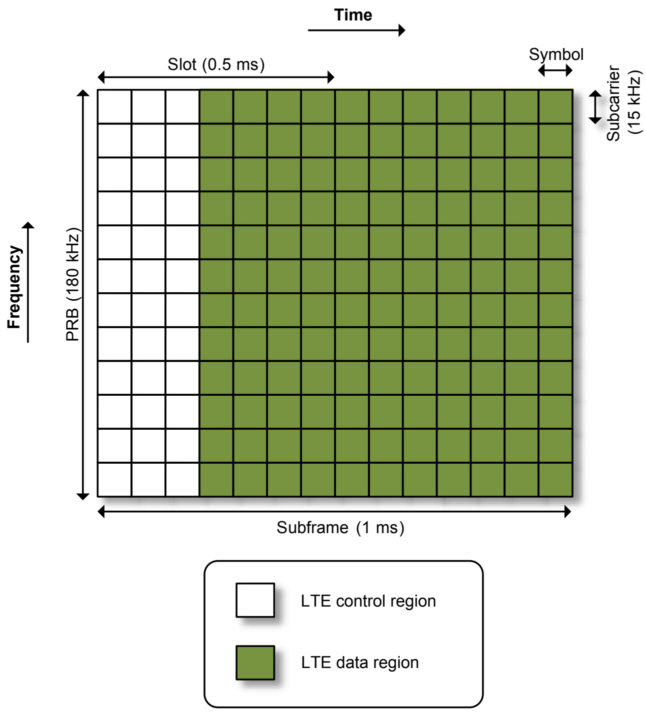

FIG. 5.6 Downlink subframe structure in LTE.

except for the smallest system bandwidth (1.4 MHz) where the possible LTE-M starting symbols are the third, fourth, and fifth symbol [15]. In the example in Fig. 5.6, the starting symbol is the fourth symbol. In the TDD case, in subframes #1 and #6, the LTE-M starting symbol is no later than the third symbol because of the position of PSS/SSS (see Section 5.2.4.2).

When an LTE-M device needs to retune from one downlink narrowband in a first subframe to another downlink narrowband in a second subframe (or from an uplink narrowband to a downlink narrowband with a different center frequency in case of TDD), the device is allowed to create a *guard period for narrowband retuning* by not receiving the first two OFDM symbols in the second subframe [10]. This means that the guard period falls partly or completely within the LTE control region and that the impact on the LTE-M transmission can be expected to be minimal. A similar retuning gap is inserted in uplink (see Section 5.2.5.1).

In Release 14, it is possible for the device to indicate that it can do faster frequency retuning (in downlink and uplink) so that the guard period can be smaller than two symbols. The device can thus indicate that it needs one symbol or even zero symbols—the latter value is mainly intended for ordinary LTE devices with CE mode capabilities, which may have no need to do retuning to move between different narrowbands when operating in CE mode (because ordinary LTE devices can receive and transmit the full LTE system bandwidth rather than just a narrowband or wideband). Faster retuning means somewhat less truncation of the transmitted signal and therefore somewhat better link performance.

5.2.4.2 *Synchronization signals*

5.2.4.2.1 PSS and SSS

Subframes in FDD	#0 and #5 for both PSS and SSS
Subframes in TDD	#1 and #6 for PSS, #0 and #5 for SSS
Subframe periodicity	5 ms for both PSS and SSS
Sequence pattern periodicity	5 ms for PSS, 10 ms for SSS
Subcarrier spacing	15 kHz
Bandwidth	62 subcarriers (not counting the DC subcarrier)
Frequency location	At the center of the LTE system bandwidth

LTE-M devices rely on LTE's *Primary Syncronization Signal* (PSS) and *Secondary Synchronization Signal* (SSS) for acquisition of a cell's carrier frequency, frame timing, CP length, duplex mode, and *Physical Cell Identity* (PCID). For more details on the cell selection procedure including the time and frequency synchronization and cell identification, see Section 5.3.1.1.

The LTE signals can be used without modification even by LTE-M devices in challenging coverage conditions. Because PSS and SSS are transmitted periodically, the device can accumulate the received signal over multiple frames to achieve sufficient acquisition performance, without the need to introduce additional repetitions on the transmit side (at the cost of increased acquisition delay).

LTE supports 504 PCIDs divided into 168 groups where each group contains 3 identities. In many cases the 3 identities correspond to 3 adjacent cells in the form of sectors served by the same base station. The 3 identities are mapped to 3 PSS sequences and one of these PSS sequences is transmitted every 5 ms in the cell, which enables the device to acquire the "half-frame" timing of the cell. For each PSS sequence there are 168 SSS sequences indicative of the PCID group. Like PSS, SSS is transmitted every 5 ms, but the 2 SSSs within every 10 ms are different. This enables the device to acquire the PCID as well as the frame timing. The same SSS sequence pattern repeats itself every 10 ms. The same PCID can be used in two or more cells as long as they are far apart enough to avoid ambiguity due to overhearing, so the number of PCIDs does not impose a limit on the total number of cells in a network.

Fig. 5.7 and 5.8 illustrate the PSS/SSS resource mapping for FDD cells and TDD cells, respectively. In the FDD case, PSS is mapped to the last OFDM symbol in slots #0 and #10 and SSS is mapped to the symbol before PSS. In the TDD case, PSS is mapped to the third OFDM symbol in subframes #1 and #6 and SSS is mapped to the symbol three symbols before PSS [10]. This means that the duplex mode (FDD or TDD) can be detected from the synchronization signals, although this is normally not needed because a given frequency band typically only supports one of the duplex modes [9]. The exact PSS/SSS symbol positions vary slightly depending on the CP length, which means that the device can also detect whether it should assume normal or extended CP length based on the detection of the synchronization signals.

As shown in the figures, PSS and SSS are mapped to the center 62 subcarriers (around the DC subcarrier) of the LTE carrier. This means that the signal fits within the smallest LTE-M

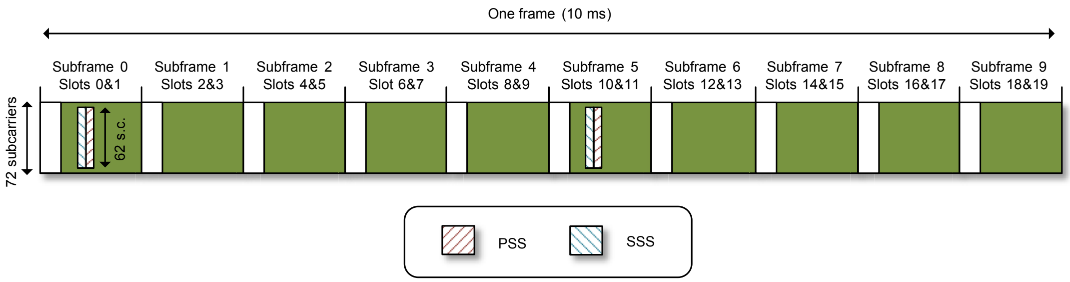

FIG. 5.7 Primary and secondary synchronization signals in LTE FDD.

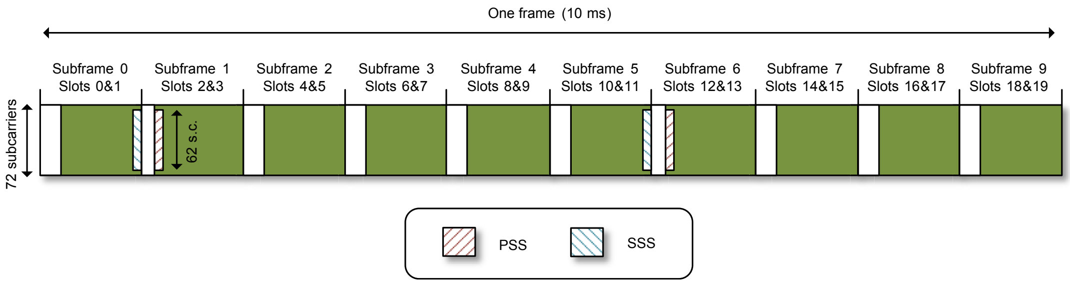

FIG. 5.8 Primary and secondary synchronization signals in LTE TDD.

device bandwidth that corresponds to 72 subcarriers. The PSS/SSS region is not aligned with any of the narrowbands (see Section 5.2.2.2) except when the smallest system bandwidth (1.4 MHz) is used, which means that the LTE-M device may need to do frequency retuning (see Section 5.2.4.1) whenever it needs to receive PSS/SSS.

5.2.4.2.2 RSS

Subframe	Configurable starting frame
Basic transmission time interval (TTI)	8, 16, 32, 40 ms
Periodicity	160, 320, 640, 1280 ms
Subcarrier spacing	15 kHz
Bandwidth	2 PRBs
Frequency location	Any 2 adjacent PRBs

The *Resynchronization Signal* (RSS) was introduced in 3GPP Release 15 for enhancing energy efficiency when a device needs to re-acquire time and frequency synchronization toward a cell. It is optional for the base station to transmit RSS and optional for the device to use it. If RSS is transmitted, it is transmitted less often than PSS/SSS, but each RSS transmission contains more energy, which can substantially help reduce the device power consumption related to reacquisition of time and frequency synchronization toward a cell. For low-mobility devices experiencing very challenging coverage conditions, it may be possible to reduce the resynchronization time from over a second using PSS/SSS to the duration of an RSS, for example 40 ms. The device still needs to rely on PSS/SSS for initial synchronization to a cell, but once the device has received SI containing an RSS configuration, the device can use RSS. The sparse nature of RSS may also allow the device to skip SFN acquisition through MIB decoding.

The RSS sequence depends on the PCID and on a *System Info Unchanged* flag. The flag allows the device to detect from RSS whether the SI has been updated in the cell, something that would otherwise require the device to monitor MIB or SIB1, which would typically be a more energy consuming operation for the device compared to receiving RSS (for more details on the flag see Section 5.3.1.2.3).

In frequency domain, RSS is mapped to 2 adjacent PRB pairs, and there is no frequency hopping. In time domain, RSS is mapped to the last 11 OFDM symbols in each subframe in the configured RSS duration. The RSS base sequence is generated using a pseudo-random sequence based on PCID that has a length of one subframe, and extended to multiple subframes by following a binary code that maps the base sequence or its conjugate to as many subframes as the RSS length. Furthermore, RSS is punctured by CRS (described in Section 5.2.4.3.1). The resulting RSS resource mapping within a subframe looks the same as the MWUS (described in Section 5.2.4.5) resource mapping illustrated in Fig. 5.14.

RSS can be used alone or in tandem with MWUS (see Section 5.2.4.5) in a wake-up receiver, something that will be discussed further in Section 5.3.1.4. The RSS bandwidth of 2 PRBs (360 kHz) is small enough to facilitate efficient wake-up receiver implementations using a relatively low sampling rate. The low complexity for RSS detection is particularly welcome in case multiple hypotheses regarding the time/frequency error need to be tested, which may be the case if the device experiences a large frequency error, e.g. as a result of a long sleep time. Additionally, the repeated structure of RSS allows for low-complexity reception due to the possibility of reusing previous outputs of a time-domain correlator.

The RSS configuration indicates a frequency location, periodicity, time offset, duration, and potential power boosting. The network can choose the RSS frequency location to be any 2 adjacent PRBs within the LTE system bandwidth. The RSS periodicity is configured to 160, 320, 640, or 1280 ms. The RSS starting frame is given by a time offset relative to SFN #0. For the lowest periodicities 160 and 320 ms, any frame can be configured as the starting frame, while for the higher periodicities 640 and 1280 ms, the allowed time offsets are restricted to every second and every fourth frame, respectively. The duration is configured to 8, 16, 32, or 40 ms. Finally, RSS can be configured with a power boosting of 0, 3, 4.8, or 6 dB. Power boosting allows RSS to be configured with a similar power level as it would have had without boosting if it had been designed to be transmitted over the full 6-PRB narrowband rather than over just 2 PRBs.

In case an RSS PRB pair overlaps in a subframe with any PRB pair carrying PSS, SSS, PBCH or a PDSCH carrying system information, then that RSS subframe is dropped (not transmitted). This behavior is needed for backwards compatibility reasons since not all devices may be aware of the presence of RSS.

5.2.4.3 *Downlink reference signals*

5.2.4.3.1 CRS

Subframes	Any
Subcarrier spacing	15 kHz
Bandwidth	Full system bandwidth (Release 15 supports CRS muting)
Frequency location	According to Fig. 5.9 in affected PRBs

Downlink reference signals (RS) are predefined signals transmitted by the base station to allow the device to estimate the downlink propagation channel to be able to demodulate the downlink physical channels [10] and perform downlink reference signal strength or quality measurements [16]. The physical layer allows demodulation and measurements to be performed even at relatively high device velocities, as discussed in Section 5.3.2.5.

The *Cell-specific Reference Signal* (CRS) can be used for demodulation of PBCH or PDSCH and is transmitted from one, two, or four logical antenna ports numbered 0−3, where in the typical case each logical antenna port corresponds to a physical antenna. The CRS for different antenna ports is mapped to REs in every PRB and in every (non-MBSFN) subframe in the cell as shown in Fig. 5.9, unless *CRS muting* is used. The CRS mapping shown in Fig. 5.9 is one example and may be frequency shifted up by one or more subcarriers depending on the PCID value.

The CRS muting feature is introduced in Release 15, and it enables the base station to turn off some of the CRS transmissions when they are not needed by Cat-M devices for demodulation or measurements. Somewhat simplified, Cat-M devices that indicate support of CRS muting can assume that the base station transmits CRS within the channel bandwidth of the device during transmission to the device and can furthermore assume that CRS is always transmitted in the central region of the system bandwidth and also over the full system bandwidth every 10th or 20th subframe (for more details, see Refs. [9,17]). This feature helps reduce the inter-cell interference experienced in neighbor cells, thereby improving the downlink throughput in neighbor cells, and may also be useful in NR coexistence scenarios (see Section 5.4).

5.2.4.3.2 DMRS

Subframe	Any
Subcarrier spacing	15 kHz
Bandwidth	Same as associated MPDCCH/PDSCH
Frequency location	According to Fig. 5.10 in affected PRBs

The downlink *Demodulation Reference Signal* (DMRS) can be used for demodulation of PDSCH or MPDCCH and is configured per device and is not PCID dependent, except in case of *MPDCCH Common Search Space* (see Section 5.3.3.1) where the *DMRS sequence initialization* is based on PCID. The DMRS is transmitted on the same logical antenna port as the associated PDSCH or MPDCCH. If the logical antenna port is mapped to multiple

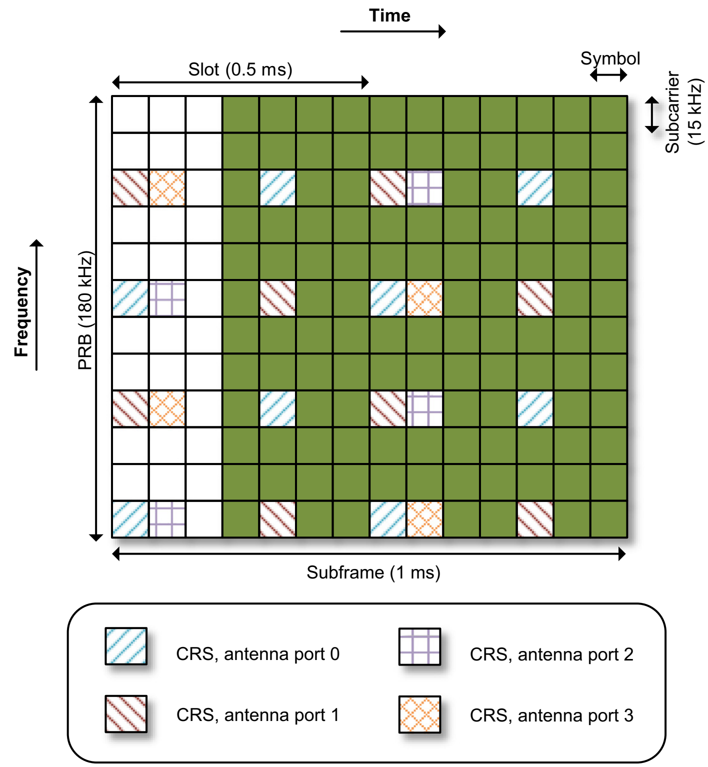

FIG. 5.9 Cell-specific CRS in LTE and LTE-M.

physical antennas, the coverage and capacity can be improved through antenna techniques such as beamforming. DMRS can be transmitted to different devices from up to 4 logical antenna ports, numbered 7–10 for PDSCH and 107–110 for MPDCCH, mapped to REs as shown in Fig. 5.10. CRS is also transmitted but not shown in Fig. 5.10. As can be seen from the figure, DMRS for antenna ports 7 and 8 is mapped to the same set of REs but separated by an *orthogonal cover code*, and the same holds for DMRS for antenna ports 9 and 10. The DMRS for the four different antenna ports can thus be distinguished by the device.

5.2.4.3.3 PRS

Subframe	Configurable by LPP signaling
Basic transmission time interval (TTI)	1 ms
Repetitions	1, 2, 4, 6 ms (Release 14 also supports 10, 20, 40, 80, 160 ms)
Periodicity	160, 320, 640, 1280 ms (Release 14 also supports 10, 20, 40, 80 ms)
Subcarrier spacing	15 kHz
Bandwidth	1.4, 3, 5, 10, 15, 20 MHz
Frequency location	At the center of the LTE system bandwidth
Frequency hopping	Between 2 or 4 locations if configured (the location in the center plus 1 or 3 narrowbands)

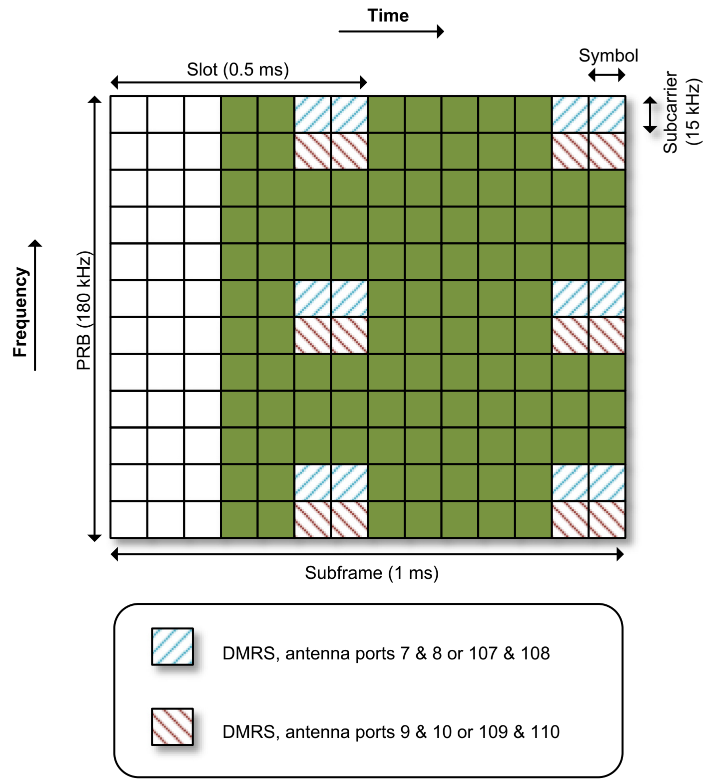

FIG. 5.10 User-specific DMRS in LTE and LTE-M.

The *Positioning Reference Signal* (PRS) is used for the *Observed Time Difference of Arrival* (OTDOA) multilateration positioning method, where the position of a receiving device is determined based on differences in time of arrival between PRS signals from different, time-synchronized base stations (see Section 5.3.2.5 for general information about the positioning methods in LTE-M).

PRS is a broadcast signal. The device receives the PRS configuration through the *LTE Positioning Protocol* (LPP) [18] from a positioning server known as the *Evolved Serving Mobile Location Center* (E-SMLC). The E-SMLC negotiates the PRS configuration with the base stations via the *LPPa* protocol [19].

Resource mapping in a PRS subframe is illustrated in Fig. 5.11. A PRS symbol sequence in a PRS subframe is a pseudo-random sequence, and each symbol is quadrature phase shift keying (QPSK) modulated. The pseudo-random sequence is cell dependent and the sequence changes in different PRS subframes. Observe that the resource mapping patterns can be shifted up or down in the frequency dimension to create 6 different,

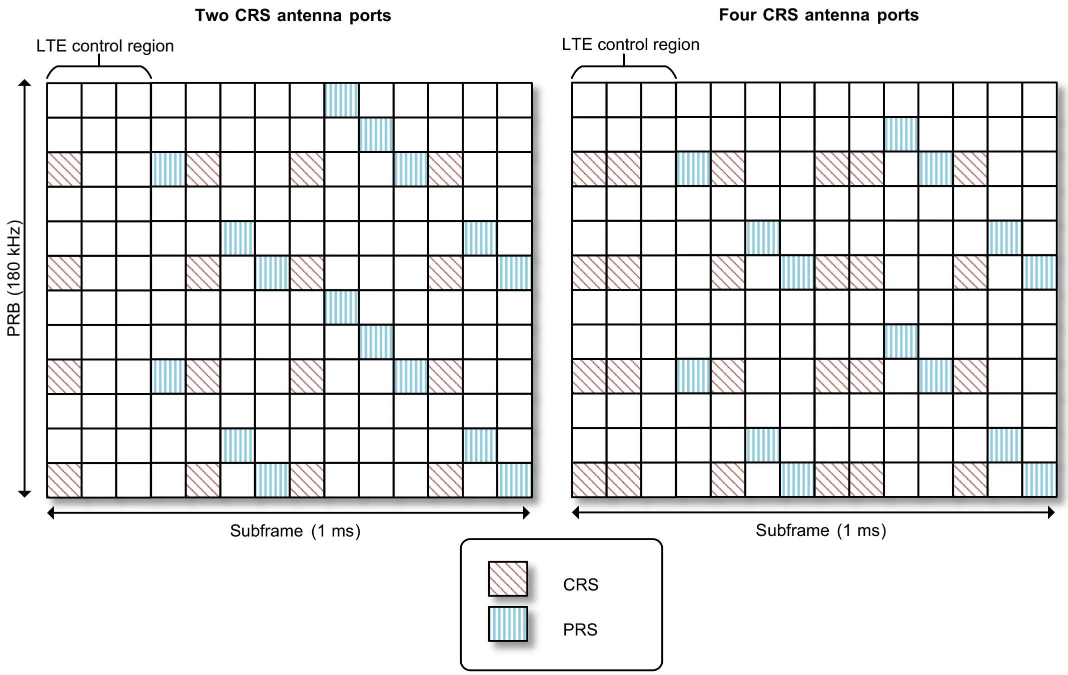

FIG. 5.11 Positioning reference signal in LTE and LTE-M.

orthogonal mapping patterns. These orthogonal mapping patterns can be used in neighboring cells in a synchronized network to avoid inter-cell interference. The mapping pattern used by a cell is determined by a configurable PRS identity, with a default value equal to the *Cell Identity* (CID).

Release 14 introduces *OTDOA enhancements* with respect to the configuration of the associated PRS the in time and frequency domains. Because the low-cost LTE-M devices have limited receive bandwidth (1.4 MHz for Cat-M1, and 5 MHz for Cat-M2), they will benefit from a PRS that is mapped over a longer duration in the time domain rather than over a wide bandwidth in the frequency domain. Therefore, Release 14 introduces the possibility to configure PRS that are transmitted with a longer duration at every PRS occasion and/or at more frequent PRS occasions (the available parameter values are listed in the table in the beginning of this section).

Also, optional PRS frequency hopping is introduced in Release 14 to provide frequency diversity gains also to narrowband LTE-M devices (configuration of PRS frequency hopping is described in Table 5.35).

Furthermore, Release 14 allows configuring a cell with multiple PRS configurations, for example a first PRS configuration with 20 MHz bandwidth but short duration for ordinary

LTE devices, a second PRS configuration with 5 MHz bandwidth and somewhat longer duration for Cat-M2 devices, and a third PRS configuration with 1.4 MHz bandwidth and even longer duration for Cat-M1 devices. A device that is able to receive all these PRS signals (or at least parts of the signals) can make use of PRS signals of multiple bandwidths, since Release 14 allows configuring not only a cell but also a device with up to three simultaneous PRS configurations. By receiving multiple PRS signals, the device may be able to further improve its positioning performance.

The new PRS configurations in Release 14 allow LTE-M devices to achieve comparable positioning accuracy as ordinary LTE devices. The exact PRS configuration in a cell will depend on the desired trade-off between PRS overhead and positioning accuracy.

5.2.4.4 PBCH

Subframes in FDD	#0 for core part, #9 for repetitions
Subframes in TDD	#0 for core part, #5 for repetitions
Basic transmission time interval (TTI)	40 ms
Repetitions	Core part plus 0 or 4 repetitions
Subcarrier spacing	15 kHz
Bandwidth	72 subcarriers (not counting the DC subcarrier)
Frequency location	At the center of the LTE system bandwidth

The *Physical Broadcast Channel* (PBCH) is used to deliver the MIB that provides essential information for the device to operate in the network (see Section 5.3.1.1.3 for more details on MIB).

The PBCH is mapped to the center 72 subcarriers in the LTE system bandwidth. The PBCH of LTE serves as the *PBCH core part* in LTE-M and the LTE-M specification adds additional *PBCH repetitions* for improved coverage. The repetitions can be used in all system bandwidths except the smallest one (1.4 MHz). It is up to the network whether to enable the PBCH repetitions in a cell. Enabling the repetitions is only motivated in cells that need to support deep coverage.

The TTI for PBCH is 40 ms and the *transport block size* (TBS) is 24 bits. The MIB content changes from TTI to TTI but typically in a predictable way, which makes it possible to improve the reception performance by accumulating the PBCH transmissions from two consecutive 40-ms periods (see Section 5.3.1.1.3).

A 16-bit *cyclic redundancy check* (CRC) is attached to the transport block. The CRC is masked with a bit sequence that depends on the number of CRS transmit antenna ports on the base station (see Section 5.2.4.3), which means that the device learns the number of CRS transmit antenna ports as a by-product in the process of decoding PBCH [20].

Together, the 40 bits from the 24-bit transport block and the 16-bit CRC are encoded using the *LTE tail-biting convolutional code* (TBCC), and rate matched to generate 1920 encoded bits.

The encoded bits are scrambled with a cell-specific sequence (for randomization of inter-cell interference) and segmented into four segments distributed to four consecutive frames. Each segment is 480 bits long and mapped to 240 QPSK symbols distributed over the 72 subcarriers. Transmit diversity is applied for PBCH based on *Space-Frequency Block Coding* (SFBC) in case of two antenna ports and on a combination of SFBC and *Frequency-Switched Transmit Diversity* (FSTD) in case of four antenna ports [10].

The PBCH core part is always transmitted as four OFDM symbols in subframe #0 in every frame. When the PBCH repetitions are enabled, they are transmitted in subframes #0 and #9 in the FDD case and in subframes #0 and #5 in the TDD case, as illustrated in Fig. 5.12 and 5.13. Note that the zoomed-in parts only show the first 12 of 72 subcarriers. The PBCH repetitions part contains four copies of each one of the four OFDM symbols in the PBCH core part, resulting in a repetition factor of five for each OFDM symbol. If the copied OFDM symbol contains CRS, the CRS is also copied. In the FDD case, the fact that subframes 0 and 9 are adjacent facilitates coherent combination across PBCH repetitions, for example for frequency estimation purposes. In the TDD case, the fact that subframes 0 and 5 have been selected means that PBCH repetition can be supported in all UL–DL configurations because these subframes are downlink subframes in all UL–DL configurations (see Table 5.3).

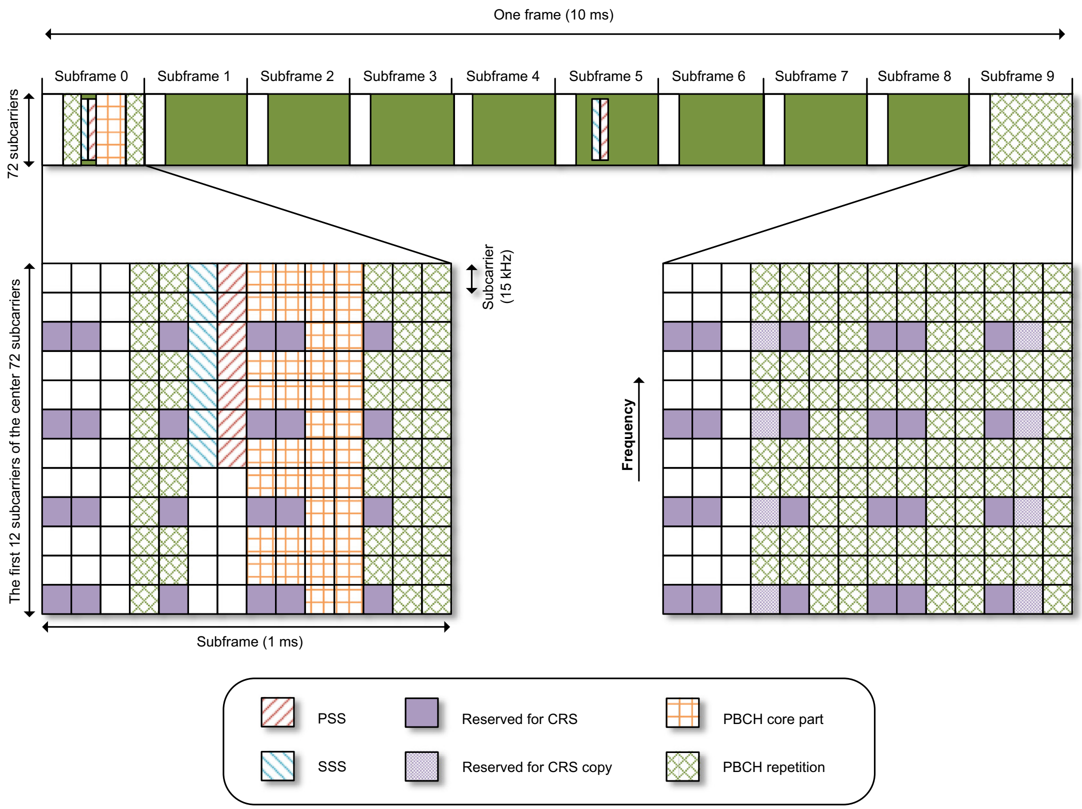

FIG. 5.12 PBCH core part and PBCH repetition in LTE FDD.

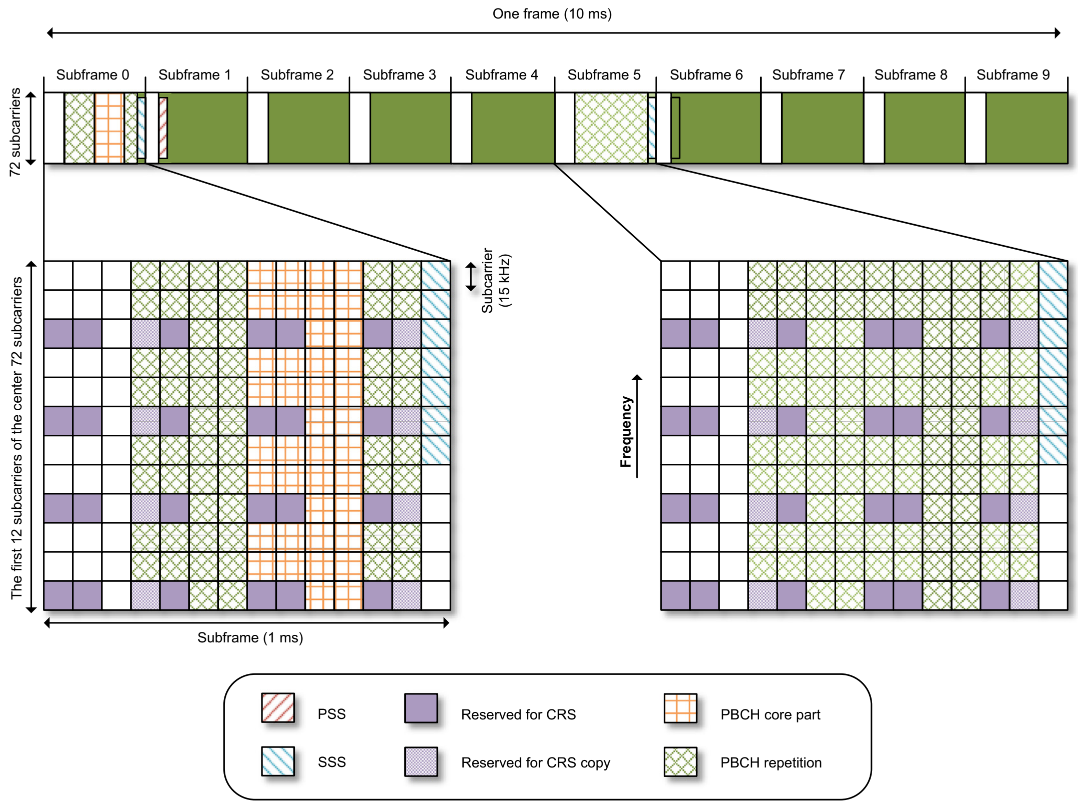

FIG. 5.13 PBCH core part and PBCH repetition in LTE TDD.

5.2.4.5 *MWUS*

Subframe	Configurable
Basic TTI	1 ms
Repetitions	$R_{max}/4$, $R_{max}/8$, $R_{max}/16$, $R_{max}/32$
	R_{max}: maximum number of MPDCCH repetitions for paging
Subcarrier spacing	15 kHz
Bandwidth	2 PRBs
Frequency location	2 adjacent PRBs within a narrowband

The *MTC Wake-Up Signal* (MWUS) was introduced in 3GPP Release 15 to further improve the device battery lifetime. An LTE-M device is most of the time in idle mode, during which it wakes up periodically to monitor a *paging occasion* (PO) to determine whether it is *paged*. A detailed description of the paging procedure will be given in Section 5.3.1.4. For now, it suffices to note that a paging indicator is transmitted in MPDCCH by using DCI format 6-2, which has 10-13 information bits (see Table 5.23). As in most paging occasions no paging indicator is sent, a device usually ends up waking up to look for a paging signal only to find that no paging indicator is sent. By only providing a 1-bit wake-up indication, a much shorter MWUS can be transmitted before a device would need to wake up to look for paging to indicate whether the device needs to monitor the subsequent paging occasion(s) or can go back to sleep immediately. In the following, we focus on the MWUS physical layer aspects, but more information about the paging procedure including the use of wake-up signaling can be found in Section 5.3.1.4.

MWUS resource mapping within a subframe is shown in Fig. 5.14. In frequency domain, MWUS is mapped to 2 PRB pairs within a 6-PRB narrowband (either the 2 lowest PRB pairs, or the 2 center PRB pairs, or the 2 highest PRB pairs), and there is no frequency hopping.

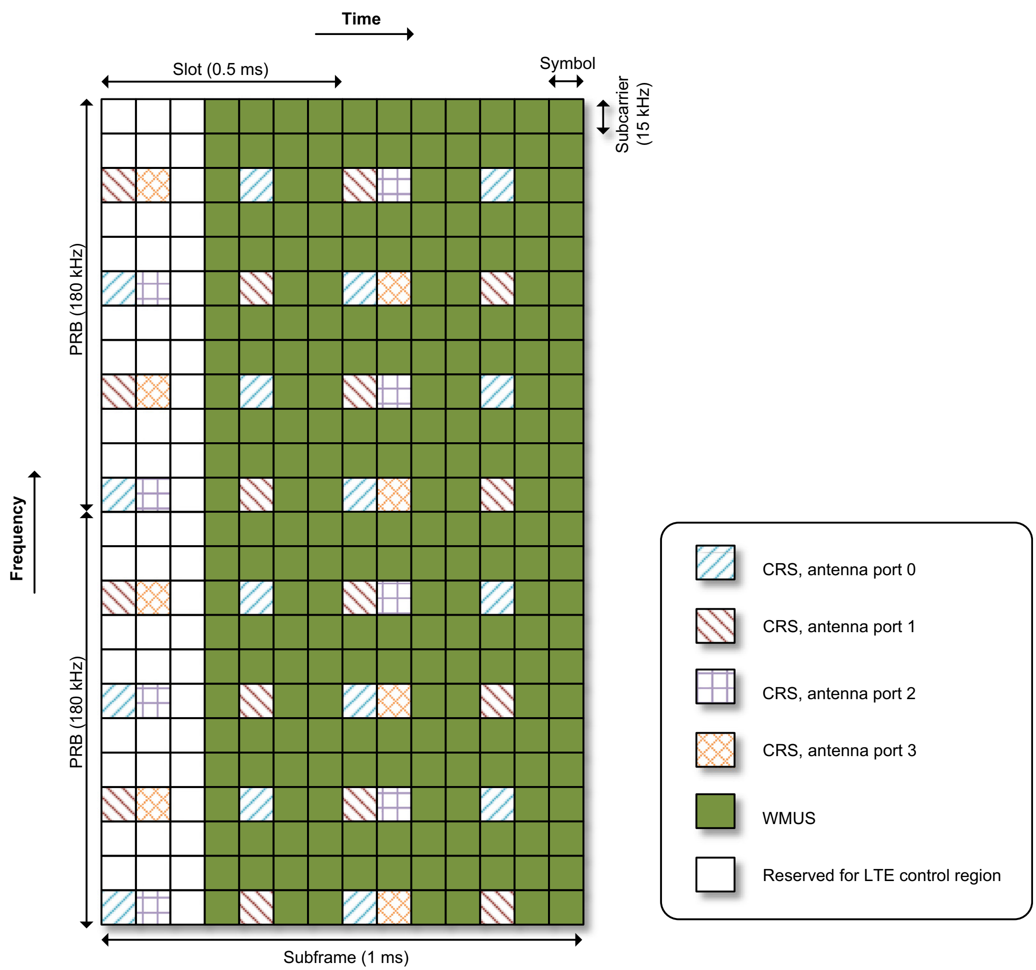

FIG. 5.14 MWUS resource mapping.

In time domain, MWUS is mapped to the last 11 OFDM symbols in a subframe, and subframe repetition is applied to reach enough coverage. The number of MWUS repetitions R_{MWUS} is configured to be 1/4, 1/8, 1/16, or 1/32 of the maximum number of MPDCCH repetitions configured for paging, $R_{\max}$ (see Sections 5.2.4.6, 5.3.1.4, and 5.3.3.1).

The same length-132 MWUS sequence is mapped to each one of the two PRB pairs. The sequence is generated based on an extended length-131 *Zadoff–Chu* (ZC) sequence, which is scrambled using a pseudo-random scrambling mask that extends over the whole MWUS transmission and varies from subframe to subframe when R_{MWUS} exceeds 1. As illustrated in Fig. 5.14, the MWUS sequence is then *punctured* by CRS.

The MWUS sequence design is the same as for the corresponding NB-IoT signal NWUS (see Section 7.2.4.8) except that the MWUS has the sequence mapped to 2 PRB pairs instead of just 1. The MWUS bandwidth of 2 PRBs (360 kHz) is small enough to facilitate efficient wake-up receiver implementations using a relatively low sampling rate compared to the sampling rate required to receive the full MPDCCH narrowband of 6 PRBs (1.08 MHz).

In case an MWUS PRB pair overlaps in a subframe with any PRB pair carrying PSS, SSS, RSS, PBCH or a PDSCH carrying system information, then that MWUS subframe is dropped (not transmitted). This behavior is needed for backwards compatibility reasons since not all devices support MWUS.

5.2.4.6 MPDCCH

Subframe	Any
Basic TTI	1 ms
Repetitions	1, 2, 4, 8, 16, 32, 64, 128, 256
Subcarrier spacing	15 kHz
Bandwidth	2, 4 or 6 PRBs
Frequency location	Within a narrowband
Frequency hopping	Between 2 or 4 narrowbands if configured

The *MTC Physical Downlink Control Channel* (MPDCCH) is used to carry *Downlink Control Information* (DCI). An LTE-M device needs to monitor MPDCCH for the following types of information [20].

- Uplink power control command (using DCI Format 3/3A, see Section 5.3.2.4)
- Uplink grant information (using DCI Format 6-0A/6-0B, see Table 5.28)
- Downlink scheduling information (using DCI Format 6-1A/6-1B, see Table 5.25)
- Indicator of paging or system information update (using DCI Format 6-2, see Table 5.23)
- Order to initiate a random access procedure (using DCI Format 6-1A/6-1B, see Section 5.3.2.3)
- Notification of changes in multicast control channel (using DCI Format 6-1A/6-1B/6-2, introduced in Release 14, see Section 5.3.1.9)
- Explicit positive HARQ-ACK feedback (using DCI Format 6-0A/6-0B, introduced in Release 15, see Section 5.3.2.1.2)

The MPDCCH design is based on the EPDCCH of LTE, which was introduced in LTE in Release 11. This means that the REs in one PRB pair are divided into 16 *enhanced resource-element groups* (EREGs) with each EREG containing 9 REs, as illustrated in Fig. 5.15, where EREG #0 is highlighted. Furthermore, EREGs can be further combined into *enhanced control channel elements* (ECCEs). In normal subframes with normal CP length, each ECCE is composed of 4 EREGs and thus 36 REs.

An MPDCCH can span 2, 4, or 6 PRB pairs, and within these PRB pairs the transmission can either be *localized* or *distributed*. Localized transmission means that each ECCE is composed of EREGs from the same PRB pair, and distributed transmission means that each ECCE is composed of EREGs from different PRB pairs [10]. Distributed transmission provides frequency diversity, but localized transmission is more suitable for beam forming or when it is desired to frequency multiplex MPDCCH with other transmissions (e.g. PDSCH) within a narrowband.

To achieve sufficient coverage, multiple ECCEs can furthermore be aggregated in an MPDCCH, according to the *ECCE aggregation level* of the MPDCCH. In normal subframes with normal CP length, aggregation of 2, 4, 8, 16, or 24 ECCEs is supported, where the highest

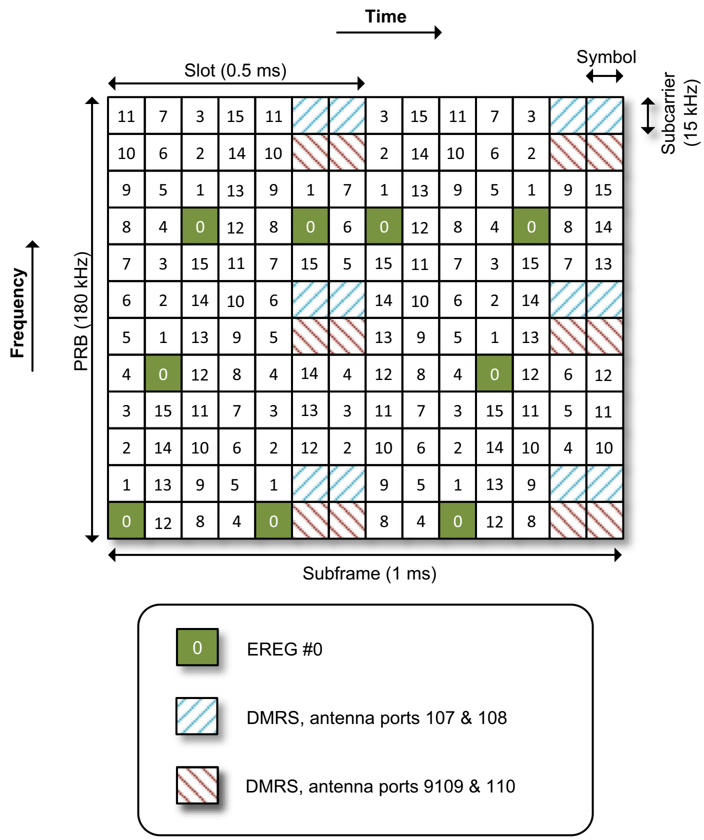

FIG. 5.15 Enhanced resource-element groups (EREGs) for MPDCCH.

aggregation level corresponds to aggregation of all REs in 6 PRB pairs. The device attempts to decode multiple MPDCCH candidates according to the *MPDCCH search space* as discussed in Section 5.3.3.1.

The MPDCCH carries the DCI and a 16-bit CRC is attached to the DCI. The CRC is masked with a sequence determined by the *Radio Network Temporary Identifier* (RNTI). The RNTI is an identifier used for addressing one or more devices and the RNTIs that can be monitored by a device are listed in Table 5.32 in Section 5.3.3.1. 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 for MPDCCH transmission. The determination of the number of available bits takes into account the MPDCCH aggregation level, modulation scheme (QPSK) and the REs not available for MPDCCH, i.e., the REs before the LTE-M starting symbol (see Section 5.2.4.1) in the subframe and the REs occupied by CRS and DMRS (see Section 5.2.4.3). The MPDCCH transmission and its associated DMRS are masked with a scrambling sequence which is cell- or user-specific depending on whether it addresses a common or dedicated RNTI (see mapping between MPDCCH search spaces, RNTIs, DCI formats, and their uses in idle and connected mode in Table 5.32 in Section 5.3.3.1).

Further MPDCCH coverage enhancement beyond what can be achieved with the highest ECCE aggregation level can be provided by repeating the subframe up to 256 times. For CE mode B, to simplify frequency error estimation and combination of the repetitions in receiver implementations that use combining on I/Q sample level, the scrambling sequence is repeated over multiple subframes (4 subframes in FDD and 10 subframes in TDD). Furthermore, the device can assume that any potential precoding matrix (for beamforming) stays the same over a number of subframes indicated in the SI (see Section 5.3.3.2).

5.2.4.7 PDSCH

Subframe	Any
Basic TTI	1 ms
Repetitions	Maximum 32 in CE mode A, maximum 2048 in CE mode B
Subcarrier spacing	15 kHz
Bandwidth	1−6 PRBs in CE mode A, 4 or 6 PRBs in CE mode B (Release 14 supports additional bandwidths)
Frequency location	Within a narrowband (Release 15 supports more flexible location)
Frequency hopping	Between 2 or 4 narrowbands if configured

The *Physical Downlink Shared Channel* (PDSCH) is primarily used to transmit unicast data. The data packet from higher layers is segmented into one or more *transport blocks* (TB), and PDSCH transmits one TB at a time. For information on PDSCH scheduling, refer to Section 5.3.2.1.1.

PDSCH is also used to broadcast information such as system information (see Section 5.3.1.2), paging messages (see Section 5.3.1.4), and random access related messages (see Section 5.3.1.6).

In this section we first go through the Release 13 functionality before we turn to the Release 14 and 15 enhancements for PDSCH. The Release 14 and 15 enhancements mainly concern unicast transmission in connected mode, while broadcast transmissions are in general still according to the Release 13 specification.

Table 5.8 shows the *modulation and coding schemes* (MCS) and TBS for PDSCH in CE mode A and B in Release 13. However, the low-cost LTE-M device Cat-M1 is restricted to a maximum TBS of 1000 bits, so the TBS values larger than 1000 bits do not apply to Cat-M1, only to higher device categories configured with CE mode A (see Section 5.2.2.3 for information on the CE modes and Section 5.2.3 for information about device categories).

TABLE 5.8 PDSCH modulation and coding schemes and transport block sizes in LTE-M (configured with max 1.4 MHz channel bandwidth and not configured with Release 14 modulation scheme restriction or Release 15 feature for 64QAM support).

MCS index	Modulation scheme	TBS index	Transport block sizes in CE mode A						Transport block sizes in CE mode B	
			# PRB pairs						# PRB pairs	
			1	**2**	**3**	**4**	**5**	**6**	**4**	**6**
0	QPSK	0	16	32	56	88	120	152	88	152
1	QPSK	1	24	56	88	144	176	208	144	208
2	QPSK	2	32	72	144	176	208	256	176	256
3	QPSK	3	40	104	176	208	256	328	208	328
4	QPSK	4	56	120	208	256	328	408	256	408
5	QPSK	5	72	144	224	328	424	504	328	504
6	QPSK	6	328	176	256	392	504	600	392	600
7	QPSK	7	104	224	328	472	584	712	472	712
8	QPSK	8	120	256	392	536	680	808	536	808
9	QPSK	9	136	296	456	616	776	936	616	936
10	16QAM	9	136	296	456	616	776	936	Unused	
11	16QAM	10	144	328	504	680	872	1032		
12	16QAM	11	176	376	584	776	1000	1192		
13	16QAM	12	208	440	680	904	1128	1352		
14	16QAM	13	224	488	744	1000	1256	1544		
15	16QAM	14	256	552	840	1128	1416	1736		

Further restrictions apply when PDSCH is used for broadcast. The modulation scheme is then restricted to QPSK and special TBS may apply (see Section 5.3.1).

A 24-bit CRC is attached to the TB. The channel coding is the standard *LTE turbo coding* with 1/3 code rate, 4 redundancy versions (RV), rate matching, and interleaving 12]. PDSCH is not mapped to REs before the LTE-M starting symbol (see Section 5.2.4.1) and not to REs occupied by RS (see Section 5.2.4.3).

In CE mode A in Release 13, the PDSCH is modulated with QPSK or 16QAM and mapped to between 1 and 6 PRB pairs anywhere within a narrowband. In CE mode B in Release 13, the PDSCH is modulated with QPSK and mapped to 4 or 6 PRB pairs within a narrowband. The modulation scheme restrictions facilitate low-cost LTE-M device receiver implementations with relaxed requirements on demodulation accuracy compared to ordinary LTE devices which support at least up to 64QAM.

Coverage enhancement can be provided by repeating the subframe up to 2048 times. The maximum numbers of repetitions in CE modes A and B, respectively, are configurable per cell according to Tables 5.10 and 5.11.

LTE-M supports the following PDSCH transmission modes inherited from LTE:

- **TM1**: Single-antenna transmission (supported in both CE mode A and B)
- **TM2**: Transmit diversity (supported in both CE mode A and B)
- **TM6**: Closed-loop codebook-based precoding (supported in CE mode A only)
- **TM9**: Non-codebook-based precoding (supported in both CE mode A and B)

TM2 is based on *Space-Frequency Block Coding* (SFBC) in case of two antenna ports and on a combination of SFBC and *Frequency-Switched Transmit Diversity* (FSTD) in case of four antenna ports [10]. Feedback of precoding matrix recommendations for TM6 and TM9 and other feedback (downlink channel quality indicator and HARQ feedback) are discussed in Sections 5.2.5.5 and 5.3.2.2. Because most LTE-M devices are expected to be low-cost devices with a single receive antenna, *multiple-input multiple-output* (MIMO) operation is not supported.

For PDSCH demodulation, the device uses CRS for TM1/TM2/TM6 and DMRS for TM9 (see Section 5.2.4.3). The PDSCH is masked with a scrambling sequence generated based on the PCID and the RNTI. For CE mode B, to simplify frequency error estimation and combination of the repetitions in receiver implementations that use combining on I/Q sample level, the same scrambling sequence and the same RV are repeated over multiple subframes (4 subframes in FDD and 10 subframes in TDD). Furthermore, the device can assume that any potential precoding matrix (for beamforming) stays the same over a number of subframes indicated in the SI (see Section 5.3.3.2).

Release 14 introduces the possibility to *restrict the PDSCH modulation scheme to QPSK* in connected mode. It has been observed that the combinations of TBS and modulation scheme standardized in Release 13 (shown in Table 5.8) are not always optimal when repetition is applied. The link performance can sometimes be better if the modulation scheme is restricted to QPSK when 16QAM should be selected according to the tables. When a device is configured with this feature, PDSCH transmission will be limited to QPSK whenever PDSCH is scheduled with repetition. Support of PDSCH modulation scheme restriction is bundled into a single capability indication and configuration parameter with two other related Release 14 features (PUSCH modulation scheme restriction, and new PUSCH repetition factors) described in Section 5.2.5.4.

Release 14 also introduces the possibility to use *larger maximum channel bandwidth* than 6 PRBs for PDSCH in CE mode A and B (and for PUSCH in CE mode A), as shown in Table 5.5. A device configured with 5 MHz maximum PDSCH channel bandwidth supports a maximum downlink TBS of 4008 bits (which matches the maximum downlink TBS of device category Cat-M2 and can also be configured for higher-category devices that support CE mode operation), and a device configured with 20 MHz maximum PDSCH channel bandwidth supports a maximum downlink TBS of 27376 bits. The associated resource allocation methods are summarized in Table 5.26.

Release 15 introduces *downlink 64QAM support* for PDSCH unicast transmission without repetition in CE mode A to increase the spectral efficiency. When this feature is configured, MCS and TBS are according to Table 5.9, where the MCS field has been extended from 4 bits to 5 bits (see Section 5.3.2.1.1). However, there is no intention to increase the device peak rate, so the TBS is capped by the maximum TBS for the device category. See Section 5.3.2.2 for information on *Channel Quality Information* (CQI) reporting for 64QAM support.

5.2.5 Uplink physical channels and signals

LTE-M supports the set of uplink channels depicted in Fig. 5.16. The physical layer provides data transport services to higher layers through the use of transport channels via the MAC layer [13]. The *Uplink Control Information* (UCI) is not a transport channel, which is indicated by the dashed line. The MAC layer in turn provides data transport services through the use of logical channels, which are also shown in the figure for completeness [14]. For more information on the higher layers, refer to Section 5.3.

In this section we focus on the uplink physical channels. Due to the adopted uplink transmission scheme in LTE (i.e., SC-FDMA), the transmission from a device needs to be contiguous in the frequency domain. To maximize the chances that large contiguous allocations are available for uplink data transmission on the PUSCH for LTE and LTE-M users, it is often considered beneficial to allocate the resources for *Physical Random Access Channel* (PRACH) and *Physical Uplink Control Channel* (PUCCH) near the edges of the system bandwidth. The uplink RS are not shown in Fig. 5.16 but are transmitted together with PUSCH or PUCCH or separately for sounding of the radio channel.

5.2.5.1 Uplink subframes

A cell-specific *subframe bitmap* can be broadcasted in the SI (see Section 5.3.1.2) to indicate which subframes are valid for LTE-M transmission. For FDD uplink, the bitmap length is 10 bits corresponding to the uplink subframes within 1 frame. For TDD, the bitmap length is 10 or 40 bits corresponding to the subframes within 1 or 4 frames. This bitmap could, for example, facilitate so-called dynamic TDD operation within the LTE cell. Typically, all uplink subframes are configured as valid.

When an LTE-M device needs to retune from one uplink narrowband in a first subframe to another uplink narrowband in a second subframe, the device creates a *guard period for narrowband retuning* by not transmitting two of the SC-FDMA symbols [10]. If the two

TABLE 5.9 PDSCH modulation and coding schemes and transport block sizes in LTE-M when configured with Release 15 feature for 64QAM support.

MCS index	Modulation scheme	TBS index	CE mode A					
			# PRB pairs					
			1	2	3	4	5	6
0	QPSK	0	16	32	56	88	120	152
1	QPSK	1	24	56	88	144	176	208
2	QPSK	2	32	72	144	176	208	256
3	QPSK	3	40	104	176	208	256	328
4	QPSK	4	56	120	208	256	328	408
5	QPSK	5	72	144	224	328	424	504
6	QPSK	6	328	176	256	392	504	600
7	QPSK	7	104	224	328	472	584	712
8	QPSK	8	120	256	392	536	680	808
9	QPSK	9	136	296	456	616	776	936
10	16QAM	9	136	296	456	616	776	936
11	16QAM	10	144	328	504	680	872	1032
12	16QAM	11	176	376	584	776	1000	1192
13	16QAM	12	208	440	680	904	1128	1352
14	16QAM	13	224	488	744	1000	1256	1544
15	16QAM	14	256	552	840	1128	1416	1736
16	16QAM	15	280	600	904	1224	1544	1800
17	64QAM	15	280	600	904	1224	1544	1800
18	64QAM	16	328	632	968	1288	1608	1928
19	64QAM	17	336	696	1064	1416	1800	2152
20	64QAM	18	376	776	1160	1544	1992	2344
21	64QAM	19	408	840	1288	1736	2152	2600
22	64QAM	20	440	904	1384	1864	2344	2792
23	64QAM	21	488	1000	1480	1992	2472	2984
24	64QAM	22	520	1064	1608	2152	2664	3240
25	64QAM	23	552	1128	1736	2280	2856	3496
26	64QAM	24	584	1192	1800	2408	2984	3624
27	64QAM	25	616	1256	1864	2536	3112	3752
28	64QAM	26	712	1480	2216	2984	3752	4392
29	QPSK	Reserved	TBS from previous DCI for TB					
30	16QAM	Reserved	TBS from previous DCI for TB					
31	64QAM	Reserved	TBS from previous DCI for TB					

TABLE 5.10 PDSCH/PUSCH repetition factors in CE mode A.

Broadcasted maximum number repetitions for CE mode A (separately configured for PDSCH and PUSCH)	PDSCH repetition factors that can be selected from the DCI on MPDCCH	PUSCH repetition factors that can be selected from the DCI on MPDCCH	
		When Release 14 feature for new PUSCH repetition factors is NOT configured	When Release 14 feature for new PUSCH repetition factors is configured
No broadcasted value (default)	1, 2, 4, 8	1, 2, 4, 8	1, 2, 4, 8, 12, 16, 24, 32
16	1, 4, 8, 16	1, 4, 8, 16	1, 2, 4, 8, 12, 16, 24, 32
32	1, 4, 16, 32	1, 4, 16, 32	1, 2, 4, 8, 12, 16, 24, 32

TABLE 5.11 PDSCH/PUSCH repetition factors in CE mode B.

Broadcasted maximum number repetitions for CE mode B (separately configured for PDSCH and PUSCH)	PDSCH/PUSCH repetition factors that can be selected from the DCI on MPDCCH
No broadcasted value (default)	4, 8, 16, 32, 64, 128, 256, 512
192	1, 4, 8, 16, 32, 64, 128, 192
256	4, 8, 16, 32, 64, 128, 192, 256
384	4, 16, 32, 64, 128, 192, 256, 384
512	4, 16, 64, 128, 192, 256, 384, 512
768	8, 32, 128, 192, 256, 384, 512, 768
1024	4, 8, 16, 64, 128, 256, 512, 1024
1536	4, 16, 64, 256, 512, 768, 1024, 1536
2048	4, 16, 64, 128, 256, 512, 1024, 2048

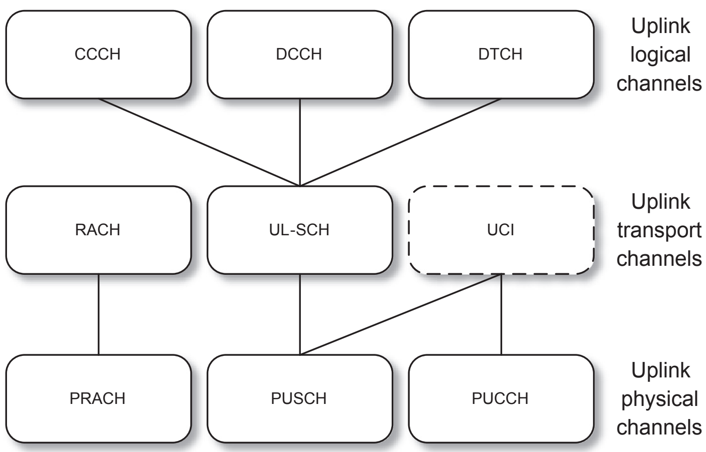

FIG. 5.16 Uplink channels used in LTE-M.

subframes both carry PUSCH or they both carry PUCCH, the guard period is created by truncating the last symbol in the first subframe and the first symbol in the second subframe. If one of the subframes carries PUSCH and the other one carries PUCCH, truncation of PUCCH is avoided by instead truncating up to two symbols of PUSCH. The rationale for this rule is that PUSCH is protected by more robust channel coding and retransmission scheme compared to PUCCH. A similar retuning gap is inserted in downlink (see Section 5.2.4.1). In Release 14, it is possible for the device to indicate that it can do faster frequency retuning (in uplink and downlink) so that the guard period can be smaller than two symbols (for details see Section 5.2.4.1).

A *shortened format* may be used for PUSCH/PUCCH to make room for *Sounding Reference Signal* (SRS) transmission in the last SC-FDMA symbol in an uplink subframe (see Section 5.2.5.3).

5.2.5.2 PRACH

Subframe	Any
Basic TTI	1, 2, or 3 ms
Repetitions	1, 2, 4, 8, 16, 32, 64, 128
Subcarrier spacing	1.25 kHz
Bandwidth	839 subcarriers (ca. 1.05 MHz)
Frequency location	Any
Frequency hopping	Between two frequency locations if configured

The *Physical Random Access Channel* (PRACH) is used by the device to initialize connection and allows the serving base station to estimate the time of arrival of uplink transmission. For more information on the random access procedure in idle and connected mode, see Sections 5.3.1.6 and 5.3.2.3.

The time of arrival of the received PRACH signal reflects the round-trip propagation delay between the base station and device. Fig. 5.17 shows the structure of the LTE PRACH preamble.

LTE-M reuses the LTE PRACH formats listed in Table 5.12, where T_s is the *basic LTE time unit* $1/(15{,}000 \times 2{,}048)$ s.

In LTE, the *PRACH configuration* is cell-specific and there are many possible configurations in terms of mapping the signal on the subframe structure (the PRACH configurations are listed in Section 5.7.1 in Ref. [10]). A configuration can be sparse or dense in time, as

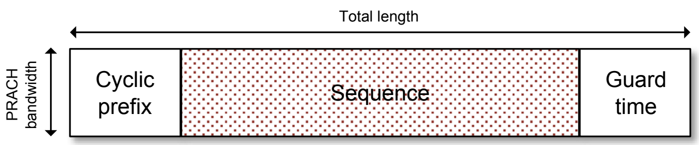

FIG. 5.17 LTE PRACH preamble structure.

TABLE 5.12 PRACH formats in LTE-M.

PRACH format	CP length	Sequence length (ms)	Total length	Cell range from guard time	FDD PRACH configurations	TDD PRACH configurations
0	3,168 $T_s \approx 0.10$ ms	0.8	1 ms	15 km	0–15	0–19
1	21,024 $T_s \approx 0.68$ ms	0.8	2 ms	78 km	16–31	20–29
2	6,240 $T_s \approx 0.20$ ms	1.6	2 ms	30 km	32–47	30–39
3	21,024 $T_s \approx 0.68$ ms	1.6	3 ms	108 km	48–63	40–47

illustrated by the examples for PRACH Format 0 in Fig. 5.18, where FDD PRACH configuration 2 uses every 20th subframe and FDD PRACH configuration 14 uses every subframe. A device can make a PRACH attempt in any PRACH opportunity using one out of the (max 64) configured PRACH preamble sequences.

LTE-M introduces PRACH coverage enhancement (CE) through up to 128 times repetition of the basic PRACH preamble structure in Fig. 5.17. The repetitions are mapped onto the PRACH subframes that are included in the PRACH configuration.

In a cell supporting CE mode B, up to 4 *PRACH CE levels* can be defined. If the cell only supports CE mode A, up to 2 PRACH CE levels can be defined. The network has several options for separating the PRACH resources that correspond to different PRACH CE levels.

- **Frequency domain**: The network can separate the PRACH resources of the PRACH CE levels by configuring different *PRACH frequencies* for different PRACH CE levels.

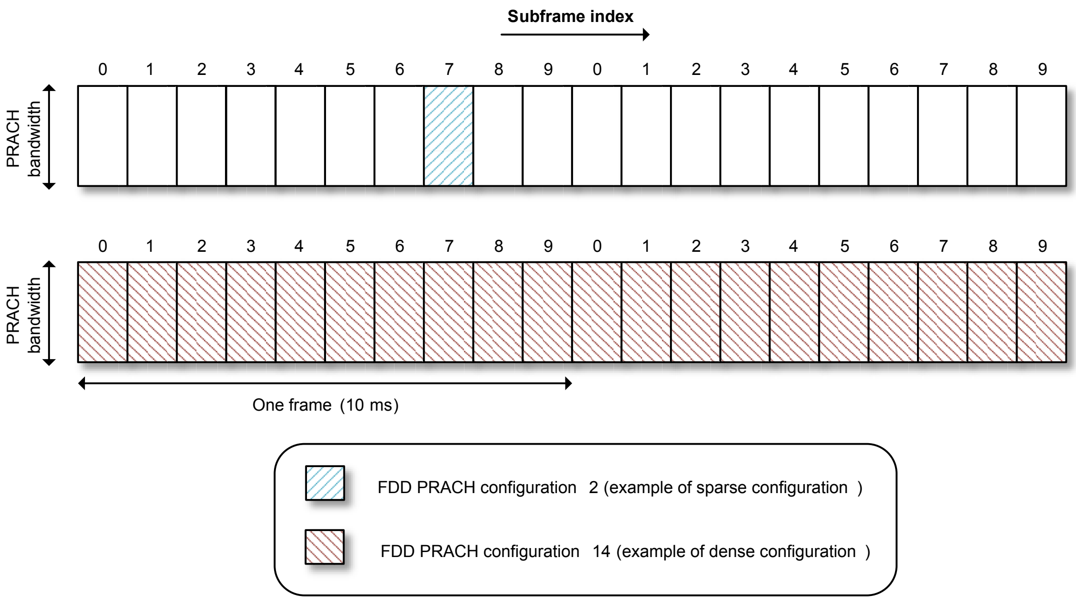

FIG. 5.18 Example PRACH configurations for FDD PRACH Format 0 in LTE and LTE-M.

- **Time domain**: The network can separate the PRACH resources of the PRACH CE levels by configuring different *PRACH configurations* and *PRACH starting subframe periodicities* for different PRACH CE levels.
- **Sequence domain**: The network can separate the PRACH resources of the PRACH CE levels by configuring nonoverlapping *PRACH preamble sequence groups* for different PRACH CE levels.

Fig. 5.19 shows a rather elaborate example of how 4 PRACH CE levels can be multiplexed in the frequency and time domains. For simplicity, this example uses relatively small repetition factors (1, 2, 4, and 8) for the 4 PRACH CE levels, and all PRACH CE levels are configured with the dense PRACH configuration 14 (see Fig. 5.18). PRACH CE level 0 is configured with its own PRACH frequency so that devices accessing PRACH CE level 0 can transmit a 1-ms PRACH transmission in any subframe. PRACH CE levels 1, 2, and 3 are configured to time share a second PRACH frequency.

The reason that the all 4 PRACH CE levels in this example seem to use both PRACH frequencies is that all PRACH CE levels have been configured to use frequency hopping, and the PRACH frequency hopping offset has been carefully selected to be 25 PRBs which is half the system bandwidth of 50 PRBs, which results in the two PRACH frequencies swapping places with each other at every frequency hop (i.e. every 2 ms, since this is the configured uplink frequency hopping interval). For more information on frequency hopping, see Section 5.3.3.2.

The time sharing between PRACH CE levels 1, 2, and 3 in this example is achieved by configuring a PRACH starting subframe periodicity of 16 ms. When a PRACH starting subframe periodicity is configured for a PRACH CE level, the PRACH opportunity in each period for that level starts after one repetition factor, meaning that is starts after 2 ms for PRACH CE level 1, after 4 ms for PRACH CE level 2, and after 8 ms for PRACH CE level 3. A device accessing PRACH CE level 1 will therefore transmit a 2-ms PRACH transmission in a subframe '2a' and the following subframe '2b' in the figure, whereas a device accessing PRACH CE level 2 will transmit a 4-ms PRACH transmission in subframes '4a' through '4d', and a device accessing PRACH CE level 3 will transmit an 8-ms PRACH transmission in subframes '8a' through '8h'.

It should be noted that in this example we did not even make use of the possibility to separate the PRACH CE levels using different *PRACH configurations* or different *PRACH preamble sequence groups*, so there are many other possible configurations beside this example.

5.2.5.3 Uplink reference signals

5.2.5.3.1 DMRS

Subframe	Any
Subcarrier spacing	15 kHz
Bandwidth	Same as associated PUSCH/PUCCH
Frequency location	Same as associated PUSCH/PUCCH

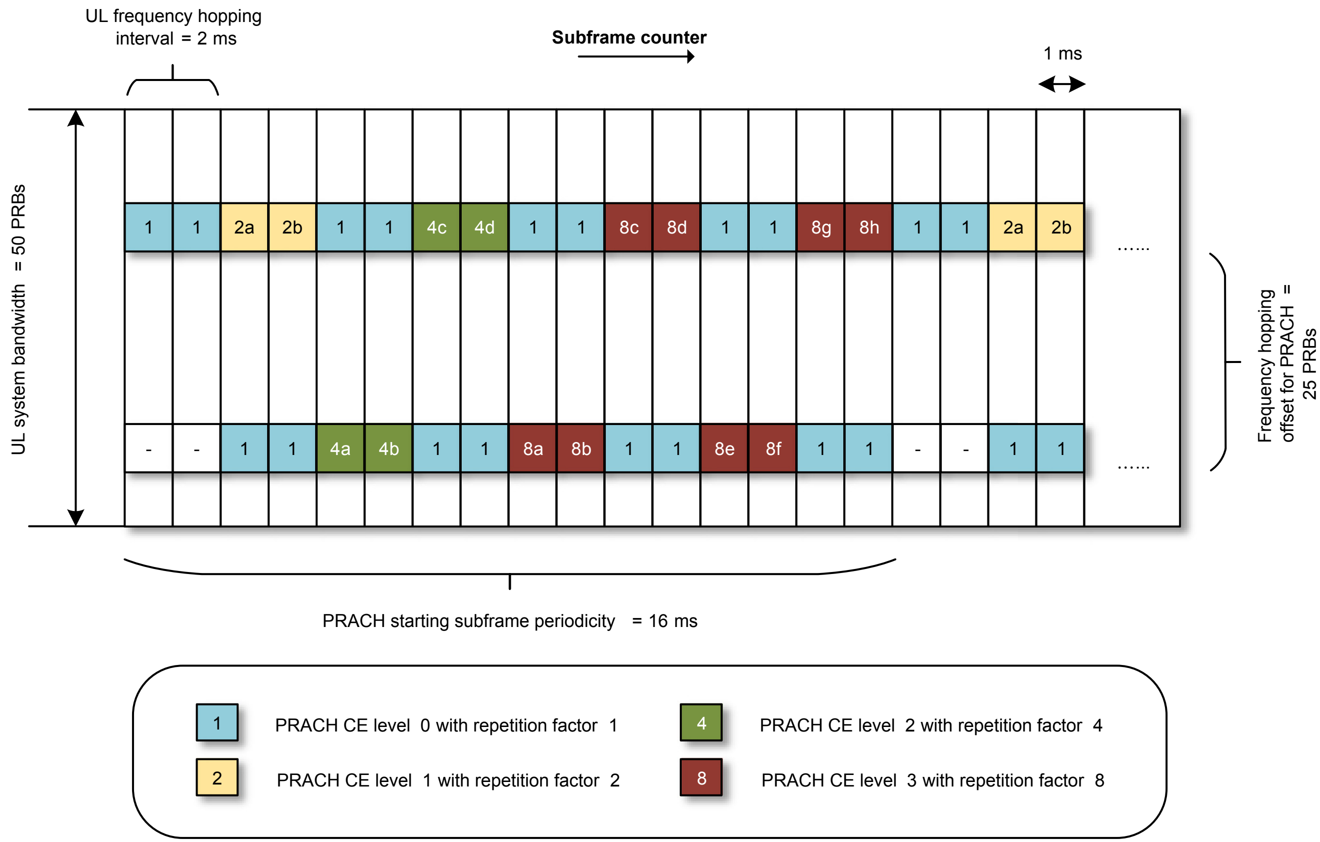

FIG. 5.19 Example of PRACH CE level multiplexing in LTE-M.

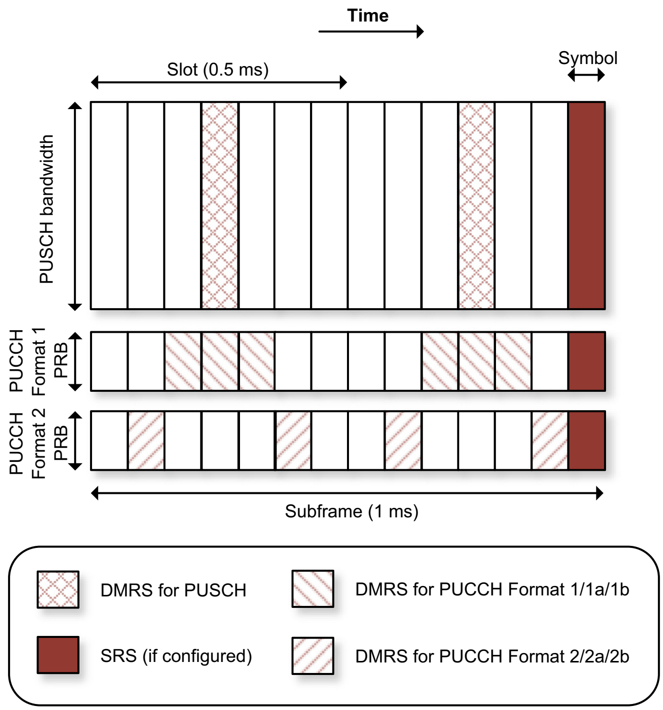

FIG. 5.20 Uplink reference signals for LTE-M.

Uplink reference signals (RS) [10] are predefined signals transmitted by the device to allow the base station to estimate the uplink propagation channel to be able to demodulate uplink physical channels, perform uplink quality measurements, and issue timing advance (TA) commands. Fig. 5.20 depicts the uplink RS for LTE-M.

The uplink *Demodulation Reference Signal* (DMRS) for PUSCH and PUCCH is transmitted in the SC-FDMA symbols indicated in Table 5.13 in each slot in the transmitted uplink

TABLE 5.13 Uplink DMRS locations in LTE-M.

Physical channel	DMRS position within each slot (SC-FDMA symbol indices starting with 0)	
	Normal CP length (7 symbols per slot)	**Extended CP length (6 symbols per slot)**
PUSCH	3	2
PUCCH Format 1/1a/1b	2, 3, 4	2, 3
PUCCH Format 2	1, 5	3
PUCCH Format 2a/2b	1, 5	N/A

subframe. The DMRS bandwidth is equal to the channel bandwidth of the associated PUSCH or PUCCH transmission. For PUCCH the channel bandwidth is always 1 PRB, but for PUSCH the channel bandwidth is variable (see Section 5.2.5.4 for details).

Multiplexing of multiple PUCCH in the same time-frequency resource is enabled by the possibility to generate multiple orthogonal DMRS sequences by applying a *cyclic time shift*, and in case of PUCCH Format 1/1a/1b also by applying an *orthogonal cover code* on top of the cyclic time shift.

5.2.5.3.2 SRS

Subframe	Any
Subcarrier spacing	15 kHz
Bandwidth	4 PRBs
Frequency location	Configurable

The network can reserve the last SC-FDMA symbol of some uplink subframes in a cell for *Sounding Reference Signal* (SRS) transmission for sounding of the radio channel. The device will then use shortened format for PUSCH and PUCCH in the affected subframes to make room for potential SRS transmission from itself or another device. Periodic SRS transmission can be configured through RRC configuration, whereas aperiodic SRS transmission can be triggered by setting the SRS request bit in DCI (see Tables 5.25 and 5.28). CE mode A supports both periodic and aperiodic SRS transmission. CE mode B does not support SRS transmission but will use shortened formats for PUSCH and PUCCH according to the SRS configuration in the cell to avoid collision with SRS transmissions from other devices.

All LTE-M physical channels support coverage enhancement through repetition in Release 13 but the SRS does not. Release 14 introduces the possibility to use the uplink part of the special subframe in TDD (described in Section 5.2.2.1) for transmission of SRS symbol repetitions. This can be used to improve the link adaptation in both uplink and downlink by exploiting the uplink—downlink channel reciprocity in TDD.

5.2.5.4 PUSCH

Subframe	Any
Basic TTI	1 ms (for full-PRB transmission) or 2/4/8 ms (for Release 15 sub-PRB transmission)
Repetitions	Maximum 32 in CE mode A, maximum 2048 in CE mode
Subcarrier spacing	15 kHz
Bandwidth	1—6 PRBs in CE mode A, 1 or 2 PRBs in CE mode B (Release 14 and 15 support additional bandwidths)
Frequency location	Within a narrowband (Release 15 supports more flexible location)
Frequency hopping	Between 2 narrowbands if configured

The *Physical Uplink Shared Channel* (PUSCH) is primarily used to transmit unicast data. The data packet from higher layers is segmented into one or more TB, and PUSCH transmits one TB at a time. For information on PUSCH scheduling, refer to Section 5.3.2.1.2.

PUSCH is also used for transmission of UCI when aperiodic *Channel State Information* (CSI) transmission (see Table 5.30) is triggered by setting the CSI request bit in DCI (see Table 5.28) or in case of collision between PUSCH and PUCCH (see Section 5.2.5.5).

In this section we first go through the Release 13 functionality before we turn to the Release 14 and 15 enhancements for PUSCH.

Table 5.14 shows the MCS and TBS for PUSCH in CE mode A and B in Release 13. However, in Release 13 the low-cost LTE-M device Cat-M1 is restricted to a maximum TBS of 1000 bits, so the TBS values larger than 1000 bits do not apply to Cat-M1, only to higher

TABLE 5.14 PUSCH modulation and coding schemes and transport block sizes in LTE-M (when not configured with Release 14 feature for larger uplink TBS and not using sub-PRB allocation introduced in Release 15).

MCS index	Modulation scheme	TBS index	Transport block sizes in CE mode A						Transport block sizes in CE mode B	
			# PRB pairs						# PRB pairs	
			1	2	3	4	5	6	1	2
0	QPSK	0	16	32	56	88	120	152	56	152
1	QPSK	1	24	56	88	144	176	208	88	208
2	QPSK	2	32	72	144	176	208	256	144	256
3	QPSK	3	40	104	176	208	256	328	176	328
4	QPSK	4	56	120	208	256	328	408	208	408
5	QPSK	5	72	144	224	328	424	504	224	504
6	QPSK	6	328	176	256	392	504	600	256	600
7	QPSK	7	104	224	328	472	584	712	328	712
8	QPSK	8	120	256	392	536	680	808	392	808
9	QPSK	9	136	296	456	616	776	936	456	936
10	QPSK	10	144	328	504	680	872	1032	504	1032
11	16QAM	10	144	328	504	680	872	1032	Unused	
12	16QAM	11	176	376	584	776	1000	1192		
13	16QAM	12	208	440	680	904	1128	1352		
14	16QAM	13	224	488	744	1000	1256	1544		
15	16QAM	14	256	552	840	1128	1416	1736		

device categories configured with CE mode A (see Section 5.2.2.3 for more information on the CE modes and Section 5.2.3 for information about device categories).

A 24-bit CRC is attached to the TB. The channel coding is the standard LTE turbo coding with 1/3 coding rate, 4 redundancy versions (RV), rate matching, and interleaving [20]. PUSCH is mapped to the SC-FDMA symbols that are not used by DMRS (see Section 5.2.5.3).

In CE mode A in Release 13, the PUSCH is modulated with QPSK or 16QAM and mapped to between 1 and 6 PRB pairs anywhere within a narrowband. In CE mode B in Release 13, the PUSCH is modulated with QPSK and mapped to 1 or 2 PRB pairs within a narrowband.

Coverage enhancement can be provided by repeating the subframe up to 2048 times. The maximum numbers of repetitions in CE modes A and B, respectively, are configurable per cell according to Tables 5.10 and 5.11. HD-FDD devices supporting CE mode B can indicate to the network that they need to insert periodic *uplink transmission gaps* in case of long PUSCH transmissions in which case the device will insert a 40-ms gap every 256 ms [10]. This gap is used by the device to correct frequency and time errors by measuring the downlink RS.

PUSCH is masked with a scrambling sequence generated based on the PCID and the RNTI. For CE mode B, to simplify frequency error estimation and combination of the repetitions in receiver implementations that use combining on I/Q sample level, the same scrambling sequence and the RV are repeated over multiple subframes (4 subframes in FDD, 5 subframes in TDD).

Release 14 introduces the possibility for a device to support a *new range of PUSCH repetition factors* in order to facilitate efficient, delay-sensitive scheduling. The set of available PUSCH repetition factors for CE mode A in Release 13 listed in Table 5.10 are powers of two, which is not considered optimal in order to support delay-sensitive services such as VoLTE in CE mode A. During a VoLTE call, a *speech frame* is produced every 20 ms. If no *speech frame bundling* is applied, it needs to be possible to transmit a transport block each direction (uplink and downlink) every 20 ms. If speech frame bundling is applied, each transport block can carry multiple (e.g., 2 or 3) speech frames, meaning that the TBs are larger but less frequent (e.g., every 40 or 60 ms). The new range is {1, 2, 4, 8, 12, 16, 24, 32}, where 12 and 24 are new values compared to Release 13. Furthermore, the whole range is immediately available through a 3-bit field in the DCI, i.e., the interpretation of the DCI field for number of PUSCH repetitions no longer depends on any higher layer parameter (the one referred to as *Broadcasted maximum number of repetitions for CE mode A* in Table 5.10).

Release 14 introduces the possibility to *restrict the PUSCH modulation scheme to QPSK*. It has been observed that the standardized combinations of TBS and modulation scheme (shown in Table 5.14) are not always optimal when repetition as applied. The link performance can sometimes be better if the modulation scheme is restricted to QPSK when 16QAM should be selected according to the tables. In uplink, QPSK may also have an additional benefit in terms of lower *Peak-to-Average Power Ratio* (PAPR) compared to 16QAM, allowing for higher transmit power. When a device is configured with this feature, PUSCH transmission will be limited to QPSK when a new 1-bit field in the DCI indicates that QPSK should be used instead of the default modulation scheme for the indicated MCS. Support of PUSCH modulation scheme restriction and the new PUSCH repetition factors mentioned above are bundled into a single capability indication and configuration parameter with another related Release 14 feature (PDSCH modulation scheme restriction) described in Section 5.2.4.7.

TABLE 5.15 PUSCH modulation and coding schemes and transport block sizes in LTE-M when configured with Release 14 feature for larger uplink TBS.

MCS index	Modulation scheme	TBS index	Transport block sizes in CE mode A					
			# PRB pairs					
			1	2	3	4	5	6
0	QPSK	0	16	32	56	88	120	152
1	QPSK	2	32	72	144	176	208	256
2	QPSK	4	56	120	208	256	328	408
3	QPSK	5	72	144	224	328	424	504
4	QPSK	6	328	176	256	392	504	600
5	QPSK	8	120	256	392	536	680	808
6	QPSK	10	144	328	504	680	872	1032
7	16QAM	10	144	328	504	680	872	1032
8	16QAM	12	208	440	680	904	1128	1352
9	16QAM	14	256	552	840	1128	1416	1736
10	16QAM	16	328	632	968	1288	1608	1928
11	16QAM	17	336	696	1064	1416	1800	2152
12	16QAM	18	376	776	1160	1544	1992	2344
13	16QAM	19	408	840	1288	1736	2152	2600
14	16QAM	20	440	904	1384	1864	2344	2792
15	16QAM	21	488	1000	1480	1992	2472	2984

Release 14 also introduces support for *larger uplink TBS for Cat-M1* in CE mode A. The background is described in Section 5.2.3, and the MCS and TBS values that apply when the feature is configured are listed in Table 5.15.

Release 14 also introduces the possibility to use *larger maximum channel bandwidth* than 6 PRBs for PUSCH in CE mode A (and for PDSCH in CE mode A and B), as shown in Table 5.5. A device configured with 5 MHz maximum PUSCH channel bandwidth supports a maximum uplink TBS of 6968 bits (which matches the maximum uplink TBS of device category Cat-M2). The associated resource allocation method is briefly described in Section 5.3.2.1.2.

Release 14 also introduces support for *device transmit antenna selection* in CE mode A. For (higher-category LTE) devices that support it, the base station can indicate what antenna the device should transmit from by masking the CRC bits in DCI Format 6-0A. This can provide substantial gains in case the device is physically oriented in such a way that the two antennas experience very different radio conditions.

TABLE 5.16 PUSCH resource unit (RU) lengths in Release 15.

Resource allocation size	Modulation scheme	Resource unit (RU) length
1 or more PRBs (as in Release 13/14)	QPSK or 16QAM	1 subframe
6 subcarriers	QPSK	2 subframes
3 subcarriers	QPSK	4 subframes
2 out of 3 subcarriers	$\pi/2$-BPSK	8 subframes

Release 15 introduces *PUSCH sub-PRB allocation* in CE mode A and B, allowing a smaller PUSCH resource allocation than 1 PRB, increasing the multiplexing capacity significantly for users that are coverage limited rather than bandwidth limited. New allocation sizes are $^1/_2$ PRB (6 subcarriers) and $^1/_4$ PRB (3 subcarriers), which are used with QPSK modulation. In the latter case, a new *π/2-BPSK modulation* can also be used to produce a single subcarrier commuting between two adjacent subcarrier positions leaving the third subcarrier unused in the cell (the exact subcarrier positions also depend on whether the PCID is odd or even, to achieve some inter-cell interference randomization). The DMRS alternates between the same two subcarriers. This new modulation can achieve near 0 dB peak-to-average power ratio (PAPR), which is beneficial for uplink data coverage and for device power consumption. Rate-matching is performed over time-domain *resource units* (RU) whose lengths are defined according to Table 5.16 (the case with a resource allocation length of 1 subframe is not explicitly referred to as a resource unit in the specifications but is nevertheless included in the table for completeness). The maximum number of repetitions of the RUs is limited by the maximum total transmission time of 32 subframes in CE mode A and 2048 subframes in CE mode B. The allowed TBS values for sub-PRB allocation are listed in Table 5.17.

5.2.5.5 PUCCH

Subframe	Any
Basic TTI	1 ms
Repetitions in CE mode A	1, 2, 4, 8
Repetitions in CE mode B	4, 8, 16, 32 (Release 14 also supports 64 and 128)
Subcarrier spacing	15 kHz
Bandwidth	1 PRB
Frequency location	Any PRB
Frequency hopping	Between 2 PRB locations

The *Physical Uplink Control Channel* (PUCCH) is used to carry the following types of *Uplink Control Information* (UCI).

TABLE 5.17 PUSCH modulation and coding schemes and transport block sizes in LTE-M when using sub-PRB allocation introduced in Release 15.

MCS index	Modulation scheme	Transport block sizes				
		CE mode A			CE mode B	
		1 RU	2 RUs	4 RUs	2 RUs	4 RUs
0	QPSK or $\pi/2$-BPSK	32	88	328	88	328
1	QPSK or $\pi/2$-BPSK	56	144	408	144	408
2	QPSK or $\pi/2$-BPSK	72	176	504	176	504
3	QPSK or $\pi/2$-BPSK	104	208	600	208	600
4	QPSK or $\pi/2$-BPSK	120	224	712	224	712
5	QPSK or $\pi/2$-BPSK	144	256	808	256	808
6	QPSK or $\pi/2$-BPSK	176	328	936	328	936
7	QPSK or $\pi/2$-BPSK	224	392	1000	392	1000

- Uplink scheduling request (SR)
- Downlink HARQ feedback (ACK or NACK)
- Downlink channel state information (CSI)

A PUCCH transmission is mapped to a configurable *PUCCH region* that consists of two PRB locations with equal distance to the center frequency of the LTE system bandwidth, typically chosen to be close to the edges of the system bandwidth. Inter-subframe (not intra-subframe) frequency hopping takes place between the two PRB locations in the PUCCH region (see Fig. 5.25 and 5.26 and Section 5.3.3.2). PUCCH is mapped to the SC-FDMA symbols that are not used by DMRS (see Section 5.2.5.3). Coverage enhancement can be provided by repeating the subframe up to 32 times in Release 13 (and up to 128 times in Release 14).

The PUCCH formats supported by LTE-M are listed in Table 5.18. If a device in connected mode has a valid periodic PUCCH resource for *Scheduling Request* (SR), it can use it to request an uplink grant when needed, otherwise it has to rely on the random access procedure for this. A PUCCH resource for *HARQ feedback (ACK or NACK)* is allocated when a downlink data (PDSCH) transmission is scheduled, and since Release 14 the HARQ feedback for up to 4 downlink TB can be bundled into a single ACK or NACK using the *HARQ-ACK bundling* feature (see Section 5.3.2.1.1). *Channel State Information* (CSI) reporting is described in Section 5.3.2.2.

Typically, PUCCH Format 1/1a/1b and PUCCH Format 2/2a/2b would be mapped to different PUCCH regions, meaning at least 2 PUCCH regions corresponding to at least $2 + 2 = 4$ PRB locations. However, if the system bandwidth is small, one possibility is to map PUCCH Format 1/1a/1b and PUCCH Format 2/2a/2b so that they are both allocated to a PRB at a system bandwidth edge, both of them frequency hopping between the two

TABLE 5.18 PUCCH formats in LTE-M.

PUCCH format	Description	Modulation scheme	Comment
1	Scheduling request	On-off keying (OOK)	Supported in CE mode A and B
1a	1-bit HARQ feedback	BPSK	Supported in CE mode A and B
1b	2-bit HARQ feedback for TDD	QPSK	Only supported in CE mode A
2	10-bit CSI report	QPSK	Only supported in CE mode A
2a	10-bit CSI report + 1-bit HARQ feedback	QPSK + BPSK	Only supported in CE mode A
2b	10-bit CSI report + 2-bit HARQ feedback in TDD	QPSK + QPSK	Only supported in CE mode A

edges at the same time, but never mapped to the same edge at the same time. In this way, fewer PRB location are consumed by PUCCH and more PRB locations are available for uplink data (PUSCH) transmission.

It is in principle possible to multiplex up to 36 PUCCH Format 1/1a/1b in the same time-frequency resource by applying different *cyclic time shifts* and *orthogonal cover codes*, and up to 12 PUCCH Format 2/2a/2b in the same time-frequency resource by applying different cyclic time shifts (see Section 5.2.5.3). However, usually only half of these cyclic time shifts are considered useable in practical radio propagation conditions, i.e. 18 for PUCCH Format 1/1a/1b and 6 for PUCCH Format 2/2a/2b.

The PUCCH resources for SR and CSI are semi-statically configured via user-specific RRC signaling. The allocation of a PUCCH resource for HARQ feedback is more complicated since it would be too costly to allocate it semi-statically per user. The PUCCH resource for HARQ feedback is determined based on both semi-static and dynamic information, including a semi-static PUCCH resource starting offset configured per MPDCCH PRB set, a dynamic offset within the MPDCCH PRB set derived from the ECCE index for the first ECCE used by the MPDCCH (see Section 5.2.4.6) carrying the DCI scheduling the downlink data (PDSCH) transmission, another dynamic offset (0, -1, -2, or +2) indicated by a 2-bit field in the DCI (see Section 5.3.2.1.1) allowing the base station to avoid collision between PUCCH transmissions from different users, and additional offsets in case of localized MPDCCH transmission or TDD (for details see Section 10.1 in Ref. [15]).

The number of PUCCH repetitions to use in connected mode is configured per device. In CE mode A, the possible PUCCH repetition numbers are {1, 2, 4, 8} and different repetition numbers can be configured for PUCCH Format 1/1a/1b and PUCCH Format 2/2a/2b. In CE mode B, the possible repetition numbers for PUCCH Format 1/1a/1b are {4, 8, 16, 32} in Release 13 and {4, 8, 16, 32, 64, 128} in Release 14. Similar ranges apply for the PUCCH carrying HARQ feedback for the PDSCH carrying Message 4 during the random access procedure described in Section 5.3.1.6, but the values are broadcasted in System Information Block 2 (SIB2).

Simultaneous transmission of more than one PUSCH or PUCCH transmission from the same device is not supported. If a device is scheduled to transmit both PUSCH and UCI in a subframe, and both PUSCH and PUCCH are without repetition, then the UCI is multiplexed into the PUSCH according to ordinary LTE behavior, but if PUSCH or PUCCH is with repetition then PUSCH is dropped in that subframe. If a device is scheduled to transmit two or more of HARQ feedback, SR, and periodic CSI in a subframe, and PUCCH is without repetition, then ordinary LTE behavior applies, but if PUCCH is with repetition then only the highest priority UCI is transmitted, where HARQ feedback has the highest priority and periodic CSI has the lowest priority.

5.3 Idle and connected mode procedures

In this section, we describe LTE-M physical layer procedures and higher layer protocols, including all activities from initial cell selection to setting up and controlling a connection. This section uses physical layer related terminology introduced in Section 5.2.

The idle mode procedures include the initial cell selection, system information (SI) acquisition, cell reselection, paging, and multicast procedures. The transition from idle to connected mode involves the procedures for random access, and access control. The connected mode operation includes procedures for scheduling, retransmission, power control, mobility support, and positioning. Idle mode procedures and connected mode procedures are treated in Sections 5.3.1 and 5.3.2, respectively. Additional physical layer procedures common for idle and connected mode are treated in Section 5.3.3.

The LTE-M radio protocol stack is inherited from LTE [13] and is described in Section 2.2. The main changes are in the physical layer, but there are also changes to the higher layers. Changes to the control plane are mainly covered in Section 5.3.1 and changes to the user plane are mainly covered in Section 5.3.2. The mappings between physical channels, transport channels, and logical channels are illustrated in Fig. 5.4 and 5.16.

5.3.1 Idle mode procedures

The first idle mode procedure that the device needs to carry out is cell selection. Once a cell has been selected, most of the interaction between the device and the base station relies on transmissions addressed by the base station to the device using a 16-bit *Radio Network Temporary Identifier* (RNTI) [14]. The RNTIs monitored by LTE-M devices in idle mode are listed in Table 5.32 in Section 5.3.3.1 together with references to the relevant book sections.

5.3.1.1 Cell selection

The main purpose of cell selection is to identify, synchronize to, and determine the suitability of a cell. The general steps in the LTE-M cell selection procedure (which to a large extent follows the LTE cell selection procedure) are as follows:

1. Search for the PSS to identify the presence of an LTE cell and to synchronize in time and frequency to the LTE carrier frequency and half-frame timing.

2. Synchronize to the SSS to identify the frame timing, PCID, CP length, and duplex mode (FDD or TDD).
3. Acquire the MIB to identify the SFN, the downlink system bandwidth, the scheduling information for the LTE-M-specific SIB1, and (since Release 15) a flag bit for unchanged SI.
4. Acquire the SIB1 to identify, for example, the H-SFN, public land mobile network (PLMN) identity, tracking area, unique cell identity, UL−DL configuration (in case of TDD), and scheduling information for other SI messages and to prepare for verification of the cell suitability.

These procedures are in detail described in the next few sections.

5.3.1.1.1 Time and frequency synchronization

The *initial cell selection* procedure aims to time-synchronize to PSS and to obtain a *carrier frequency error* estimation. As shown in Fig. 5.7 and 5.8, PSS is transmitted every 5 ms at the center 62 subcarriers of the downlink carrier. The device can assume that the allowed carrier frequencies are aligned with a 100-kHz channel raster [9], i.e., the carrier frequencies to search for are multiples of 100 kHz. The initial oscillator inaccuracy for a low-cost device may be as high as 20 ppm (parts per million), corresponding to, for example, 18 kHz initial carrier frequency error for a 900-MHz band. This means that there is relatively large uncertainty both regarding time and frequency during initial cell selection, which means that time and frequency synchronization at initial cell selection can take significantly longer than at *non-initial cell selection* or *cell reselection* (cell reselection is described in Section 5.3.1.3).

By time synchronizing to PSS the device detects the 5-ms (half-frame) timing. PSS synchronization can be achieved by correlating the received signal with the three predefined PSS sequences. Time and frequency synchronization can be performed in a joint step using subsequent PSS transmissions. For further details on the synchronization signals, refer to Section 5.2.4.2.

Release 15 introduces a possibility for *EARFCN pre-provisioning*, where the device is provided with an EARFCN list (see Section 5.2.1.1) and the geographical area where each EARFCN applies, which can help speed up the initial cell acquisition [21]. The information can be stored in SIM [22]. It is up to the device implementation whether and how to use this information. This feature is introduced for both LTE-M and NB-IoT.

Release 15 furthermore introduces the *Resynchronization Signal* (RSS) which cannot be used for initial synchronization to a cell but for maintaining or re-acquiring time and frequency synchronization toward the cell if needed (for details, see Section 5.2.4.2.2).

5.3.1.1.2 Cell identification and initial frame synchronization

Like the PSS, the SSS is transmitted every 5 ms at the center 62 subcarriers of the downlink carrier. As discussed in Section 5.2.4.2, the SSS can be used to acquire the frame timing, the PSS and SSS sequences together can be used to identify the cell's physical cell identity (PCID), and the relative positions of the PSS and SSS transmissions within a frame can be used to detect the duplex mode (FDD or TDD) and the CP length (normal or extended).

5.3.1.1.3 MIB acquisition

After acquiring the PCID, the device knows the CRS placement within a resource block as the subcarriers that CRS REs are mapped to are determined by PCID. It can thus demodulate and decode PBCH, which carries the *Master Information Block* (MIB). For further details on PBCH, refer to Section 5.2.4.4. One of the information elements carried in the MIB is the 8 most significant bits of the SFN. Because the SFN is 10 bits long, the 8 MSBs of SFN change every 4 frames, i.e., every 40 ms. As a result, the TTI of PBCH is 40 ms. A MIB is encoded to a PBCH code block, consisting of 4 code subblocks. PBCH is transmitted in subframe 0 in every frame, and each PBCH subframe carries a code subblock. A code subblock can be repeated as explained in Section 5.2.4.4 for enhanced coverage. Initially the device does not know which subblock is transmitted in a specific frame. Therefore, the device needs to form four hypotheses to decode a MIB during the initial cell selection process. This is referred to as blind decoding. In addition, to correctly decode the MIB CRC the device needs to hypothesize whether 1, 2, or 4 antenna ports are used for CRS transmission at the base station. A successful MIB decoding is indicated by having a correct CRC. At that point, the device has acquired the information listed below:

- Number of antenna ports for CRS transmission
- System frame number (SFN)
- Downlink system bandwidth
- Scheduling information for the LTE-M-specific SIB1
- Flag bit for unchanged system information (introduced in Release 15, see Section 5.3.1.2.3)

Typically, the system bandwidth is the same in downlink and uplink but in principle they can be different. The downlink system bandwidth is indicated in MIB, whereas the uplink system bandwidth is indicated in SIB2, which is described in Section 5.3.1.2.2. Table 5.4 lists the supported system bandwidths.

The presence of the scheduling information for the LTE-M-specific SIB1 is an indication that LTE-M is supported by the cell. Hereafter the LTE-M-specific SIB1 will be referred to as SIB1 for short. (However, in the standard specifications it is referred to as *SIB1-BR*, where BR stands for *bandwidth-reduced*.)

The SFN field in MIB changes every 40 ms but most other MIB fields do not change very often, if ever. Therefore, the MIB content changes from TTI to TTI, but typically in a predictable way. This knowledge can be exploited to improve the reception performance by accumulating the PBCH transmissions from two or more consecutive 40-ms periods, and therefore Release 15 introduces more stringent reading delay requirements for the *Cell Global Identity* (CGI) reading based on PBCH accumulation across two 40-ms periods (see Section 5.3.1.2.1).

5.3.1.1.4 CID and H-SFN acquisition

After acquiring the MIB including the scheduling information about SIB1 the device is able to locate and decode SIB1. We will describe more about how device acquires SIB1 in Section 5.3.1.2.1. From a cell search perspective, it is important to know that the SIB1 carries the hyper

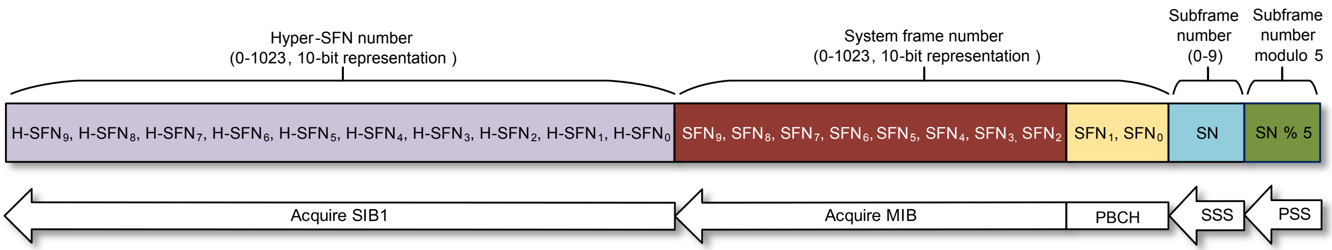

FIG. 5.21 Illustration of how the LTE-M device acquires complete timing information during the initial cell search.

system frame number (H-SFN), the public land mobile network (PLMN) identity, tracking area, and cell identity (CID). Unlike the PCID, the CID is unique within the PLMN. After acquiring SIB1, the device has achieved complete synchronization to the framing structure shown in Fig. 5.1. Based on the information provided in SIB1, the device will be able to determine whether the cell is suitable for camping, and whether the device can attempt to attach to the network. Somewhat simplified, a cell is considered suitable if the PLMN is available, the cell is not barred, and the cell's signal strength exceeds a minimum requirement. There are separate signal strength requirements for CE mode A and CE mode B.

Fig. 5.21 illustrates how the device acquires complete framing information during the initial cell search procedure.

After completing the initial cell search, the device is expected to have a time and frequency accuracy that offers robust operation in subsequent transmission and reception during connected and idle mode operations.

5.3.1.2 System Information acquisition

After selecting a suitable cell to camp on a device needs to acquire the full set of *system information* (SI). Table 5.19 summarizes the supported SIB types [13]. SIB1 and SIB2 contain the most critical SI, required by the device to be able to select the cell for camping and for accessing the cell. The other SIBs may or may not be transmitted in a given cell depending on the network configuration. LTE-M inherits the SIBs from LTE. LTE SIBs related to functionality not supported by LTE-M are not included in the table. Interested readers can refer to Ref. [23] for additional details regarding SIBs.

Although LTE-M reuses the SIB definitions from LTE, it should be noted that the SI for LTE-M devices is transmitted separately from the SI for ordinary LTE devices. The main reason for this is that the SI transmissions in LTE are scheduled using LTE's PDCCH, and may be scheduled to use any number of PRB pairs for PDSCH, which together means SI transmission occupies in general a too large channel bandwidth to be received by LTE-M devices with reduced receive bandwidth, and as a consequence LTE-M devices are not able to receive LTE's ordinary SI transmissions. SI transmissions for LTE-M devices are transmitted without an associated PDCCH on the PDSCH described in Section 5.2.4.7, masked with a scrambling sequence generated using the SI-RNTI defined in the standard [14].

5.3.1.2.1 System Information Block 1

SIB1 carries information relevant when evaluating if the device is allowed to camp on and access the cell, as well as scheduling information for the other SIBs. SIB1 for LTE-M is referred to as *SIB1-BR* in the specifications, where BR stands for *bandwidth-reduced*, but it is here referred to as SIB1 for brevity.

The information relevant when evaluating whether the device is allowed to access the cell includes, for example, the PLMN identity, the tracking area identity, cell barring and cell reservation information, and the minimum required *Reference Signal Received Power* (RSRP) and *Reference Signal Received Quality* (RSRQ) to camp on and access the cell. Cell selection and cell reselection are described in Sections 5.3.1.1 and 5.3.1.3.

The scheduling information for the other SIBs is described in Section 5.3.1.2.2. In addition, SIB1 contains information critical for scheduling of downlink transmissions in general.

TABLE 5.19 SIB types in LTE-M.

SIB	Content
SIB1	Information relevant when evaluating if a device is allowed to access a cell and scheduling information for other SIBs (see Section 5.3.1.2.1)
SIB2	Configuration information for common and shared channels
SIB3	Cell reselection information, mainly related to the serving cell
SIB4	Information about the serving frequency and intrafrequency neighboring cells relevant for cell reselection
SIB5	Information about other frequencies and interfrequency neighboring cells relevant for cell reselection
SIB6	Information about UMTS 3G frequencies and neighboring cells relevant for cell reselection
SIB7	Information about GSM frequencies cells relevant for cell reselection
SIB8	Information about CDMA2000 3G frequencies and neighboring cells relevant for cell reselection
SIB9	Name of the base station in case it is a small so-called home base station (femto base station)
SIB10	Earthquake and Tsunami Warning System (ETWS) primary notification
SIB11	ETWS secondary notification
SIB12	Commercial Mobile Alert System warning notification
SIB14	Information about Extended Access Barring for access control (see Section 5.3.1.8)
SIB15	Information related to multicast (introduced in Release 14, see Section 5.3.1.9)
SIB16	Information related to GPS time and Coordinated Universal Time
SIB17	Information relevant for traffic steering between E-UTRAN and WLAN
SIB20	Information related to multicast (introduced in Release 14, see Section 5.3.1.9)

This information includes the H-SFN, the UL−DL configuration (in case of TDD), the LTE-M downlink subframe bitmap, and the LTE-M starting symbol. For further information on these timing aspects, refer to Sections 5.2.1.2, 5.2.2.1 and 5.2.4.1.

The scheduling information for SIB1 itself is signaled using 5 bits in MIB [15]. If the value is zero then the cell is an LTE cell that does not support LTE-M devices, otherwise the TBS and number of repetitions for SIB1 are derived according to Table 5.20.

A SIB1 transport block is transmitted on PDSCH according to an 80 ms long pattern that starts in frames with SFN exactly divisible by 8 [10]. As indicated in Table 5.20, the PDSCH is repeated in 4, 8, or 16 subframes during this 80-ms period (except for system bandwidths smaller than 5 MHz, which only support 4 repetitions). Exactly what subframes are used for SIB1 transmission depends on the PCID and duplex mode according to Table 5.21. The PCID helps randomize the interference between SIB1 transmissions from different cells.

The LTE-M downlink subframe bitmap signaled in SIB1 has no impact on the SIB1 transmission itself. Similarly, the LTE-M starting symbol signaled in SIB1 does not apply to the

TABLE 5.20 Transport block size and number of PDSCH repetitions for SIB1 in LTE-M.

SIB1 scheduling information signaled in MIB	SIB1 transport block size in bits	Number of PDSCH repetitions in an 80-ms period
0	LTE-M not supported in the cell	
1	208	4
2		8
3		16
4	256	4
5		8
6		16
7	328	4
8		8
9		16
10	504	4
11		8
12		16
13	712	4
14		8
15		16
16	936	4
17		8
18		16
19–31	Reserved values	

TABLE 5.21 Subframes for SIB1 transmission.

System bandwidth (MHz)	Number of PDSCH repetitions in an 80-ms period	PCID	Subframes with SIB1 transmission in FDD case	Subframes with SIB1 transmission in TDD case
<5	4	Even	Subframe #4 in even frames	Subframe #5 in odd frames
		Odd	Subframe #4 in odd frames	Subframe #5 in odd frames
≥ 5	4	Even	Subframe #4 in even frames	Subframe #5 in odd frames
		Odd	Subframe #4 in odd frames	Subframe #0 in odd frames
	8	Even	Subframe #4 in every frame	Subframe #5 in every frame
		Odd	Subframe #9 in every frame	Subframe #0 in every frame
	16	Even	Subframes #4 and #9 in every frame	Subframes #0 and #5 in every frame
		Odd	Subframes #0 and #9 every frame	Subframes #0 and #5 in every frame

SIB1 transmission. Instead, the starting symbol for the PDSCH carrying SIB1 is always the fourth OFDM symbol in the subframe except for the smallest system bandwidth (1.4 MHz) where it is always the fifth OFDM symbol in the subframe [15].

SIB1 is transmitted on PDSCH with QPSK modulation using all 6 PRB pairs in a narrowband and RV cycling across the repetitions. The frequency locations and frequency hopping for SIB1 are fixed in the standard as described in Section 5.3.3.2. In case the scheduling causes collision between SIB1 and other MPDCCH/PDSCH transmission in a narrowband in a subframe, the SIB1 transmission takes precedence and the other transmission is dropped in that narrowband in that subframe.

The SIB1 information is unchanged at least during a *modification period* of 5.12 s, except in the rare cases of *Earthquake and Tsunami Warning System* (ETWS) or *Commercial Mobile Alert System* (CMAS) notifications, or when the ACB information changes (see Section 5.3.1.8 for more information). In practice the time between SI updates is typically much longer than 5.12 s. Release 15 introduces more stringent reading delay requirements for the *Cell Global Identity* (CGI) reading based on PBCH accumulation across two 40-ms periods (see Section 5.3.1.1.3) and SIB1 accumulation within one modification period assuming MIB and SIB1 do not change frequently. This enables reduction of the allowed CGI identification time for Cat-M1 from 5120 ms to 3200 ms at a low SNR level of -15 dB [24].

5.3.1.2.2 System Information Blocks 2-20

SIB1 contains scheduling information for the other SIBs listed in Table 5.19. SIBs other than SIB1 are carried in *SI messages*, where each SI message can contain one or more SIBs [23]. Each SI message is configured with an *SI periodicity*, a TBS and a starting narrowband. The possible periodicities are {8, 16, 32, 64, 128, 256, 512} frames, and the possible TBS are {152, 208, 256, 328, 408, 504, 600, 712, 808, 936} bits. Each SI message can also be configured with its own *SI value tag* as described in Section 5.3.1.2.3.

The SI messages are periodically broadcasted during specific, periodic, and nonoverlapping time domain windows known as *SI windows* of configurable length. Possible SI window lengths are {1, 2, 5, 10, 15, 20, 40, 60, 80, 120, 160, 200} ms, where the smallest values are inherited from LTE and probably not that relevant for LTE-M. If the periodicity for the nth SI message is T_n frames, then that SI message is transmitted in the nth SI window after every frame that has an SFN evenly divisible by T_n. The intention with the specified behavior is to map different SI messages to different SI windows even if they have the same periodicity.

Furthermore, to support operation in extended coverage, SI messages can be repeated within their respective SI windows. Possible repetition patterns are {every frame, every second frame, every fourth frame, and every eighth frame} throughout the SI window. All SI messages have the same repetition pattern.

Each SI message is transmitted on PDSCH with QPSK modulation using all 6 PRB pairs in its narrowband and RV cycling across the repetitions. Frequency hopping is supported as described in Section 5.3.3.2. In case the scheduling causes collision between SI messages and other MPDCCH/PDSCH transmission than SIB1 in a narrowband in a subframe, the SI message transmission takes precedence and the other transmission is dropped in that narrowband in that subframe [15].

The SI message content is unchanged during a configurable modification period where the possible values are {2, 4, 8, 16, 64} times the cell paging cycle. In practice the time between SI updates is typically much longer than this.

5.3.1.2.3 System Information update

When the network modifies the SI in a cell, it can indicate this to the devices through the SI value tag [23]. The SI value tag is a 5-bit field in SIB1 that is changed every time the SI content has changed. It is also possible for the network to signal an SI value tag per SI message, which enables the device to just reacquire the SI messages that have actually changed instead of having to reacquire them all, which can be power consuming for the device. These SI value tags are 2-bit fields.

When the SI has changed, the network can also explicitly notify the devices through so-called *direct indication* in the DCI used for paging [20]. The meaning of the 8-bit direct indication field is described in Table 5.22 [23]. Paging and eDRX are discussed in Section 5.3.1.4.

Note that some SI updates, for example regularly changing parameters such as time information and access barring information, may not result in any SI value tag changes or explicit SI update notifications from the network. Also, when a device is configured with an eDRX cycle that is longer than the SI modification period, the device verifies that the stored SI is valid before trying to establish a connection or receive paging.

An LTE-M device considers its stored SI to be valid for several hours from the moment it was acquired, where the number of hours is either 3 or 24 h depending on network configuration [23]. When the SI has become invalid, the device should reacquire the SI before it accesses the network. An LTE-M device also verifies the validity of the SI every time it is released from connected mode to idle mode.

Release 15 introduces a flag bit in MIB indicating unchanged SI, and this flag bit helps reduce the need for the device to reacquire SIB1 just to read the SI value tag (see Section 5.3.1.1.3). The flag bit is set to true when no change has occurred in SIB1 or SI during the last 3 or 24 h (the configured SI validity time). Furthermore, if the resynchronization signal

TABLE 5.22 SI update notification through direct indication in DCI format for paging in LTE-M.

Bit	Meaning
1	General SI update notification to devices not configured with eDRX
2	SIB10/11 update notification
3	SIB12 update notification
4	SIB14 update notification
5	General SI update notification to devices configured with eDRX
6	Reserved
7	Reserved
8	Reserved

(RSS, also introduced in Release 15) is transmitted in the cell, then the device may even be able to skip MIB reacquisition, since the mentioned flag bit is also replicated in RSS (see Section 5.2.4.2.2).

5.3.1.3 *Cell reselection*

After selecting a cell, a device is required to evaluate the serving cell using a cell selection criterion, *S*, in terms of RSRP and RSRQ. If the serving cell can no longer fulfill the criterion, the device initiates the measurements of neighbor cells. In simple words, in case the device detects that a neighbor cell has become stronger in terms of the RSRP and RSRQ than the currently serving cell, then the cell reselection procedure is triggered. A hysteresis value provided in SIB3 helps prevent ping-pong reselection [23].

If both the cell and the device support CE mode B, and the device has not been restricted by the network from using CE mode B, then separate signal strength conditions apply for CE mode A and B, so that a cell supporting CE mode B can be selected at lower RSRP or RSRQ levels than a cell that only supports CE mode A.

Devices that are in good coverage, i.e., experience a sufficiently high RSRP and RSRQ levels in the serving cell, can choose to not perform measurements for cell reselection, provided that the current cell fulfills the cell selection/suitability criterion, *S*. The thresholds for RSRP and RSRQ are configured in SIB3 separately for the intra-frequency and inter-frequency measurement cases. This helps improve the battery life of these devices. Besides securing that a device camps on the best cell, the cell reselection procedure is the main mechanism for idle mode mobility.

Release 15 introduces a possibility for relaxed monitoring of neighbor cells also for devices that are experiencing weak coverage provided that certain relaxation criteria are met. If the feature is enabled in the cell, after 5 minutes with normal neighbor cell measurements, the device can suspend neighbor cell measurements unless it detects that the serving-cell RSRP degrades and the degradation exceeds a configured hysteresis value, in which case the device again performs normal neighbor cell measurements as usual for 5 more minutes. If measurements do not lead to a cell reselection within a 5-minute window, the device can stop neighbor cell monitoring for up to 24 hours, after which the process repeats. This will allow a stationary device in challenging coverage conditions to avoid wasting power on trying to find a stronger cell when it has already found the strongest cell in the vicinity.

5.3.1.4 *Paging, DRX and eDRX*

In idle mode, the device monitors periodic *paging occasions* (PO) in a *paging narrowband* in the downlink for potential attempts from the network to contact the device [25]. The paging transmission can contain multiple *paging records* intended for different devices in the cell. When a device receives a paging transmission at its paging occasion in its paging narrowband, it checks whether any of the paging records matches its device identity, and if there is a match, the device responds by initiating a connection to the cell using the random access procedure described in Section 5.3.1.6. The device can be identified either using a *System Architecture Evolution Temporary Mobile Subscriber Identity* (S-TMSI) or the more rarely used global *International Mobile Subscriber Identity* (IMSI).

The monitoring of paging has implications on device battery lifetime and the latency of downlink data delivery to the device. A compromise is achieved by configuring a *discontinuous reception* (DRX) cycle and/or an *extended DRX* (eDRX) cycle. The maximum DRX cycle is 256 frames (2.56 s) in both idle and connected mode, and the maximum eDRX cycle is 256 hyperframes (about 44 min) in idle mode and 1024 frames (10.24 s) in connected mode. After each eDRX cycle, a *paging time window* (PTW) occurs, configurable in multiples of 128 frames up to 2048 frames (20.48 s) during which downlink reachability is achieved through the configured DRX cycle. Fig. 7.49 can serve as an illustration of these concepts, although it should be noted that the maximum values of the parameters are different in LTE-M and NB-IoT. The paging occasions for a device are determined by the DRX/eDRX configuration and the device identity (IMSI for DRX, S-TMSI for eDRX).

The total number of narrowbands that are used for paging is configurable per cell, and among these narrowbands the device determines its paging narrowband based on its device identity (IMSI). Frequency hopping is supported as described in Section 5.3.3.2.

The monitored physical channel is MPDCCH. MPDCCH repetition is supported using the *Type-1 MPDCCH Common Search Space* (CSS) described in Section 5.3.3.1. The MPDCCH carries DCI using DCI Format 6-2 [20]. This DCI format can either be used for carrying a direct indication field according to Table 5.22 or for scheduling a PDSCH carrying paging record(s) according to Table 5.23. The DCI CRC is masked with the *Paging RNTI* (P-RNTI), which is defined in the standard [14].

TABLE 5.23 DCI Format 6-2 for paging and direct indication for LTE-M.

Information	Size [bits]	Possible settings
Flag for paging/direct indication	1	Paging or direct indication (If this flag bit indicates direct indication then the remaining DCI content is according to Table 5.22)
PDSCH narrowband	1–4	Any narrowband in the system bandwidth
PDSCH TBS	3	{40, 56, 72, 120, 136, 144, 176, 208} bits
Number of PDSCH repetitions	3	One of the following ranges, depending on the setting of the DCI field "Number of MPDCCH repetitions": 00: {1, 2, 4, 8, 16, 32, 64, 128} 01: {4, 8, 16, 32, 64, 128, 192, 256} 10: {32, 64, 128, 192, 256, 384, 512, 768} 11: {192, 256, 384, 512, 768, 1024, 1536, 2048}
Number of MPDCCH repetitions	2	One of the following ranges, depending on the setting of the SIB2 parameter for max number of repetitions R_{max}: $R_{max} = 1$: {1} $R_{max} = 2$: {1, 2} $R_{max} = 4$: {1, 2, 4} $R_{max} = 8$: {1, 2, 4, 8} $R_{max} = 16$: {1, 4, 8, 16} $R_{max} = 32$: {1, 4, 16, 32} $R_{max} = 64$: {2, 8, 32, 64} $R_{max} = 128$: {2, 16, 64, 128} $R_{max} = 256$: {2, 16, 64, 256}

When the DCI schedules a PDSCH, the PDSCH is transmitted with QPSK modulation using all 6 PRB pairs in the narrowband [15]. PDSCH repetition is supported in a similar way as for downlink unicast transmission as described in Section 5.3.2.1.1. The number of paging records that can be carried in one transport block depends on the size of each device identity. The size of each paging record can vary between 25 and 61 bits, meaning that the largest TBS (208 bits) can carry between 3 and 8 paging records.

When the *Mobility Management Entity* (MME) in the *core network* needs to page an LTE-M device, it will inform the involved base station(s) that the device is an LTE-M device so that the paging can be transmitted using the right format (with DCI Format 6-2, MPDCCH, and so on). The MME can also optionally provide a *Paging Coverage Enhancement Level*, which is an estimate between 1 and 256 of the required number of repetitions for MPDCCH [26]. In that case, the MME has been keeping the value as device history information since an earlier session in the same cell [23]. If the device is, for example, a stationary metering device that needs large coverage enhancement because it is in a basement, it might be a good *paging strategy* to page the device right away with many MPDCCH repetitions in the cell where the device last accessed the network. However, if the device moves around when in idle mode there may not be any adequate history information in the MME because an LTE-M device in idle mode does not inform the network when the coverage situation changes [13]. For potential IoT use cases where the device is mobile but anyway frequently experiences bad coverage conditions, it may be difficult to find a suitable paging strategy, because it may not be acceptable from overhead point of view to page the device with many repetitions in multiple cells. In this case, some level of *Mobile Originated* (MO) traffic may be used to assist the network in keeping track of the device and thereby improve the downlink reachability for the device. One example of this is device-triggered tracking area updates.

To further improve device battery lifetime, Release 15 introduced the *MTC Wake-Up Signal* (MWUS) described in Section 5.2.4.5. MWUS facilitates device energy saving by indicating whether a paging indicator will be sent in an associated paging occasion. As this in essence is a single bit information (i.e., paging indicator present or not present), the total transmission time required is much shorter than that required for MPDCCH with DCI format 6-2. The number of repetitions for MWUS, R_{MWUS}, is a fraction (1/4, 1/8, 1/16, or 1/32) of the maximum number of repetitions configured for MPDCCH for paging, $R_{\max}$ (with the restriction that R_{MWUS} is never less than 1). Thus, MWUS enables the device to go back to sleep sooner, thereby achieving energy saving.

The time gap between the MWUS and the paging occasion (where the MPDCCH starts) is configurable. When MWUS is used with either DRX or eDRX, a “short” gap length of 40, 80, 160 or 240 ms can be configured, but in the eDRX case it is also possible to configure a “long” gap length of 1 or 2 s. The longer gaps are intended to facilitate device implementations with *wake-up receivers*, where a less complex detector is used for MWUS and the ordinary receiver is only started up if an MWUS was indeed detected.

When MWUS is used with eDRX, it is furthermore possible to configure MWUS to be associated with more than one paging occasion, achieving even bigger energy saving. In this case, when the device detects an MWUS, it will stay awake for the configured number of paging occasions (allowed values are 1, 2, and 4). This allows an MWUS to apply to (a part of) a paging time window (as illustrated in Fig. 7.50 for the corresponding mechanism in NB-IoT).

MWUS can be used in tandem with the *Resynchronization Signal* (RSS), which was also introduced in Release 15. Since MWUS is only transmitted when there is an actual paging, the device may need to receive some other signal than MWUS in order to maintain a sufficient level of time and frequency synchronization for reliable MWUS detection performance. RSS is a relatively dense synchronization signal transmitted according to a known pattern (see Section 5.2.4.2.2) which is particularly well suited for this purpose in a low-complexity wake-up receiver.

5.3.1.5 Power Saving Mode

The DRX and eDRX mechanisms described in the previous section provide minimum device power consumption for IoT applications where it needs to be possible to reach the device for *Mobile Terminated* (MT) traffic through paging within seconds or minutes. For applications where it is not required to be able to reach the device through paging faster than within half an hour or more, the PSM may be able to provide further power saving. The device will still be able to perform MO transmission in uplink without delay. PSM is a standalone feature applicable to all 3GPP radio access technologies. For information about PSM, refer to Sections 2.2.3 and 7.3.1.5.

5.3.1.6 Random access in idle mode

The random access procedure in LTE-M follows the same steps as in LTE [14]. After synchronizing to the network, confirming that access is not barred (as described in Section 5.3.1.8) and reading the PRACH configuration information in SIB2, the device can send a PRACH preamble to access the network (as described in Section 5.2.5.2). The random access procedure is illustrated in Fig. 5.22, and it is also used when the device responds to a paging message. Use of random access in connected mode is described in Section 5.3.2.3.

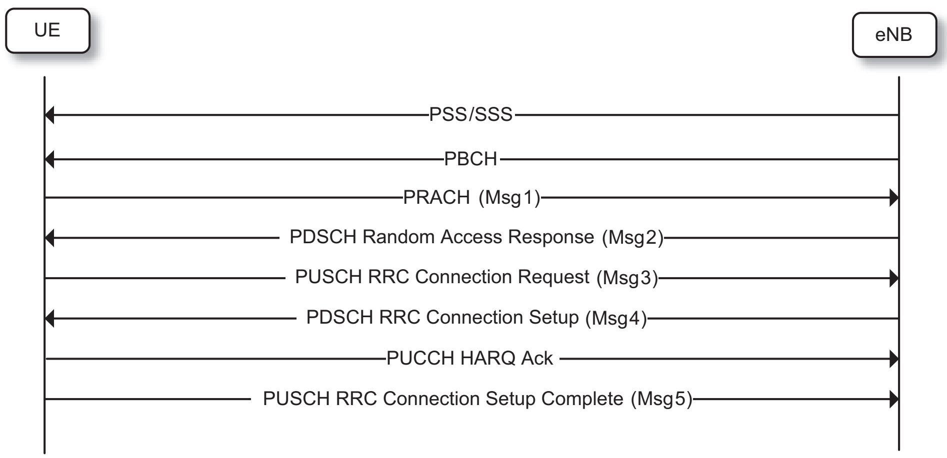

FIG. 5.22 Random access procedure in LTE and LTE-M.

If the base station detects a PRACH preamble, it sends back a *Random Access Response* (RAR), also known as *Message 2*. The RAR contains an uplink *timing advance* (TA) command. The RAR further contains scheduling information pointing to the radio resources that the device can use to transmit a request to connect, also known as *Message 3*. In Message 3, the device will include its identity as part of an RRC message. The device can in some cases include its buffer status in Message 3 to facilitate the scheduling for subsequent uplink transmissions. In *Message 4*, the network transmits a connection setup/resume message and contention resolution data that resolves any contention due to multiple devices transmitting the same preamble in the first step. The device finally replies with a connection setup/resume complete message to terminate the random access procedure and complete the transition to connected mode. The device may also append uplink data in the MAC layer of this message to optimize the latency of the data transfer.

LTE-M supports the ordinary RRC connection setup procedure described in Section 2.3.2 with the message transfer illustrated in Fig. 2.5 and the latency evaluated in Section 6.4. For devices for which small infrequent data transmission is the dominating use case, Release 13 and 15 furthermore introduce three optimizations reducing the connection setup signaling (*RRC Suspend/Resume*, *Data over NAS*, and *Early Data Transmission*), and these are described in Section 5.3.1.7.

Before the initial PRACH transmission, the device needs to determine an appropriate PRACH resource configuration according to its coverage level estimation. The cell can configure up to three RSRP thresholds that are used by the device to select the PRACH resource configuration appropriate for its level of coverage. The PRACH resource configurations are signaled in SIB2. An example is given in Fig. 5.23, in which three RSRP thresholds are configured and therefore there are four PRACH resources for four *PRACH CE levels*, respectively. The device performs a CRS-based RSRP measurement and selects a PRACH CE level in line with the measurement result. The higher the PRACH CE level, the larger the number of PRACH repetitions. If the device does not receive a RAR message in response to a PRACH attempt, it will make further attempts until it receives RAR or until it has reached the maximum allowed number of attempts. As in ordinary LTE operation, PRACH preamble power ramping is applied, but in LTE-M the device will also be able to do PRACH CE level ramping, meaning that the device moves to the next PRACH CE

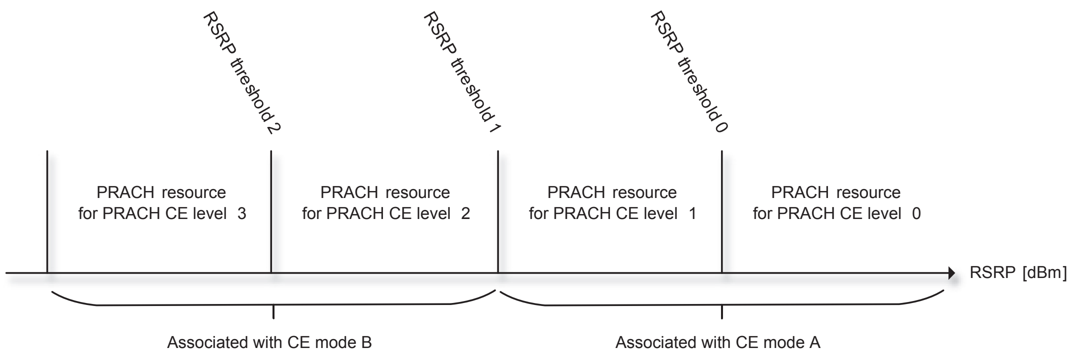

FIG. 5.23 PRACH configurations and RSRP thresholds for LTE-M.

level (increasing the number of PRACH repetitions per attempt) after a few unsuccessful attempts on one PRACH CE level.

After the PRACH preamble transmission, the device monitors a *RAR window* in the downlink for a potential MPDCCH transmission that schedules a PDSCH transport block containing 56-bit RAR messages for one or more devices. The MPDCCH uses the *Type-2 MPDCCH CSS* described in Section 5.3.3.1. The DCI CRC is masked with the *Random Access RNTI* (RA-RNTI), which is determined from the PRACH transmission time according to a predefined rule in the standard [14]. The RAR message contains a *Temporary Cell-RNTI* (TC-RNTI) and a *RAR grant* and these are used to schedule the initial Message 3 transmission on PUSCH. Potential PUSCH HARQ retransmissions for Message 3 and all PDSCH HARQ (re) transmissions for Message 4 are scheduled using MPDCCH in Type-2 MPDCCH CSS with TC-RNTI. The HARQ-ACK feedback for Message 4 is transmitted on PUCCH, so the random access procedure makes use of five physical channels (PRACH for Message 1, MPDCCH + PDSCH for Message 2, PUSCH + MPDCCH for Message 3, and MPDCCH + PDSCH + PUCCH for Message 4).

The device is strictly speaking not configured in CE mode A or B (as described in Section 5.2.2.3) until it has entered connected mode. However, the PRACH CE levels are associated with the CE modes as illustrated in Fig. 5.23. This means that if a PRACH preamble is successfully received on PRACH CE level 0 or 1 then the following messages (RAR, Message 3, and Message 4) will use DCI formats and various parameters signaled in SIB (e.g., maximum numbers of repetition and frequency hopping intervals) intended for CE mode A, and similarly if the PRACH preamble is successfully received on PRACH CE level 2 or 3 then the following messages will use DCI formats and SIB parameters intended for CE mode B. This means that the description of downlink scheduling in connected mode in Section 5.3.2.1.1 is to a large extent valid for RAR and Message 4, and the description of uplink scheduling in Section 5.3.2.1.2 is to a large extent valid for Message 3.

However, there are some differences compared to ordinary unicast in connected mode. RAR is restricted to QPSK modulation and does not support HARQ retransmission, and the initial Message 3 transmission is not scheduled from MPDCCH but from a grant field in the RAR message. The RAR grant contains a PUSCH grant, which includes narrowband index, resource allocation within the narrowband and TBS (typically 56, 72, or 88 bits), and an MPDCCH narrowband for scheduling of both potential HARQ retransmission(s) of Message 3 and HARQ (re)transmission(s) of Message 4. For further details on the RAR grant, refer to Section 6.2 in Ref. [15].

5.3.1.7 Connection establishment

LTE-M supports the ordinary RRC connection setup procedure described in Section 2.3.2 with the message transfer illustrated in Fig. 2.5 and the latency evaluated in Section 6.4. For devices for which small infrequent data transmission is the dominating use case, Release 13 and 15 furthermore introduce the three optimizations reducing the connection setup signaling described in this section.

5.3.1.7.1 RRC resume

The first method for signaling reductions is known as the *RRC Suspend/Resume* procedure, or just the *RRC Resume* procedure. It is part of the *User Plane CIoT EPS optimizations*. It allows a device to resume a connection previously suspended including the PDCP state, the access stratum security and RRC configurations. This eliminates the need to negotiate access stratum security as well as configuring the radio interface, including the *data radio bearers* carrying the data over the air interface, at connection setup. It also supports the PDCP to make efficient use of its *Robust Header Compression* (RoHC) already from the first data transmission in a resumed connection.

This functionality is based on a resume identity which identifies a suspended connection. It is signaled in the RRC Connection release message from the network to a device when a connection is suspended. The device signals the resume identity back to the network when it wants to resume a connection using Message 3 including the RRC Connection resume request message. Fig. 5.24 illustrates the complete procedure.

The RRC resume procedure allows uplink data to be multiplexed with the RRC signaling already in Message 5. This multiplexing between RLC packet data units containing user data and control signaling is achieved in the MAC layer.

5.3.1.7.2 Data over Non-access Stratum

The second method for signaling reductions is known as the *Data over NAS* (DoNAS) procedure and it is part of the *Control Plane CIoT EPS optimization*. In Message 5, the RRC Connection setup complete message, a *Non-Access Stratum* (NAS) container is used for transmitting uplink user data over the control plane. This method was primarily designed with NB-IoT use cases in mind but is optionally supported also in LTE-M. For details on this method, refer to Section 7.3.1.7.2.

5.3.1.7.3 Early Data Transmission

As described above uplink data and downlink data can at the earliest be delivered in *Message 5* and *Message 6*, respectively. This leaves room for further enhancements. Release 15 introduces a feature called *Early Data Transmission* (EDT) that allows a device to transmit

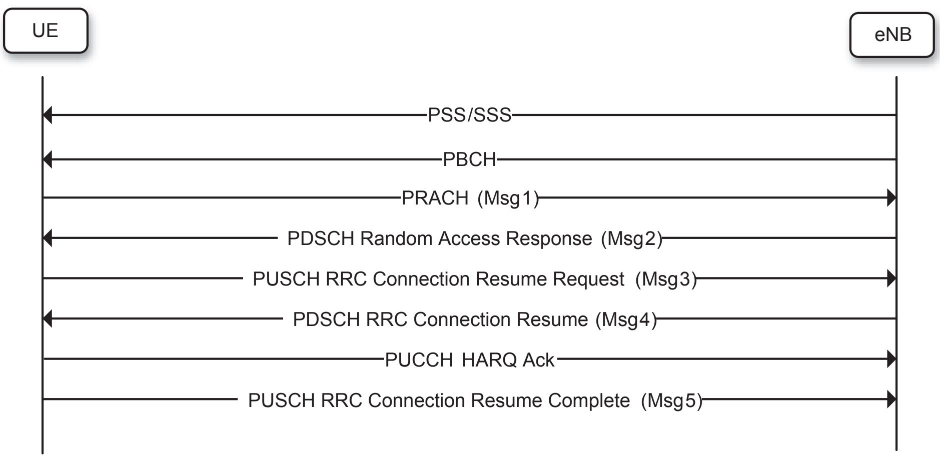

FIG. 5.24 RRC Resume procedure.

its uplink data in *Message 3*. In this case, the device can complete its data transmission in idle mode without a need to transition to connected mode.

EDT is however limited to small data payloads. Uplink EDT supports the TBS range {328, 408, 504, 600, 712, 808, 936, 1000} bits in CE mode A and {328, 408, 456, 504, 600, 712, 808, 936} bits in CE mode B. While these TBS values are not very large, they are significantly larger than an ordinary Message 3 which is typically in the range 56–88 bits (corresponding to the size of an RRC Connection Request or RRC Connection Resume Request message). The SI indicates a maximum TBS per PRACH CE level. Thus, a device can use the EDT procedure to transmit its uplink data only when the number of payload bits is less than the maximum TBS permitted. A device indicates its intent to use EDT by initiating a random access procedure with an PRACH preamble randomly selected from a set of preambles configured per PRACH CE level for the EDT procedure. In this case, upon detecting the PRACH preamble, the base station knows that the device attempts to transmit its uplink data through EDT, and therefore can include an EDT uplink grant for *Message 3* in *Message 2*. The base station can optionally allow devices to use a smaller TBS than the configured maximum TBS, and in this case the device can select a TBS for Message 3 based on its data buffer status. Message 2 indicates how many subframe repetitions the device should use for Message 3 transmission assuming that the maximum TBS is used, but if the device selects a smaller TBS then it scales down the number of repetitions proportionally, which helps reduce power consumption.

Since the device-selected TBS requires the base station to do blind decoding of a number of possible TBS hypotheses, it is up to the base station to indicate (per PRACH CE level) whether it is allowed or not, and the maximum number of TBS values that the device can select from (1, 2, or 4). The frequency domain (PRB) resource allocation is according to the UL grant indicated in Message 2 regardless of whether the device uses the maximum TBS or chooses a smaller TBS, and the modulation scheme is fixed to QPSK, so the base station does not need to use multiple hypotheses in the demodulation process, only in the decoding process.

Furthermore, since a Message 3 carrying user data is more resource-demanding than an ordinary Message 3, the base station always has the possibility to deny an EDT request by indicating in Message 2 that the device should fall back to ordinary random access procedure, in which case the device transmits an ordinary Message 3 instead of a Message 3 for EDT.

EDT also supports downlink data transmission in Message 4. This may be used to provide an application layer acknowledgment to the Message 3 uplink transmission and additional data if available.

EDT is in Release 15 enabled for MO access both for the User Plane CIoT EPS optimization procedure and Control Plane CIoT EPS optimization procedure. The user plane version builds on the RRC Resume procedure and makes use of the RRC Connection resume request in Message 3. Message 4, including potential downlink data, is defined by the RRC connection release message in case the connection is suspended or released immediately following the uplink data transmission. For the control plane solution, a pair of new RRC messages were defined for Message 3 and 4, both including the needed NAS container carrying the data.

5.3.1.8 *Access control*

LTE-M supports *access class barring* (ACB) and *extended access barring* (EAB) as described in Section 2.2.1. SIB1 contains the scheduling information for SIB14 that carries the extended access barring information. Absence of SIB14 scheduling information in SIB1 implies that barring is not activated, whereas presence of SIB14 scheduling information informs the devices that a barring is activated. A change of the barring parameters can occur at any time, triggering the base station to also change the SIB14 scheduling information.

A device in bad coverage locations requires a high repetition factor to be configured for its dedicated physical channels. During high network loads, it may be desirable to bar devices in bad coverage locations and use the available resources to serve many more devices in good coverage locations. Release 15 introduces PRACH CE level specific barring to prevent devices at certain coverage level, or worse, from accessing the network. This is enabled by providing an RSRP threshold in SIB14. If a device has measured RSRP below this threshold, it is barred from accessing the network. It should back off and then reattempt access at a later point in time.

5.3.1.9 *Multicast*

Support for multicast transmission is seen as beneficial for some IoT applications where there is, for example, a need for efficient distribution of software/firmware upgrades to a large number of devices. However, due to the inherent narrowband property of LTE-M, it does not support LTE's Multimedia Broadcast Multicast Service Single Frequency Network functionality since that is based on a channel bandwidth equal to the full LTE system bandwidth.

Release 14 introduces support for LTE-M multicast transmission based on the *Multimedia Broadcast Multicast Service* (MBMS) framework in the form of *Single-Cell Point-to-Multipoint* (SC-PTM) transmission. The solution is based on the SC-PTM feature introduced for ordinary LTE devices in Release 13, which follows LTE's MBMS architecture shown in Fig. 5.25, where the *Broadcast/Multicast Service Center* (BM-SC) and the *MBMS Gateway* are the MBMS-specific nodes.

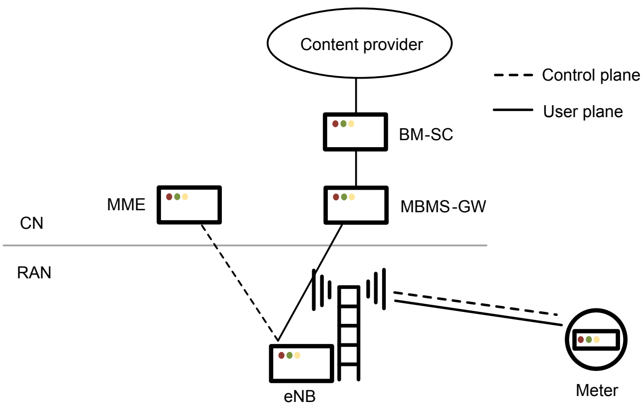

FIG. 5.25 MBMS architecture.

TABLE 5.24 MPDCCH search spaces, RNTIs, and DCI formats for SC-PTM for LTE-M.

Mode	MPDCCH search space	RNTI	Usage	DCI format
Idle	–	SI-RNTI	Broadcast of system information	–
	Type-1A common	SC-RNTI	Scheduling of SC-MCCH	6–2
	Type-2A common	G-RNTI	Scheduling of SC-MTCH	6-1A, 6-1B

SC-PTM support was introduced in Release 14 for both LTE-M and NB-IoT, and the standardization work was partly carried out as a joint effort because the objectives were the same (to extend Release 13 SC-PTM to support narrowband operation and coverage enhancement), so the SC-PTM solutions are very similar, although they use different physical channels in the physical layer. NB-IoT SC-PTM is described in Section 7.3.1.11, where the general procedure illustrated in Fig. 7.55 is applicable also for LTE-M SC-PTM.

SC-PTM for LTE-M (and NB-IoT) is only supported in idle mode. The new SIB20 can contain scheduling information for one *Single Cell Multicast Control Channel* (SC-MCCH) per cell, and SC-MCCH can contain scheduling information for one *Single Cell Multicast Traffic Channel* (SC-MTCH) per multicast service. The maximum channel bandwidth of an SC-MTCH can be either 1.4 or 5 MHz, with a maximum TBS of 1000 and 4008 bits, respectively (matching the maximum capabilities of Cat-M1 and Cat-M2). Both SC-MCCH and SC-MTCH are transmitted on PDSCH transmissions scheduled by MPDCCH. There is no retransmission mechanism, but both MPDCCH and PDSCH can be repeated to achieve the required coverage.

Table 5.24 lists the MPDCCH search spaces, RNTIs, and DCI formats used for SC-PTM. When the listed DCI formats are used for scheduling SC-MCCH or SC-MTCH, they include a DCI field for indication of SC-MCCH update notification, which means that the device does not need to waste power on re-acquiring SC-MCCH unless it has actually changed. Configuration of MPDCCH search spaces is further discussed in Section 5.3.3.1, and configuration of frequency hopping is discussed in Section 5.3.3.2.

5.3.2 Connected mode procedures

Most of the interaction between the device and the base station relies on transmissions addressed by the base station to the device using a 16-bit *Radio Network Temporary Identifier* (RNTI) [14]. The RNTIs monitored by LTE-M devices in connected mode are listed in Table 5.32 together with references to the relevant book sections.

5.3.2.1 Scheduling

In this section, we describe how scheduling for downlink and uplink transmissions works. When the base station needs to schedule a device dynamically, it sends a DCI which includes the resource allocation (in both time and frequency domains), modulation and coding scheme, and information needed for supporting the HARQ retransmission scheme. The DCI is carried on an MPDCCH, which is transmitted in an MPDCCH search space that the device is known to be monitoring (see Section 5.3.3.1) and the DCI has a CRC attached, which is masked with a user-specific *Cell RNTI* (C-RNTI) so that only the device for which the DCI is intended will decode it successfully, whereas other devices monitoring the same MPDCCH search space will discard the DCI because the CRC does not pass for them when they try to unmask the CRC using their C-RNTIs.

This section describes this *dynamic scheduling* of downlink and uplink as well as *semipersistent scheduling (SPS)*.

5.3.2.1.1 Dynamic downlink scheduling

To allow low-complexity device implementation, LTE-M adopts the following scheduling principles:

- Cross-subframe scheduling (i.e., DCI and the scheduled data transmission do not occur in the same subframe) with relaxed processing time requirements.
- Optionally, HD-FDD operation at the device (i.e., no simultaneous transmission and reception at the device) allows time for the device to switch between transmission and reception modes.

Fig. 5.26 shows an LTE-M downlink scheduling example without repetition, with MPDCCH and PDSCH transmissions scheduled in parallel to a device in the same downlink narrowband, and with the HARQ-ACK feedback transmitted on PUCCH in the uplink. In ordinary LTE, the PDCCH or EPDCCH carrying the DCI and the PDSCH carrying the data are transmitted in the same downlink subframe, but LTE-M has a cross-subframe scheduling delay of 2 ms that shows in the figure as a 1-ms gap between the end of the MPDCCH transmission carrying the DCI and the start of the scheduled PDSCH transmission. Other than that, the timing relationships are similar to ordinary LTE, with a 3-ms gap between the end of the PDSCH transmission and the start of the PUCCH transmission carrying the associated HARQ-ACK feedback, and another 3-ms gap before a potential HARQ retransmission of the same data is scheduled. Due to the extra 2-ms scheduling delay, the downlink HARQ *round-trip time* (RTT) is increased from $4 + 4 = 8$ to $2 + 4 + 4 = 10$ ms. The maximum number of downlink HARQ processes depends on the duplex mode and CE mode as indicated in Table 5.25. HD-FDD devices cannot be scheduled more frequently than in this example because they cannot transmit and receive simultaneously and furthermore need a guard subframe at every switching between downlink and uplink (as discussed in Section 5.2.2.1). For a discussion on the impact of the 10-ms RTT on the downlink peak rate in (half-duplex and full-duplex) FDD, see Section 6.3 and later in this section.

The base station schedules downlink transmission on PDSCH dynamically using DCI Format 6-1A and 6-1B in CE mode A and B, respectively. Table 5.25 shows the information carried in these DCI formats [20]. Some of the fields are specific to LTE-M and some of them are basically inherited from the ordinary LTE DCI formats. An effort has been made to make the DCI format for CE mode B as compact as possible because it is intended for situations where the device experiences a weak downlink signal implying large numbers of repetitions, and every extra bit is expensive in terms of coverage and/or resource consumption. The most important fields are present in both DCI formats, such as the PDSCH MCS, PDSCH resource block assignment, number of PDSCH repetitions, and number of repetitions of the MPDCCH carrying the DCI itself. The information about the number of MPDCCH repetitions is needed

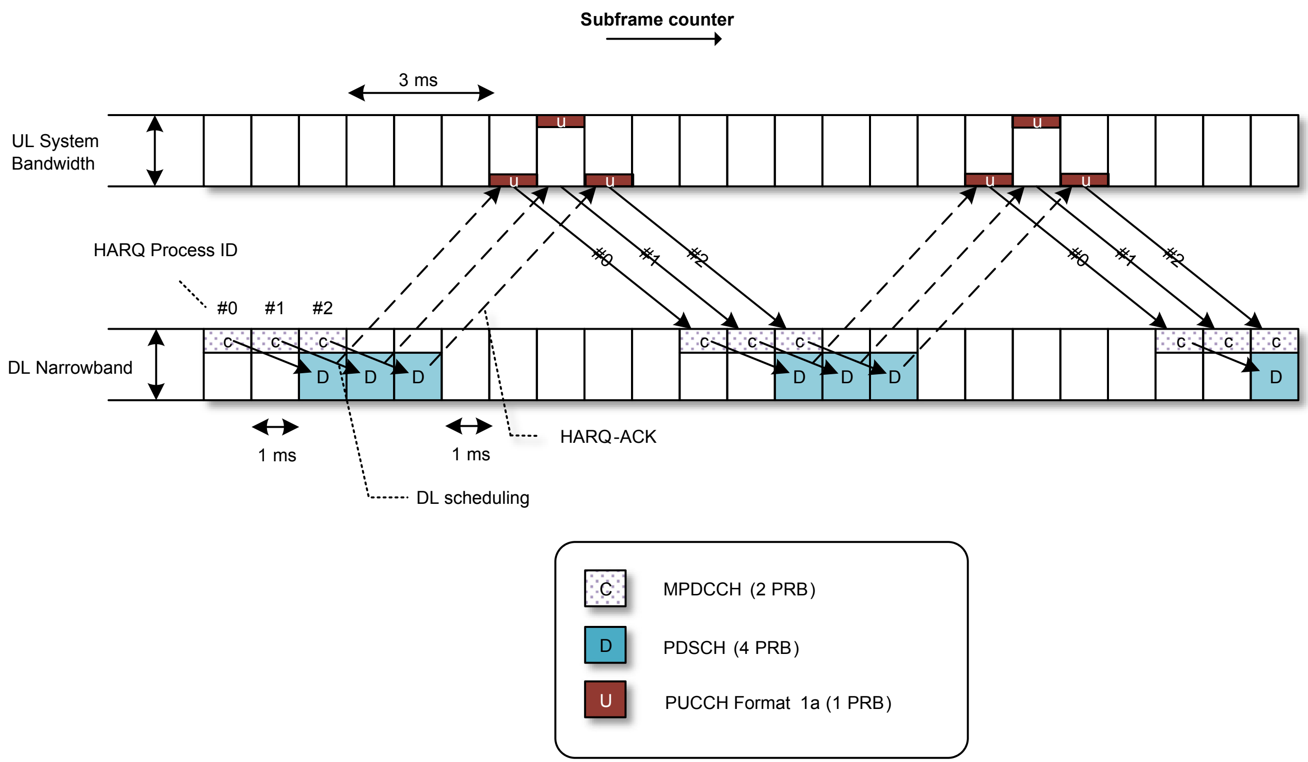

FIG. 5.26 LTE-M downlink scheduling example with MPDCCH and PDSCH transmitted without repetition in the same downlink narrowband.

TABLE 5.25 DCI Formats 6-1A and 6-1B used for scheduling PDSCH in CE modes A and B in Release 13.

	DCI format 6-1A		**DCI format 6-1B**	
Information	**Size [bits]**	**Possible settings**	**Size [bits]**	**Possible settings**
Format 6-0/6-1 differentiation	1	1	1	1
Frequency hopping flag	1	See Section 5.3.3.2	–	–
MCS	–	–	4	See Table 5.8
Resource block assignment	0–4	Narrowband index	0–4	Narrowband index
	5	0–20: Allocation of 1–6 PRB pairs	1	0: 4 PRB pairs (#0, …, #3)
		21–31: Unused in Release 13		1: 6 PRB pairs (#0, …, #5)
MCS	4	See Table 5.8	–	–
Number of PDSCH repetitions	2	See Table 5.10	3	See Table 5.11
HARQ process number	3–4	FDD: 0–7, TDD: 0–15	1	0–1
New data indicator	1	Toggle bit for new data	1	Toggle bit for new data
Redundancy version	2	0–3	–	–
PUCCH power control	2	See Section 5.3.2.4	–	–
Downlink assignment index	2	TDD-specific field	–	–
Antenna port and scrambling ID	2	TM9-specific field	–	–
SRS request	1	See Section 5.2.5.3	–	–
Precoding information	2 or 4	TM6-specific field	–	–
PMI confirmation	1	TM6-specific field	–	–
HARQ-ACK resource offset	2	See Section 5.2.5.5	2	See Section 5.2.5.5
Number of MPDCCH repetitions	2	See Table 5.33	2	See Table 5.33

when calculating the starting subframe for the PDSCH transmission. When these DCI formats are used to schedule RAR as described in Section 5.3.1.6, some fields are reserved or repurposed (refer to Reference [20] for the detailed definition).

Fig. 5.27 shows an LTE-M downlink scheduling example where some repetition has been applied to enhance the coverage of the transmissions. The MPDCCH carrying the DCI is repeated in four subframes, the PDSCH carrying the data in eight subframes, and the PUCCH carrying the HARQ-ACK feedback in four subframes. All subframes are assumed to be configured as valid for transmission (see Sections 5.2.4.1 and 5.2.5.1). Note that the

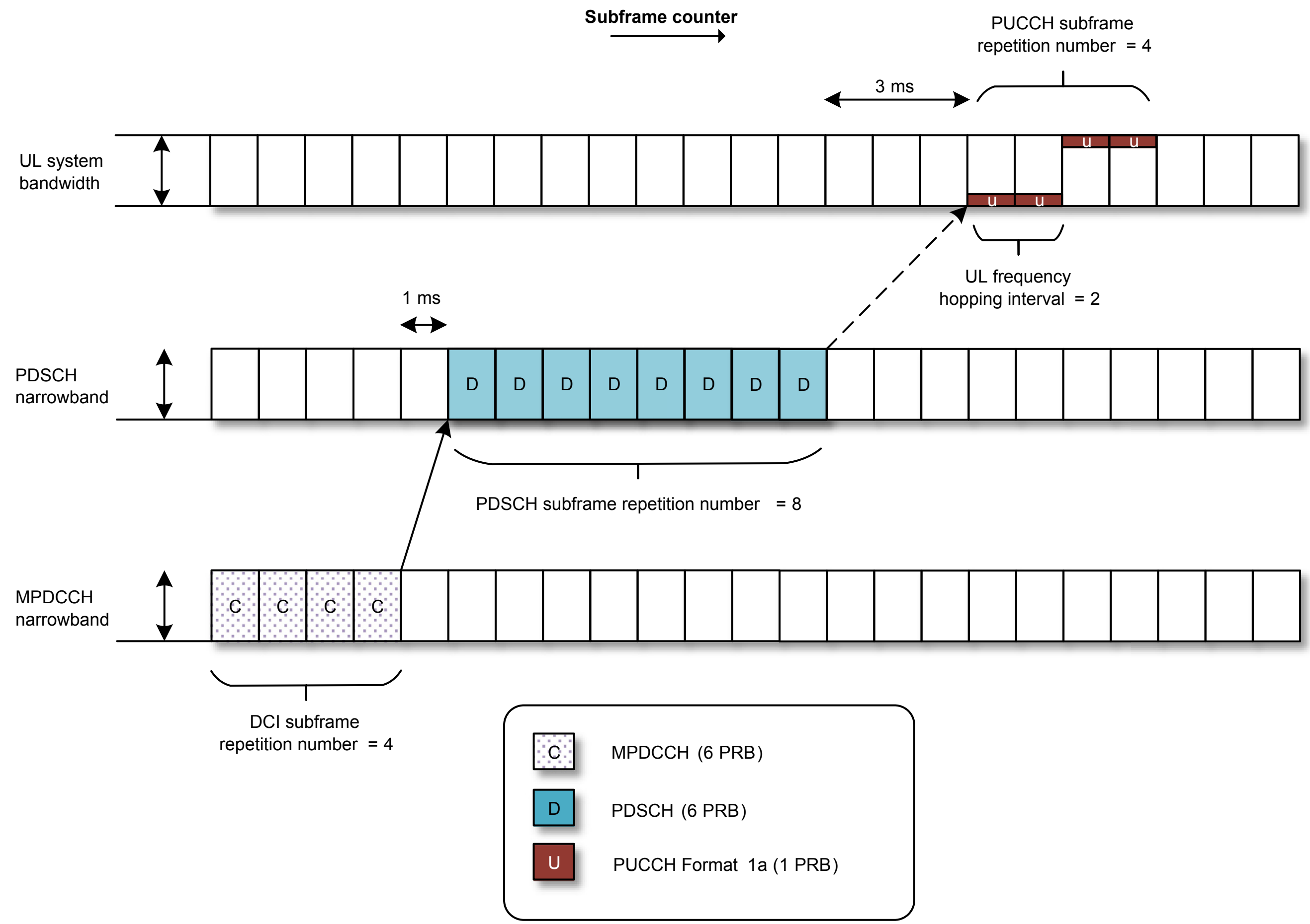

FIG. 5.27 LTE-M downlink scheduling example with MPDCCH and PDSCH transmitted with repetition in different downlink narrowbands.

example makes use of the possibility to schedule PDSCH in a different narrowband than the MPDCCH narrowband. Furthermore, both MPDCCH and PDSCH are transmitted with the maximum channel bandwidth supported in the CE modes in Release 13, which is 1 narrowband (6 PRBs). This is in general beneficial for the device from coverage point of view. The reason for this is that because the total downlink transmit power on the cell-carrier is typically (more or less) evenly distributed over all the PRBs in the system bandwidth, a large downlink channel bandwidth usually also means a large chunk of the available transmit power.

The DCI field for *Number of PDSCH repetitions* contains a 2- or 3-bit value which is interpreted according to Tables 5.10 and 5.11. The DCI field for *Number of MPDCCH repetitions* is interpreted according to Table 5.33. Configuration of repetitions for PUCCH is discussed in Section 5.2.5.5. In the example in Fig. 5.27, a 2-ms uplink frequency hopping interval is assumed. Frequency hopping is discussed in Section 5.3.3.2. In CE mode A, the base station's scheduling decisions for PDSCH can be assisted by periodic or aperiodic CSI reports from the device, which is described in Section 5.3.2.2.

Release 14 introduces several options for *larger maximum channel bandwidths* for PDSCH and PUSCH as described in Sections 5.2.2.3 and 5.2.4.7. In Release 13 LTE-M, no physical channels have a larger channel bandwidth than 6 PRBs. Table 5.26 shows a summary of the associated PDSCH resource allocation methods (refer to Section 7.1.6 in Ref. [15] for details). Each resource allocation method has been designed to provide enough scheduling flexibility to exploit the wider bandwidth without increasing the DCI size more than necessary.

Release 14 introduces the possibility to support up to *10 downlink HARQ processes in FDD*. As discussed in Sections 5.3.2.1.1 and 6.3, there is a relationship between the HARQ RTT and number of HARQ processes. LTE-M has inherited the number of downlink HARQ processes for FDD (eight processes) from LTE even though LTE-M has a somewhat larger RTT than LTE (10 ms for LTE-M vs. 8 ms for LTE). This means that in CE mode A in FD-FDD in Release 13, downlink data can be scheduled in eight consecutive subframes, but then there will be a 2-ms gap before the downlink data transmission can continue. Therefore, FD-FDD devices supporting 10 downlink processes will be able to receive the maximum downlink TBS in every subframe. This can be done without the need to increase the number of soft channel bits that need to be stored in the decoder in the device because the maximum number of processes is only expected to be utilized under good channel conditions when relatively high code rate is used (see description of *Limited Buffer Rate Matching* in Ref. [12]). This increases the downlink MAC-layer peak rate for Cat-M1 from 800 kbps to 1 Mbps in FD-FDD. The HARQ process number field in DCI format 6-1A is increased from 3 to 4 bits to be able to indicate 10 processes.

Release 14 also introduces the possibility to support *HARQ-ACK bundling in HD-FDD*. In Release 13, every downlink data transmission is associated with a HARQ-ACK feedback transmission in uplink, as described in Section 5.2.5.5. Because the LTE-M uplink in Release 13 does not support transmission of more than one HARQ-ACK feedback per subframe, a device in HD-FDD operation will (in the non-repetition case) spend as long transmitting HARQ-ACK feedback in uplink as it spends on the actual downlink data reception. As can be seen in Fig. 5.26, an HD-FDD device will not be able to spend more than 3 of 10 subframes on actual downlink data reception. Instead of just receiving three consecutive downlink data subframes with the corresponding HARQ-ACK, a device supporting HARQ-ACK bundling

TABLE 5.26 PDSCH resource allocation methods in CE mode A and B.

Configured maximum PDSCH channel bandwidth	CE mode A	CE mode B
1.4 MHz	A narrowband index is indicated in the DCI and 1-6 contiguous PRBs can be allocated anywhere within that narrowband.	A narrowband index is indicated in the DCI and the first 4 or all 6 PRBs can be allocated anywhere within that narrowband.
5 MHz	The narrowband index in the DCI is used to indicate a starting narrowband. Anywhere within the starting narrowband, 1-6 contiguous PRBs can be allocated. A 3-bit bitmap indicates whether the allocation within the starting narrowband also applies to one or more of the 3 next narrowbands (i.e., the allocation used in the starting narrowband is reused in the other enabled narrowbands).	Up to 2 bits in the DCI are used to indicate a wideband index (see Section 5.2.2.2). For the indicated wideband, a 4-bit bitmap indicates which up to 4 narrowbands to allocate. All PRBs within the indicated narrowbands are allocated.
20 MHz	A 1-bit field in the DCI indicates whether to interpret the remainder of the DCI as in the 5-MHz case described above or as a resource block group (RBG) bitmap, where the RBG size is 6 PRBs (in 10−15 MHz system bandwidth) or 9 PRBs (in 20 MHz system bandwidth).	Like the 5-MHz case described above except that the 2-bit wideband index is extended to form a 3-bit wideband combination index where the first 4 values indicate the 4 widebands (respectively) and the next 4 values indicate the 2 lowest widebands, the 2 highest widebands, the 3 lowest widebands, and all 4 widebands (respectively)

will be able to transmit up to three consecutive so-called *HARQ-ACK bundles* where each bundle contains acknowledgements for up to 4 downlink data subframes, as illustrated in Fig. 5.28. If the device also supports 10 downlink HARQ processes as described above, then the 3 bundles can acknowledge up to 10 consecutive downlink data subframes. In the illustrated example, the bundles are sent back-to-back and then the corresponding HARQ-ACK feedbacks are sent back-to-back. There will only be a single HARQ-ACK bit per bundle—the device sends ACK if all downlink TBs within a bundle were successfully decoded, otherwise it sends NACK (Negative Acknowledgment) which means that the whole bundle will be retransmitted by the base station. This means that use of HARQ-ACK bundling is mainly useful for device that experience rather good channel conditions (which is often the case for many devices in a typical cell). The result is that a Cat-M1 device supporting HARQ-ACK bundling and 10 downlink processes can receive data in 10 out of 17 subframes in HD-FDD and thereby almost double its downlink MAC-layer peak rate from 300 to 588 kbps.

Release 14 furthermore introduces a *dynamic HARQ-ACK delay* allowing the base station to control the delay between the end of a PDSCH transmission and the beginning of the associated HARQ-ACK feedback on PUCCH or PUSCH dynamically through a new 3-bit field in the DCI. In LTE-M in Release 13, for FDD, this delay is fixed to 4 ms as shown in Fig. 5.21 and 5.22. With a less rigid timing relationship, efficient scheduling of VoLTE

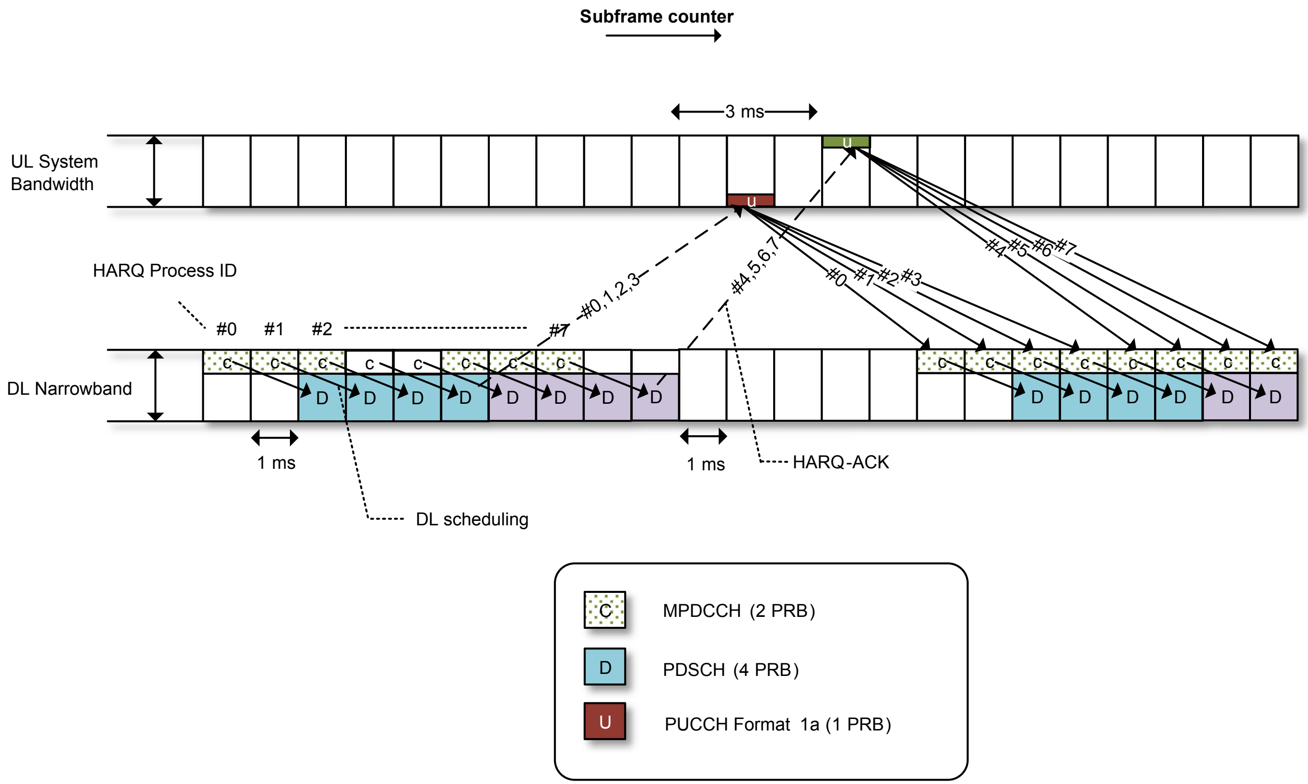

FIG. 5.28 HARQ-ACK bundling in CE mode A.

transmissions is facilitated, especially in HD-FDD. This feature can be seen as a subset of the functionality introduced by the HARQ-ACK bundling feature described above. The interpretation of the 3-bit DCI field depends on the RRC configuration and it is either {4, 5, 6, 7, 8, 9, 10, 11} subframes or {4, 5, 7, 9, 11, 13, 15, 17} subframes, where the former range is intended for VoLTE scheduling with up to 4 MPDCCH repetitions (and for HARQ-ACK bundling) and the latter range is intended for VoLTE scheduling with more than 4 MPDCCH repetitions.

Release 14 also introduces a *PDSCH modulation scheme restriction*, allowing the modulation to be limited to QPSK whenever PDSCH is scheduled with repetition (for more details see Section 5.2.4.7).

Release 15 introduces *downlink 64QAM support* for devices configured with max 1.4 MHz PDSCH channel bandwidth in CE mode A, as described in Section 5.2.4.7. The MCS field is extended from 4 to 5 bits by repurposing the frequency hopping flag in DCI Format 6-1A. If the device is configured with 64QAM enabled and the DCI indicates that PDSCH is without repetition, then the frequency hopping flag is interpreted as the MSB of the 5-bit MCS.

Release 15 also introduces resource allocation with *flexible starting PRB* for both PDSCH (and PUSCH) for devices configured with max 1.4 MHz channel bandwidth in CE mode A and B. In case of PDSCH, one of the main purposes is to make it easier for the base station to pack transmissions for narrowband-based LTE-M users and *resource block group* (RBG) based LTE users as efficiently as possible within the system bandwidth. The narrowbands and the RBGs do not typically line up, and this feature tries to achieve the desired alignment in downlink. In case of PUSCH, the purpose is mainly to be able to place the LTE-M transmissions as close to the carrier edges as possible, right beside any PUCCH or PRACH resources that may be configured closest to the carrier edges. Frequency hopping can also be used both in downlink and uplink together with this feature but note that it still essentially follows the Release 13 LTE-M frequency hopping pattern, not the LTE frequency hopping. The feature for flexible starting PRB is summarized in Table 5.27. As can be seen from the table, the flexible starting PRB is signaled in the DCI in CE mode A but configured via RRC in CE mode B (to avoid a DCI size increase and associated MPDCCH coverage degradation in CE mode B).

TABLE 5.27 Flexible starting PRB for PDSCH and PUSCH in CE mode A and B (with configured maximum channel bandwidth of 1.4 MHz).

	CE mode A	**CE mode B**
PDSCH	Use of flexible resource allocation via DCI is enabled by dedicated RRC signaling, and then previously unused values in the Resource block assignment field in the DCI are used to indicate a number of more RGB-aligned resource allocations.	Dedicated RRC signaling is used to enable shifting of narrowbands to align them with RBG. The shift of the narrowband depends on the system bandwidth and the allocated narrowband.
PUSCH	Use of flexible resource allocation via DCI is enabled by dedicated RRC signaling, and then the DCI can indicate allocation of up to 6 consecutive PRBs anywhere in the LTE system bandwidth (not restricted by the narrowband borders).	Dedicated RRC signaling is used to configure a fixed shift of all narrowbands by -1, +1, +2, or +3 PRBs.

5.3.2.1.2 Dynamic uplink scheduling

If a device in connected mode has data to transmit but no PUSCH resource, it can request a PUSCH resource by transmitting a *scheduling request* (SR) on PUCCH as described in Section 5.2.5.5. If the device has no valid PUCCH resource either, it will use the random access procedure instead as described in Section 5.3.2.3.

Fig. 5.29 shows an LTE-M uplink scheduling example without repetition. Similar to LTE, a DCI carried on MPDCCH schedules a PUSCH transmission with a 3-ms gap between the end of the MPDCCH transmission and the start of the PUSCH transmission. A difference compared to LTE is that the uplink HARQ scheme is asynchronous in LTE-M, whereas it is synchronous in LTE with a *Physical HARQ Indicator Channel* (PHICH) for HARQ feedback. This means that HARQ retransmissions in LTE-M are always explicitly scheduled using a DCI on an MPDCCH, i.e., there is no PHICH in LTE-M. Other than that, the HARQ operation in LTE-M is similar to the HARQ operation in LTE (this can be said for both uplink HARQ and downlink HARQ). The maximum number of uplink HARQ processes depends on the CE mode as indicated in Table 5.28.

The base station schedules uplink transmission on PUSCH dynamically using DCI Format 6-0A and 6-0B in CE mode A and B, respectively. Table 5.28 shows the information carried in these DCI formats [20]. Many aspects are similar to the PDSCH case described in the previous section. For example, there are fields indicating the number of repetitions for the PUSCH and for the MPDCCH itself, respectively, and a field for indicating the PUSCH narrowband. One notable difference compared to the downlink case described in the previous section is that PUSCH transmission in CE mode B is always scheduled on very few PRB pairs (1 or 2 PRB pairs), whereas PDSCH transmission in CE mode B is always scheduled on a large portion of the allocated narrowband (4 or 6 PRB pairs). Unlike in downlink, in uplink an increase in channel bandwidth may not enable the transmitter to allocate higher power to the transmission—the device is probably already transmitting with maximum power and a larger bandwidth may simply be a waste of bandwidth.

The following uplink resource allocation types are defined for LTE-M in Section 8.1 in Ref. [15]:

- **Uplink resource allocation type 0** (introduced in Release 13) is used for allocating 1-6 contiguous PRBs in CE mode A when the device is configured with 1.4 MHz max PUSCH channel bandwidth.
- **Uplink resource allocation type 2** (introduced in Release 13) is used for allocating 1-2 contiguous PRBs in CE mode B.
- **Uplink resource allocation type 4** (introduced in Release 14) is used for allocating 9-24 contiguous PRBs (with a granularity of 3 PRBs) in CE mode A when the device is configured with 5 MHz max PUSCH channel bandwidth.
- **Uplink resource allocation type 5** (introduced in Release 15) is used for allocating 2-6 contiguous subcarriers (i.e. sub-PRB allocation) in CE mode A and B.

Release 14 introduces support for *larger uplink TBS for Cat-M1* in CE mode A. The background is described in Sections 5.2.3, and when the feature is configured, the MCS field in DCI Format 6-0A is interpreted according to Table 5.15.

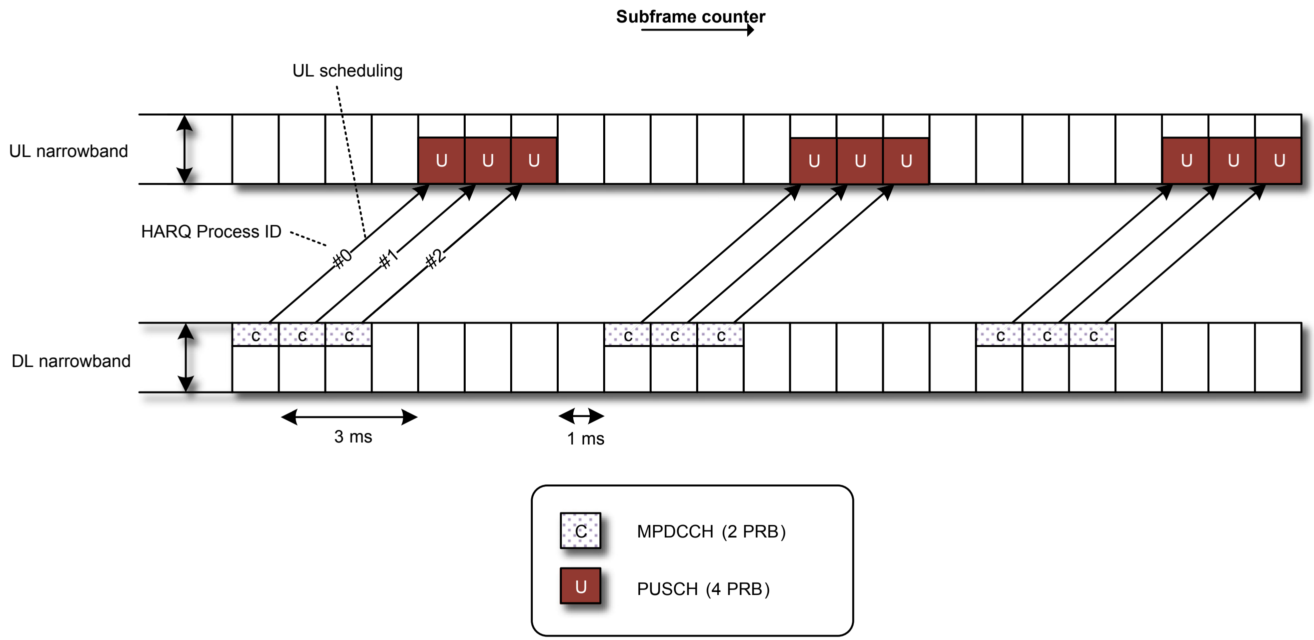

FIG. 5.29 LTE-M uplink scheduling example without repetition.

TABLE 5.28 DCI Formats 6-0A and 6-0B used for scheduling PUSCH in CE modes A and B in Release 13.

	DCI format 6-0A		DCI format 6-0B	
Information	**Size [bits]**	**Possible settings**	**Size [bits]**	**Possible settings**
Format 6-0/6-1 differentiation	1	0	1	0
Frequency hopping flag	1	See Section 5.3.3.2	–	–
Resource block assignment	0–4	Narrowband index	0–4	Narrowband index
	5	0–20: Allocation of 1–6 PRB pairs	3	0–5: PRB index for 1 PRB pair
				6: 2 PRB pairs (#0 and #1)
		21–31: Unused in Release 13		7: 2 PRB pairs (#2 and #3)
MCS	4	See Table 5.14	4	See Table 5.14
Number of PUSCH repetitions	2	See Table 5.10	3	See Table 5.11
HARQ process number	3	0–7	1	0–1
New data indicator	1	Toggle bit for new data	1	Toggle bit for new data
Redundancy version	2	0–3	–	–
PUSCH power control	2	See Section 5.3.2.4	–	–
Uplink index	2	TDD-specific field	–	–
Downlink assignment index	2	TDD-specific field	–	–
CSI request	1	See Section 5.3.2.2	–	–
SRS request	1	See Section 5.2.5.3	–	–
Number of MPDCCH repetitions	2	See Section 5.3.3.1	2	See Section 5.3.3.1

Release 14 introduces several options for *larger maximum channel bandwidths* for PUSCH and PDSCH as described in Sections 5.2.2.3 and 5.2.5.4. In Release 13 LTE-M, no physical channels have a larger channel bandwidth than 6 PRBs. When the device is configured with max 5 MHz PUSCH channel bandwidth in CE mode A, the ordinary DCI Format 6-0A is still used for allocation of 1–6 PRBs, but in addition some previously reserved values in the Resource block assignment field in the DCI are now used for allocation of 9–24 PRBs with a granularity of 3 PRBs.

Release 14 introduces a *PUSCH modulation scheme restriction*, allowing the modulation to be limited to QPSK when a new 1-bit field in the DCI indicates that QPSK should be used instead of the default modulation scheme for the indicated MCS. This feature is bundled with *new PUSCH repetition factors* which can be selected more dynamically with a finer granularity using another new 1-bit field in the DCI. Both sub-features are described in Section 5.2.5.4.

Also introduced in Release 14 is the support for *device transmit antenna selection* in CE mode A as described in Section 5.2.5.4. The antenna selection is controlled by the base station through masking of the CRC in DCI format 6-0A.

Release 15 introduces resource allocation with *flexible starting PRB* in CE mode A and B for both PDSCH and PUSCH. Both cases are described in Section 5.3.2.1.1 and Table 5.27.

Release 15 also introduces *PUSCH sub-PRB allocation* in CE mode A and B, as described in Section 5.2.5.4. In CE mode A, the DCI is extended with a 2-bit field for number of *resource units* (RU), and if its value is '00' then the rest of the DCI is interpreted as in earlier releases, otherwise the DCI is a grant for sub-PRB allocation with the indicated number of RUs (1, 2, or 4). In CE mode B, the DCI is extended with a 1-bit flag indicating whether the DCI should be interpreted as in earlier releases or as a grant for sub-PRB allocation, in which case a 1-bit field is used to indicate the number of RUs (2 or 4). In CE mode A, the DCI can indicate a narrowband and a PRB position (0, 1, 2, 3, 4, 5) within that narrowband and a set of allocated subcarriers within the PRB, but in CE mode B, the DCI only indicates a narrowband and a set of allocated subcarriers within a PRB where the PRB position (0, 1, 2, 3, 4, or 5) within the narrowband is configured by RRC (in order to keep the DCI size small). In both CE mode A and B, the MCS index field is reduced from 4 bits to 3 bits (see Table 5.17) and the set of allocated subcarriers within the PRB is indicated using 10 values according to Table 5.29.

Release 15 introduces a possibility to send a *positive HARQ-ACK feedback* to the device via DCI Format 6-0A/6-0B. For FD-FDD and TDD devices, this enables the base station to order *early termination of PUSCH transmission* in CE mode A or B. If the base station has been able to decode the uplink data before the scheduled end of the PUSCH transmission, there is no

TABLE 5.29 PUSCH sub-PRB allocation options in CE mode A and B in Release 15.

Resource allocation field	Resource allocation size	Modulation scheme	Set of allocated subcarriers
0	2 out of 3 subcarriers	$\pi/2$-BPSK	{0, 1} in cell with even PCID {1, 2} in cell with odd PCID
1	2 out of 3 subcarriers	$\pi/2$-BPSK	{3, 4} in cell with even PCID {4, 5} in cell with odd PCID
2	2 out of 3 subcarriers	$\pi/2$-BPSK	{6, 7} in cell with even PCID {7, 8} in cell with odd PCID
3	2 out of 3 subcarriers	$\pi/2$-BPSK	{9, 10} in cell with even PCID {10, 11} in cell with odd PCID
4	3 subcarriers	QPSK	{0, 1, 2}
5	3 subcarriers	QPSK	{3, 4, 5}
6	3 subcarriers	QPSK	{6, 7, 8}
7	3 subcarriers	QPSK	{9, 10, 11}
8	6 subcarriers	QPSK	{0, 1, 2, 3, 4, 5,}
9	6 subcarriers	QPSK	{6, 7, 8, 9, 10, 11}

reason for the device to waste time and energy on continuing to transmit, so the base station can then either send an *explicit HARQ-ACK* in DCI (this is done by setting the *'Resource block assignment'* field in DCI Format 6-0A or the *'MCS'* field in DCI Format 6-0B to all '1's) which will make the device stop its ongoing transmission, or an *implicit HARQ-ACK* by sending an ordinary uplink grant in DCI which will make the device stop its ongoing transmission and start the new transmission defined in the uplink grant. Early termination of PUSCH transmission cannot be supported by HD-FDD devices since they cannot monitor the downlink while performing uplink transmission. However, the HARQ-ACK also enables an *early termination of MPDCCH monitoring* which saves device energy. The HARQ-ACK can be used when a connection is being released, to inform the device that the final RLC ACK from the device has been successfully received and that the device does not need to monitor the MPDCCH for potential retransmission requests (which it would otherwise do until a retransmission timer expires) and can then enter idle mode. This *early termination of MPDCCH monitoring* can be supported by HD-FDD, FD-FDD and TDD devices.

5.3.2.1.3 Semipersistent scheduling

Beside the dynamic scheduling described in the previous sections, LTE-M supports *semi-persistent scheduling* (SPS) in CE mode A (but not in CE mode B) for downlink and uplink in a similar manner as LTE [14]. In LTE, SPS is mainly motivated by *Voice over Internet Protocol* (VoIP) services where periodic speech frames need to be scheduled and it is desired to avoid the physical control channel overhead associated with dynamic scheduling. For LTE-M devices, periodic sensor reporting could be a potential use case for SPS beside Voice over Internet Protocol.

When SPS is configured, the device is configured by higher layers with a SPS-C-RNTI and a time interval. The SPS operation can then be activated or deactivated by a DCI addressed to the SPS-C-RNTI of the device. The activation DCI indicates what frequency resources, MCS, number of repetitions, etc. that should be used at the periodic persistent resources. The SPS-C-RNTI is also used for scheduling potential HARQ retransmissions. Note that SPS can be overridden by dynamic scheduling at any time if needed.

5.3.2.2 Channel quality reporting

CE mode A supports downlink *Channel State Information* (CSI) reporting from the device in order to assist the base station's scheduling decisions. Both RRC-configured periodic reporting on PUCCH (see Section 5.2.5.5) and DCI-triggered aperiodic reporting on PUSCH (see Section 5.2.5.4 and Table 5.28) are supported. The CSI modes supported by LTE-M are listed in Table 5.30 [15].

The *Channel Quality Information* (CQI) report reflects the device's recommendation regarding what PDSCH MCS to use when targeting 10% BLock Error Rate for the first HARQ transmission. The *Precoding Matrix Indicator* (PMI) report is the device's recommendation (a 2-bit or 4-bit value depending on the number of antenna ports) regarding what precoding matrix to use in PDSCH TM6 and TM9 (see Section 5.2.4.7). For PDSCH TM9, either closed-loop or open-loop beamforming may be used, and in the latter case no PMI reporting is needed. In LTE-M, the CQI and PMI reports are based on CRS measurements in the narrowbands monitored by the device for MPDCCH monitoring. The wideband CQI report reflects the quality when all monitored narrowbands are used for a transmission

TABLE 5.30 Downlink CSI modes in LTE-M.

CSI mode	Description	Triggering	Physical channel	Comment
1–0	Wideband CQI in TM1/TM2/TM9	Periodic	PUCCH Format 2/2a/2b	Only supported in CE mode A
1–1	Wideband CQI and PMI in TM6/TM9	Periodic	PUCCH Format 2/2a/2b	Only supported in CE mode A
2–0	Subband CQI in TM1/TM2/TM6/TM9	Aperiodic	PUSCH	Only supported in CE mode A

TABLE 5.31 Downlink CQI tables in LTE-M.

	Release 13 CQI table			Release 15 CQI table with 64QAM			Release 15 alternative CQI table		
CQI index	Modulation	Code rate x 1024 x R^{CSI}	Efficiency x R^{CSI}	Modulation	Code rate x 1024	Efficiency	Modulation	Code rate x 1024	Repetition
0	Out of range			Out of range			Out of range		
1	QPSK	40	0.0781	QPSK	40	0.0781	QPSK	56	32
2	QPSK	78	0.1523	QPSK	78	0.1523	QPSK	207	16
3	QPSK	120	0.2344	QPSK	120	0.2344	QPSK	266	4
4	QPSK	193	0.3770	QPSK	193	0.3770	QPSK	195	2
5	QPSK	308	0.6016	QPSK	308	0.6016	QPSK	142	1
6	QPSK	449	0.8770	QPSK	449	0.8770	QPSK	266	1
7	QPSK	602	1.1758	QPSK	602	1.1758	QPSK	453	1
8	16QAM	378	1.4766	16QAM	378	1.4766	QPSK	637	1
9	16QAM	490	1.9141	16QAM	490	1.9141	16QAM	423	1
10	16QAM	616	2.4063	16QAM	616	2.4063	16QAM	557	1
11	Reserved			64QAM	466	2.7305	16QAM	696	1
12	Reserved			64QAM	567	3.3223	16QAM	845	1
13	Reserved			64QAM	666	3.9023	64QAM	651	1
14	Reserved			64QAM	772	4.5234	64QAM	780	1
15	Reserved			64QAM	873	5.1152	64QAM	888	1

(averaged over these narrowbands), whereas the subband CQI report additionally contains one separate CQI report for the best one of the monitored narrowbands, information that can help guide the base station's scheduling decisions.

Table 5.31 shows the three CQI tables supported by LTE-M in Release 15. The reported 4-bit CQI index corresponds to a recommended modulation, code rate, and number of useful bits per symbol (efficiency or number of repetitions). The leftmost column shows the original Release 13 CQI table which is calibrated according to the coverage situation for the device using the parameter for the *number of subframes for the CSI reference resource* (R^{CSI}) in the range {1, 2, 4, 8, 16, 32} subframes, where R^{CSI} is an RRC configuration parameter. The base station is expected to configure the device with an R^{CSI} that roughly matches the foreseen required number of repetitions for reliable PDSCH transmission. Release 15 introduces two new CQI tables to support the downlink 64QAM feature (see Section 5.2.4.7). The CQI table in the center column is optimized for good coverage and assumes an R^{CSI} of 1 subframe, whereas the CQI table in the rightmost column is an *alternative CQI table* which spans a larger SNR range. The CQI range of the alternative CQI table can also be supported by LTE-M devices that do not support 64QAM, but in that case the reported CQI index is up to 12, which is the highest CQI value for 16QAM in the alternative CQI table. The alternative CQI table has a coarser granularity but a larger range than the other CQI tables, which means that it may be suitable for devices experiencing varying channel conditions which might otherwise require impractically frequent RRC reconfiguration of the R^{CSI} parameter in order to adjust the CQI reporting range.

5.3.2.3 Random access in connected mode

The device can initiate the random access procedure in connected mode when it needs to request an uplink TA command and/or an uplink grant. A *contention-based random access* is then performed, with similar RAR and random access message 3 transmissions as in the idle mode random access procedure described in Section 5.3.1.6. However, unlike in idle mode, message 3 does not include an RRC message, and because the device has already been assigned with a C-RNTI, which the device includes in message 3, the contention resolution in the fourth step is in this case performed using C-RNTI rather than TC-RNTI.

The base station can also order a device in CE mode A or B to initiate a random access procedure by sending a so-called *MPDCCH order* to the device. This is useful during handover to another cell or when downlink data transmission is resumed after a period of inactivity and the base station wants the device to reacquire uplink time alignment for the expected uplink responses to the downlink data transmission. A modified version of DCI Format 6-1A or 6-1B is used to transmit the order. A starting PRACH CE level can be indicated in the order. As in LTE, a dedicated PRACH preamble index can be indicated already in the MPDCCH order to allow *contention-free random access*, and in this case no explicit contention resolution phase is needed and the random access procedure ends already with the reception of the RAR. If no PRACH preamble index is indicated in the order, a contention-based random access is performed in the same way as for device-triggered connected mode random access.

5.3.2.4 Power control

Uplink closed-loop *transmit power control* (TPC) commands for PUSCH/PUCCH can be sent to LTE-M devices in CE mode A using the transmit power control field in the DCI Format 6-0A/6-1A described in Sections 5.3.2.1.1 and 5.3.2.1.2, or using DCI Format 3/3A addressed with TPC-PUSCH-RNTI or TPC-PUCCH-RNTI in *Type-0 MPDCCH CSS* (see Section 5.3.3.1). A single DCI with DCI Format 3/3A can carry power control commands to multiple devices. The standard supports several power control command mappings but the most commonly used one uses 2 bits to command a transmit power change of {-1, 0, +1, +3} dB. This is similar to the power control behavior in LTE.

However, LTE-M devices in CE mode B are expected to be in bad coverage and will therefore always transmit using the configured maximum transmission power. Similarly, in the random access procedure, when a device reaches the highest PRACH CE level (PRACH CE level 3), it will always transmit at maximum power during PRACH transmission.

5.3.2.5 Mobility support

Beside the cell selection and cell reselection mechanisms in idle mode described in Sections 5.3.1.1 and 5.3.1.3, LTE-M devices support connected mode mobility mechanisms such as handover, RRC connection release with redirection, RRC reestablishment, measurement reporting, etc., similarly as LTE devices [13].

Unlike ordinary LTE devices, low-cost LTE-M devices with reduced bandwidth support need *measurement gaps* not only for *interfrequency* measurements in connected mode but also for *intrafrequency* measurements in connected mode because they may need to retune their narrowband receiver to the center of the system bandwidth to receive the center 72 subcarriers where the PSS/SSS signals (used for acquisition and maintenance of downlink time and frequency synchronization and for identification of cells) are transmitted. The device may also perform *Radio Resource Management* (RRM) measurements such as RSRP while it has its receiver retuned to the center.

LTE-M supports intrafrequency RSRP measurements in connected mode in Release 13, and Release 14 introduces complete mobility support in idle and connected mode in the form of intrafrequency RSRP/RSRQ measurements and interfrequency RSRP/RSRQ measurements. These measurements are important for mobile and real-time use cases, such as wearables and voice services.

The LTE-M standard was initially developed with applications characterized by relatively low mobility in mind. However, the specified LTE-M physical layer is robust enough to be able to maintain good link quality also at somewhat higher device velocities. Since this is an attractive property for many IoT application, *enhanced performance requirements for higher velocity* were introduced for CE mode A in Release 15. These requirements are defined assuming that devices fulfilling the requirements should be able to support at least 240 km/h at 1 GHz or 120 km/h at 2 GHz carrier frequency.

A device in connected mode performs *Radio Link Monitoring* to determine whether it is *in sync* or *out of sync* with respect to the serving cell by comparing CRS-based measurements with thresholds known as *Qin* and *Qout* that correspond to 2% and 10% BLock Error Rate of hypothetical MPDCCH transmissions, respectively [17]. The comparison is done over a period known as the *evaluation period*. If the evaluation results in out of sync for more than a certain number of times (which is a configurable parameter *N310*) over a certain period of time (upon expiry of the *T310* timer), the device declares *Radio Link Failure* and turns off its transmitter to avoid causing unwanted interference. The device may be able to find a better cell through cell selection and reestablish the connection. The radio link monitoring procedure was further improved in Release 14 where two new reporting events were introduced, known as *earlyQin* and *earlyQout*, which are triggered earlier in time than the *Qin* and *Qout* events to give the network more time adapt the radio sources accordingly.

5.3.2.6 Positioning

Beside basic *Cell Identity* (CID) based positioning, LTE-M supports the LTE positioning techniques *Enhanced Cell Identity* (E-CID) and *Observed Time Difference of Arrival* (OTDOA). From protocol point of view, E-CID and OTDOA were supported already in Release 13, but complete measurement performance requirements for E-CID and OTDOA were not introduced for LTE-M devices until in Release 14. For a description of the general principles behind the E-CID and OTDOA positioning techniques, see Section 7.3.2.6 (the section concerns NB-IoT, but the principles are equally applicable to LTE-M).

Release 14 furthermore introduces *OTDOA enhancements* with respect to the configuration of the associated PRS the in time and frequency domains (see Section 5.2.4.3.3). The new PRS configurations in Release 14 allow LTE-M devices to achieve comparable positioning accuracy as ordinary LTE devices. The exact PRS configuration in a cell will depend on the desired trade-off between PRS overhead and positioning accuracy.

Release 15 introduced *new PRS measurement gap patterns* that enable devices to do OTDOA positioning measurements during measurement gaps in connected mode for PRS durations longer than 6 subframes, which facilitates positioning in challenging coverage conditions.

5.3.3 Procedures common for idle and connected mode

5.3.3.1 MPDCCH search spaces

The transmission opportunities for MPDCCH (described in Section 5.2.4.6) are defined in the form of *search spaces*. Each device monitors an MPDCCH search space for potential DCI transmissions addressed to one of the RNTIs monitored by the device. An MPDCCH search space typically contains *blind decoding candidates* with different numbers of MPDCCH repetitions.

Release 13 supports the following MPDCCH search spaces [15]:

1. *Type-1 common search space* (Type1-CSS) is monitored by the device at its paging occasions in idle mode.
2. *Type-2 common search space* (Type2-CSS) is monitored by the device during the random access procedure in idle and connected mode.
3. *UE-specific search space* (USS) is a user-specific search space monitored by the device in connected mode. This is where scheduling of downlink and uplink data transmissions usually take place.
4. *Type-0 common search space* (Type0-CSS) is monitored by the device when it is configured with CE mode A in connected mode. It can be used for power control commands and as fallback if the user-specific search space fails.

Release 14 introduces the following additional MPDCCH search spaces for multicast (see Section 5.3.1.9):

1. *Type-1A common search space* (Type1A-CSS) is monitored by the device at the transmission opportunities for the multicast control channel (SC-MCCH) in idle mode. It is largely based on the Type1-CSS design.

2. *Type-2A common search space* (Type2A-CSS) is monitored by the device at the transmission opportunities for the multicast traffic channel (SC-MTCH) in idle mode. It is largely based on the Type2-CSS design.

An MPDCCH search space is defined by the following key parameters [23]:

1. *The MPDCCH narrowband index* indicates one of the narrowbands within the system bandwidth. The total number of narrowbands for each system bandwidth is shown in Table 5.4.
2. *The number of MPDCCH PRB pairs* is in the range {2, 4, 6} PRB pairs. For Type1-CSS and Type2-CSS, the number of MPDCCH PRB pairs is fixed to 6 PRB pairs.
3. *The MPDCCH resource block assignment* indicates the positions of the PRB pairs. If the number of PRB pairs is six (as is always the case for Type1-CSS and Type2-CSS) then this parameter is not needed because all PRB pairs within the narrowband are then included in the resource block assignment.
4. *The maximum MPDCCH repetition factor* ($R_{\max}$) indicates the repetition factor for the candidate with the largest repetition factor in the search space. The range for this parameter is {1, 2, 4, 8, 16, 32, 64, 128, 256}.
5. *The relative MPDCCH starting subframe periodicity* (G) is used to determine the starting subframe periodicity for the search space. The range for this parameter is {1, 1.5, 2, 2.5, 4, 5, 8, 10} in FDD and {1, 2, 4, 5, 8, 10, 20} in TDD. The *absolute MPDCCH starting subframe periodicity* (T) in terms of subframes is calculated as $T = R_{max}G$.

The configuration parameters for Type1-CSS and Type2-CSS are signaled in SIB2, whereas the configuration parameters for USS and Type0-CSS are signaled in user-specific RRC signaling. A device in CE mode A monitors both USS and Type0-CSS, but this is facilitated in the device by the fact that these two search spaces share the same properties listed above. LTE-M devices in CE mode B or in idle mode never need to monitor more than a single search space at a time.

Further details about the search spaces are listed in Table 5.32 [15].

Within an MPDCCH search space, different candidates can have different ECCE aggregation levels and different repetition factors (R). As explained in Section 5.2.4.6, in normal subframes with normal CP length, aggregation of 2, 4, 8, 16 or 24 ECCEs is supported. With the smallest ECCE aggregation level (i.e., 2), half of the ECCEs available in a PRB pair are aggregated, and with the highest ECCE aggregation level (i.e., 24), all the ECCEs available in a narrowband are aggregated. The available repetition levels R_1, R_2, R_3, and R_4 depend on $R_{\max}$ according to Table 5.33. For more details on search space definitions, see Section 9.1.5 in Reference [15].

Fig. 5.30 shows an MPDCCH search space example with $R_{\max} = 4$ and $G = 1.5$. In this search space, an MPDCCH can be scheduled without repetition ($R = 1$) in the subframes marked *A*, *B*, *C*, and *D*, or with two times repetition ($R = 2$) in the subframes marked *AB* and *CD*, or with four times repetition ($R = 4$) in the subframes marked *ABCD*. If an MPDCCH is transmitted according to candidate *A* then candidates *AB* and *ABCD* are blocked in that T period but candidates *B*, *C*, *D*, and *CD* can still be used in the same T period. The $T - R_{\max} = 2$ subframes between consecutive search spaces are not included in the search

TABLE 5.32 MPDCCH search spaces, RNTIs, and DCI formats monitored by LTE-M devices.

Mode	MPDCCH search space	RNTI	Usage	DCI format	Section
Idle	–	SI-RNTI	Broadcast of system information	–	5.3.1.2
	Type-1 common	P-RNTI	Paging and SI update notification	6–2	5.3.1.4
	Type-2 common	RA-RNTI	Random access response	6-1A, 6-1B	5.3.1.6
		TC-RNTI	HARQ retransmission of random access message 3	6-0A, 6-0B	5.3.1.6
		TC-RNTI	Random access contention resolution with message 4	6-1A, 6-1B	5.3.1.6
	Type-1A common	SC-RNTI	Scheduling of SC-MCCH	6–2	5.3.1.9
	Type-2A common	G-RNTI	Scheduling of SC-MTCH	6-1A, 6-1B	5.3.1.9
Connected	UE-specific	C-RNTI	Random access order	6-1A, 6-1B	5.3.2.3
		C-RNTI	Dynamic downlink scheduling	6-1A, 6-1B	5.3.2.1.1
		C-RNTI	Dynamic uplink scheduling	6-0A, 6-0B	5.3.2.1.2
		SPS-C-RNTI	Semipersistent downlink scheduling	6-1A	5.3.2.1.3
		SPS-C-RNTI	Semipersistent uplink scheduling	6-0A	5.3.2.1.3
	Type-0 common (only in CE mode A)	C-RNTI	Random access order	6-1A	5.3.2.3
		C-RNTI	Dynamic downlink scheduling	6-1A	5.3.2.1.1
		C-RNTI	Dynamic uplink scheduling	6-0A	5.3.2.1.2
		SPS-C-RNTI	Semipersistent uplink scheduling	6-0A	5.3.2.1.3
		TPC-PUCCH-RNTI	PUCCH power control	3, 3A	5.3.2.4
		TPC-PUSCH-RNTI	PUSCH power control	3, 3A	5.3.2.4
	Type-2 common	RA-RNTI	Random access response	6-1A, 6-1B	5.3.2.3
		TC-RNTI	HARQ retransmission of random access message 3	6-0A, 6-0B	5.3.2.3
		C-RNTI	Random access contention resolution	6-0A, 6-0B, 6-1A, 6-1B	5.3.2.3

space (which means that the device can go to sleep during these subframes unless it has some other reason to stay awake during these subframes).

Fig. 5.31 shows an MPDCCH search space example for Type1-CSS, the CSS used for paging. As can be seen, all candidates in the search space start in the same subframe.

TABLE 5.33 Repetition levels for MPDCCH search spaces.

R_{max}	Repetition levels for Type1-CSS				Repetition levels for USS, Type0-CSS and Type2-CSS			
	R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4
256	2	16	64	256	32	64	128	256
128	2	16	64	128	16	32	64	128
64	2	8	32	64	8	16	32	64
32	1	4	16	32	4	8	16	32
16	1	4	8	16	2	4	8	16
8	1	2	4	8	1	2	4	8
4	1	2	4	–	1	2	4	–
2	1	2	–	–	1	2	–	–
1	1	–	–	–	1	–	–	–

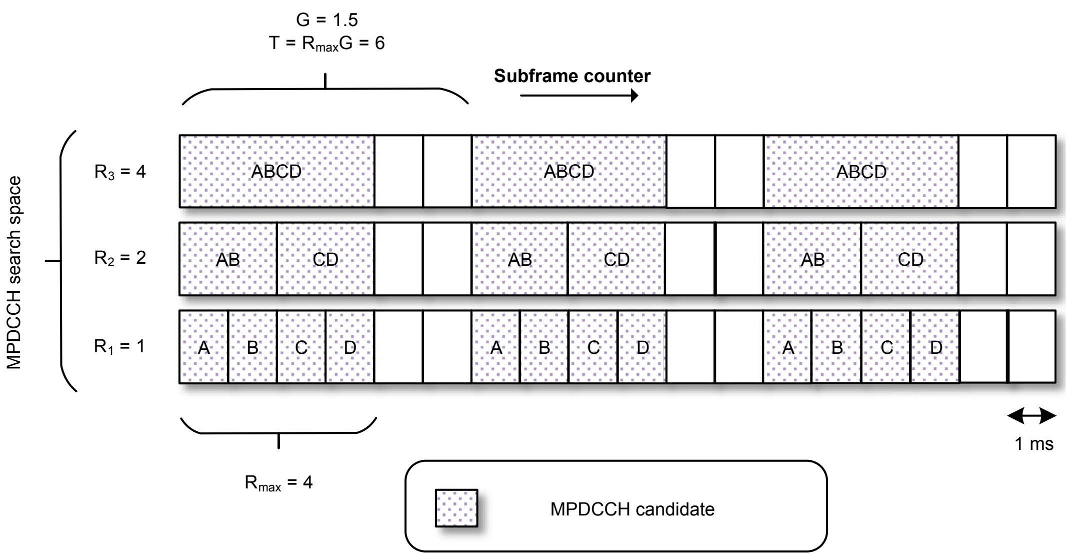

FIG. 5.30 MPDCCH search space example for USS, Type0-CSS and Type2-CSS.

This allows devices in good coverage to go to sleep after they have detected that there is no transmission intended for them in the first subframe of the search space (i.e., in candidate *A*). If a search space such as the one in Fig. 5.30 was used also for paging, the device would have to stay awake longer since it would have to be prepared for the eventuality that the base station choses to page the device in candidates *B*, *C* or *D*.

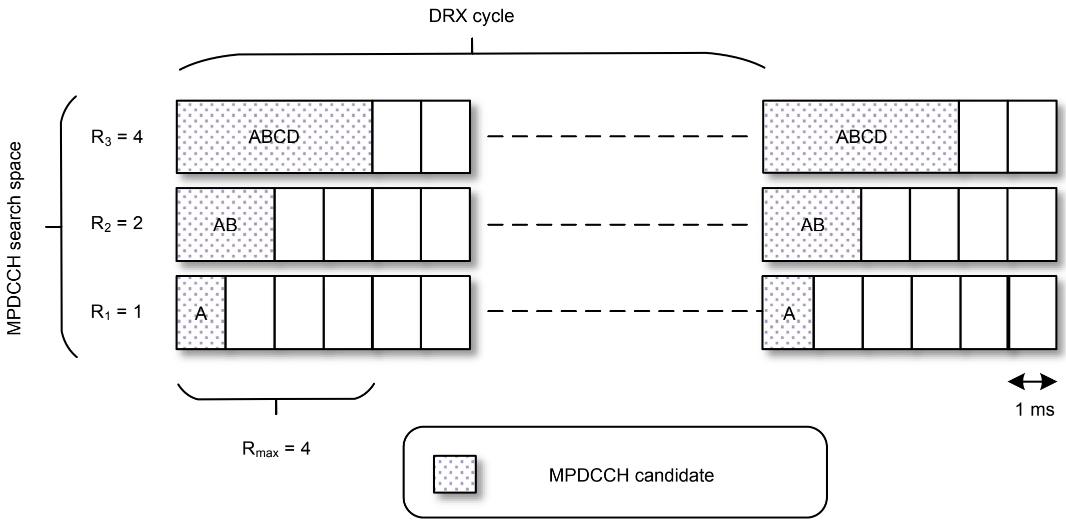

FIG. 5.31 MPDCCH search space example for Type1-CSS.

5.3.3.2 Frequency hopping

LTE-M transmissions are restricted to a narrowband, but LTE-M provides means for frequency diversity through frequency hopping between different narrowbands for all physical channels and signals except PSS/SSS, PBCH, RSS, MWUS, and SRS. As described in Sections 5.2.4.2 and 5.2.4.4, PSS/SSS and PBCH are always located at the center of the system bandwidth, similarly as in ordinary LTE. If RSS or MWUS is supported in the cell, the configuration information in SIB2 includes their frequency locations (see Sections 5.2.4.2.2 and 5.2.4.5).

Table 5.34 lists cell-specific configuration parameters for the time intervals and frequency offsets for frequency hopping in LTE-M. The time intervals indicate when the hops should take place in the time domain and the offsets indicate how large the hops should be in the frequency domain. The time intervals are synchronized so that the frequency hops for transmissions to/from different devices can take place at the same time. The frequency hops take place during the guard periods for frequency retuning described in Sections 5.2.4.1 and 5.2.5.1. The parameters for frequency hopping intervals for MPDCCH/PDSCH serve a double purpose since they also indicate the interval during which the device can assume that the MPDCCH/PDSCH precoding remains the same (as mentioned in Sections 5.2.4.6 and 5.2.4.7).

For SIB1 and PUCCH, the frequency hopping is fixed in the LTE-M standard but for all other types of transmission it is up to the network whether to use frequency hopping or not. Table 5.35 lists the frequency hopping activation methods for different types of LTE-M transmission.

When frequency hopping is used in downlink, a parameter in SIB1 (listed in Table 5.34) controls whether the hopping is between 2 and 4 narrowbands. The number of narrowbands

TABLE 5.34 Cell-specific time intervals and frequency offsets for frequency hopping in LTE-M.

Parameter	Possible values in FDD	Possible values in TDD	Signaled in
Number of narrowbands for frequency hopping for MPDCCH/PDSCH	2, 4	2, 4	SIB1
Frequency hopping interval [ms] for MPDCCH/PDSCH in CE mode A and during random access procedure for PRACH CE levels 0 and 1	1, 2, 4, 8	1, 5, 10, 20	SIB1
Frequency hopping interval [ms] for MPDCCH/PDSCH in CE mode B and during random access procedure for PRACH CE levels 2 and 3	2, 4, 8, 16	5, 10, 20, 40	SIB1
Frequency hopping interval [ms] for PUCCH/PUSCH in CE mode A and during random access procedure for PRACH CE levels 0 and 1	1, 2, 4, 8	1, 5, 10, 20	SIB2
Frequency hopping interval [ms] for PUCCH/PUSCH in CE mode B and during random access procedure for PRACH CE levels 2 and 3	2, 4, 8, 16	5, 10, 20, 40	SIB2
Frequency hopping offset for MPDCCH/PDSCH [narrowbands]	1–16	1–16	SIB1
Frequency hopping offset for PUSCH [narrowbands]	1–16	1–16	SIB2
Frequency hopping offset for PRACH [PRBs]	0–94	0–94	SIB2

used for frequency hopping for the PDSCH transmission that carries the SIB1 itself is fixed in the standard (as described in Table 5.35). The hopping pattern for the SIB1 transmission starts in a frame with an SFN evenly divisible by 8, in a narrowband that depends on the PCID, and hops between 2 and 4 narrowbands that have been selected so that they avoid the two center narrowbands in the system bandwidth to avoid collision with the center 72 subcarriers (the PSS/SSS/PBCH region).

When frequency hopping is used in uplink, the hopping is always between two frequency locations. For PUCCH, frequency hopping is always active, and the hopping occurs between two PRB locations that are symmetric with respect to the center frequency of the LTE system bandwidth. It should be noted that typically it is only PUCCH transmissions that are longer than the uplink frequency hopping interval that enjoy a frequency diversity gain from one or more frequency hops during the PUCCH transmission, whereas shorter PUCCH transmissions are short enough to be transmitted in their entirety in one of the two PRB locations before the time comes for a frequency hop. Fig. 5.32 shows an example of uplink frequency hopping with an uplink frequency hopping interval of 2 ms, a PUCCH transmission with repetition factor 4, a PUSCH transmission with repetition factor 8, and a PUSCH frequency hopping offset of two narrowbands.

TABLE 5.35 Frequency hopping activation methods available in an LTE-M cell.

Type of transmission	Physical channel(s)	Frequency hopping activation method(s)
SIB1	PDSCH	The number of narrowbands for SIB1 transmission depends strictly on the downlink system bandwidth signaled in MIB: For 1.4 MHz: no frequency hopping. For 3, 5, or 10 MHz: hopping between 2 narrowbands. For 15 or 20 MHz: hopping between 4 narrowbands.
SI message	PDSCH	Frequency hopping for SI messages and paging messages is activated by a common activation bit in SIB1.
Paging	MPDCCH, PDSCH	
Random access preamble	PRACH	Frequency hopping for PRACH is activated by an activation bit per PRACH CE level in SIB2.
Random access response and random access messages 3 and 4	MPDCCH, PDSCH, PUSCH, PUCCH	Frequency hopping for RAR, message 3, and message 4 is activated by an activation bit per PRACH CE level in SIB2.
Unicast downlink data transmission	MPDCCH, PDSCH	Frequency hopping for unicast downlink data transmission is activated by an activation bit in user-specific RRC signaling.
		In CE mode A, the frequency hopping can furthermore be deactivated by the frequency hopping bit in DCI Format 6-1A.
Unicast uplink data transmission	MPDCCH, PUSCH	Frequency hopping for unicast uplink data transmission is activated by an activation bit in user-specific RRC signaling.
		In CE mode A, the frequency hopping can furthermore be deactivated by the frequency hopping bit in DCI Format 6-0A.
HARQ-ACK, SR, CSI	PUCCH	Frequency hopping for PUCCH is always activated.
Multicast control channel	MPDCCH, PDSCH	Frequency hopping for the multicast control channel (SC-MCCH) is activated by a parameter in SIB20, and the parameter also indicates whether the hopping should follow the SIB2 frequency hopping parameters for CE mode A or B.
Multicast traffic channel	MPDCCH, PDSCH	Frequency hopping for a multicast traffic channel (SC-MTCH) is activated by a parameter in SC-MCCH, and another parameter indicates whether the hopping should follow the SIB2 frequency hopping parameters for CE mode A or B. If the hopping follows CE mode A, it can furthermore be deactivated by the frequency hopping bit in DCI Format 6-1A.
Positioning reference signal	PRS	Frequency hopping for PRS can be configured in LTE Positioning Protocol (LPP) between 2 or 4 frequency locations if the PRS bandwidth is 6 PRBs. The first frequency location is in the center of the LTE system bandwidth and the other frequency locations(s) are in configurable narrowbands.

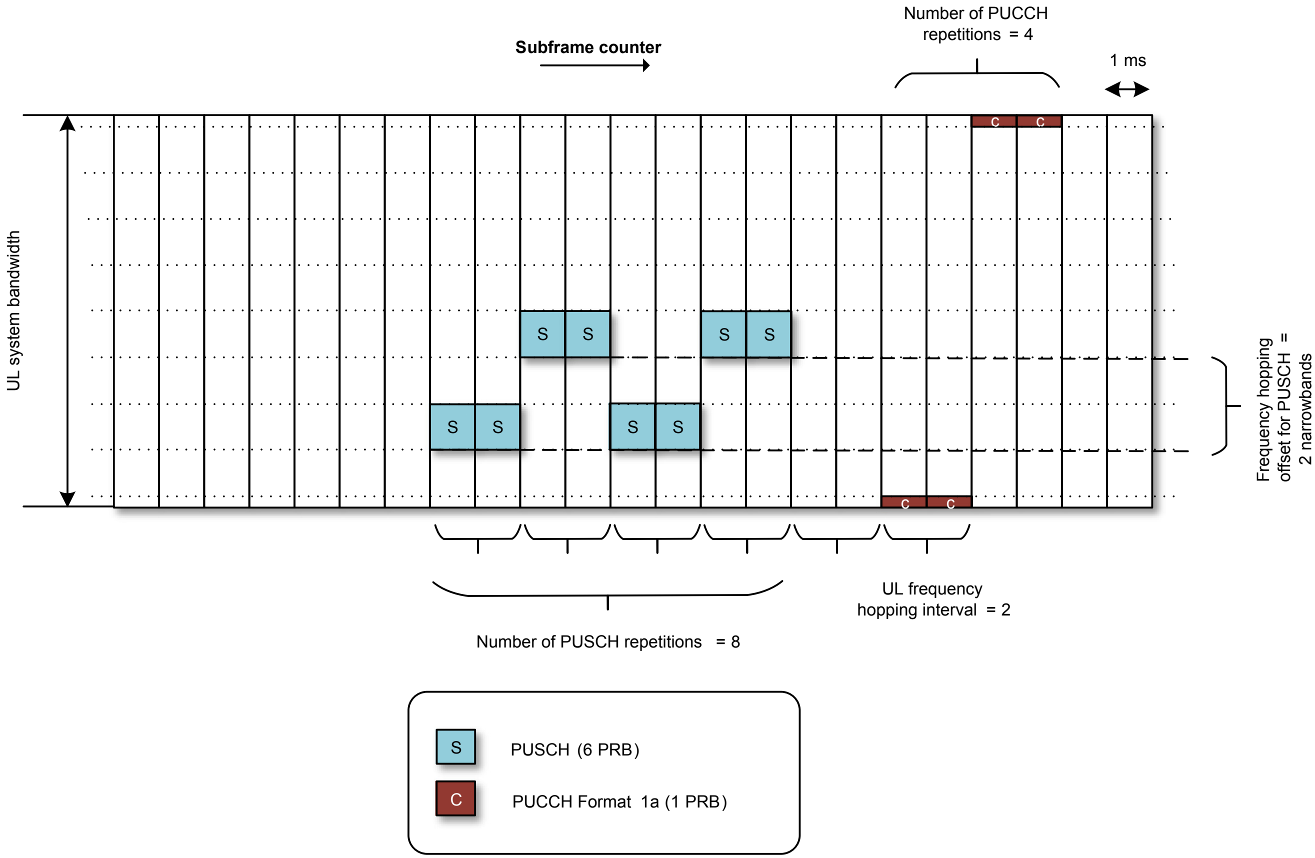

FIG. 5.32 Uplink frequency hopping in LTE-M.

5.4 NR and LTE-M coexistence

3GPP Release 15 introduces a NR-access technology known as *New Radio* (NR), which offers significant performance advantages over LTE in terms of data rates, latency, deployment flexibility and energy efficiency (see Chapter 2.4 for an introduction of NR and Reference [27] for detailed description of NR). NR is designed for enhancing the performance of mobile broadband and *ultra-reliable low-latency communications* (URLLC) services (described in Chapter 11), whereas *low-power wide-area* (LPWA) IoT use cases are expected to already be adequately addressed by existing 3GPP technologies such as LTE-M and NB-IoT. It has been shown that LTE-M and NB-IoT fulfill the 5G massive MTC requirements (see performance evaluations in Chapters 6 and 8, respectively) and thus qualify as 5G component technologies. Therefore, it is desired that LTE-M and NB-IoT can coexist efficiently with NR also after a potential migration from LTE to NR. NR coexistence with LTE-M is covered in this section, and NR coexistence with NB-IoT is covered in Section 7.4.

LTE-M is defined in LTE bands 1, 2, 3, 4, 5, 7, 8, 11, 12, 13, 14, 18, 19, 20, 21, 25, 26, 27, 28, 31, 39, 40, 41, 66, 71, 72, 73, 74 and 85 (see Table 5.3 for the frequency ranges of these bands). Many of these bands are also defined for NR [28]. Table 5.36 lists all the bands that are defined for both NR and LTE-M. These bands can thus be used to deploy both NR and LTE-M.

LTE-M is an extension of LTE and can therefore operate seamlessly within an LTE carrier, as described in Section 5.1.2.6. As we will see in this section, LTE-M and NR support several mechanisms that can enable almost as seamless operation of LTE-M within an NR carrier. It should be noted that in an NR coexistence scenario, the LTE-M system bandwidth can be smaller than the NR system bandwidth (this is different from LTE coexistence scenarios, where the LTE-M system bandwidth is always the same as the LTE system bandwidth).

It is up to the base station implementation whether the time-frequency resource split between LTE-M and NR is completely static or more dynamic. Fig. 5.33 illustrates static resource sharing, where a small slice of the available spectrum is allocated to LTE-M and not used for NR, and the rest of the spectrum is used for NR. The slice corresponds to the number of PRBs in the configured LTE-M system bandwidth (see Table 5.4), i.e. it can be as narrow as 6 PRBs and only contain a single LTE-M narrowband if it is desired to minimize the impact on the amount of resources available for NR. If the foreseen amount of LTE-M traffic is relatively small, a static resource split between NR and LTE-M with a small LTE-M system bandwidth may be a suitable configuration.

A more flexible resource sharing is illustrated in Fig. 5.34, where a large portion of the available resources serves as a common resource pool for NR and LTE-M, and it is up to the base station to allocate resources dynamically from this resource pool to NR and LTE-M devices. The shared part corresponds to the number of PRBs in the configured LTE-M system bandwidth. As shown in Table 5.4, the LTE-M system bandwidth can range from 6 to 100 PRBs and contain as few as a single narrowband or as many as 16 narrowbands. A more dynamic resource sharing has the potential to provide more efficient resource utilization through resource pooling but may require a more complex base station implementation. The standardized mechanisms for supporting static or dynamic resource sharing will be described in the remainder of this section.

TABLE 5.36 Frequency bands that are defined for both NR and LTE-M.

Band	Duplex mode	Uplink [MHz]	Downlink [MHz]	NR channel bandwidth for 15 kHz subcarrier spacing [MHz]	NR channel raster [kHz]
1	FDD	1920–1980	2110–2170	5, 10, 15, 20	100
2	FDD	1850–1910	1930–1990	5, 10, 15, 20	100
3	FDD	1710–1785	1805–1880	5, 10, 15, 20, 25, 30	100
5	FDD	824–849	869–894	5, 10, 15, 20	100
7	FDD	2500–2570	2620–2690	5, 10, 15, 20	100
8	FDD	880–915	925–960	5, 10, 15, 20	100
12	FDD	699–716	729–746	5, 10, 15	100
20	FDD	832–862	791–821	5, 10, 15, 20	100
25	FDD	1850–1915	1930–1995	5, 10, 15, 20	100
28	FDD	703–748	758–803	5, 10, 15, 20	100
39	TDD	1880–1920	1880–1920	5, 10, 15, 20, 25, 30, 40	100
40	TDD	2300–2400	2300–2400	5, 10, 15, 20, 25, 30, 40, 50	100
41	TDD	2496–2690	2496–2690	10, 15, 20, 40, 50	15 or 30
66	FDD	1710–1780	2110–2200	5, 10, 15, 20, 40	100
71	FDD	636–698	617–652	5, 10, 15, 20	100
74	FDD	1427–1470	1475–1518	5, 10, 15, 20	100

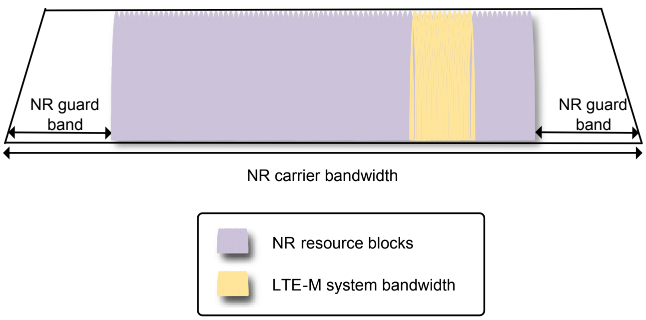

FIG. 5.33 Static resource sharing between LTE-M and NR.

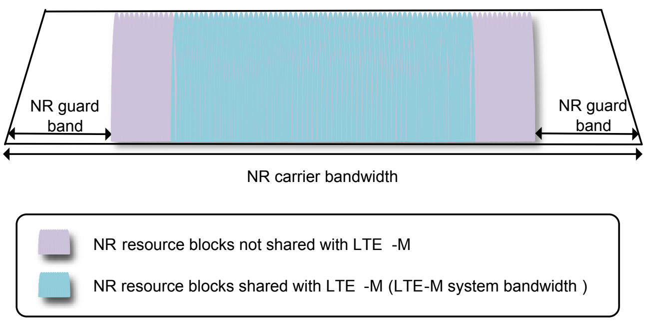

FIG. 5.34 Dynamic resource sharing between LTE-M and NR.

To ensure that LTE-M legacy devices can operate without knowing any NR-specific operation, one fundamental aspect is that an LTE-M device can identify an LTE-M cell during the initial cell selection process (see Section 5.3.1.1). To achieve this, the LTE-M carrier center frequency needs to be placed according to a 100-kHz channel raster (see Section 5.2.1.1). Furthermore, as PSS, SSS and PBCH are the signals used by the LTE-M device during cell search, they need to be preserved.

Similarly, to ensure that NR devices can operate regardless of whether there is an LTE-M carrier deployed in the same band or not, the NR carrier needs to be placed according to NR channel raster shown in Table 5.36. In most cases, the NR channel raster is 100 kHz. Furthermore, the NR *synchronization signal block* (SSB) needs to be preserved as it is used by the NR device during cell search.

Meanwhile, the interference between NR and LTE-M should be minimized so that the impact on NR and LTE-M performance is negligible when they are deployed in the same band. Unlike LTE and LTE-M, NR supports multiple subcarrier configurations. If the NR carrier is configured with the same subcarrier spacing as LTE-M, i.e., 15 kHz subcarrier spacing, it is desirable to align the NR and LTE-M subcarriers on the same subcarrier grids, with the frequencies of an NR subcarrier and an LTE-M subcarrier differing by an integer multiple of 15 kHz. With this, if the NR and LTE-M networks are synchronized, NR subcarriers and LTE-M subcarriers are mutually orthogonal. If the NR carrier is configured with subcarrier spacing other than 15 kHz, a guard band is needed between NR and LTE-M to ensure minimal inter-subcarrier interference.

It can be shown that for 15 kHz NR subcarrier spacing and 100 kHz NR carrier raster, every 20th NR subcarrier (i.e., every 300 kHz) relative to the NR channel raster will coincide with an LTE-M raster position [29]. One out of three possible LTE-M channel raster positions fulfills this condition. If the carrier positions are selected according to this relation, subcarrier grid alignment between NR and LTE-M is achieved in downlink (but not necessarily in uplink, which will be discussed next).

LTE-M, like LTE but unlike NR, has an unused *DC subcarrier* at the center of the downlink system bandwidth (see Section 5.2.2). However, no DC subcarrier is inserted in uplink. As a result, the LTE-M downlink system bandwidth is one subcarrier wider than the LTE-M uplink system bandwidth and one subcarrier wider than the NR system bandwidth. This is illustrated in Fig. 5.35. In order to achieve subcarrier grid alignment also in uplink, the DC subcarrier needs to be considered. In LTE-M, the channel raster points to the unused DC subcarrier in the center of the LTE downlink system bandwidth, whereas the NR channel raster points to an ordinary NR subcarrier near the middle of the NR carrier. For an NR carrier with N resource blocks, both in downlink and uplink there are $12\,N$ subcarriers indexed from 0 to $12N\text{-}1$, and the channel raster is mapped to subcarrier $6\,N$ [27]. For an LTE-M carrier with M resource blocks, there are $12\,M + 1$ downlink subcarriers (including the DC subcarrier) indexed from 0 to $12\,M$ and the channel raster is mapped to subcarrier $6\,M$, but there are only $12\,M$ uplink subcarriers (no DC subcarrier). In order to enable simultaneous subcarrier grid alignment between NR and LTE-M in both downlink and uplink, NR supports a *configurable uplink half-subcarrier shift*. When the base station has enabled this shift in the cell, a half subcarrier (+7.5 kHz) shift is applied to the NR uplink. Release 15 supports this shift in NR FDD but not in NR TDD, so coexistence between NR and LTE-M in TDD

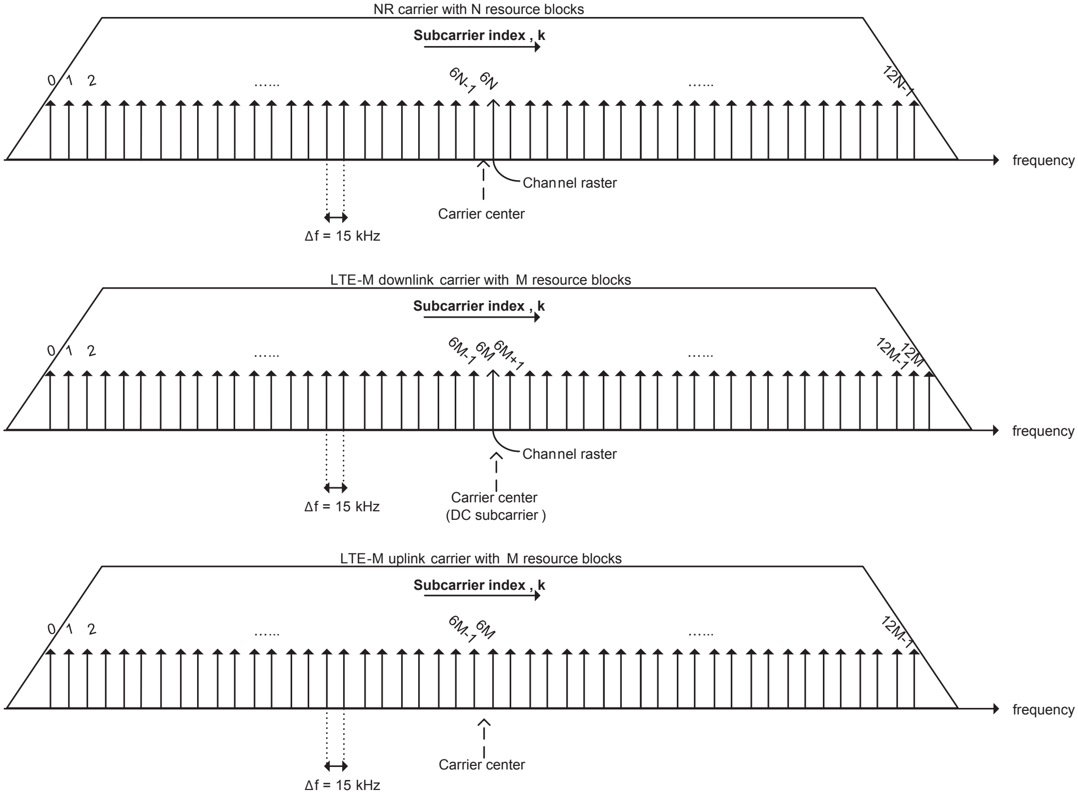

FIG. 5.35 Locations of NR and LTE-M channel raster (assuming the NR carrier is configured with 15 kHz subcarrier spacing).

bands cannot use this shift and instead need to rely on a sufficiently large inter-carrier guard band between NR and LTE-M.

It should be noted that due to the mentioned DC subcarrier, perfect alignment between NR resource blocks and LTE-M resource blocks is not possible. When alignment cannot be achieved, it may be necessary to reserve $M + 1$ NR downlink resource blocks in order to fit M LTE-M resource blocks.

Collision between NR and LTE-M transmissions can be avoided by exploiting the mechanisms for resource reservation that are available in LTE-M and NR.

On the LTE-M side, the base station can use the *LTE-M downlink subframe bitmap* and the *LTE-M starting symbol* (both described in Section 5.2.4.1) to restrict the LTE-M transmissions within the cell. The downlink subframe bitmap can be used to protect periodic NR transmissions such as NR SSB, and the LTE-M starting symbol should be configured large enough to avoid collision with NR PDCCH transmissions in the beginning of the downlink subframe. Similarly, the *LTE-M uplink subframe bitmap* (described in Section 5.2.5.1) can be used to protect potential periodic NR uplink resources if needed.

On the NR side, the base station can use *NR downlink resource reservation bitmaps* to indicate to NR devices that some particular resource blocks and/or OFDM symbols are restricted from NR PDSCH transmission. The NR devices will take these restrictions into account in the NR PDSCH rate-matching. These reservation mechanisms can be used for protecting periodic LTE-M transmissions such as PSS, SSS, PBCH, SIB1 and SI messages.

NR also supports resource element (RE) level *reservation of REs occupied by LTE CRS*. If the base station indicates that an LTE or LTE-M carrier is transmitted in some part of the NR carrier, the NR devices will take the LTE CRS into account in the NR PDSCH rate-matching. This mechanism is an important enabler for the more dynamic resource sharing approach illustrated in Fig. 5.34, where a portion of the NR system bandwidth can be used as a resource pool shared between NR and LTE-M, achieving the same LTE-M scheduling flexibility within an NR carrier as within an LTE carrier (as described in Section 5.1.2.6). The *CRS muting* feature introduced in LTE-M in Release 15 (see Section 5.2.4.3.1) can potentially be useful in this context for reducing the amount of LTE CRS transmission that needs to take place within the NR carrier.

When deciding how to use these tools for coexistence between NR and LTE-M, the foreseen traffic mix should be considered. If only a small LTE-M traffic load is expected, it may be enough to configure a small LTE-M system bandwidth, whereas LTE-M traffic with high average load or large traffic peaks may require configuration of a larger LTE-M system bandwidth. If a large LTE-M system bandwidth is configured, dynamic resource sharing (as depicted in Fig. 5.33) between LTE-M and NR may be needed in order to be able to utilize the resource efficiently, whereas static resource sharing (as depicted in Fig. 5.33) may be considered sufficiently efficient if the LTE-M system bandwidth is small enough compared to the NR system bandwidth.

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