

A Short Introduction to LTE

A. OFDMA, OFDM and SC-FDMA

LTE uses OFDMA in downlink. More specifically, multiple sub-carriers are spread over the entire bandwidth. It is important to point out that LTE uses a reuse factor of 1, i.e., all available bandwidth is reused in each cell. There are various means of Inter-Cell Interference Coordination (ICIC), i.e., methods to limit inter-cell interference by coordinating resource allocation between different cells, already defined in the standard.

Sub-carrier spacing depends on the symbol duration. More specifically, $\Delta f = 1/T_{\text{symp}}$. In each subcarrier a typical narrow-band modulation technique (QPSK, 16-QAM, 64-QAM) is used. The appropriate modulation technique is chosen based on the channel state (CSI).

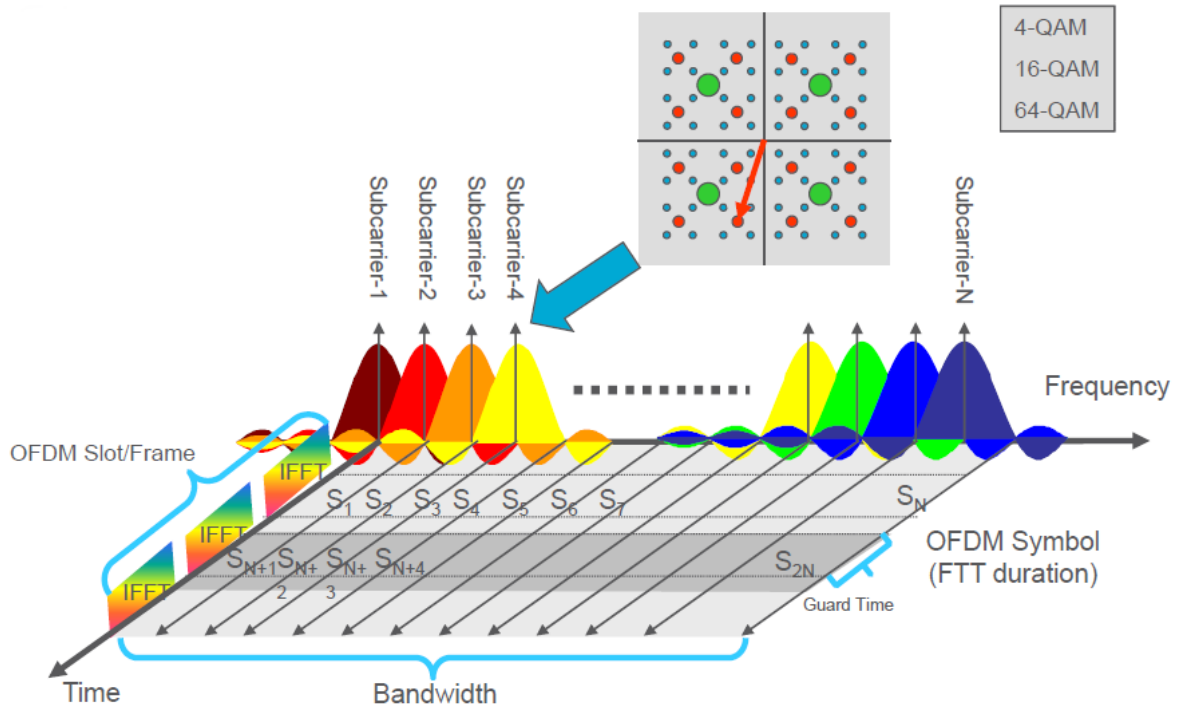


Figure A.1. Overview of the LTE system

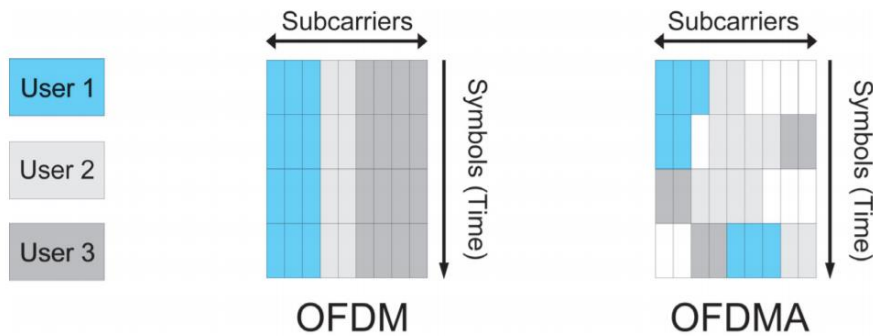


Figure A.2. OFDM vs OFDMA

Note that in OFDM, contrary to OFDMA, the subcarrier allocations are fixed for each user and performance can suffer from narrowband fading and interference. OFDMA

incorporates elements of Time Division Multiple Access (TDMA) so that the subcarriers can be allocated dynamically among the different users of the channel (see Fig. A.2). The result is a more robust system with increased capacity. The capacity comes from the trunking efficiency gained by multiplexing low rate users onto a wider channel to provide dynamic capacity when needed, and the robustness comes from the ability to schedule users by frequency to avoid narrowband interference and multipath fading.

In the uplink, LTE uses Single Carrier FDMA (SC-FDMA) due to power consumption considerations. More specifically, SC-FDMA has a smaller Peak-to-average power ratio, i.e., it requires less power, which is critical for power-constraint UEs. SC-FDMA is similar to OFDM (see Fig. A.3). Real uplink SC-FDMA signals are allocated in units of 12 adjacent subcarriers (known as Resource Blocks (RB), see below). The most obvious difference between the two schemes is that OFDMA transmits the 12 (four in the example) QPSK data symbols in parallel, one per subcarrier, while SC-FDMA transmits the 12 (four in the example) QPSK data symbols in series at 12 (four in the example) times the rate, with each data symbol occupying a wider 12 x 15 kHz (4x 15 kHz in the example) bandwidth. Note that OFDMA and SC-FDMA symbol lengths are the same at 66.7 μ s; however, the SC-FDMA symbol contains 12 (4 in the example) “sub-symbols” that represent the modulating data. Finally, observe that, an SC-FDMA signal uses a RB and this is compatible with the strategy used in LTE to allocate resources in units of RBs, i.e., as an integer multiple of RB (see below).

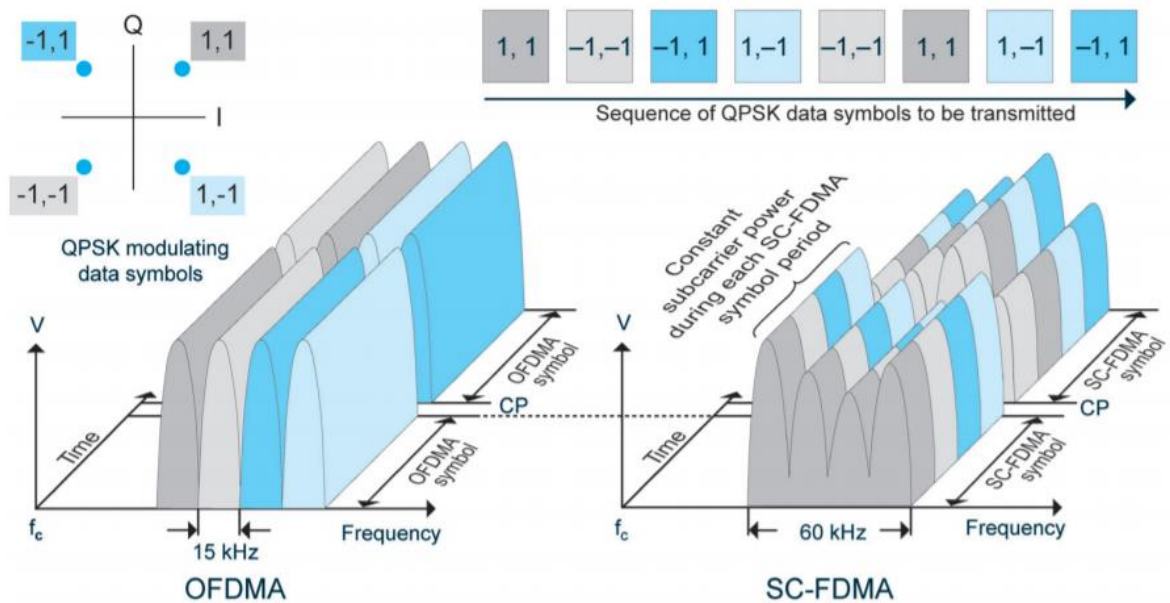


Figure A.3. Comparison of OFDMA and SC-FDMA transmitting a series of QPSK symbols (example uses only four sub-carriers for SC-FDMA instead of 12)

B. LTE Bandwidth Usage

A cell can be configured with several different bandwidths as shown in Table A.1. The sub-carriers for OFDM are located with a difference of 15 kHz. Thus, different bandwidths correspond to different numbers of sub-carriers. Guard band are used usually in the upper and lower edge of the frequency bands. For example, in the 5

MHz configuration the occupied bandwidth is 4.5 MHz (300 sub-carriers x 15 KHz) and 0.5 MHz are used for two guard bands of 0.25 MHz each.

Total bandwidth	Number of resource blocks	Number of sub-carriers	Occupied bandwidth	Usual guard bands
1.4 MHz	6	72	1.08 MHz	2×0.16 MHz
3 MHz	15	180	2.7 MHz	2×0.15 MHz
5 MHz	25	300	4.5 MHz	2×0.25 MHz
10 MHz	50	600	9 MHz	2×0.5 MHz
15 MHz	75	900	13.5 MHz	2×0.75 MHz
20 MHz	100	1200	18 MHz	2×1 MHz

Table B.1. Total bandwidth used in LTE

Channel Bandwidth (MHz)	1.25	2.5	5	10	15	20
Frame Duration (ms)	10					
Subframe Duration (ms)	1					
Sub-carrier Spacing (kHz)	15					
Sampling Frequency (MHz)	1.92	3.84	7.68	15.36	23.04	30.72
FFT Size	128	256	512	1024	1536	2048
Occupied Sub-carriers (inc. DC sub-carrier)	76	151	301	601	901	1201
Guard Sub-carriers	52	105	211	423	635	847
Number of Resource Blocks	6	12	25	50	75	100
Occupied Channel Bandwidth (MHz)	1.140	2.265	4.515	9.015	13.515	18.015
DL Bandwidth Efficiency	77.1%	90%	90%	90%	90%	90%
OFDM Symbols/Subframe	7/6 (short/long CP)					
CP Length (Short CP) (μ s)	5.2 (first symbol) / 4.69 (six following symbols)					
CP Length (Long CP) (μ s)	16.67					

Table B.2. LTE Downlink Physical Layer Parameters

In LTE FDD the bandwidth is usually the same in both directions, i.e., either 1.25, 2.5, 5, 10, 15 or 20 MHz. [On the other hand LTE FDD usually uses 20 MHz.](#)

C. Resource Grid Structure

In LTE, information is organized as a function of frequency as well as time, using a resource grid (see Fig. B.1). The resource grid contains all the sub-carriers (in the Frequency dimension) and evolves over time in time frames. One Resource Element (RE) is defined as the duration of an OFDM symbol in one sub-carrier. Each RE carries either 2, 4 or 6 bits depending on the modulation technique (either QPSK, 16-QAM or 64-QAM) chosen based on the channel state (CSI). A Resource Block (RB) is defined as a group of Res. More specifically a RB consists of 84 REs, i.e., it is 12 sub-carriers by 7 OFDM symbols (180 KHz x 1 time slot) wide.

*BS uses RBs for frequency dependent scheduling, by allocating the symbols and subcarriers within each subframe in units of **pairs of RBs**.*

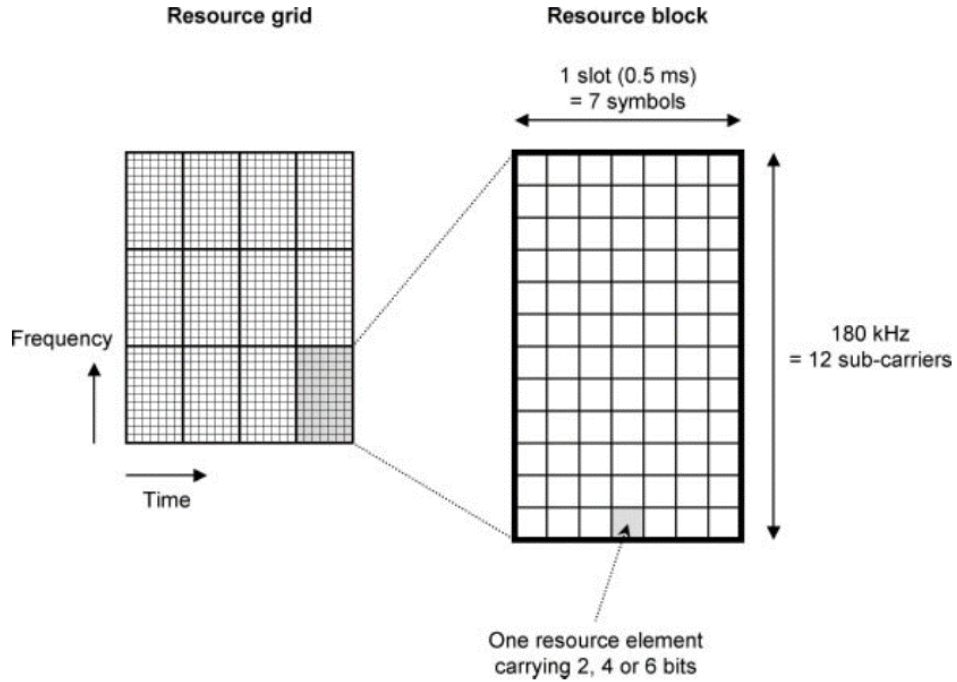


Figure C.1. Structure of the LTE resource grid (time and frequency domain) with a normal CP (there is a similar grid for the extended CP, which uses six symbols per slot rather than seven)

D. LTE frame

i. Type 1 (FDD)

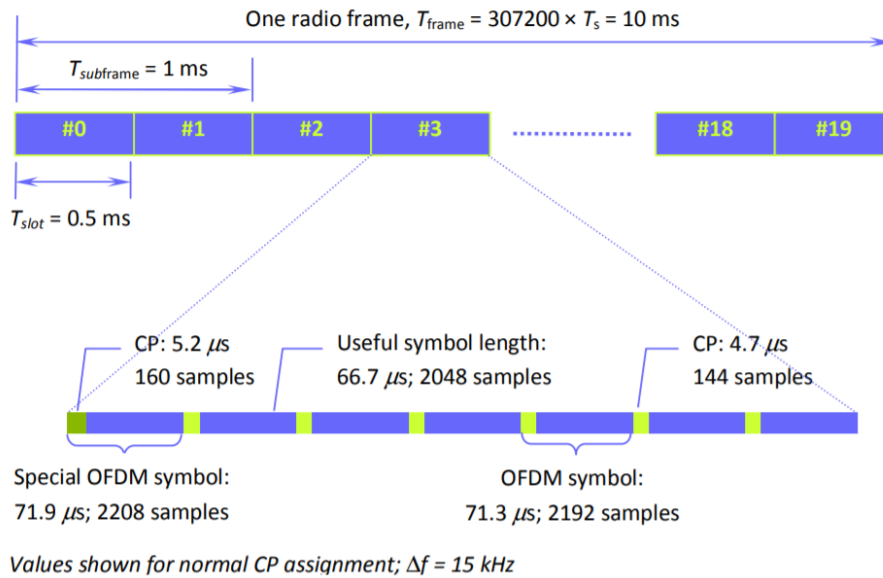


Figure C.1. Frame structure in LTE FDD

One frame in LTE is 10 ms long, i.e., $T_{fr} = 10 \text{ ms}$ and consists of 10 subframes each one with a duration of 1 ms ($T_{subfr} = 1 \text{ ms}$). There are 2 time slots per subframe and 20 total in each frame each with a duration of 0.5 ms, i.e., $T_{slot} = 0.5 \text{ ms}$.

Each slot consists of 7 OFDM symbols (including CP). The OFDM symbol duration in LTE (T_{symb}) is $66.7 \mu\text{s}$ without cyclic prefix (CP), i.e., $T_{\text{symb}} = 66.7 \mu\text{s}$. Typically, the CP duration is $4.7 \mu\text{s}$ long except for a special OFDM symbol in the beginning of a slot where the CP duration is $5.2 \mu\text{s}$.

Transmission of the downlink radio frame from the UE starts before the corresponding uplink radio frame at the UE (see Fig. C.2).

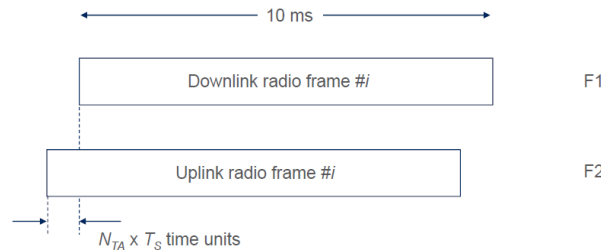


Figure C.2. Time synchronization between uplink and downlink frames

ii. Type 2 (TDD)

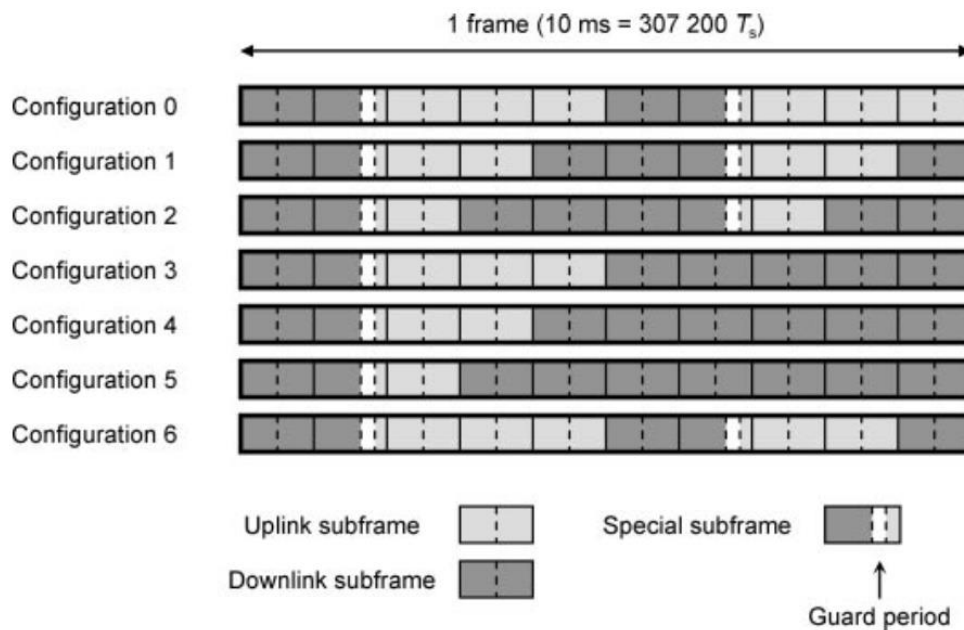


Figure C.3. Configurations for assigning subframes to UL and DL in LTE TDD.

The duration of frame, subframe and slot are all the same as in the FDD case. Each subframe can be allocated to either uplink or downlink using one of the TDD configurations shown in figure 2.

Different cells can have different TDD configurations, which are advertised as part of the cells' system information. Different configurations can fit different traffic patterns. For example, Configuration 1 might be suitable if the data rates are similar on the uplink and downlink whereas Configuration 5 might be used in cells that are dominated by downlink transmissions. Nearby cells should generally use the same TDD configuration, to minimize the interference between uplink and downlink.

E. PRACH Structure

i. FDD

The PRACH channel is designed to allow random access of a UE in several cases such as when recovering from radio link failure, when in `RCC_CONNECTED` state but uplink-synchronization is lost, when in `RCC_CONNECTED` state and handed over, when timing advance is needed for UE positioning purposes but most important when an UE requests a transition from the `RCC_IDLE` state to `RCC_CONNECTED`, i.e., it requests a connection set-up.

An UE transmits a preamble that is randomly chosen from a pool of 64 preambles. In fact, this pool of preambles is partitioned in two distinct groups. One group represents preambles that support contention-free access while the second contains preambles that correspond to contention-based access.

The PRACH is time- and frequency-multiplexed with PUSCH and PUCCH as illustrated in Fig. E.1. The PRACH slots shown in this figure can be configured to occur in up to 16 different layouts, or resource configurations. Depending on the RACH load, one or more PRACH resources may need to be allocated per PRACH slot period. In case of more than one PRACH resource per PRACH period it is generally preferable to multiplex the PRACH resources in time (Fig.E.2 – right) rather than in frequency (Fig.E.2 – left). This helps to avoid processing peaks at the eNodeB.

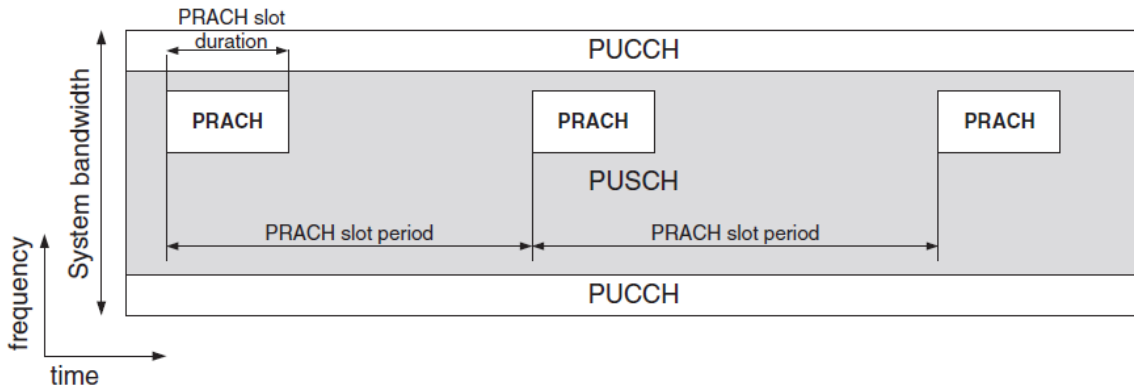


Figure E.1. PRACH multiplexing with PUSCH and PUCCH

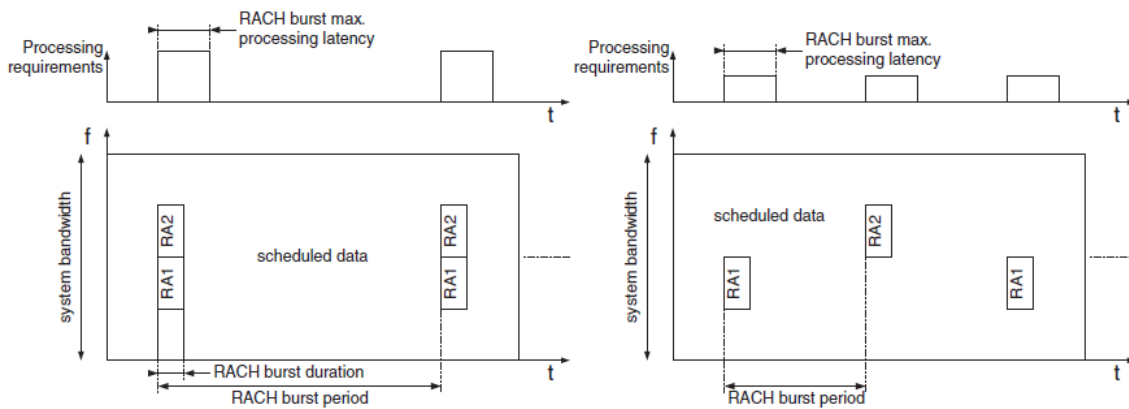


Figure E.2. Processing peaks of the random access preamble receiver

Fig. E.3. illustrates the 16 different resource layouts for PRACH for different system bandwidths and different numbers of cells per eNodeB. Resource configurations 0–2

and 15 use a 20 ms PRACH period, which can be desirable for small bandwidths (e.g. 1.4 MHz) in order to reduce the PRACH overhead at the price of higher waiting times. The variety of configurations provided enables efficient dimensioning of a multicell PRACH receiver.

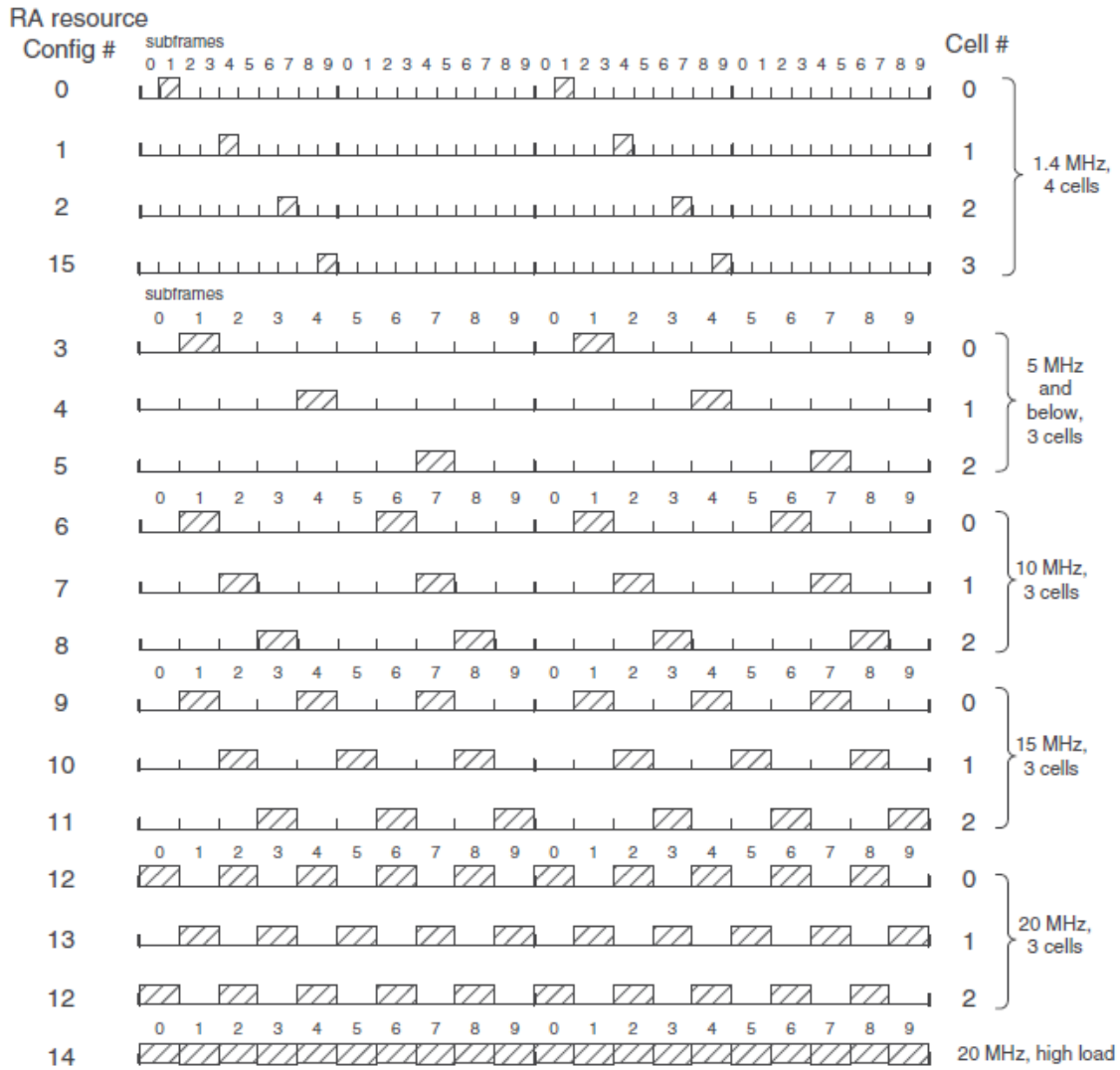


Figure E.3. Random Access resource configurations

Preamble format	T_{CP} (μ s)	T_{SEQ} (μ s)	Typical usage
0	103.13	800	Normal 1 ms random access burst with 800 μ s preamble sequence, for small to medium cells (up to $\sim$ 14 km)
1	684.38	800	2 ms random access burst with 800 μ s preamble sequence, for large cells (up to $\sim$ 77 km) without a link budget problem
2	203.13	1600	2 ms random access burst with 1600 μ s preamble sequence, for medium cells (up to $\sim$ 29 km) supporting low data rates
3	684.38	1600	3 ms random access burst with 1600 μ s preamble sequence, for very large cells (up to $\sim$ 100 km)

Table E.1. Random access preamble formats

Four Random Access preamble formats are defined for Frequency Division Duplex (FDD) operation. Each format is defined by the durations of the sequence and its CP, as listed in Table E.1. The format configured in a cell is broadcast in the System Information. The different formats support cells of different sizes and delay spreads as shown in Table E.2.

Preamble format	Number of allocated subframes	CP duration		GT duration		Max. delay spread (μ s)	Max. cell radius (km)
		in μ s	as multiple of T_S	in μ s	as multiple of T_S		
0	1	103.13	3168	96.88	2976	6.25	14.53
1	2	684.38	21024	515.63	15840	16.67	77.34
2	2	203.13	6240	196.88	6048	6.25	29.53
3	3	684.38	21024	715.63	21984	16.67	100.16

Table E.2. Field durations and achievable cell radius of the PRACH preamble formats

Preamble bandwidth: In order to ease the frequency multiplexing of the PRACH and the PUSCH resource allocations, a PRACH slot must be allocated a bandwidth BW_{PRACH} equal to an integer multiple of Resource Blocks (RBs), i.e. an integer multiple of 180 kHz. For simplicity, BW_{PRACH} in LTE is constant for all system bandwidths; it is chosen to optimize both the detection performance and the timing estimation accuracy. The latter drives the lower bound of the PRACH bandwidth. Indeed, a minimum bandwidth of ~ 1 MHz¹ is necessary to provide a one-shot accuracy of about 0.5 μ s, which is an acceptable timing accuracy for PUCCH/PUSCH transmissions. *Therefore, a PRACH allocation of 6 RBs (i.e., $6 \times 12 \times 15$ KHz = 1.08 MHz) provides a good trade-off between PRACH overhead, detection performance and timing estimation accuracy.* system bandwidth (1.4 MHz, 6 RBs) the PRACH overlaps with the PUCCH; it is left to the eNodeB implementation whether to implement scheduling restrictions during PRACH slots to avoid collisions, or to let PRACH collide with PUCCH and handle the resulting interference.

ii. TDD

One design principle of LTE is to maximize the commonality of FDD and TDD transmission modes. With this in mind, the random access preamble formats 0 to 3 are supported in both FDD and TDD operation. In addition, a short preamble format, ‘format 4’, is supported for TDD operation. Format 4 is designed to fit into the short uplink special field known as UpPTS for small cells. *Unlike in FDD where there can be at most one PRACH opportunity in one subframe, TDD allows frequency multiplexing of up to six PRACH opportunities in one subframe, to compensate for the smaller number of uplink subframes.*

F. Random Access Procedure

The LTE random access procedure comes in two forms, allowing access to be either contention-based (implying an inherent risk of collision) or contention-free. In this procedure, a random-access preamble signature is randomly chosen by the UE,

¹ Note that the preamble uses more carriers with a smaller spacing for a total bandwidth of ~ 1 MHz

which may result in more than one UE simultaneously transmitting the same signature, leading to a need for a subsequent contention resolution process. For two cases [a) when new downlink data need to be transmitted in the UE and the synchronization is lost, and b) when a handover occurs] the eNodeB has the option of preventing contention occurring by allocating a dedicated signature to a UE, resulting in contention-free access. A fixed number (64) of preamble signatures is available in each LTE cell, and the operation of the two types of RACH procedure depends on a partitioning of these signatures between those for contention-based access and those reserved for allocation to specific UEs on a contention-free basis.

The contention-based procedure consists of four-steps as shown in Figure F.1:

- Step 1: Preamble transmission;
- Step 2: Random access response;
- Step 3: Layer 2 / Layer 3 (L2/L3) message;
- Step 4: Contention resolution message.

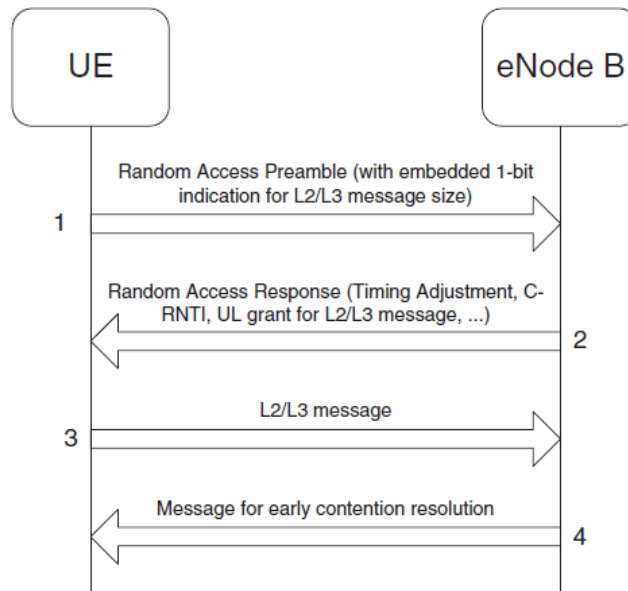


Figure F.1. Contention-based random access procedure

i. Step 1: Preamble Transmission

The UE selects one of the $64 - N_{cf}$ available PRACH contention-based signatures, where N_{cf} is the number of signatures reserved by the eNodeB for contention-free RACH. The set of contention-based signatures is further subdivided into two subgroups, so that the choice of signature can carry one bit of information relating to the amount of transmission resource needed to transmit the message at Step 3. The broadcast system information indicates which signatures are in each of the two subgroups (each subgroup corresponding to one value of the one bit of information), as well as the meaning of each subgroup. The UE selects a signature from the subgroup corresponding to the size of transmission resource needed for the appropriate RACH use case (some use cases require only a few bits to be transmitted at Step 3, so choosing the small message size avoids allocating unnecessary uplink resources). In selecting the appropriate resource size to indicate, the UE takes into account the current downlink path-loss and the required transmission power for the Step 3 message, in order to avoid being

granted resources in Step 3 for a message size that would need a transmission power exceeding that which the UE's maximum power would allow. The transmission power required for the Step 3 message is calculated based on some parameters broadcast by the eNodeB, in order that the network has some flexibility to adapt the maximum size for the Step 3 message. The eNodeB can control the number of signatures in each subgroup according to the observed loads in each group.

The initial preamble transmission power setting is based on an open-loop estimation with full compensation for the path-loss. This is designed to ensure that the received power of the preambles is independent of the path-loss. The UE estimates the path-loss by averaging measurements of the downlink Reference Signal Received Power (RSRP). The eNodeB may also configure an additional power offset, depending for example on the desired received Signal to Interference plus Noise Ratio (SINR), the measured uplink interference and noise level in the time-frequency slots allocated to RACH preambles, and possibly also on the preamble format.

ii. Step 2: Random Access Response

The Random Access Response (RAR) is sent by the eNodeB on the Physical Downlink Shared CHannel (PDSCH), and *addressed with an ID, the Random Access Radio Network Temporary Identifier (RA-RNTI), identifying the time-frequency slot² in which the preamble was detected*. If multiple UEs had collided by selecting the same signature in the same preamble time-frequency resource, they would each receive the RAR.

The RAR *conveys the identity of the detected preamble*, a timing alignment instruction to synchronize subsequent uplink transmissions from the UE, an initial uplink resource grant for transmission of the Step 3 message, *and an assignment of a temporary Cell Radio Network Temporary Identifier (C-RNTI)* (which may or may not be made permanent as a result of the next step – contention resolution). **The RAR message can also include a 'backoff indicator' which the eNodeB can set to instruct the UE to back off for a period of time before retrying a random access attempt.**

The UE expects to receive the RAR within a time window, of which the start and end are configured by the eNodeB and broadcast as part of the cell-specific system information. The earliest subframe allowed by the specifications occurs 2 ms after the end of the preamble subframe, as illustrated in Figure F.2. However, a typical delay (measured from the end of the preamble subframe to the beginning of the first subframe of RAR window) is more likely to be 4 ms. Figure F.2 shows the RAR consisting of the step 2 message (on PDSCH) together with its downlink transmission resource allocation message 'G' (on the Physical Downlink Control CHannel (PDCCH)).



Figure F.2. Timing of the Random Access Response (RAR) window

² This is because the eNodeB may respond with a delay. Thus, there is the need to identify the PRACH slot in which the preamble was detected.

If the UE does not receive a RAR³ within the configured time window, it selects a signature again (as in Step 1) and transmits another preamble. The minimum delay for the transmission of another preamble after the end of the RAR window is 3 ms. If the UE receives the PDCCH signalling the downlink resource used for the RAR but cannot satisfactorily decode the RAR message itself, the minimum delay is increased to 4 ms to allow for the time taken by the UE in attempting to decode the RAR.

The eNodeB may configure preamble power ramping so that the transmission power for each transmitted preamble is increased by a fixed step. However, since the random access preambles in LTE are normally orthogonal to other uplink transmissions, it is less critical than it was in WCDMA to ensure that the initial preamble power is kept low to control interference. Therefore, the proportion of random access attempts which succeed at the first preamble transmission is likely to be higher than in WCDMA, and the need for power ramping is likely to be reduced.

iii. Step 3: Layer 2/Layer 3 (L2/L3) Message

This message is the first scheduled uplink transmission on the PUSCH and makes use of Hybrid Automatic Repeat reQuest (HARQ). It conveys the actual random access procedure message, such as an *RRC connection request*, tracking area update, or scheduling request, but no Non-Access Stratum (NAS) message. *It is addressed to the temporary C-RNTI allocated in the RAR at Step 2 and carries either the C-RNTI if the UE already has one (RRC_CONNECTED UEs) or an initial UE identity (the SAE2 Temporary Mobile Subscriber Identity (S-TMSI) or a random number).* In case of a preamble collision having occurred at Step 1, the colliding UEs will receive the same temporary C-RNTI through the RAR and will also collide in the same uplink time-frequency resources when transmitting their L2/L3 message. *This may result in such interference that no colliding UE can be decoded, and the UEs restart the random access procedure after reaching the maximum number of HARQ retransmissions.* However, if one UE is successfully decoded, the contention remains unresolved for the other UEs. The following downlink message (in Step 4) allows a quick resolution of this contention.

If the UE successfully receives the RAR, the UE minimum processing delay before message 3 transmission is 5 ms minus the round-trip propagation time. This is shown in Figure F.3 for the case of the largest supported cell size of 100 km.

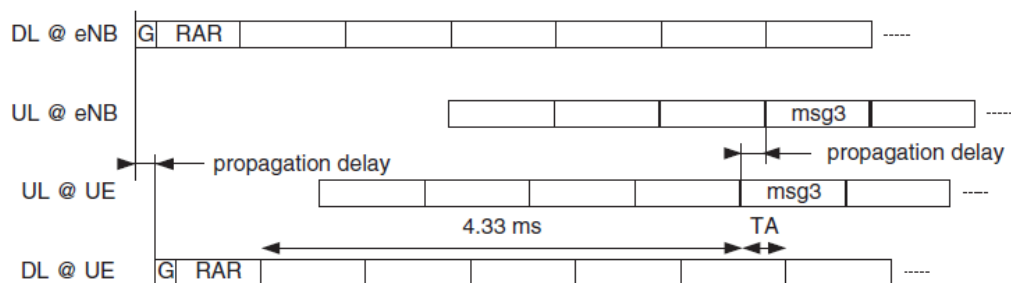


Figure F.3. Timing of the message 3 transmission

³ Probably this is possible if the eNode can not provide downlink grants

iv. Step 4: Contention Resolution Message

The contention resolution message uses HARQ. *It is addressed to the C-RNTI (if indicated in the L2/L3 message) or to the temporary C-RNTI, and, in the latter case, echoes the UE identity contained in the L2/L3 message.* In case of a collision followed by successful decoding of the L2/L3 message, the HARQ feedback is transmitted only by the UE which detects its own UE identity (or C-RNTI); *other UEs understand there was a collision, transmit no HARQ feedback, and can quickly exit the current random access procedure and start another one.* The UE's behavior upon reception of the contention resolution message therefore has three possibilities:

- The UE correctly decodes the message and detects its own identity: it sends back a positive ACKnowledgement, 'ACK'
- The UE correctly decodes the message and discovers that it contains another UE's identity (contention resolution): it sends nothing back (Discontinuous Transmission, 'DTX')
- The UE fails to decode the message or misses the DL grant: it sends nothing back ('DTX')