# 1

# Enabling Technologies for 3GPP LTE-Advanced Networks

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The specifications of Long Term Evolution (LTE) in 3rd Generation Partnership Project (3GPP) (Release 8) were just finished when work began on the new Long Term Evolution Advanced (LTE-A) standard (Release 9 and beyond). LTE-A meets or exceeds the requirements imposed by International Telecommunication Union (ITU) to Fourth Generation (4G) mobile systems, also called International Mobile Telecommunication Advanced (IMT-A). These requirements were unthinkable a few years ago, but are now a reality. Peak data rates of 1 Gbps with bandwidths of 100 MHz for the downlink, very low latency, more efficient interference management and operational cost reduction are clear examples of why LTE-A is so appealing for operators. Moreover, the quality breakthrough affects not only operators but also end users, who are going to experience standards of quality similar to optical fiber. To reach these levels of capacity and quality, the international scientific community, in particular the 3GPP, are developing different technological enhancements on LTE. The most important technological proposals for LTE-A are: support of wider bandwidth (carrier aggregation), advanced Multiple Input Multiple Output (MIMO) techniques, Coordinated Multipoint transmission or reception (CoMP), relaying, enhancements for Home eNodeB (HeNB) and machine-type communications. To analyze both the context of LTE-A and the new enabling technologies, this chapter is divided as follows:

- Section 1.1: This section introduces LTE-A as an IMT-A technology.
- Section 1.2: This section summarizes the main IMT-A features and its requirements in terms of services, spectrum and performance.
- Section 1.3: This section highlights LTE-A requirements. From a direct comparison with the previous section, it is shown that they are more challenging than those established by the ITU for IMT-A.

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- Section 1.4: This section shows the technological proposals being studied in 3GPP: carrier aggregation, new transmission schemes in both uplink and downlink, CoMP, the use of relays, enhancements for HeNB and machine-type communications and other improvements related to the reduction of latency in the user and control plane.

## 1.1 Introduction

Along its standardization LTE was designed as an evolution of legacy Third Generation (3G) mobile systems due to the incorporation of a set of technological improvements, such as:

- Dynamic allocation of variable bandwidth.
- New MIMO schemes.
- New transmission schemes with multiple carriers, like Orthogonal Frequency Division Multiplexing (OFDM) in the DownLink (DL) and DFT Spread- OFDM (DFTS-OFDM), also known as Single Carrier Frequency Division Multiple Access (SC-FDMA), in the UpLink (UL).
- Very low latency in the user and control plane.

All these new features represent a qualitative and quantitative leap in system performance that is motivated by different reasons. Market globalization and liberalization and the increasing competence among vendors and operators coming from this new framework has led to the emergence of new technologies. This fact comes together with the popularization of Institute of Electrical & Electronics Engineers (IEEE) 802 technologies within the mobile communications sector. Finally, end users are becoming more discerning and demand new and better services such as Voice over IP (VoIP), video-conference, Push-to-talk over Cellular (PoC), multimedia messaging, multiplayer games, audio and video streaming, content download of ring tones, video clips, virtual private network connections, web browsing, email access, file transfer, and so on. It is precisely this increasing market demand and its enormous economic benefits, together with the new challenges that come with the requirements in higher spectral efficiency and services aggregation that raised the need to allocate new frequency channels to mobile communications systems. That is why the International Telecommunication Union – Radiocommunication Sector (ITU-R) WP 8F started in October 2005 the definition of the future 4G, also known as IMT-A, following the same model of global standardization used with 3G systems. The objective of IMT-A is to specify a set of requirements in terms of transmission capacity and quality of service, in such a way that if a certain technology fulfils all these requirements it is included by the ITU in the IMT-A set of standards. This inclusion firstly endorses technologies and motivates operators to invest in them, but furthermore it allows these standards to make use of the frequency bands specially designated for IMT-A, which entails a great motivation for mobile operators to increase their offered services and transmission capacity. Given this economic outlook, the 3GPP established the LTE standardization activity as an ongoing task to build up a framework for the evolution of the 3GPP radio technologies, concretely Universal Mobile Telecommunication System (UMTS), towards 4G. The 3GPP divided this work into two phases: the former concerns the completion of the first LTE standard (Release 8), whereas the latter intends to adapt LTE to the requirements of 4G through the specification of a new technology called LTE-A (from Release 9 on). Following this plan, the LTE-A Study Item was launched in April 2008 to analyze IMT-A requirements and pose conditions to the new standard:

- LTE-A would be an evolution of LTE. Therefore, backward compatibility between LTE-A and LTE Release 8 must be guaranteed.
- LTE-A requirements should exceed IMT-A ones, following the ITU-R agenda.
- LTE-A would support higher peak data rates, with the aim of fulfilling ITU-R conditions, focusing on low mobility users.

## 1.2 General IMT-Advanced Features and Requirements

IMT-A systems comprise new capabilities and new services, migrating towards an all-IP network. As happened with the IMT-2000 family of standards, it is expected that IMT-A becomes, through a continuous evolution, the dominant technology designed to support new applications, products and services. Moreover, IMT-A systems must support applications for both low and high speed mobility and for different data rates. The main characteristics of IMT-A systems are:

- Ease of use of applications while maintaining a wide range of services at a reasonable cost.
- Compatibility with International Mobile Telecommunication (IMT) standards and with other fixed networks.
- Interconnection capacity with other radio access systems.
- High quality mobile services.
- Global roaming capabilities.
- Peak data rates of 100 Mbps for high mobility users and 1 Gbps for low mobility users.

Requirements established by ITU-R can be classified in three main categories: services, spectrum and technical aspects. The aim of these requirements is not to limit the performance of the candidate technologies, but to ensure that the IMT-A radio interface technologies fulfil these minimum conditions to become a member of the 4G family of standards.

### *1.2.1 Services*

IMT-A requirements do not specify a set of services but a structure of services that includes service parameters, service classifications and some examples [1]. Capacity requirements are based on the support of a wide range of services comprising basic conversational, advanced and low delay services.

### *1.2.2 Spectrum*

The radio spectrum is a scarce resource that has a considerable economic and social importance. Albeit in the last analysis the governments of every nation must decide on the spectrum allocation, global coordination of the spectrum usage is responsibility of the ITU, which, through spectrum regulation, aims to facilitate the global roaming and to decrease equipment cost by means of global economies of scale. Since 1992, and in the framework of the ITU-R, United Nations have come to quite significant agreements at a global level to designate some specific frequency bands to IMT standards. With the aim of coordinating the global use of spectrum, every three to four years ITU-R holds the World Radiocommunication Conference (WRC), where ITU radio regulations that govern spectrum distribution are adapted.

ITU-R has already started the spectrum regulation tasks concerning IMT-A. The first step was performing an in-depth study of the mobile market forecast and the development of spectrum requirements for the increasing service demand. Reports predicted the total spectrum bandwidth requirements for mobile communication systems in the year 2020 to be 1280 MHz and 1720 MHz for low and high user demand scenarios, respectively. Bearing in mind that the spectrum bandwidth designed by ITU as IMT was much lower than this forecast (693 MHz in Region 1 (Europe, Middle East and Africa, and Russia), 723 MHz in Region 2 (Americas) and 749 MHz in Region 3 (Asia and Oceania)), and given that the time elapsed since the adaptation of the radio regulations until the definitive allocation of a frequency band to operators takes from 5 to 10 years, the WRC-07 that took place in Geneva ended with the identification of new frequency bands for IMT technologies.

Figure 1.1 depicts the current state of the frequency bands reserved for IMT. Despite not fully corresponding to what was targeted, the new spectrum allocated for mobile communications will allow operators to satisfy the initial deployment of technologies towards IMT-A. Furthermore, the increasing demand for mobile services has been progressively recognized with additional spectrum, a trend that is expected to be maintained in future World Radiocommunication Conference (WRC).

### 1.2.3 Technical Performance

So far, the above requirements may be seen as recommendations. In terms of technical performance requirements, there are ten major indicators [2]. Table 1.1 shows the evaluation method for each technical feature. To calculate cell spectral efficiency, cell edge spectral efficiency and VoIP capacity it is necessary to take into account those signals and channels that consume resources and reduce the capacity of the Physical Downlink Shared Channel (PDSCH) and Physical Uplink Shared Channel (PUSCH). Depending on whether the transmission is uplink or downlink, or the duplexing is Frequency Division

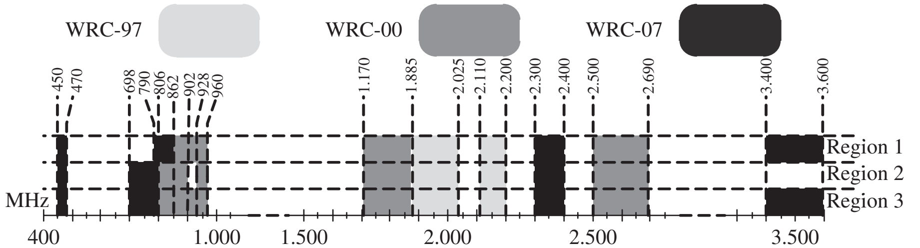


**Figure 1.1** Frequency bands allocated to IMT-A.

**Table 1.1** Features and their assessment method

| Feature | Simulation | Analytical | Inspection |
|---|---|---|---|
| Cell spectral efficiency | ×* | | |
| Peak spectral efficiency | | × | |
| Bandwidth | | | × |
| Cell edge user spectral efficiency | ×* | | |
| Control plane latency | | × | |
| User plane latency | | × | |
| Mobility | ×** | | |
| Handover interruption time | | × | |
| Inter-system handover | | | × |
| VoIP capacity | ×* | | |

*System-level simulation.
**System and link-level simulation.

Duplexing (FDD) or Time Division Duplexing (TDD), these available resources will be different. For the exact mapping of signals and physical channels, see [3].

Evaluation activities are carried out by analytical means, by inspection or by simulation. The simulation methods are divided into link-level simulations and system-level simulations. The former focuses on defining a simple scenario with one transmitter and one receiver, while system-level simulations aim at studying the global characteristics of a communication system with several mobile users. The IMT-A requirements must be checked for all configurations of the radio access technology, including both the FDD and the TDD mode, for different scenarios and for UL and DL. A technology meets requirements if, for a given configuration, results exceed the established thresholds. For example, LTE-A could meet the requirements on cell edge spectral efficiency with Multi-User MIMO (MU-MIMO) but without using CoMP.

There are four different test environments defined by ITU-R:

- **Indoor**: This is a high user density scenario with high data rate experiences. Cells are considered very small.
- **Microcellular**: This is a dense urban scenario with high traffic and user density. Pedestrian and slow vehicular users are assumed. Distance between base stations is small and antenna mounting is below rooftop.
- **Base Coverage Urban**: Urban scenario with pedestrian and high speed users. Base stations are above rooftop.
- **High Speed**: Macrocellular scenario for high speed vehicles and trains.

Each test environment has one or several deployment scenarios. Table 1.2 summarizes this mapping. The acronyms Indoor Hotspot (InH), Urban Microcell (UMi), Urban Macrocell (UMa) and Rural Macrocell (RMa) are widely used to refer to these scenarios.

The next subsections describe the meaning of the performance indicators included in Table 1.1. All figures are extracted from [2].

**Table 1.2** Test deployment scenarios

| Test Environment | Indoor | Microcellular | Base Coverage Urban | High Speed |
|---|---|---|---|---|
| Deployment Scenario | Indoor Hotspot (InH) | Urban Microcell (UMi) | Urban Macrocell (UMa) | Rural Macrocell (RMa) |

#### 1.2.3.1 Cell Spectral Efficiency

Cell spectral efficiency is probably the most important parameter that defines the actual capacity of the system. It is defined as the aggregate capacity of all users, that is, the total number of bits that are delivered to the layer 3 in a given time interval, normalized by the channel bandwidth and the number of cells. Cell spectral efficiency has units of b/s/Hz/cell. In a system with $N$ users and $M$ cells, the overall efficiency of the cell is expressed by Equation 1.1.

$$\eta = \frac{\sum_{i=1}^{N} \chi_i}{T \cdot BW \cdot M}, \tag{1.1}$$

where $\chi_i$ is the number of bits correctly received by the $i$-th user, $T$ is the considered time interval and $BW$ the channel bandwidth.

Requirements related to cell spectral efficiency ($\eta$) are summarized in Table 1.3 for each environment. These values were derived assuming four transmit antennas and two receive antennas in DL and two transmit antennas and four receive antennas for the UL. It is worth noting that these antenna configurations are not mandatory.

#### 1.2.3.2 Peak Spectral Efficiency

Another parameter to be assessed is the peak spectral efficiency. For its calculation, it is assumed perfect communication and hence coding rate is equal to 1. The minimum values for peak spectral efficiency are shown in Table 1.4.

#### 1.2.3.3 Bandwidth and Scalability

The bandwidth in IMT-A technologies should be scalable to operate in different bands of the spectrum through a single or multiple carriers. Each radio interface technology should be scalable to at least 40 MHz with a recommended maximum bandwidth of 100 MHz.

**Table 1.3** Requirements on cell spectral efficiency

| | DL Efficiency (b/s/Hz/cell) (4 × 2) | UL Efficiency (b/s/Hz/cell) (2 × 4) |
|---|---|---|
| Indoor | 3 | 2.25 |
| Microcellular | 2.6 | 1.80 |
| Base Coverage Urban | 2.2 | 1.4 |
| High Speed | 1.1 | 0.7 |

**Table 1.4** Requirements on peak spectral efficiency in downlink and uplink

| | Peak spectral efficiency (b/s/Hz) |
|---|---|
| Uplink (2 × 4) | 6.75 |
| Downlink (4 × 4) | 15 |

#### 1.2.3.4 Cell Edge User Spectral Efficiency

Cell edge user spectral efficiency is defined as the 5th percentile of user spectral efficiency, that is, the value over which 95% of users spectral efficiency falls. The spectral efficiency of user $i$-th ($\gamma_i$) is defined as:

$$\gamma_i = \frac{\chi_i}{T_i \cdot BW} \tag{1.2}$$

Requirements established by ITU-R concerning cell edge user spectral efficiency are collected in Table 1.5.

#### 1.2.3.5 Latency in the User and Control Plane

Latency is one of the parameters that most influences the perception of the end user. There are several applications where capacity is not as important as transmission latency, such as VoIP, real-time games, interactive applications, and so on. There are two types of latency: the latency at the user and control plane. The latency at the control plane is the time in the transition between two connection states, for example, from the idle state to the active state.

Figure 1.2 shows the set of connection modes used for the latency analysis and the requirements established by ITU-R. Transition between the dormant and the active state entails that the user is already synchronized.

On the other hand, user plane latency is defined as the time elapsed since the Internet Protocol (IP) packet is available at the base station until this packet is properly received by the IP layer of the end user. ITU-R fixed a maximum latency for this transmission of 10 ms in case of low load of the base station (a single active user) and low size IP packets.

**Table 1.5** Cell edge spectral efficiency

| | DL Efficiency (b/s/Hz/cell) (4 × 2) | UL Efficiency (b/s/Hz/cell) (2 × 4) |
|---|---|---|
| Indoor | 0.1 | 0.07 |
| Microcellular | 0.075 | 0.05 |
| Base Coverage Urban | 0.06 | 0.03 |
| High Speed | 0.04 | 0.015 |

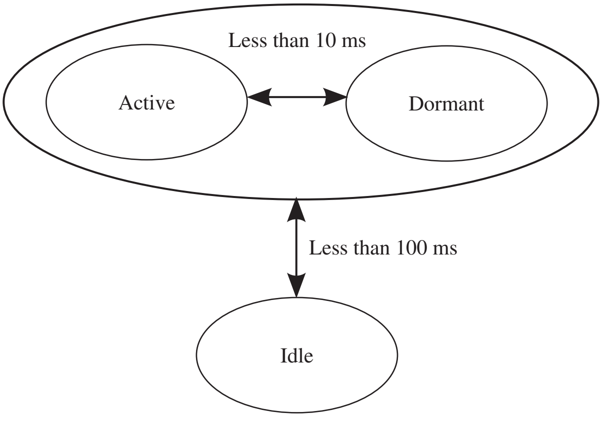


**Figure 1.2** Latency in the control plane.

#### 1.2.3.6 Mobility

The proper management of mobility is another feature that ITU-R defined as critical for IMT-A systems. The requirements summarized in Table 1.6 are evaluated for different scenarios and user velocity, both for DL and UL. Spectral efficiency values are assumed for a $4 \times 2$ configuration in DL and $2 \times 4$ in UL.

#### 1.2.3.7 Handover

Handover time is the time during which the user terminal cannot exchange packets with any base station since it is in the transfer phase from one cell to another. The requirements can be divided into two cases, as shown in Table 1.7: if base stations are transmitting on the same frequency carrier or on different carriers, either in the same band or in different bands.

The handovers described so far are all within the same technology. However, it could be the case that the terminal had to move to another technology. IMT-A systems should be able to ensure that such handovers are also supported.

**Table 1.6** Spectral efficiency to assess mobility

| | Velocity (km/h) | Efficiency (b/s/Hz/cell) |
|---|---|---|
| Indoor | 10 | 1.0 |
| Microcellular | 30 | 0.75 |
| Base Coverage Urban | 120 | 0.55 |
| High Speed | 350 | 0.25 |

**Table 1.7** Handover interruption time

| Handover type | Interruption time (ms) |
|---|---|
| Intra-frequency | 27.5 |
| Inter-frequency within a spectrum band | 40 |
| Inter-frequency between spectrum bands | 50 |

#### 1.2.3.8 VoIP Capacity

Finally, VoIP Capacity is another parameter to be assessed both for DL and UL, assuming a 12.2 kbps coder and a 50% activity factor. The percentage of users with interruption should be less than 2%, where a user suffers interruption if less than 98% of VoIP packets have been delivered successfully. A package is delivered successfully if transmission delay is less or equal to 50 ms. This delay is the latency in the transmission from the encoder at the transmitter to the decoder at the receiver. The VoIP Capacity is defined as the minimum capacity in both links (DL and UL) normalized by the used bandwidth. Table 1.8 summarizes the IMT-A requirements regarding VoIP Capacity.

## 1.3 Long Term Evolution Advanced Requirements

The race towards IMT-A was officially started in March 2008, when the ITU-R issued a circular letter asking for the submission of new technology proposals. Previous to this official call, the 3GPP established in 2004 the LTE standardization activity as an ongoing task to build up a framework for the evolution of the 3GPP radio technologies, concretely UMTS, towards 4G. The 3GPP divided this work into two phases: the former concerns the completion of the first LTE standard (Release 8), whereas the latter intends to adapt LTE to the requirements of 4G through the specification of a new technology called LTE-A (Release 9 and beyond). Following this plan, in December 2008 the 3GPP approved the specifications of LTE Release 8 which encompasses the Evolved UTRAN (EUTRAN) and the Enhanced Packet Core (EPC). Otherwise, the LTE-A Study Item was launched in May 2008, being completed in October 2009 according to the ITU-R

**Table 1.8** VoIP Capacity

| | Minimum VoIP Capacity (Active Users/cell/MHz) |
|---|---|
| Indoor | 50 |
| Microcellular | 40 |
| Base Coverage Urban | 40 |
| High Speed | 30 |

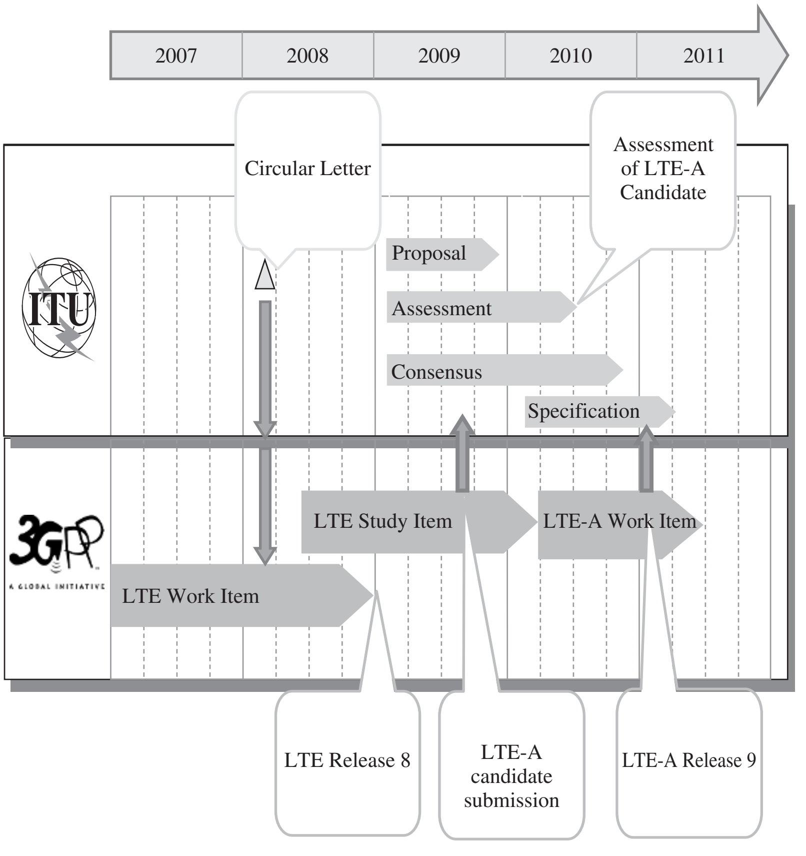


**Figure 1.3** LTE specification roadmap.

schedule for the IMT-A process. It was in November 2008 when ITU-R established the technical requirements of radio interface candidates for IMT-A [2]. Figure 1.3 depicts the standardization process of LTE and LTE-A. In September 2009, the 3GPP submitted to the ITU-R the main features of LTE-A candidate for IMT-A. In fact the 3GPP submitted a set of radio interface candidates comprising FDD and TDD modes. The 3GPP also assessed its own candidates, demonstrating that they fulfill IMT-A requirements. Three documents were included in the proposal: a template that describes the main features of the technology [4], a template with a link budget analysis of the four environments [5] and a template with a summary of the self-evaluation of service, spectrum and technical performance requirements [6]. The full self-evaluation can be found in section 16 of [7].

Despite the tight requirements of ITU-R, the 3GPP fixed its own requirements for the development of LTE-A. These requirements are divided into seven items: capacity, system performance, deployment, architecture and migration, radio resource management, complexity, cost and services. Only the first three are further described in this section, since the others are either a consequence of them or the same as for LTE. For more details about LTE-A requirements refer to [8].

## *1.3.1 Requirements Related with Capacity*

### 1.3.1.1 Peak Data Rate

The minimum requirements for LTE-A, in terms of capacity, are marked by the ITU-R, that is, 100 Mbps for high mobility users and 1 Gbps for low mobility users. Yet this goal is further specified pursuing data rates of 1 Gbps just for the downlink, being 500 Mbps for the uplink.

### 1.3.1.2 Latency

The expected latency for the control plane in LTE-A must be much smaller than the latency set for LTE Release 8. This latency takes into account the radio access network and core network (excluding the latency of the S1 interface, that is, the interface between the radio access network and the core network) with a lightly loaded system. The transition time from the Camped state (after the allocation of the IP address) to the Active state, including the establishment time of the user plane, but excluding the delay associated with S1 interface, must be less than 50 ms. Latency from the Inactive to Active state must be less than 10 ms. Finally, the standard establishes that the system must support 300 active users in a bandwidth of 5 MHz.

## *1.3.2 System Performance*

### 1.3.2.1 Peak Spectral Efficiency

As discussed in Section 1.2.3, the peak spectral efficiency is the highest data rate normalized by the bandwidth, considering that the communication is free of errors. With a multi-antenna maximum configuration of up to $8 \times 8$, the peak spectral efficiency is 30 b/s/Hz in the downlink, while in the uplink the peak spectral efficiency is 15 b/s/Hz for a maximum configuration of up to $4 \times 4$.

### 1.3.2.2 Mean Spectral Efficiency

Another parameter even more important than peak spectral efficiency, and perhaps more realistic, is the mean spectral efficiency, defined as the sum of users data rates normalized by the bandwidth and the number of cells. In the current definition of LTE-A requirements, the spectral efficiency is calculated using a channel model that is different from the one defined by the ITU-R. The description of this channel model can be found in [9] and is the same as the channel used for the evaluation of LTE. Four different cases were defined including main parameters such as carrier frequency, inter-site distance, bandwidth, penetration losses and speed. Case 1 is used to verify the requirements, which corresponds to the urban macrocellular channel of ITU-R. This channel was used to compare LTE-A to LTE. The results shown in Table 1.9 are a compilation of results of the technical report for LTE Release 8 [8, 10] for LTE-A and [2] for IMT-A. If a resource manager only provides resources to the user with best channel, then that user would enjoy a high spectral efficiency, but others would be penalized thus having a poor spectral efficiency. Therefore, the mean spectral efficiency does not show the reality that

**Table 1.9** Mean spectral efficiency requirements

| | | Antenna Conf. | LTE Rel 8 | (LTE-A) | (IMT-A) |
|---|---|---|---|---|---|
| Capacity (b/s/Hz/cell) | DL | 2 × 2 | 1.69 | 2.4 | - |
| | | 4 × 2 | 1.87 | 2.6 | 2.2 |
| | | 4 × 4 | 2.67 | 3.7 | - |
| | UL | 1 × 2 | 0.74 | 1.2 | - |
| | | 2 × 4 | - | 2.0 | 1.4 |

is occurring, as it omits a fair resource allocation. It is in this case when the cell-edge user spectral efficiency metric seems the most appropriate as it ensures that 95% of users are above a certain value of efficiency. Obviously, in a real situation the resource manager offers resources more equitably, reaching an equilibrium.

#### 1.3.2.3 Cell Edge User Spectral Efficiency

The requirements on cell edge user spectral efficiency are summarized in Table 1.10, which shows that these requirements are more stringent than those set by the ITU-R. LTE-A requirements were set considering a gain of 1.4 to 1.6 over LTE Release 8. Moreover, cell edge user spectral efficiency is calculated under the assumption of 10 users uniformly distributed per cell.

#### 1.3.2.4 Others

Requirements of VoIP capacity, mobility, coverage, multicast and broadcast transmission and network synchronization are assumed to be higher than those achieved with LTE Release 8.

### *1.3.3 Deployment*

The deployment of LTE-A is an evolution of LTE deployment since LTE-A could use new frequency bands. One of the most important aspects is that LTE-A was designed to be backward compatible with LTE, so that a LTE user equipment can work in an LTE-A network and vice versa. Still, it is expected that there might be some incompatibility when

**Table 1.10** Cell edge user spectral efficiency requirements

| | | Antenna Conf. | LTE Rel 8 | LTE-A | IMT-A |
|---|---|---|---|---|---|
| Capacity (b/s/Hz/cell) | DL | 2 × 2 | 0.05 | 0.07 | - |
| | | 4 × 2 | 0.06 | 0.09 | 0.06 |
| | | 4 × 4 | 0.08 | 0.12 | - |
| | UL | 1 × 2 | 0.024 | 0.04 | - |
| | | 2 × 4 | - | 0.07 | 0.03 |

deploying the network. Another aspect that is being emphasized is the development of femtocellular services, such as remote access of home security, which implies the need of a better indoor deployment of LTE-A.

As discussed in Section 1.2.2, new frequency bands have been reserved for IMT-A. In LTE-A, spectrum can be aggregated up to 100 MHz, either in a contiguous or noncontiguous manner. Moreover, LTE-A and LTE Release 8 must be able to coexist in the same spectrum band.

## 1.4 Long Term Evolution Advanced Enabling Technologies

To meet the demanding requirements of LTE-A, the 3GPP is in the process of development of certain technological proposals. To this end, 3GPP has focused its attention on different points that required technological innovations: support of wider bandwidth (carrier aggregation), advanced MIMO techniques, relaying, enhancements for HeNB, and so on. Another relevant feature of LTE-A is that latency requirements are more strict than ITU-R ones. The proposed changes to improve LTE-A performance indicators are discussed in the following subsections.

### *1.4.1 Carrier Aggregation*

Carrier aggregation is one of the most important technologies to ensure the success of 4G technologies. This concept involves transmitting data in multiple contiguous or non-contiguous Component Carriers (CCs). Each Component Carrier (CC) takes a maximum bandwidth of 20 MHz to be compatible with LTE Release 8. The maximum number of Resource Blocks (RBs) in a CC is 110 and the bandwidth will be assigned following the same structure as in LTE, that is, 1.4 MHz (6 RB), 3 MHz (15 RB), 5 MHz (25 RB), 10 MHz (50 RB), 15 MHz (75 RB) and 20 MHz (100 RB). However, it is possible that there are certain CCs that are not compatible with LTE.

Carrier aggregation allows both an efficient use of spectrum already deployed and the required support for the resource allocation in new frequency bands. Figure 1.4 shows a schematic of the concept of carrier aggregation in LTE-A. Depending on the capabilities of the mobile terminal, the user may transmit and/or receive from multiple CC, in case

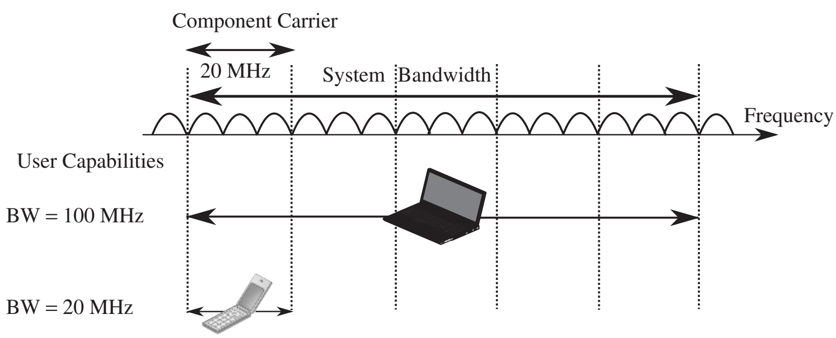


**Figure 1.4** Carrier aggregation in LTE-A.

of an LTE-A terminal with a maximum bandwidth of 100 MHz. Meanwhile, an LTE Release 8 equipment may only transmit and/or receive in a single CC, with a maximum bandwidth of 20 MHz. Given the possible bandwidth configurations, the transmitter should support, depending on the capabilities of the mobile terminal, three possible scenarios: aggregation of several contiguous CCs within the same band, aggregation of several non-contiguous CCs within the same band and aggregation of several non-contiguous CCs located in different bands. In [11] various deployment scenarios were considered to meet the requirements of ITU-R. Among them, four scenarios are the most significant, being summarized in Table 1.11 for the FDD and TDD modes. As an example, new frequency bands could be added to existing UMTS bands of 1.8 GHz, 2.1 GHz and 2.6 GHz or new bands could be added at 3.5 GHz.

When working on non-contiguous CCs, it is required null interference between carriers and, therefore, guard bands are added. Otherwise, in cases of aggregation of contiguous CC, there is not such a large guard band, which allows a more efficient use of spectrum. However, in order to be compatible with the LTE frequency raster of 100 kHz and, in turn, preserve the orthogonality of the subcarriers with a spacing of 15 kHz, the distance between carriers must be a multiple of 300 kHz. This can cause certain subcarriers not to be used. Still, these could be used as guard bands.

Based on the three scenarios seen above, there are several architectural alternatives for the transmitter. Figure 1.5 illustrates four of them. As an example, two CCs are frequency multiplexed. Option 1 (first scheme), works on contiguous CCs within the same band, so that two frequency multiplexed signals are mapped to the time domain through an Inverse Fast Fourier Transform (IFFT) and then go through a digital to analog converter. Then the signal is modulated to the corresponding carrier frequency and amplified in power. Option 2 (second diagram), implements the transmission of information conveyed on various CCs contiguously and non-contiguously within the same frequency band. With this aim, it combines both baseband waveforms operating in a first intermediate frequency within the band of the second CC. After this step, the broadband signal is modulated in frequency. Option 3 (third diagram), implements, like option 2, the case of contiguous carrier aggregation within the same frequency band. The difference is that both CCs are modulated to an intermediate frequency before being combined and amplified in power. Option 4 (fourth chart), is the only option that allows for contiguous

**Table 1.11** Deployment scenarios of LTE-A

| | Deployment scenario | Carrier aggregation | Frequency (GHz) |
|---|---|---|---|
| FDD | Contiguous within the same band | UL: 2 × 20 MHz CC | 3.5 |
| | | DL: 4 × 20 MHz CC | |
| | Non-contiguous in different bands | UL/DL: 1 × 10 MHz | 1.8 |
| | | UL/DL: 1 × 10 MHz | 2.1 |
| | | UL/DL: 1 × 20 MHz | 2.6 |
| TDD | Contiguous within the same band | 5 × 20 MHz | 2.3 |
| | Non-contiguous in different bands | 2 × 20 MHz | 1.8 |
| | | 10 MHz | 2.1 |
| | | 2 × 20 MHz | 2.3 |

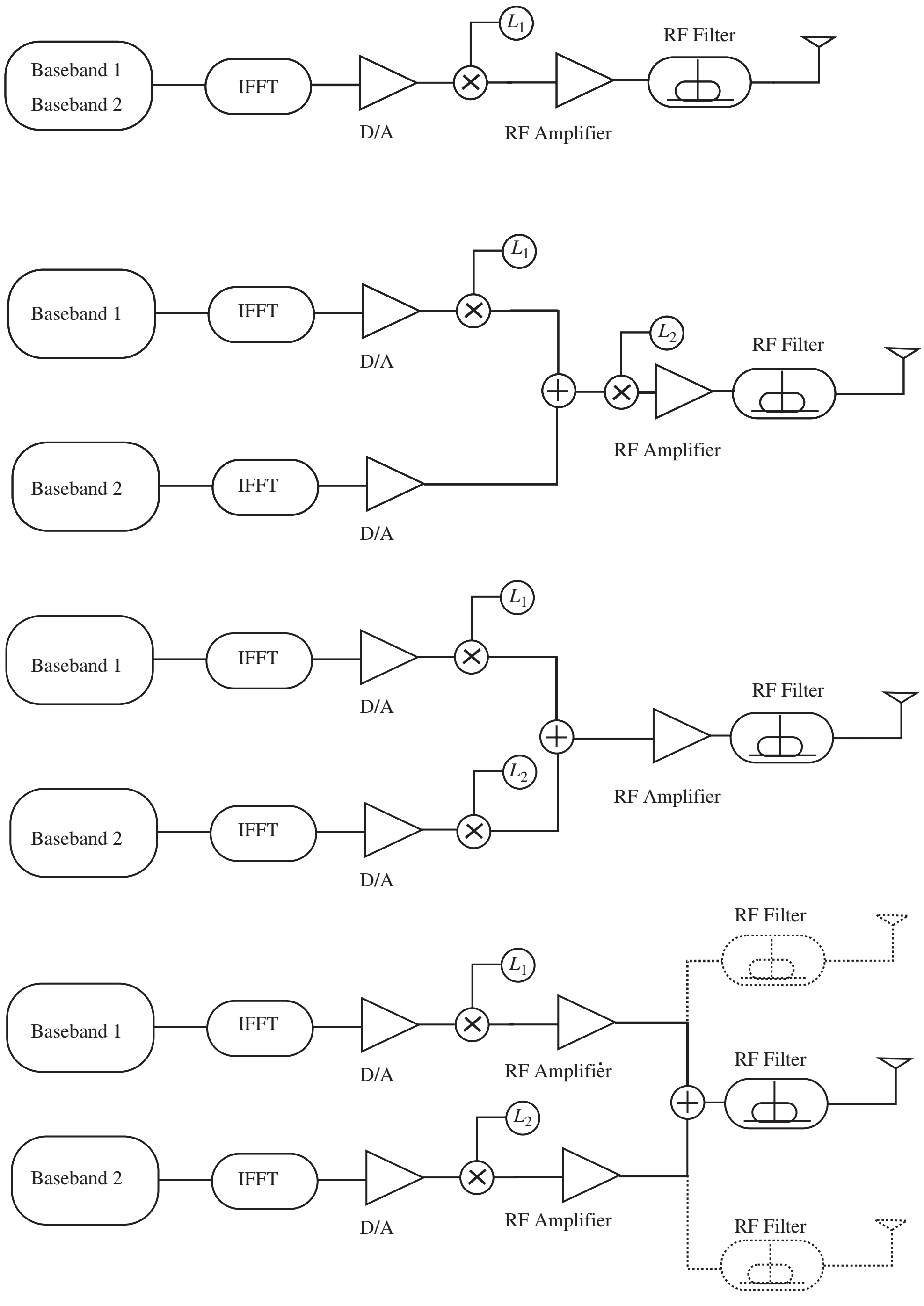


**Figure 1.5** Possible architectures for the transmitter in three aggregation scenarios. In order, from top to bottom, are options from 1 to 4.

and non-contiguous aggregation within the same band or in different frequency bands. This scheme employs multiple radio frequency chains and multiple power amplifiers. The combination, therefore, is performed over amplified signals that are transmitted through a single antenna. The choice of the proper architecture depends on the cost, complexity, bandwidth of the amplifier and if the CCs are contiguous or non-contiguous.

In the uplink, one of the problems caused by carrier aggregation is the loss of efficiency in the power amplifier. The cubic metric parameter defined in [12] is useful for assessing the efficiency of power amplifiers. In [13] it is shown that the higher the number of CCs assigned, the higher the cubic metric in case of SC-FDMA. This increase is significant when using two CCs, while from 3 CCs this increment occurs more gradually. Still, the cubic metric is smaller than in the case of Orthogonal Frequency Division Multiple Access (OFDMA). The transmission over multiple carriers is usually restricted to users with good channel conditions, which will reduce the effect of this loss of efficiency. Moreover, cell-edge users will generally not aggregate carriers, so they will not be affected either.

In the physical layer of LTE-A, a single transport block (two in the case of spatial multiplexing) and a single Hybrid Automatic Repeat reQuest (HARQ) entity will be associated with a CC. This allows separate link adaptation to improve the transmission of data from each CC since it will adapt better to the conditions of each CCs. Figure 1.6 shows a description of the basic structure of the physical layer and Medium Access Control (MAC) layer. As shown, LTE-A will support a maximum of five parallel LTE Release 8 processing chains. Of course, the CC may be in different frequency bands.

There are three downlink control channels: the Physical Control Format Indicator Channel (PCFICH), the Physical Downlink Control Channel (PDCCH) and the Physical Hybrid ARQ Indicator Channel (PHICH). The design principle of these channels is, in general, to ensure backward compatibility with LTE Release 8. The signaling control for carrier aggregation is still under study. So far, the following decisions have been taken with respect to these three channels:

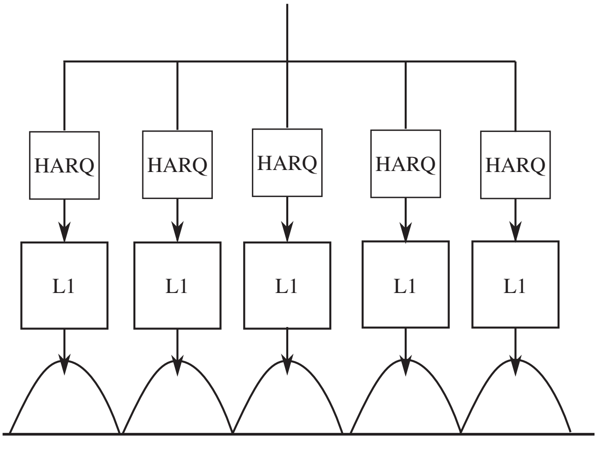


**Figure 1.6** Structure of the MAC and PHY layer of LTE-A.

- **PCFICH**. Each CC will have its own information on the size of the control region. Moreover, the same design principles of LTE Release 8 will be followed (modulation, coding and allocation of resource elements).
- **PDCCH**. In this case, there are two ways of allocating resources. On the one hand, the resource manager can allocate resources to the PDSCH and PUSCH in the same CC. The same PDCCH as in LTE Release 8 could be used in each CC as well as the Data Control Indicator (DCI) formats. This allows link adaptation for each CC, so as to improve transmission capacity since each transmission can get adapted to the channel conditions of each CC. The other possibility is that, from a single CC, resources for PDSCH and PUSCH on multiple CCs could be allocated using the Carrier Indicator Field (CIF). This implies that this CC is not compatible with LTE Release 8. However, this option allows for higher scheduling flexibility, being able to balance the load dynamically and reduce interference among CCs.
- **PHICH**. For this channel the same aspects of transmission of LTE Release 8 will be reused, that is, modulation, scrambling code and allocation of resource elements. It will be only transmitted in the CC that was used to transmit scheduling information on the uplink.

Concerning the UL control signaling, HARQ ACK/NACK signaling, scheduling requests and Channel State Information (CSI) have to support up to five DL CCs. A User Equipment (UE) must send a HARQ Acknowledgement (ACK)/Negative Acknowledgement (NACK) for every transport block transmitted in a given CC. Unlike Release 8, in Release 10 if the UE has data to transmit on PUSCH then control signaling (HARQ signaling and CSI) can be time multiplexed with data on the PUSCH.

## *1.4.2 Advanced MIMO Techniques*

In LTE Release 10 spatial multiplexing was extended to support up to four layers in the UL and up to eight layers in the DL. This update improves cell spectral efficiency but also implies changes in the design of the reference signals and in the DL control signaling. The main characteristics of these and other changes are explained below.

### 1.4.2.1 Uplink Transmission Scheme

In [14] it was specified that spatial multiplexing can be used in the UL with two transport blocks, also called codewords. Each codeword would have its own Modulation and Coding Scheme (MCS). Figure 1.7 shows the structure of the transmitter in the UL. The maximum number of layers supported by LTE-A is four. Depending on the number of layers, modulated symbols associated with each codeword will be mapped using the same philosophy as LTE Release 8. The spatial multiplexing in the UL has the option of using layer shifting in the time domain [14]. If layer shifting is activated, the two transport blocks will have an associated shared HARQ-ACK, New Data Indicator (NDI) and Redundancy Version (RV). Otherwise, each transport block will have associated its own MCS (see Figure 1.7). In the case of layer shifting, when the feedback information from the base station is a NACK without any additional information, the user equipment cannot know the number of transport blocks that have been correctly decoded, if any.

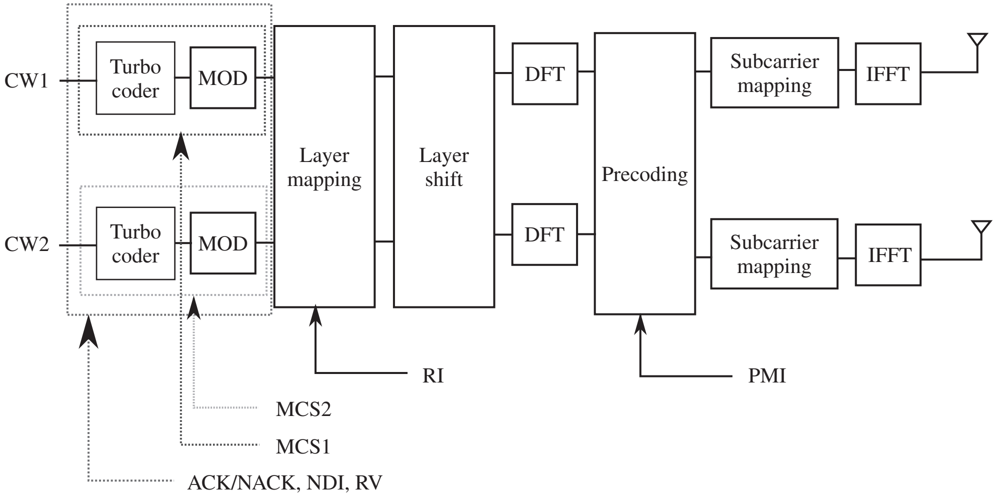


**Figure 1.7** Transmitter structure for a ACK/NACK with layer shift.

It is therefore necessary to use any special flag that marks the transport block to be retransmitted so as to avoid redundant information. However, depending on whether both transport blocks have been decoded correctly or incorrectly, two new transport blocks will be transmitted or erroneous ones will be retransmitted. In this last case, the amount of resources allocated to the PHICH could be reduced with the consequent possible increase in data rate.

For both FDD and TDD modes, precoding is performed based on a predefined set of matrices for each CC. To date, these matrices are only defined for two and four antennas with a number of layers less than three [14].

Spatial Orthogonal-Resource Transmit Diversity (SORTD), a kind of UL transmit diversity scheme, is supported in Release 10 for the Physical Uplink Control Channel (PUCCH) with two antenna ports. For four antenna ports, antenna virtualization is used, which consists of managing multiple physical antennas as a single virtual antenna.

Concerning UL reference signals, both Demodulation Reference Signal (DM RSs) and Sounding Reference Signal (SRSs) have been adapted in order to support Single-User MIMO (SU-MIMO). Like DL DM RSs, the UL DM RS are precoded using the same precoding as PUSCH. The generation and mapping of these reference signals can be found in [3]. On the other hand, Release 10 introduced the concept of aperiodic Sounding SRS, which can be dynamically configured through Radio Resource Control (RRC) signaling.

#### 1.4.2.2 Downlink Transmission Scheme

To achieve higher data rates, LTE-A base station supports up to eight antennas. As happened in LTE Release 8, up to two codewords can be transmitted to the same user per CC. Each codeword will have its own encoding and modulation and the HARQ feedback from the user consists of one bit per codeword. So far, the symbols mapping is defined

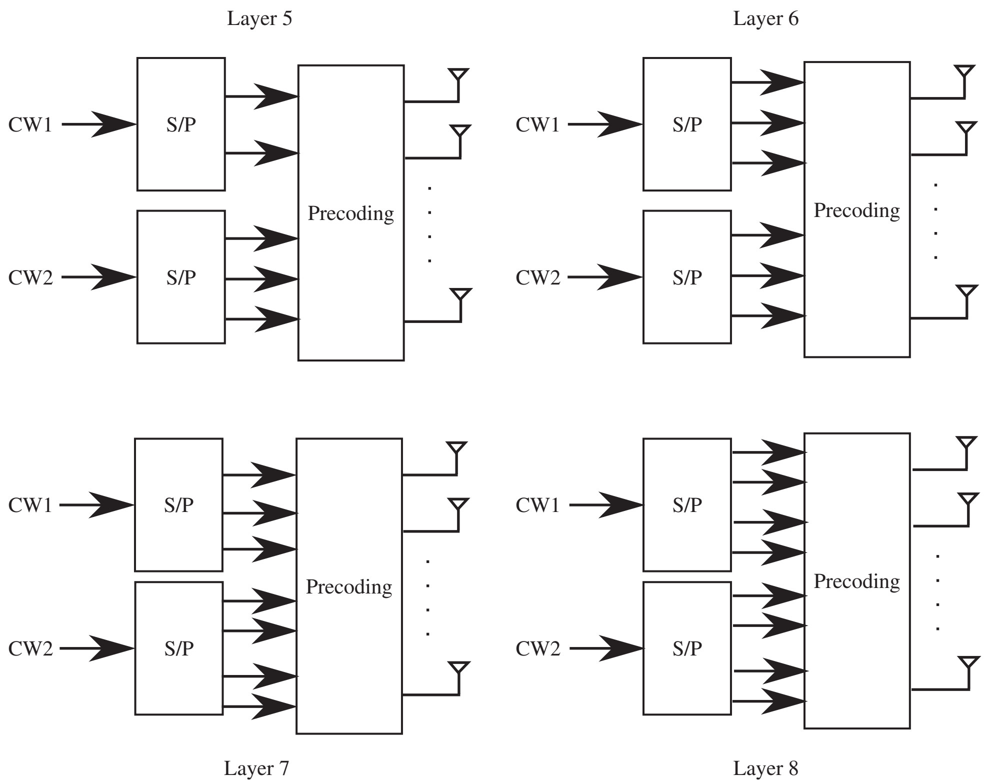


**Figure 1.8** Codeword mapping to spatial multiplexing layers.

in [14]. This mapping is the same as in LTE with less than four layers. The mapping of codewords to a number greater than or equal to five layers is depicted in Figure 1.8.

In LTE-A two types of reference signals are used in DL: the DM RS, also known as UE-specific reference signals, and the Channel State Information – Reference Signal (CSI-RSs). Although the CSI-RSs were already introduced in LTE Release 8, their use was limited to single-layer transmission. The DM RS are characterized by being pre-coded in the same way as the PDSCH channel, that is, they are user-specific. They only appear in the resources allocated by the base station to the user and are mutually orthogonal by Code Division Multiplexing (CDM) using Orthogonal Cover Codes (OCCs) in the different layers to avoid the interference between them. On the other hand, the CSI-RSs are cell-specific, that is, all users belonging to the same cell can read these reference signals in order to obtain channel state feedback for up to eight antennas. Mapping of both reference signals can be found in [3].

### *1.4.3 Coordinated Multipoint Transmission or Reception*

The coordinated multipoint transmission/reception is considered by many companies as a clear candidate to improve the system capacity and cell-edge user spectral efficiency, thus fulfilling the requirements of LTE-A. The current LTE Release 8 allows a certain degree of cooperation between base stations in order to reduce interference. However, a big improvement is expected in this technique with LTE-A as compared with LTE Release 8.

#### 1.4.3.1 Coordinated Transmission

In a CoMP system, multiple cells (likely from different base stations) are cooperating in the transmission of data to multiple users. We can distinguish two types of CoMP techniques:

- **Joint Processing (JP) techniques**. Multiple cells transmit the same information to a user. A cell can consist of a set of antenna elements within the base station or outside, geographically separated. This level of cooperation requires user data to be shared between cooperating cells.
- **Coordinated Scheduling and Beamforming (CS/CB) techniques**. The information is only sent from a single cell, but the scheduling and beamforming decisions are made taking into account other cells status so as to coordinate interferences. This technique does not need to share user data among cells.

Cell coverage area is usually understood as the area produced by a set of antenna elements within a base station. A cell is any transmitter that has a physical layer cell identifier, which is detected by the user during the cell search procedure based on the Primary Synchronization Channel (P-SCH) and Secondary Synchronization Channel (S-SCH). Figure 1.9 shows two possible situations of joint processing. In the first case, two base stations transmit the same information to a user (case 1), while in the second case the base station sends the information to different transmission points (cells) in different geographically separated locations (case 2). It might take a third case of coordinated transmission in which two sectors transmit the same information to a user situated in the border of two adjacent cells.

The main limitations of JP is that user data should be coordinated between various transmission points. If the transmission is performed between base stations, then there are

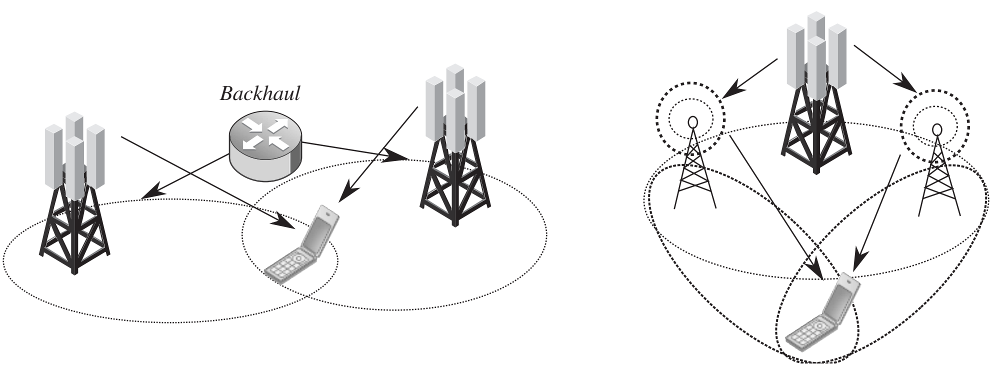


**Figure 1.9** Types of joint processing in Coordinated Multipoint transmission or reception (CoMP), case 1 (left) and case 2 (right).

limitations with the latency and backhaul capacity. On the other hand, if coordination is carried out as in case 2, that is, through a distributed antenna system or remote radio heads belonging to the same base station, communication is assumed to be faster. With regard to CS/CB its main limitations are related to the assumption of certain knowledge of the channel quality of cooperating cells. These techniques lack backhaul capacity problems, since cells do not exchange user data. However, latency remains a limitation due to the exchange of channel state information. No major changes are expected in the network architecture to implement this CoMP technique and, therefore, it seems to be the most appropriate technique in scenarios of transmission between base stations.

The LTE-A radio interface must support different feedback mechanisms of cooperating cells. The user dynamically estimates the channel for each one of the transmission points to facilitate the decision on which a set of transmitters will participate in the cooperative transmission. In the case of TDD mode, channel reciprocity could be assumed.

#### 1.4.3.2 Coordinated Reception

OFDM can eliminate the interference within the cell, since the high data rate is divided into parallel flows at lower rates, transmitted over orthogonal subcarriers. However, in a multi-cellular system OFDM cannot remove inter-cell interference. Therefore, coordinated reception has been proposed to reduce this type of interference (especially for cell-edge users), also known as Inter-Cell Interference (I-CI). Coordinated reception is not only expected to minimize interference, but also help improve the average cell efficiency of the cell and the cell-edge efficiency.

As explained before, CoMP is a cooperative technology that coordinates multiple geographically separated cells. The cooperation implies sharing user data, scheduling information and channel quality. Clearly, CoMP reception further affects the implementation rather than the specifications. Figure 1.10 shows an overview of coordinated multi-point reception. There is a base station that serves all the mobile terminals of the cell. The three mobile terminals transmit their data on the same resources simultaneously. The transmitted signal of each user to the base station corresponds to the interference to the neighboring cell shown in the figure with a dotted line. Because users whose information is processed are geographically close together, the interference might be high and there would be a degradation in performance. This interference could be reduced via joint processing. Although in Figure 1.10 it is not showed, a central server is responsible for controlling the behavior of the multiple cells involved in the cooperation. However, it could be physically integrated in any base station.

### *1.4.4 Relaying*

The use of relays was initially envisioned as a tool to increase cell coverage. With the increase of data traffic, operators thought of a new solution that could improve the data rate in certain areas. However, increasing the number of base stations entails a cost that operators cannot afford. This made operators consider the study and development of relays as a means to improve coverage in hotspots, mobility in public transportation vehicles (trains, buses, etc.) and improvement in transmission capacity on the cell edge.

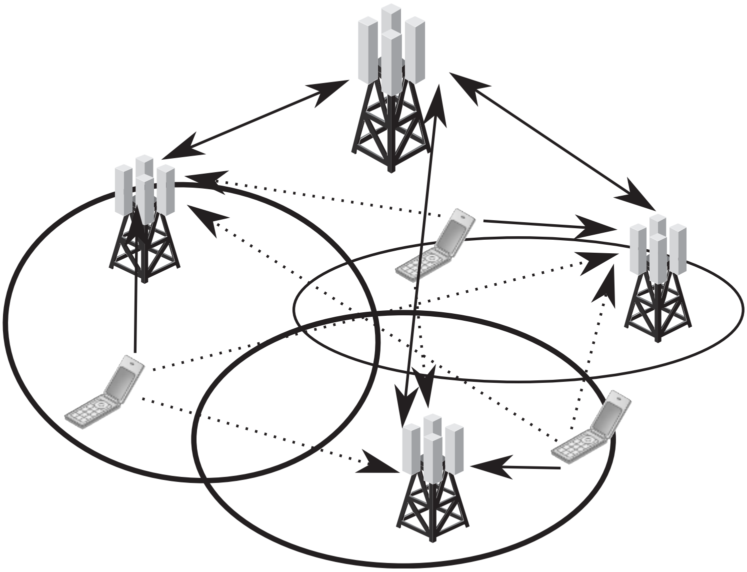

**Figure 1.10** CoMP structure in reception.

A general configuration of a relay network can be seen in Figure 1.11. There are three types of link: a base station to user link, a base station to relay link (also known as backhaul) and a relay to user link (also known as access link). It is worth noting that in the picture the relay node is wirelessly connected to the radio access network through the base station or donor cell. Moreover, although the philosophy behind the use of relays is to maintain the compatibility with Release 8 UEs, the physical layer of the access link in the case of relaying may be different from a conventional Base Station (BS) to UE direct link.

There are several classifications of relays depending on the mechanisms for interconnection, functionality and transparency towards LTE Release 8 users:

- **Interconnection**. The interconnection between a relay and a base station may be via cable (fiber, xDSL, etc.), wireless technology (the same LTE) or other technology (microwave). On the other hand, the wireless networking can be divided into in-band or out-band transmission. The difference among them depends on whether you use the same carrier frequency in the base station to relay and the relay to user links. For in-band transmissions, since the relay transmitter causes interference to its own receiver, the base station to relay and relay to user transmissions in the same frequency resources may not be possible unless there was an isolated antenna structure. Similarly, there would be interference when the relay is simultaneously receiving data from the user and transmitting to the base station. One possible solution is illustrated in Figure 1.12. The interference could be avoided by adding gaps where the relay does not transmit to the terminals when data is being received from the base station. During these gaps, the base station transmits data to the relay within the Multicast-Broadcast Single-Frequency Network (MBSFN) subframes. The relay to base station communication can be achieved

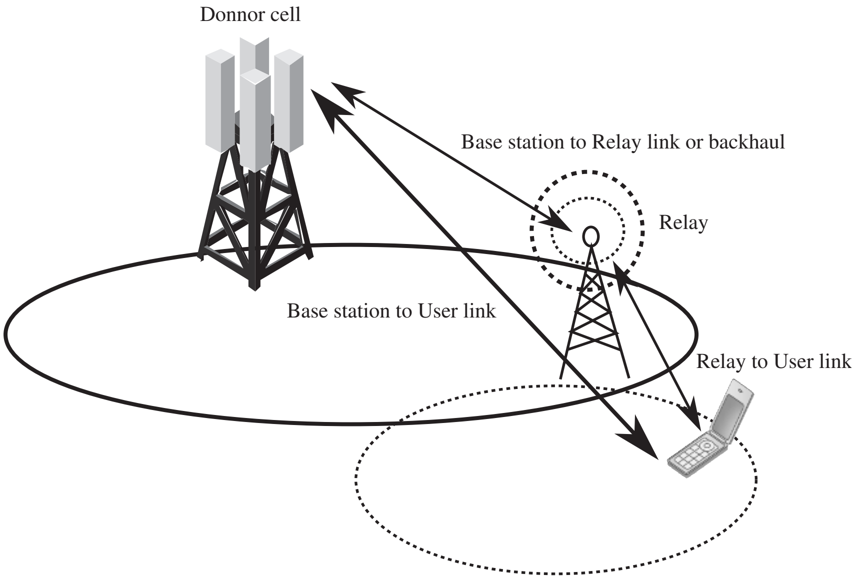


**Figure 1.11** Configuration of the relaying network.

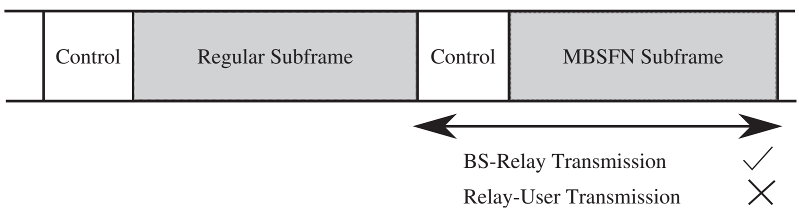


**Figure 1.12** Communication Relay-User in regular subframes and Base Station-Relay in MBSFN subframes.

by avoiding the transmission in some subframes of the user to relay link (known as blanking subframes).

- **Functionality**. They can operate as simple repeaters that only amplify and forward the received packets. Despite a repeater increasing the coverage of the cell, its main disadvantage is that it will increase not only the signal level but also interferences, maintaining signal to noise ratio. However, they are often characterized by their low cost and the small delay they introduce in transmission. Other types of relays decode and forward packets. In this case there is an additional delay as compared with repeaters. However, decode and forward relays also enhance the signal to noise ratio. Finally, there are relays whose features are similar to those of the base stations. Such relays manage user connections, schedule traffic, perform HARQ and execute IP layer functionalities. From the point of view of the base station, the relay would be in this case a subordinate in a hierarchical network.
- **Transparency**. The transparency is defined in terms of the characteristics of the link between the user and the relay node. The relay is transparent to the user if the user is

not aware of being served by an entity other than a classical base station, that is, the relay. Conversely, if the user is aware of being connected to another entity, relaying would be non-transparent.

Another possible classification differentiates if the relay depends on a donor cell or not. In the former case, the relay has not got a cell identifier but could have a relay identifier. Some of the resource management functions would take place in the base station of the donor cell and the remaining in the relay node. In the latter case, the cells created by the relay would have a unique cell identifier. From the point of view of the user, the access to a relay node would be identical to the access to a base station. In either case, the relay must support LTE Release 8 user equipments.

Based on the above classifications, 3GPP defined two types of relays:

- **Type 1**. The Type 1 relay is perceived by the user as a new LTE base station, providing support to Release 8 terminals. The cells served by the relay have their own cell identifier. Therefore, a relay type 1 is not transparent to the user that will measure the signal level received from the base station and the relay getting connected to the best server. The relay transmits its own synchronization and reference signals. Similarly, the user feeds back information about channel quality and HARQ processes to the relay. This type of relay node increases coverage. However, it implements the same functionalities as a conventional base station and, therefore, its cost could be similar. Moreover, type 1 relays can be divided into type 1a and 1b, which have the same characteristics as type 1 relays but the first operates out-band, while the second operates in-band but with isolated antennas.
- **Type 2**. The Type 2 relay is an in-band node that uses the same cell identifier as the donor cell, allowing the user to move between the base station and the relay node without handovers. Therefore, the type 2 relay would be able to serve users in a transparent manner without requiring the handover when the user moves outside the base station coverage. The CSI-RSs are not sent and, therefore, user equipments do not measure the quality of the relay to user link. A significant cost saving is made by using this type of relay nodes.

As mentioned above, in order to allow for an in-band transmission in the base station to relay link, a time division multiplexing is required. The gap during which the BS transmits data to the relay is less than the subframe duration. To manage this new situation, new physical channels have been defined: R-PDCCH, R-PDSCH and R-PUSCH. The R-PDCCH physical channel is used to allocate resources to the R-PDSCH or R-PUSCH in the backhaul in a dynamic or semi-persistent way. Resource blocks allocated to the R-PDCCH may not be fully utilized. In that case, these free resources could be used by the PDSCH or the R-PDSCH. The processing chain of the R-PDCCH should reuse the Release 8 functionality, but with the possibility of eliminating unnecessary procedures.

### *1.4.5 Enhancements for Home eNodeBs*

Mobile subscribers are increasingly demanding ubiquity connection and higher data rates. 3G Home NodeBs were introduced in the UMTS Terrestrial Radio Access Network

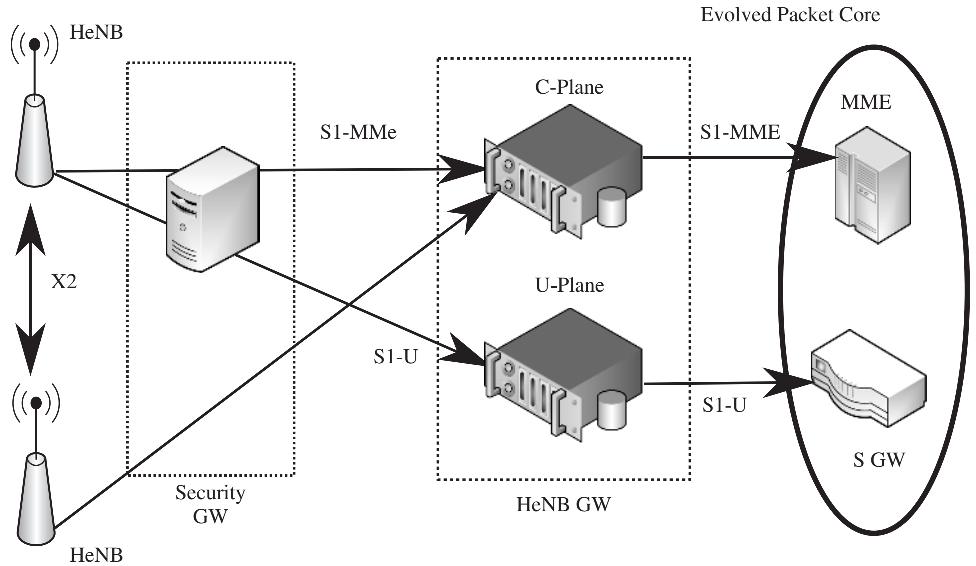


**Figure 1.13** HeNB interconnection in the E-UTRAN.

(UTRAN) architecture to provide services and data rates in home environments or small offices. Nevertheless, Home NodeBs introduce some level of lawlessness and because of this the 3GPP began a study item to improve the manageability of 3G femto/pico cells. This activity has continued in the framework of LTE and LTE-A standardization.

In 3GPP LTE terminology, femto-cells are called HeNBs. As shown in Figure 1.13, the EUTRAN architecture includes an optional HeNBs Gateway that routes the packets from different HeNBs to the EPC through the S1. The aim of this gateway is to simplify the functionality of the HeNBs so as to make them cheaper. The specifications also talk about a Security Gateway, which is optional too.

Two types of access control have been defined for LTE HeNBs: closed and open access. In the former, only a Closed Subscriber Group (CSG) can access the HeNB whereas, in the latter, all users can connect to the HeNB. Every cell is identified by CSG ID. A UE subscribed to a CSG would have one or more CSG IDs on which the UE can connect. The UE uses the CSG list along with the CSG ID to select the serving cell. There exists also an hybrid access introduced in Release 9 in which the cell can provide service to all users but still acts as a CSG cell, that is, the subscribed UEs would have higher priority than unsubscribed UEs.

Another remarkable improvement in Release 9 is the inbound handover from a macro eNodeB to a HeNB. Before making a handover decision, the UE monitors the target cell. To optimize this process in a femtocellular scenario, the UE sends the eNodeB a proximity report when camping close to a known HeNB. This allows the system to be prepared in advance to the imminent handover. Besides, to avoid the problems caused by duplicated Physical Cell Identity (PCI), the measurement reports include the Cell Global Identity (CGI) as well as the PCI.

3GPP specifications also allow limiting IP access for HeNB users to a local network, what is referred to as Local IP Access (LIPA). Release 10 extends this concept to limit the access to a corporate network. Moreover, HeNBs must support Selected IP Traffic Offload (SIPTO), which allows internet traffic to flow from the femtocell directly to the internet, bypassing the EPC. Both mechanisms can be enabled/disabled by the mobile operator.

### *1.4.6 Machine-Type Communications*

Machine-to-Machine (M2M) communications, also called Machine-Type Communications (MTC), refer to the type of communication between entities that does not need any human interaction. Some examples of MTC are domotic applications that manage heating and air conditioning systems, alarms, sensors and valves.

There is no consensus about the general network architecture of MTC. 3GPP considers three different scenarios for MTC depicted in Figure 1.14:

- **Scenario A**. The MTC application directly interacts with the UE (MTC device).
- **Scenario B**. The MTC application interacts with the MTC server that is located outside the operator domain.
- **Scenario C**. The MTC application interacts with the MTC server that is located inside the operator domain.

In all cases, the 3GPP radio access network provides transport and communication services, including 3GPP bearer services, IP Multimedia Subsystem (IMS) and Short Message Service (SMS). From Release 10 on, the 3GPP is addressing some specific problems of MTC:

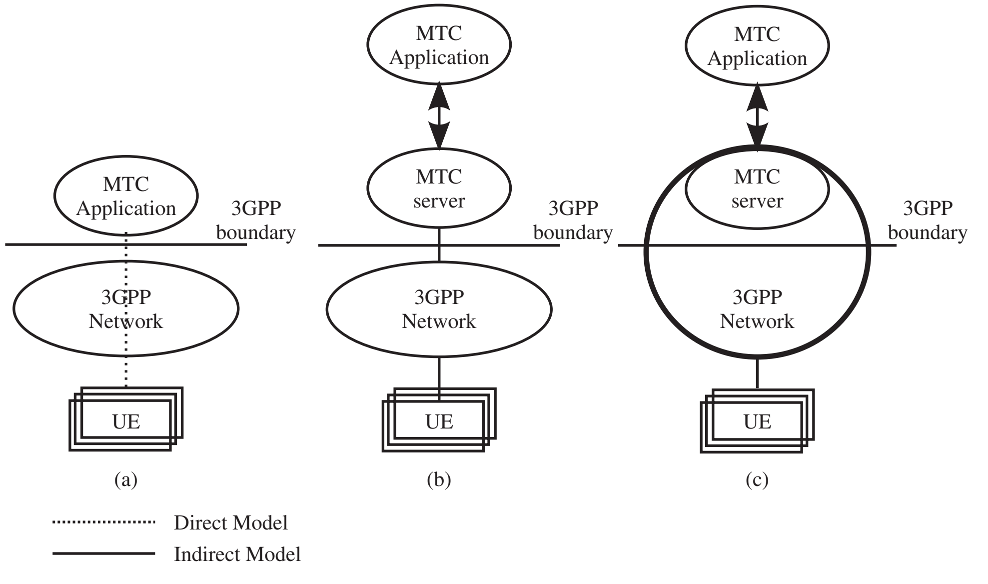


**Figure 1.14** MTC scenarios.

- **Signaling congestion and overloading of the core network**. A large number of MTC devices are deployed in a specific area. This can cause, among other things, intolerable delays, packet losses or the service failure. To reduce this problem, load control mechanisms based on different priorities between MTC devices can be implemented. In a similar way, Extended Access Barring (EAB) methods consist of restricting the access to specific UEs. Besides, separate Random Access Channel (RACH) resources could be allocated to M2M.
- **Small data transmission**. MTC does not require high peak data rates, advanced MIMO tecniques, HARQ or sophisticated channel estimations.
- **MTC addressing**. With so many devices, IP addressing can be a problem. As a solution, similar devices can be grouped sharing a common identifier.

### *1.4.7 Self-Optimizing Networks (SON)*

It is apparent that networks are becoming larger in scales and more complex in design. They have grown beyond the limit of manual administration. At the same time, reduction of cost is one of the goals of 4G systems, affecting them anywhere from the cost per transmitted bit until the CAPital EXpenditure (CAPEX) and OPerational EXpenditure (OPEX) reduction. There is a rising pressure from network operators to make networks and systems more manageable, their operations more efficient, and their deployment and maintenance more cost effective.

In the early deployment of 2G networks Operations and Maintenance (OAM) was based on in site operation. Nowadays, with 3G systems, OAM relies on software applications that manage the wireless system in a centralized way. However, the expected complexity of next generation wireless systems is increasing the research community interest towards the design of 4G systems infrastructures by exploiting "cognitive networking" capabilities. Wireless networks cannot remain primitive and the management systems omnipotent. Conversely, a large degree of self-awareness and self-governess must be considered in the new concept of networks and systems. In response, there has been a major push for self-managing networks and systems in the last five years. Although management automaton has been taken into account for decades, never before there has been such a strong concern from both academia and industry, and the need for effective solutions is immediate.

Self-Organizing Network (SON) allows the network to detect changes, make intelligent decisions based upon these inputs, and then implement the appropriate action. The systems must be location and situation-aware, and must take advantage of this information to dynamically configure themselves in a distributed fashion. Applied to resource management, SON allows, for example, making a dynamic and optimum management of radio resources at the border of cells in such a way that there exists an automatic coordination of the radio resource utilization at the cell-edge in order to avoid performance loss or even degradation of service.

In LTE Release 8, SON concepts were associated with initial equipment installation, also known as eNodeB self-configuration. Main procedures included:

- Automatic Inventory.
- Automatic Software Download.

- Automatic Neighbor Relation.
- Automatic PCI Assignment.

The next release of SON (Release 9) provided some procedures covering network optimization. More specifically, the Release 9 standard included these additional use cases:

- Mobility Robustness/Handover Optimization.
- RACH Optimization.
- Load Balancing Optimization.
- Inter-Cell Interference Coordination.

The latest release of SON that appeared in Release 10 provided additional functionalities and methods to manage heterogeneous networks:

- Coverage and Capacity Optimization.
- Enhanced Inter-Cell Interference Coordination.
- Cell Outage Detection and Compensation.
- Self-healing Functions.
- Minimization of Drive Testing.
- Energy Savings.

All SON functionalities are mostly described in [15].

#### 1.4.7.1 Inter-Cell Interference Coordination in LTE

In the downlink, a bitmap known as Relative Narrowband Transmit Power (RNTP) indicator can be exchanged among eNodeBs through the X2 interface. This ON-OFF indicator informs the neighbor cells if the eNodeB intends to transmit on a certain RB over a certain power threshold or not. One bit per RB in the frequency domain is sent. The exact value of the upper limit and the periodicity in the reporting are configurable.

The use of the RNTP indicator allows eNodeBs to choose the proper RBs when scheduling users according to the interference level introduced by their neighbors. The decision making process followed by eNodeBs after receiving RNTP indicators is not standardized, which fosters competence among different implementations.

In the uplink, two messages are exchanged: the Interference Overload Indication (IOI), which indicates the interference level on all RBs, and the High Interference Indication (HII), which informs about the future plans for the uplink transmission. The receiving cells should take this information into account by not scheduling cell-edge users in these RBs.

### *1.4.8 Improvements to Latency in the Control and User Plane*

Although LTE Release 8 technology already meets the requirements of ITU-R in terms of latency (100 ms from camped to connected state and 10 ms from dormant to active state), several mechanisms could be used to reduce latency (about 50 ms from camped to connected state). Improvements related to the transition from camped to connected state are:

- Combined request of RRC connection (User-eNodeB) and Non-Access Stratum (NAS) service (User-Mobility Management Entity (MME)). These two messages are processed in parallel in the eNodeB and the MME, respectively. The motivation for this combined request is that it reduces the amount of information of the radio link specific layers (Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC) and MAC), since the radio interface information control and the NAS signaling are multiplexed together at the RRC protocol. Besides, the request and confirmation process to deliver NAS information is not needed. This improvement is typical of LTE-A, as in 3G systems, LTE Release 8 included, the RRC connection request and the NAS service connection are performed sequentially. Figure 1.15 shows the control plane activation procedure for the FDD mode when using a single message to transmit the RRC and NAS request (in the ideal case without retransmissions). Table 1.12 complements Figure 1.15 with a temporal analysis. The reduction could be of up to 21 ms. It should be noted that in the latency analysis the delay of the interface between the eNodeB and MME (S1-C) was not taken into account, as explicitly stated in the requirements.

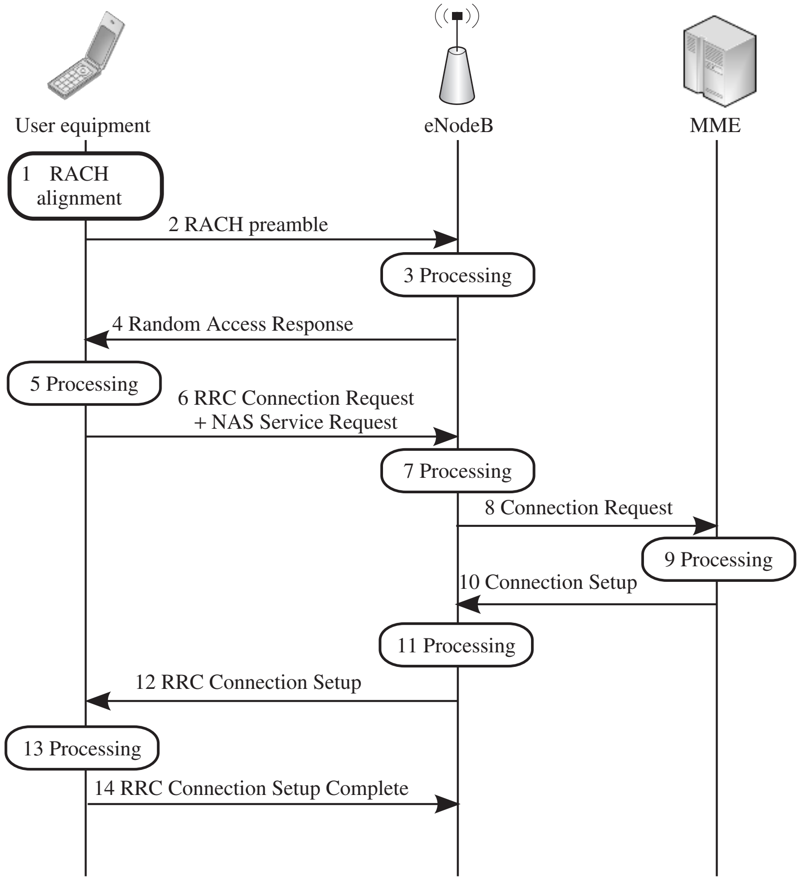


**Figure 1.15** Control plane activation procedure.

**Table 1.12** Temporal analysis in the control plane

| Step | Description | Duration |
|---|---|---|
| 1 | Mean delay due to the RACH scheduling period | 2.5 ms |
| 2 | RACH preamble | 1 ms |
| 3–4 | Preamble detection and response transmission (time between the end of the RACH transmission and the reception of the scheduling grant and the temporal alignment) + delay until the nearest downlink subframe | 5 ms |
| 5 | User processing (scheduling grant decoding, temporal alignment and C-RNTI allocation + L1 message coding of RRC Connection Request) + delay until the nearest uplink subframe | 5 ms |
| 6 | Message transmission (RRC Connection Request and NAS Service Request) | 1 ms |
| 7 | Delay of the eNodeB processing (Uu to S1-C)* + delay until the nearest downlink subframe | 4 ms |
| 8 | Transfer delay S1-C | Ts1c (2–15 ms) |
| 9 | Delay of the MME processing | 15 ms |
| 10 | Transfer delay S1-C | Ts1c (2–15 ms) |
| 11 | Delay of the eNodeB processing (S1-C to Uu)* + delay until the nearest downlink subframe | 4 ms |
| 12 | Message transmission (RRC Security Mode Command and Connection Reconfiguration) | 1.5 ms |
| 13–14 | User processing | 20 ms |
| | Total delay | 59 ms |

*Uu: Interface between user and eNodeB.
S1-C: Interface between eNodeB and MME.

- Most of the latency delay is due to the processing delay in the user and in the eNodeB. Therefore, an improvement in processing delays will clearly influence the control plane latency.
- Reduction of the RACH scheduling period.

As for the transition from dormant state to the connected state, the following mechanisms could be used in LTE-A to improve its functioning:

- A smaller PUCCH to reduce the average waiting time of a synchronized user requesting resources in the active state.
- The uplink contest entails that the users transmit data without first having to request resources in the PUCCH and, therefore, reducing the access time of synchronized users in the connected state.

The user plane latency is already below 10 ms in LTE Release 8 with synchronized users. Anyway, the improvements that reduce control plane latency could also be used in the user plane. For example, a shorter RACH scheduling period, a shorter PUCCH and a smaller processing delay would improve user plane latency.

## 1.5 Summary

This chapter has shown the technological revolution posed by new IMT-Advanced technologies and their evolution. Compared to current systems, IMT-Advanced technologies include a greater bandwidth, new network elements, like relays or femtocells, M2M communications and coordination between transmitters. The channel models that have been used traditionally are no longer valid to analyze all these technological features. Consequently, in the last years there has been significant research activity to develop new channel and propagation models adapted to the new paradigms of wireless communications. The rest of the book addresses this specific issue.

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