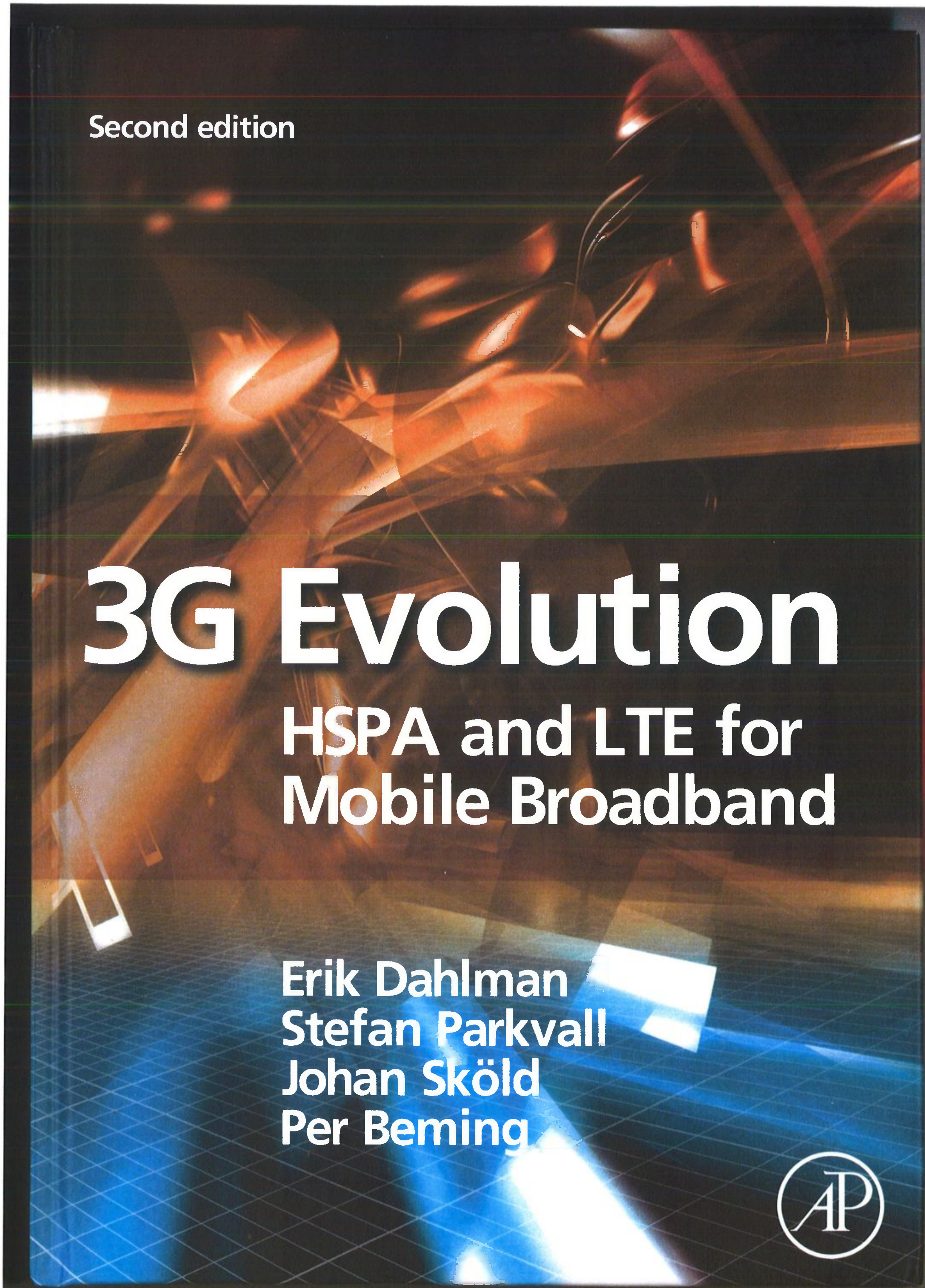

Second edition

3G Evolution

HSPA and LTE for Mobile Broadband

Erik Dahlman
Stefan Parkvall
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Part I
Introduction

1

Background of 3G evolution

From the first experiments with radio communication by Guglielmo Marconi in the 1890s, the road to truly mobile radio communication has been quite long. To understand the complex 3G mobile-communication systems of today, it is also important to understand where they came from and how cellular systems have evolved from an expensive technology for a few selected individuals to today's global mobile-communication systems used by almost half of the world's population. Developing mobile technologies has also changed, from being a national or regional concern, to becoming a very complex task undertaken by global standards-developing organizations such as the *Third Generation Partnership Project* (3GPP) and involving thousands of people.

1.1 History and background of 3G

The cellular technologies specified by 3GPP are the most widely deployed in the world, with more than 2.6 billion users in 2008. The latest step being studied and developed in 3GPP is an evolution of 3G into an evolved radio access referred to as the *Long-Term Evolution* (LTE) and an evolved packet access core network in the *System Architecture Evolution* (SAE). By 2009–2010, LTE and SAE are expected to be first deployed.

Looking back to when it all it started, it begun several decades ago with early deployments of analog cellular services.

1.1.1 Before 3G

The US *Federal Communications Commission* (FCC) approved the first commercial car-borne telephony service in 1946, operated by AT&T. In 1947 AT&T also introduced the cellular concept of reusing radio frequencies, which became fundamental to all subsequent mobile-communication systems. Commercial mobile telephony continued to be car-borne for many years because of bulky and power-hungry equipment. In spite of the limitations of the service, there were systems deployed in many countries during the 1950s and 1960s, but the users counted only in thousands at the most.

These first steps on the road of mobile communication were taken by the monopoly telephone administrations and wire-line operators. The big uptake of subscribers and usage came when mobile communication became an international concern and the industry was invited into the process. The first international mobile communication system was the analog NMT system (*Nordic Mobile Telephony*) which was introduced in the Nordic countries in 1981, at the same time as analog AMPS (*Advanced Mobile Phone Service*) was introduced in North America. Other analog cellular technologies deployed worldwide were TACS and J-TACS. They all had in common that equipment was still bulky, mainly car-borne, and voice quality was often inconsistent, with 'cross-talk' between users being a common problem.

With an international system such as NMT came the concept of 'roaming,' giving a service also for users traveling outside the area of their 'home' operator. This also gave a larger market for the mobile phones, attracting more companies into the mobile communication business.

The analog cellular systems supported 'plain old telephony services,' that is voice with some related supplementary services. With the advent of digital communication during the 1980s, the opportunity to develop a second generation of mobile-communication standards and systems, based on digital technology, surfaced. With digital technology came an opportunity to increase the capacity of the systems, to give a more consistent quality of the service, and to develop much more attractive truly mobile devices.

In Europe, the telecommunication administrations in CEPT[1] initiated the GSM project to develop a pan-European mobile-telephony system. The GSM activities were in 1989 continued within the newly formed *European Telecommunication Standards Institute* (ETSI). After evaluations of TDMA, CDMA, and FDMA-based proposals in the mid-1980s, the final GSM standard was built on TDMA. Development of a digital cellular standard was simultaneously done by TIA in the USA resulting in the TDMA-based IS-54 standard, later simply referred to as US-TDMA. A somewhat later development of a CDMA standard called IS-95 was completed by TIA in 1993. In Japan, a second-generation TDMA standard was also developed, usually referred to as PDC.

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[1] The *European Conference of Postal and Telecommunications Administrations* (CEPT) consist of the telecom administrations from 48 countries.

All these standards were 'narrowband' in the sense that they targeted 'low-bandwidth' services such as voice. With the second-generation digital mobile communications came also the opportunity to provide data services over the mobile-communication networks. The primary data services introduced in 2G were text messaging (SMS) and circuit-switched data services enabling e-mail and other data applications. The peak data rates in 2G were initially 9.6 kbps. Higher data rates were introduced later in evolved 2G systems by assigning multiple time slots to a user and by modified coding schemes.

Packet data over cellular systems became a reality during the second half of the 1990s, with *General Packet Radio Services* (GPRS) introduced in GSM and packet data also added to other cellular technologies such as the Japanese PDC standard. These technologies are often referred to as 2.5G. The success of the wireless data service iMode in Japan gave a very clear indication of the potential for applications over packet data in mobile systems, in spite of the fairly low data rates supported at the time.

With the advent of 3G and the higher-bandwidth radio interface of UTRA (*Universal Terrestrial Radio Access*) came possibilities for a range of new services that were only hinted at with 2G and 2.5G. The 3G radio access development is today handled in 3GPP. However, the initial steps for 3G were taken in the early 1990s, long before 3GPP was formed.

What also set the stage for 3G was the internationalization of cellular standardization. GSM was a pan-European project, but quickly attracted worldwide interest when the GSM standard was deployed in a number of countries outside Europe. There are today only three countries worldwide where GSM is not deployed. A global standard gains in economy of scale, since the market for products becomes larger. This has driven a much tighter international cooperation around 3G cellular technologies than for the earlier generations.

1.1.2 Early 3G discussions

Work on a third-generation mobile communication started in ITU (*International Telecommunication Union*) in the 1980s. The radio communication sector ITU-R issued a first recommendation defining *Future Public Land Mobile Telecommunications Systems* (FPLMTS) in 1990, later revised in 1997 [48]. The name for 3G within ITU had by then changed from FPLMTS to IMT-2000. The World Administrative Radio Congress WARC-92 identified 230 MHz of spectrum for IMT-2000 on a worldwide basis. Of these 230 MHz, 2 × 60 MHz were identified as paired spectrum for FDD (*Frequency Division Duplex*) and 35 MHz as unpaired spectrum for TDD (*Time Division Duplex*), both for terrestrial use. Some spectrum was also set aside for satellite services. With that, the stage was set to specify IMT-2000.

Task Group 8/1 within ITU-R developed a range of recommendations for IMT-2000, defining a framework for services, network architectures, radio interface requirements, spectrum considerations, and evaluation methodology. Both a terrestrial and a satellite component were defined.

Task Group 8/1 defined the process for evaluating IMT-2000 technologies in ITU-R recommendation M.1225 [45]. The evaluation criteria set the target data rates for the 3G circuit-switched and packet-switched data services:

- Up to 2 Mbps in an indoor environment.
- Up to 144 kbps in a pedestrian environment.
- Up to 64 kbps in a vehicular environment.

These numbers became the benchmark that all 3G technologies were compared with. However, already today, data rates well beyond 2 Mbps can be seen in deployed 3G systems.

1.1.3 Research on 3G

In parallel with the widespread deployment and evolution of 2G mobile-communication systems during the 1990s, substantial efforts were put into 3G research activities. In Europe the partially EU-funded project *Research into Advanced Communications in Europe* (RACE) carried out initial 3G research in its first phase. 3G in Europe was named *Universal Mobile Telecommunications Services* (UMTS). In the second phase of RACE, the CODIT project (Code Division Test bed) and the ATDMA project (*Advanced TDMA Mobile Access*) further developed 3G concepts based on *Wideband CDMA* (WCDMA) and Wideband TDMA technologies. The next phase of related European research was *Advanced Communication Technologies and Services* (ACTS), which included the UMTS-related project *Future Radio Wideband Multiple Access System* (FRAMES). The FRAMES project resulted in a multiple access concept that included both Wideband CDMA and Wideband TDMA components.

At the same time parallel 3G activities were going on in other parts of the world. In Japan, the *Association of Radio Industries and Businesses* (ARIB) was in the process of defining a 3G wireless communication technology based on Wideband CDMA. Also in the US, a Wideband CDMA concept called WIMS was developed within the T1.P1[2] committee. Also Korea started work on Wideband CDMA at this time.

The FRAMES concept was submitted to the standardization activities for 3G in ETSI,[3] where other multiple access proposals were also introduced by the industry, including the Wideband CDMA concept from the ARIB standardization in Japan. The ETSI proposals were merged into five concept groups, which also meant that the Wideband CDMA proposals from Europe and Japan were merged.

1.1.4 3G standardization starts

The outcome of the ETSI process in early 1998 was the selection of *Wideband CDMA* (WCDMA) as the technology for UMTS in the paired spectrum (FDD) and TD-CDMA (*Time Division CDMA*) for the unpaired spectrum (TDD). There was also a decision to harmonize the parameters between the FDD and the TDD components.

The standardization of WCDMA went on in parallel in ETSI and ARIB until the end of 1998 when the *Third Generation Partnership Project* (3GPP) was formed by standards-developing organizations from all regions of the world. This solved the problem of trying to maintain parallel development of aligned specifications in multiple regions. The present organizational partners of 3GPP are ARIB (Japan), CCSA (China), ETSI (Europe), ATIS (USA), TTA (Korea) and TTC (Japan).

1.2 Standardization

1.2.1 The standardization process

Setting a standard for mobile communication is not a one-time job, it is an ongoing process. The standardization forums are constantly evolving their standards trying to meet new demands for services and features. The standardization process is different in the different forums, but typically includes the four phases illustrated in Figure 1.1:

1. *Requirements*, where it is decided what is to be achieved by the standard.
2. *Architecture*, where the main building blocks and interfaces are decided.

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[2] The T1.P1 committee was part of T1 which presently has joined the ATIS standardization organization.
[3] The TDMA part of the FRAMES project was also fed into 2G standardization as the evolution of GSM into EDGE (Enhanced Data rates for GSM Evolution).

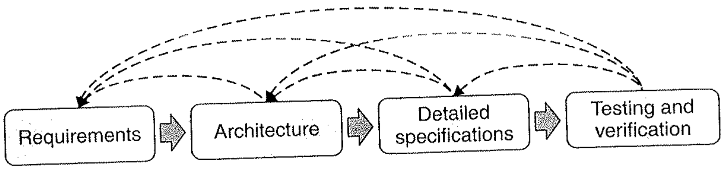

Figure 1.1 *The standardization phases and iterative process.*

3. *Detailed specifications*, where every interface is specified in detail.
4. *Testing and verification*, where the interface specifications are proven to work with real-life equipment.

These phases are overlapping and iterative. As an example, requirements can be added, changed, or dropped during the later phases if the technical solutions call for it. Likewise, the technical solution in the detailed specifications can change due to problems found in the testing and verification phase.

Standardization starts with the *requirements* phase, where the standards body decides what should be achieved with the standard. This phase is usually relatively short.

In the *architecture* phase, the standards body decides about the architecture, i.e. the principles of how to meet the requirements. The architecture phase includes decisions about reference points and interfaces to be standardized. This phase is usually quite long and may change the requirements.

After the architecture phase, the *detailed specification* phase starts. It is in this phase the details for each of the identified interfaces are specified. During the detailed specification of the interfaces, the standards body may find that it has to change decisions done either in the architecture or even in the requirements phases.

Finally, the *testing and verification* phase starts. It is usually not a part of the actual standardization in the standards bodies, but takes place in parallel through testing by vendors and interoperability testing between vendors. This phase is the final proof of the standard. During the testing and verification phase, errors in the standard may still be found and those errors may change decisions in the detailed standard. Albeit not common, changes may need to be done also to the architecture or the requirements. To verify the standard, products are needed. Hence, the implementation of the products starts after (or during) the detailed specification phase. The testing and verification phase ends when there are

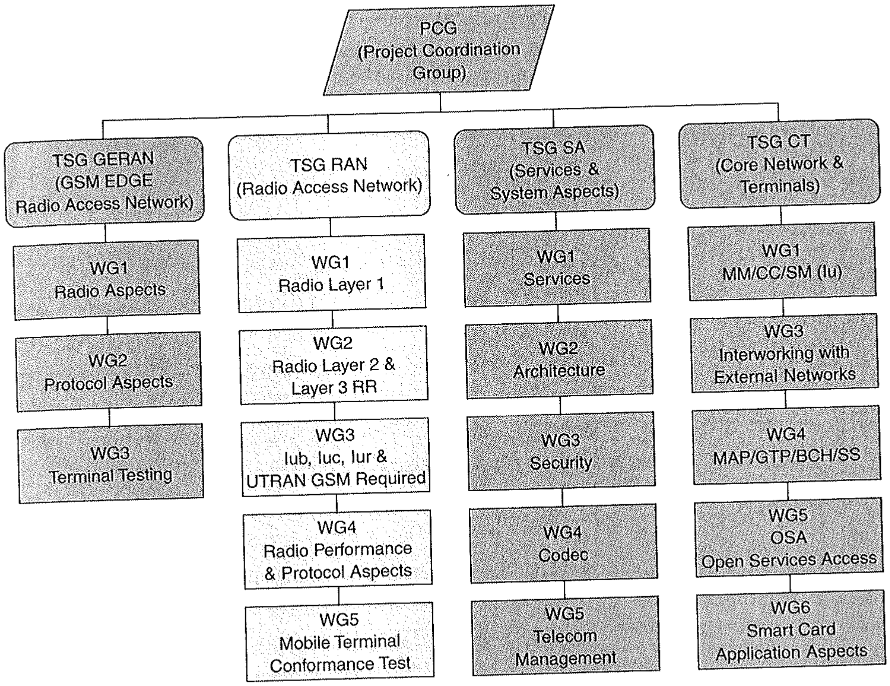

Figure 1.2 *3GPP organization.*

stable test specifications that can be used to verify that the equipment is fulfilling the standard.

Normally, it takes one to two years from the time when the standard is completed until commercial products are out on the market. However, if the standard is built from scratch, it may take longer time since there are no stable components to build from.

1.2.2 3GPP

The *Third-Generation Partnership Project* (3GPP) is the standards-developing body that specifies the 3G UTRA and GSM systems. 3GPP is a partnership project formed by the standards bodies ETSI, ARIB, TTC, TTA, CCSA and ATIS. 3GPP consists of several Technical Specifications Groups (TSGs), (see Figure 1.2).

A parallel partnership project called 3GPP2 was formed in 1999. It also develops 3G specifications, but for cdma2000, which is the 3G technology developed from the 2G CDMA-based standard IS-95. It is also a global project, and the organizational partners are ARIB, CCSA, TIA, TTA and TTC.

3GPP TSG RAN is the technical specification group that has developed WCDMA, its evolution HSPA, as well as LTE, and is in the forefront of the technology. TSG RAN consists of five working groups (WGs):

1. RAN WG1 dealing with the physical layer specifications.
2. RAN WG2 dealing with the layer 2 and layer 3 radio interface specifications.
3. RAN WG3 dealing with the fixed RAN interfaces, for example interfaces between nodes in the RAN, but also the interface between the RAN and the core network.
4. RAN WG4 dealing with the *radio frequency* (RF) and *radio resource management* (RRM) performance requirements.
5. RAN WG 5 dealing with the terminal conformance testing.

The scope of 3GPP when it was formed in 1998 was to produce global specifications for a 3G mobile system based on an evolved GSM core network, including the WCDMA-based radio access of the UTRA FDD and the TD-CDMA-based radio access of the UTRA TDD mode. The task to maintain and develop the GSM/EDGE specifications was added to 3GPP at a later stage. The UTRA (and GSM/EDGE) specifications are developed, maintained and approved in 3GPP. After approval, the organizational partners transpose them into appropriate deliverables as standards in each region.

In parallel with the initial 3GPP work, a 3G system based on TD-SCDMA was developed in China. TD-SCDMA was eventually merged into Release 4 of the 3GPP specifications as an additional TDD mode.

The work in 3GPP is carried out with relevant ITU recommendations in mind and the result of the work is also submitted to ITU. The organizational partners are obliged to identify regional requirements that may lead to options in the standard. Examples are regional frequency bands and special protection requirements local to a region. The specifications are developed with global roaming and circulation of terminals in mind. This implies that many regional requirements in essence will be global requirements for all terminals, since a roaming terminal has to meet the strictest of all regional requirements. Regional options in the specifications are thus more common for base stations than for terminals.

The specifications of all releases can be updated after each set of TSG meetings, which occur 4 times a year. The 3GPP documents are divided into releases, where

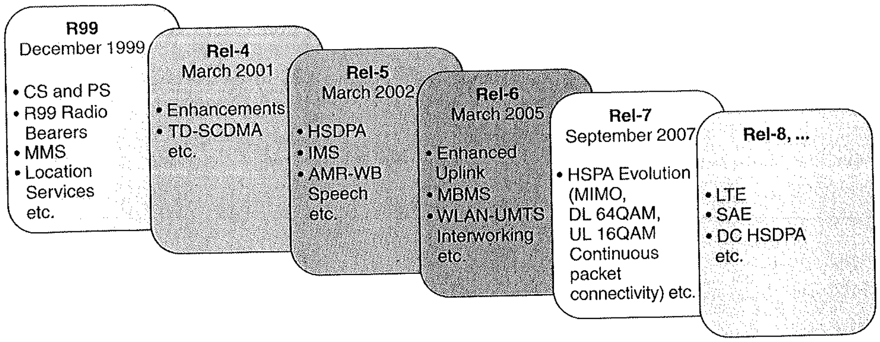

Figure 1.3 *Releases of 3GPP specifications for UTRA.*

each release has a set of features added compared to the previous release. The features are defined in Work Items agreed and undertaken by the TSGs. The releases up to Release 8 and some main features of those are shown in Figure 1.3. The date shown for each release is the day the content of the release was frozen. For historical reasons, the first release is numbered by the year it was frozen (1999), while the following releases are numbered 4, 5, etc.

For the WCDMA Radio Access developed in TSG RAN, Release 99 contains all features needed to meet the IMT-2000 requirements as defined by ITU. There are circuit-switched voice and video services, and data services over both packet-switched and circuit-switched bearers. The first major addition of radio access features to WCDMA is Release 5 with *High Speed Downlink Packet Access* (HSDPA) and Release 6 with *Enhanced Uplink*. These two are together referred to as HSPA and are described in more detail in Part III of this book. With HSPA, UTRA goes beyond the definition of a 3G mobile system and also encompasses broadband mobile data.

With the inclusion of an Evolved UTRAN (LTE) and the related *System Architecture Evolution* (SAE) in Release 8, further steps are taken in terms of broadband capabilities. The specific solutions chosen for LTE and SAE are described in Part IV of this book.

1.2.3 *IMT-2000 activities in ITU*

The present ITU work on 3G takes place in ITU-R *Working Party 5D*[4] (WP5D), where 3G systems are referred to as IMT-2000. WP5D does not write technical

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[4] The work on IMT-2000 was moved from Working Party 8F to Working Party 5D in 2008.

specifications for IMT-2000, but has kept the role of defining IMT-2000, cooperating with the regional standardization bodies and to maintain a set of recommendations for IMT-2000.

The main IMT-2000 recommendation is ITU-R M.1457 [46], which identifies the IMT-2000 *radio interface specifications* (RSPC). The recommendation contains a 'family' of radio interfaces, all included on an equal basis. The family of six terrestrial radio interfaces is illustrated in Figure 1.4, which also shows what *Standards Developing Organizations* (SDO) or Partnership Projects produce the specifications. In addition, there are several IMT-2000 satellite radio interfaces defined, not illustrated in Figure 1.4.

For each radio interface, M.1457 contains an overview of the radio interface, followed by a list of references to the detailed specifications. The actual specifications are maintained by the individual SDOs and M.1457 provides URLs locating the specifications at each SDOs web archive.

With the continuing development of the IMT-2000 radio interfaces, including the evolution of UTRA to Evolved UTRA, the ITU recommendations also need to be updated. ITU-R WP5D continuously revises recommendation M.1457 and at the time of writing it is in its seventh version. Input to the updates is provided by the SDOs and Partnership Projects writing the standards. In the latest revision of ITU-R M.1457, LTE (or E-UTRA) is included in the family through the 3GPP family members for UTRA FDD and TDD, while UMB is included through CDMA2000, as shown in the figure. WiMAX is also included as the sixth family member for IMT-2000.

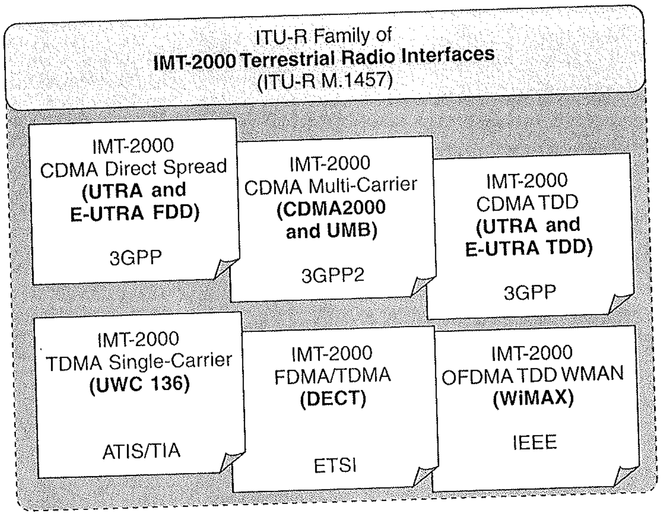

Figure 1.4 *The definition of IMT-2000 in ITU-R.*

In addition to maintaining the IMT-2000 specifications, the main activity in ITU-R WP5D is the work on systems beyond IMT-2000, named IMT-Advanced. ITU-R has concluded studies for IMT-Advanced of services and technologies, market forecasts, principles for standardization, estimation of spectrum needs, and identification of candidate frequency bands [47]. The spectrum work has involved sharing studies between IMT-Advanced and other technologies in those bands. In March 2008, ITU-R invited the submission of candidate *Radio Interface Technologies* (RIT) in a Circular letter [139]. Submission and evaluation of RITs will be ongoing through 2009 and 2010. The target date for the final ITU-R recommendation for the IMT-Advanced radio interface specifications is February 2011.

1.3 Spectrum for 3G and systems beyond 3G

Spectrum for 3G was first identified at the *World Administrative Radio Congress* WARC-92. Resolution 212 [60] identified the bands 1885–2025 and 2110–2200 MHz as intended for use by national administrations that want to implement IMT–2000. Of these 230 MHz of 3G spectrum, 2 × 30 MHz were intended for the satellite component of IMT–2000 and the rest for the terrestrial component. Parts of the bands were during the 1990s used for deployment of 2G cellular systems, especially in the Americas. The first deployment of 3G in 2001–2002 by Japan and Europe were done in this band allocation, and it is for that reason often referred to as the IMT-2000 'core band.'

Spectrum for IMT–2000 was also identified at the World Radiocommunication Conference WRC-2000 in Resolutions 223 and 224, where it was considered that an additional need for 160 MHz of spectrum for IMT-2000 was forecasted by ITU-R. The identification includes the bands used for 2G mobile systems in 806–960 MHz and 1710–1885 MHz, and 'new' 3G spectrum in the bands 2500–2690 MHz. The identification of bands assigned for 2G was also a recognition of the evolution of existing 2G mobile systems into 3G. Additional spectrum was identified at WRC'07 for IMT, encompassing both IMT-2000 and IMT-Advanced. The bands added are 450–470, 698–806, 2300–2400, and 3400–3600 MHz, but the applicability of the bands vary on a regional and national basis.

The somewhat diverging arrangement between regions of the frequency bands assigned to 3G means that there is not a single band that can be used for 3G roaming worldwide. Large efforts have however been put into defining a minimum set of bands that can be used to provide roaming. In this way, multi-band devices can provide efficient worldwide roaming for 3G. Release 8 of the 3GPP specifications includes 14 frequency bands for FDD and 8 for TDD. These are described in more detail in Chapter 20.

The worldwide frequency arrangements for IMT-2000 are outlined in ITU-R recommendation M.1036 [44]. The recommendation also identifies which parts of the spectrum that are paired and which are unpaired. For the paired spectrum, the bands for uplink (mobile transmit) and downlink (base-station transmit) are identified for *Frequency Division Duplex* (FDD) operation. The unpaired bands can for example be used for *Time Division Duplex* (TDD) operation. Note that the band that is most globally deployed for 3G is still 2 GHz.

3GPP first defined UTRA in Release 99 for the 2 GHz bands, with 2 × 60 MHz for UTRA FDD and 20 + 15 MHz of unpaired spectrum for UTRA TDD. A separate definition was also made for the use of UTRA in the US PCS bands at 1900 MHz. The concept of frequency bands with separate and release-independent requirements were defined in Release 5 of the 3GPP specifications. The release-independence implies that a new frequency band added at a later release can be implemented also for earlier releases. All bands are also defined with consideration of what other bands may be deployed in the same region through special coexistence requirements for both base stations and terminals. These tailored requirements enable coexistence between 3G (and 2G) deployments in different bands in the same geographical area and even for co-location of base stations at the same sites using different bands.

2

The motives behind the 3G evolution

Before entering the detailed discussion on technologies being used or considered for the evolution of 3G mobile communication, it is important to understand the motivation for this evolution: that is, understanding the underlying driving forces. This chapter will try to highlight some of the driving forces giving the reader an understanding of where the technical requirements and solutions are coming from.

2.1 Driving forces

A key factor for success in any business is to understand the forces that will drive the business in the future. This is in particular true for the mobile-communication industry, where the rapid growth of the number of subscribers and the global presence of the technologies have attracted several new players that want to be successful. Both new operators and new vendors try to compete with the existing operators and vendors by adopting new technologies and standards to provide new and existing services better and at a lower cost than earlier systems. The existing operators and vendors will, of course, also follow or drive new technologies to stay ahead of competition. Thus, there is a key driving force in staying competitive or becoming competitive.

From the technical perspective, the development in areas like digital cameras and color displays enables new fancier services than the existing mobile-communication services. To be able to provide those services, the mobile-communication systems need to be upgraded or even replaced by new mobile-communication technologies. Similarly, the technical advancement in digital processors enables new and more powerful systems that not only can provide the new services, but also can provide the existing successful services better and to a lower cost than the dominant mobile-communication technologies of today. Thus, the key drivers are:

- staying competitive;
- services (better provisioning of old services as well as provisioning of new services);
- cost (more cost-efficient provisioning of old services as well as cost-effective provisioning of new services).

The technology advancement is necessary to provide new and more advanced services at a reasonable cost as well as to provide existing services in a better and more cost-efficient way.

2.1.1 Technology advancements

Technology advancements in many areas make it possible to build devices that were not possible 20, 10, or even 5 years ago. Even though Moore's law[1] is not a law of physics, it gives an indication of the rapid technology evolution for integrated circuits. This evolution enables faster processing/computing in smaller devices at lower cost. Similarly, the rapid development of color screens, small digital cameras, etc. makes it possible to envisage services to a device that were seen as utopia 10 years ago. For an example of the terminal development in the past 20 years, see Figure 2.1.

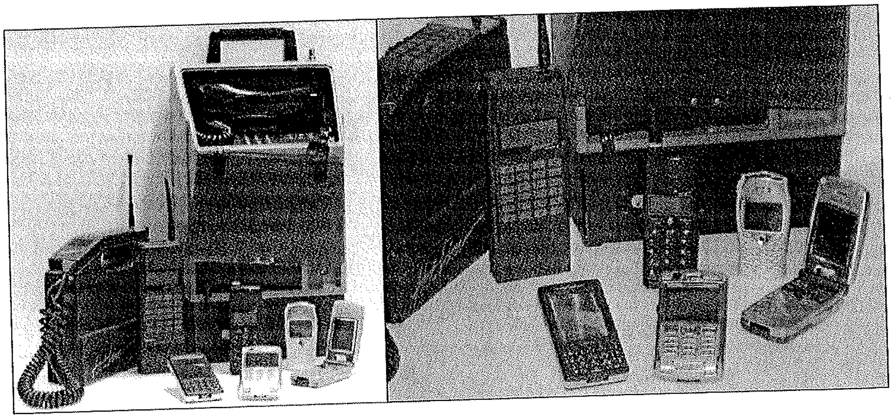

Figure 2.1 *The terminal development has been rapid the past 20 years.*

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[1] Moore's law is an empirical observation, and states that with the present rate of technological development, the complexity of an integrated circuit, with respect to minimum component cost, will double in about 18 months.

The size and weight of the mobile terminals have been reduced dramatically during the past 20 years. The standby and talk times have also been extended dramatically and the end users do not need to re-charge their devices every day. Simple black-and-white (or brown-and-gray) numerical screens have evolved into color screens capable of showing digital photos at good quality. Mega-pixel-capable digital cameras have been added making the device more attractive to use. Thus, the mobile device has become a multi-purpose device, not only a mobile phone for voice communications.

In parallel to the technical development of the mobile devices, the mobile-communication technologies are developed to meet the demands of the new services enabled, and also to enable them wireless. The development of the digital signal processors enables more advanced receivers capable of processing megabits of data in a short time, and the introduction of the optical fibers enables high-speed network connections to the base stations. In sum, this enables a fast access to information on the Internet as well as a short roundtrip time for normal communications. Thus, new and fancier services are enabled by the technical development of the devices, and new and more efficient mobile-communication systems are enabled by a similar technical development.

2.1.2 Services

Delivering services to the end users is the fundamental goal of any mobile-communication system. Knowing them, understanding them, managing them, and charging them properly is the key for success. It is also the most difficult task being faced by the engineers developing the mobile-communication system of the future. It is very difficult to predict what service(s) will be popular in a 5- to 10-year perspective. In fact, the engineers have to design a system that can adapt to any service that might become popular and used in the future. Unfortunately, there are also technical limitations that need to be understood, and also the technical innovations that in the future enable new services.

2.1.2.1 Internet and IP technology

The success of the Internet and the IP-based services delivered over the Internet is more and more going wireless. This means that the mobile-communication systems are delivering more and more IP-based services, from the best effort-Internet data to voice-over-IP, for example in the shape of push-to-talk (PoC). Furthermore, in the wireless environment it is more natural to use, for example, location-based services and tracking services than in the fixed environment.

Thus, one can talk about mobile Internet services in addition to the traditional Internet services like browsing, e-mail, etc.[2]

Essentially, IP provides a transport mechanism that is service agnostic. Albeit there are several protocols on top of IP that are service-type specific (RTP, TCP, etc.), IP in itself is service agnostic. That enables service developers to develop services that only the imagination (and technology) sets the limit to. Thus, services will pop up, some will become popular for a while and then just fade away, whereas some others will never become a hit. Some services will become classics that will live and be used for a very long time.

2.1.2.2 Traditional telephony services

Going toward IP-based services obviously does not mean that traditional services that have been provided over the circuit-switched domain, in successful mobile-communication systems like GSM, will disappear. Rather, it means that the traditional circuit-switched services will be ported over the IP networks. One particular service is the circuit-switched telephony service that will be provided as VoIP service instead. Thus, both the new advanced services that are enabled by the technology advancement of the devices and the traditional circuit-switched services will be using IP as the transporting mechanism (and are therefore called IP-based services). Hence future mobile-communication networks, including the 3G evolution, need to be optimized for IP-based applications.

2.1.2.3 Wide spectrum of service needs

Trying to predict all the services that will be used over the mobile-communication systems 10 years from now is very difficult. The technology advancements in the various areas enable higher data rate connections, more memory on local devices, and more intelligent and easy to use man–machine interfaces. Furthermore, the human need of interaction and competition with other humans drives more intensive communication needs. All these combinations point toward applications and services that consume higher data rates and require lower delays compared to what today's mobile-communication systems can deliver.

However, the relative low-rate voice service will still be a very important component of the service portfolio that mobile-network operators wish to provide. In addition, services that have very relaxed delay requirements will also be there. Thus, not only high data rate services with a low-latency requirement, but also

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[2] The common denominator between mobile Internet services and Internet services is the IP addressing technology with the IPv4 and IPv6 addresses identifying the end receiver. However, there is a need to handle the mobility provided by the cellular systems. Mobile IP is one possibility, but most of the cellular systems (if not all) have their own more efficient mobility mechanism.

low data rate best effort services will be provided. Furthermore, not only the data rate and delay are important to understand when talking about a service's need from a mobile-communication system, but also the setup time is very important, for example, a service can be totally useless if it takes too long to start it (for example making a phone call, downloading a web page). Thus the mobile-communication systems of the future, including the evolution of 3G mobile communication, need to be able to deliver short call setup times, low latency and a wide range of data rates.

2.1.2.4 Key design services

Since it is impossible to know what services that will be popular and since service possibilities and offers will differ with time and possible also with country, the future mobile-communication systems will need to be adaptive to the changing service environment. Luckily, there are a few known key services that span the technology space. Those are:

- *Real-time-gaming applications*: These have the characteristic to require small amount of data (game update information) relatively frequent with low delay requirement.[3] Only a limited delay jitter is tolerable. A first person shooter game like Counter Strike is an example of a game that has this characteristic.
- *Voice*: This has the characteristic to require small amounts of data (voice packets) frequently with no delay jitter. The end-to-end delay has to be small enough not to be noticeable.[4]
- *Interactive file download and upload applications*: These have the characteristics of requiring low delay and high data rates.
- *Background file download and upload applications*: These have the characteristics of accepting lower bit rates and longer delays. E-mail (mostly) is an example of background file download and upload.
- *Television*: This has the characteristics of streaming downlink to many users at the same time requiring low delay jitter. The service can tolerate delays, as long as it is approximately the same delay for all users in the neighborhood. The television service has moderate data rate requirements.

A mobile-communication system designed to handle these services and the services in between will be able to facilitate most services (see Figure 2.2). Unfortunately, the upper limit of the data rate demand and the lower limit of the delay requirement are difficult to provide in a cost-efficient manner. The designers

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[3] The faster the data is delivered the better. Expert Counter Strike players look for game servers with a ping time of less than 50 ms.

[4] In 3G systems the end-to-end delay requirement for circuit-switched voice is approximately 400 ms. This delay is not disturbing humans in voice communications.

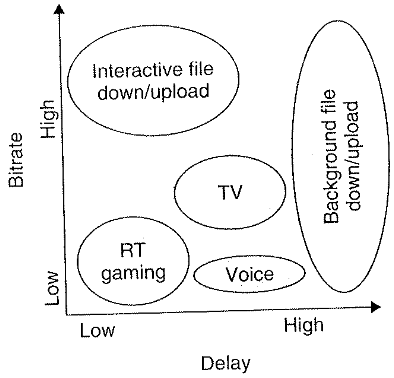

Figure 2.2 *The bit rate – delay service space that is important to cover when designing a new cellular system.*

of the mobile-communication systems need to stop at a reasonable level, a level that the technology available at the time of standardization can provide.

2.1.3 Cost and performance

There is another important driving factor for future mobile-communication systems and that is the cost of the service provisioning. The technology advancement that enables new services can also be utilized to provide better mobile-communication systems using more advanced technical features. Here IP technology is not only a key enabler to allow for new services to pop up, but also a way of reducing cost of new services. The reason is that IP as a bearer of new services can be used to introduce new services as they come, not requiring an extensive special design of the system. Of course, this requires that the devices used in the mobile-communication system can be programmed by third-party providers and that the operators allow third-party service providers to use their network for communication.

Another important factor is that operators need to provide the services to all the users. Not only one user needs to get the low delay, high data rate, etc. that its service needs, but all the users with their different service needs should be served efficiently. The processing capacity evolution and Moore's law help also for this problem. New techniques are enabled by the higher processing power in the devices – techniques that delivers more bits of data per hertz. Furthermore, the coverage is increased with more advanced antennas and receivers. This enables the operators to deliver the services to more users from one base station, thus requiring fewer sites. Fewer sites imply lower operational and capitalization costs. In essence, the operators need fewer base stations and sites to provide the service.

Obviously, all services would be 'happy' if they were provided with the highest data rate, lowest delay, and lowest jitter that the system can provide. Unfortunately, this is unattainable in practice and contradictory to the operator goal of an efficient system: in other words, the more delay a service can handle the more efficient the system can be. Thus, the cost of providing lowest possible delay, jitter and call setup time is somewhat in conflict with the need of the mobile-network operator to provide it to all the users. Hence, there is a trade-off between user experience and system performance. The better the system performance is, the lower the cost of the network. However, the end users also need to get adequate performance which often is in conflict with the system performance, thus the operator cannot only optimize for system performance.

2.2 3G evolution: Two Radio Access Network approaches and an evolved core network

2.2.1 Radio Access Network evolution

TSG RAN organized a workshop on 3GPP long-term Evolution in the fall of 2004. The workshop was the starting point of the development of the Long-Term Evolution (LTE) radio interface. After the initial requirement phase in the spring of 2005, where the targets and objectives of LTE were settled, the technical specification group TSG SA launched a corresponding work on the System Architecture Evolution, since it was felt that the LTE radio interface needed a suitable evolved system architecture.

The result of the LTE workshop was that a study item in 3GPP TSG RAN was created in December 2004. The first 6 months were spent on defining the requirements, or design targets, for LTE. These were documented in a 3GPP technical report [86] and approved in June 2005. Chapter 13 will go through the requirements in more detail. Most notable are the requirements on high data rate at the cell edge and the importance of low delay, in addition to the normal capacity and peak data rate requirements. Furthermore, spectrum flexibility and maximum commonality between FDD and TDD solutions are pronounced.

During the fall 2005, 3GPP TSG RAN WG1 made extensive studies of different basic physical layer technologies and in December 2005 the TSG RAN plenary decided that the LTE radio access should be based on *OFDM* in the downlink and *single carrier FDMA* in the uplink.

TSG RAN and its working groups then worked on the LTE specifications and the specifications were approved in December 2007. However, 3GPP TSG RAN did not stop working on LTE when the first version of the specifications was completed. In fact, 3GPP will continue to evolve LTE towards LTE Advanced. Chapters 14–20 will go through the LTE radio interface in more detail.

At the same time as the LTE discussion was ongoing, 3GPP TSG RAN and its WGs continued to evolve the WCDMA system with more functionality, most notably MBMS and Enhanced Uplink. These additions were done in a backward compatible manner: that is, terminals of earlier releases can coexist on the same carrier in the same base station as terminals of the latest release. The main argument for the backward compatibility is that the installed base of equipment can be upgraded to handle the new features while still being capable of serving the old terminals. This is a cost-efficient addition of new features, albeit the new features are restricted by the solutions for the old terminals.

Naturally, HSPA[5] does not include all the technologies considered for LTE. Therefore, a study in 3GPP was initiated to see how far it is possible to take HSPA within the current spectrum allocation of 5 MHz and still respect the backward compatibility aspect. Essentially, the target with HSPA Evolution was, and still is, to reach near the characteristics of LTE when using a 5 MHz spectrum and at the same time being backward compatible. Chapters 8–12 will go through the HSPA and the HSPA Evolution in more detail.

Thus, the 3GPP 3G evolution standard has two parts: LTE and HSPA Evolution. Both parts have their merits. LTE can operate in new and more complex spectrum arrangements (although in the same spectrum bands as WCDMA and other 3G technologies) with the possibility for new designs that do not need to cater for terminals of earlier releases. HSPA Evolution can leverage on the installed base of equipment in the 5 MHz spectrum but needs to respect the backward compatibility of earlier terminals.

2.2.1.1 LTE drivers and philosophy

The 3GPP Long-Term Evolution is intended to be a mobile-communication system that can take the telecom industry into the 2020s. The philosophy behind LTE standardization is that the competence of 3GPP in specifying mobile-communication systems in general and radio interfaces in particular shall be used, but the result shall not be restricted by previous work in 3GPP. Thus, LTE does not need to be backward compatible with WCDMA and HSPA.

Leaving the legacy terminals behind, not being restricted by designs of the late 1990s, makes it possible to design a radio interface from scratch. In the LTE case,

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[5] When operating with HSDPA and Enhanced UL, the system is known as HSPA.

the radio interface is purely optimized for IP transmissions not having to support ISDN traffic: that is, there is no requirement for support of GSM circuit-switch services, a requirement that WCDMA had. Furthermore, LTE also has a very large commonality of FDD and TDD operations, a situation that did not exist in 3GPP before LTE.

Instead new requirements have arisen, for example the requirement on spectrum flexibility, since the global spectrum situation becomes more and more complex. Operators get more and more scattered spectrum, spread over different bands with different contiguous bandwidths. LTE needs to be able to operate in all these bands and with the bandwidths that is available to the operator. However, in practice only a limited set of bandwidths can be used since otherwise the RF and filter design would be too costly. LTE is therefore targeted to operate in spectrum allocations from roughly 1 to 20 MHz. The spectrum flexibility support with the possibility to operate in other bandwidths than 5 MHz makes LTE very attractive for operators. The low-bandwidth operations are suitable for refarming of spectrum (for example GSM spectrum and CDMA2000 spectrum). The higher-bandwidth options are suitable for new deployments in unused spectrum, where it is more common to have larger chunks of contiguous spectrum.

Furthermore, when going to the data rates that LTE is targeting, achieving low delay and high data rates at the cell edges are more important requirements than the peak data rate. Thus, a more pronounced requirement for LTE is the low delay with high data rates at the cell edges than it was when WCDMA was designed in the late 1990s.

Although not backward compatible with WCDMA, LTE design is clearly influenced by the WCDMA and the HSPA work in 3GPP. It is the same body, the same people, and companies that are active and more importantly, WCDMA and HSPA protocols are a good foundation for the LTE design. The philosophy is to take what is good from WCDMA and HSPA, and redo those parts that have to be updated due to the new requirement situation: either there are new requirements such as the spectrum flexibility or there are requirements that no longer are valid such as the support of ISDN services. The technology advancement in the cellular area has, of course, also influenced the design choice of LTE.

2.2.1.2 HSPA evolution drivers and philosophy

WCDMA, HSDPA, and HSPA are in commercial operation throughout the world. This means that the infrastructure for HSPA is already in place with the network node sites, especially the base-station sites with their antenna arrangements and hardware. This equipment is serving millions of terminals with different characteristics and supported 3GPP releases. These terminals need to be supported by the WCDMA operators for many more years.

The philosophy of the HSPA Evolution work is to continue to add new and fancier technical features, and at the same time be able to serve the already existing terminals. This is the successful strategy of GSM that have added new features constantly since the introduction in the early 1990s. The success stems from the fact that there are millions of existing terminals at the launch time of the new features that can take the cost of the upgrade of the network for the initially few new terminals before the terminal fleet is upgraded. The time it takes to upgrade the terminal fleet is different from country to country, but a rule of thumb is that a terminal is used for 2 years before it is replaced. For HSPA Evolution that means that millions of HSPA-capable terminals need to be supported at launch. In other words, HSPA Evolution needs to be backward compatible with the previous releases in the sense that it is possible to serve terminals of earlier releases of WCDMA on the same carrier as HSPA-Evolution-capable terminals.

The backward compatibility requirement on the HSPA Evolution puts certain constraints on the technology that LTE does not need to consider, for example the physical layer fundamentals need to be the same as for WCDMA release 99. On the other hand, HSPA Evolution is built on the existing specifications and only those parts of the specifications that need to be upgraded are touched. Thus there is less standardization, implementation and testing work for HSPA Evolution than for LTE since the HSPA Evolution philosophy is to apply new more advanced technology on the existing HSPA standard. This will bring HSPA to a performance level comparable to LTE when compared on a 5 MHz spectrum allocation (see Chapter 23 for a performance comparison of HSPA Evolution and LTE).

2.2.2 An evolved core network: system architecture evolution

Roughly at the same time as LTE and HSPA Evolution was started, 3GPP decided to make sure that an operator can coexist easily between HSPA Evolution and LTE through an evolved core network, the *Evolved Packet Core*. This work was done under the umbrella *System Architecture Evolution* study item lead by TSG SA WG2.

The *System Architecture Evolution* study focused on how the 3GPP core network will evolve into the core network of the next decades. The existing core network was designed in the 1980s for GSM, extended during the 1990s' for GPRS and WCDMA. The philosophy of the SAE is to focus on the packet-switched domain,

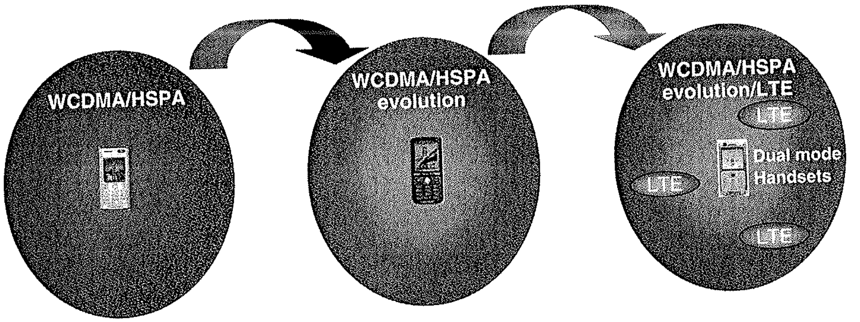

Figure 2.3 *One HSPA and LTE deployment strategy: upgrade to HSPA Evolution, then deploy LTE as islands in the WCDMA/HSPA sea.*

and migrate away from the circuit-switched domain. This is done through the coming 3GPP releases ending up with the Evolved Packet Core.

Knowing that HSPA Evolution is backward compatible and knowing that the Evolved Packet Core will support both HSPA Evolution and LTE assures that LTE can be deployed in smaller islands and thus only where it is needed. A gradual deployment approach can be selected (see Figure 2.3). First the operator can upgrade its HSPA network to HSPA-Evolution-capable network, and then add LTE cells where capacity is lacking or where the operator wants to try out new services that cannot be delivered by HSPA Evolution. This approach reduces the cost of deployment since LTE do not need to be build for nationwide coverage from day one.

15

LTE radio interface architecture

Similar to WCDMA/HSPA, as well as to most other modern communication systems, the processing specified for LTE is structured into different protocol layers. Although several of these layers are similar to those used for WCDMA/HSPA, there are some differences, for example due to the differences in the overall architecture between WCDMA/HSPA and LTE. This chapter contains an overview of these protocol layers and their interaction. A detailed description of the LTE architecture is found in Chapter 21, where the location of the different protocol entities in the different network nodes is discussed. For the discussion in this chapter, it suffices to note that the LTE radio-access architecture consists of a single node – the eNodeB.[1] The eNodeB communicates with one or several mobile terminals, also known as UEs.

A general overview of the LTE protocol architecture for the downlink is illustrated in Figure 15.1. As this will become clear in the subsequent discussion, not all the entities illustrated in Figure 15.1 are applicable in all situations. For example, neither MAC scheduling nor hybrid ARQ with soft combining is used for broadcast of system information. Furthermore, the LTE protocol structure related to uplink transmissions is similar to the downlink structure in Figure 15.1, although there are some differences with respect to, for example, transport-format selection and multi-antenna transmission.

Data to be transmitted in the downlink enters the processing chain in the form of IP packets on one of the *SAE bearers*. Prior to transmission over the radio interface,

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[1] The term eNodeB is introduced in LTE to indicate the additional functionality placed in the eNodeB compared to the functionality in the NodeB in WCDMA/HSPA.

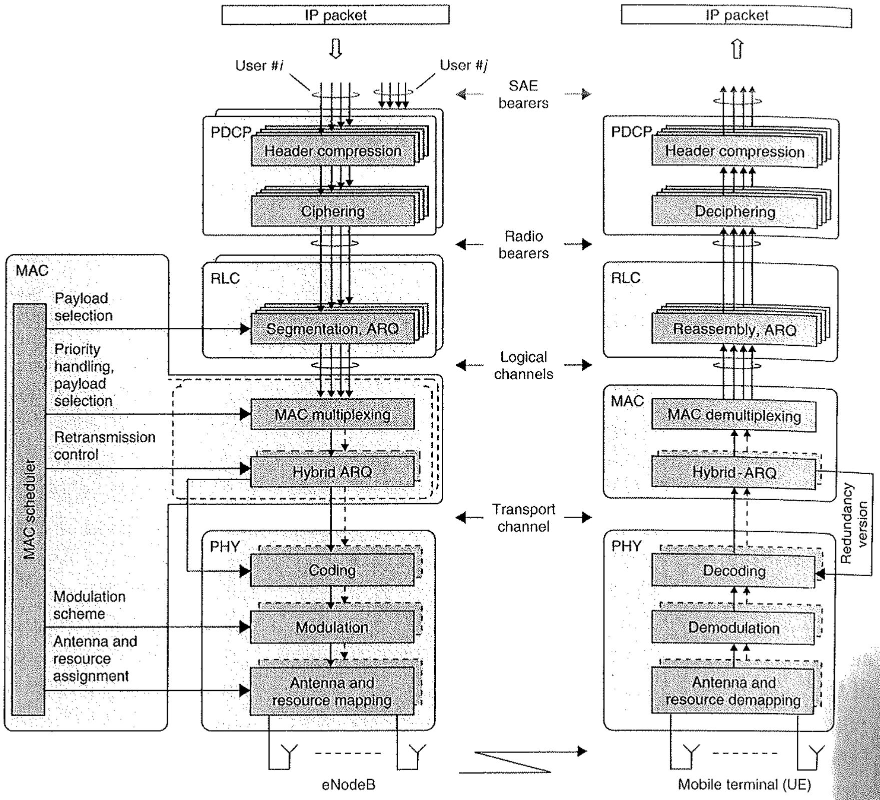

Figure 15.1 *LTE protocol architecture (downlink).*

incoming IP packets are passed through multiple protocol entities, summarized below and described in more detail in the following sections:

- *Packet Data Convergence Protocol* (PDCP) performs IP header compression to reduce the number of bits to transmit over the radio interface. The header-compression mechanism is based on Robust Header Compression (ROHC) [64], a standardized header-compression algorithm also used in WCDMA as well as several other mobile-communication standards. PDCP is also responsible for ciphering and integrity protection of the transmitted data. At the receiver side, the PDCP protocol performs the corresponding deciphering and decompression operations. There is one PDCP entity per SAE bearer configured for a mobile terminal.
- *Radio Link Control* (RLC) is responsible for segmentation/concatenation, retransmission handling, and in-sequence delivery to higher layers. Unlike WCDMA, the RLC protocol is located in the eNodeB since there is only a single type of node in the LTE radio-access-network architecture. The RLC

offers services to the PDCP in the form of *radio bearers*. There is one RLC entity per radio bearer configured for a terminal.

- *Medium Access Control* (MAC) handles hybrid-ARQ retransmissions and uplink and downlink scheduling. The scheduling functionality is located in the eNodeB, which has one MAC entity per cell, for both uplink and downlink. The hybrid-ARQ protocol part is present in both the transmitting and receiving end of the MAC protocol. The MAC offers services to the RLC in the form of *logical channels*.
- *Physical Layer* (PHY) handles coding/decoding, modulation/demodulation, multi-antenna mapping, and other typical physical layer functions. The physical layer offers services to the MAC layer in the form of *transport channels*.

The remaining of the chapter contains an overview of the RLC, MAC, and physical layers. A more detailed description of the LTE physical layer is given in Chapters 16 (downlink) and 17 (uplink), followed by an overview of LTE access procedures in Chapter 18 and transmission procedures in Chapter 19.

15.1 Radio link control

Similar to WCDMA/HSPA, LTE RLC is responsible for segmentation/concatenation of (header-compressed) IP packets, also known as RLC SDUs, from the PDCP into suitably sized RLC PDUs.[2] It also handles retransmission of erroneously received PDUs, as well as duplicate removal of received PDUs. Finally, the RLC ensures in-sequence delivery of SDUs to upper layers. Depending on the type of service, the RLC can be configured in different modes to perform some or all of these functions.

Segmentation and concatenation, one of the main RLC functions, is illustrated in Figure 15.2. Depending on the scheduler decision, a certain amount of data is selected for transmission from the RLC SDU buffer and the SDUs are segmented/concatenated to create the RLC PDU. Thus, for LTE the RLC PDU size varies *dynamically*, whereas WCDMA/HSPA prior to Release 7 uses a semi-static PDU size.[3] For high data rates, a large PDU size results in a smaller relative overhead, while for low data rates, a small PDU size is required as the payload would otherwise be too large, leading to extensive padding. Hence, as the LTE data rates may range from a few kbit/s up to 300 Mbit/s, dynamic PDU sizes are motivated for

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[2] In general, the data entity from/to a higher protocol layer is known as a Service Data Unit (SDU) and the corresponding entity to/from a lower protocol layer entity is denoted Protocol Data Unit (PDU).

[3] The possibility to segment RLC PDUs is introduced in WCDMA/HSPA Release 7 as described in Chapter 12, providing similar benefits as a dynamic PDU size.

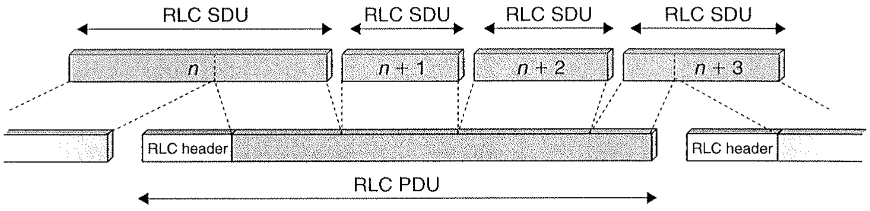

Figure 15.2 *RLC segmentation and concatenation.*

LTE. Since the RLC, scheduler, and rate adaptation mechanisms are all located in the eNodeB, dynamic PDU sizes are easily supported for LTE. In each RLC PDU, a header is included, containing, among other things, a sequence number used for in-sequence delivery and by the retransmission mechanism.

The RLC retransmission mechanism is also responsible for providing error-free delivery of data to higher layers. To accomplish this, a retransmission protocol operates between the RLC entities in the receiver and transmitter. By monitoring the sequence numbers of the incoming PDUs, the receiving RLC can identify missing PDUs. Status reports are then fed back to the transmitting RLC entity, requesting retransmission of missing PDUs. Based on the received status report, the RLC entity at the transmitter can take the appropriate action and retransmit the missing PDUs if needed.

Although the RLC is capable of handling transmission errors due to noise, unpredictable channel variations, etc., error-free delivery is in most cases handled by the MAC-based hybrid-ARQ protocol. The use of a retransmission mechanism in the RLC may therefore seem superfluous at first. However, as will be discussed in Section 15.2.3, this is not the case and the use of both RLC- and MAC-based retransmission mechanisms is in fact well motivated by the differences in the feedback signaling.

The details of RLC are further described in Chapter 19.

15.2 Medium access control

The MAC layer handles logical-channel multiplexing, hybrid-ARQ retransmissions, and uplink and downlink scheduling. In contrast to HSPA, which uses uplink macro-diversity and therefore defines both serving and non-serving cells (see Chapter 10), LTE only defines a serving cell as there is no uplink macro-diversity. The serving cell is the cell the mobile terminal is connected to and which is responsible for scheduling decisions and hybrid-ARQ operation for the mobile terminal.

15.2.1 Logical channels and transport channels

The MAC offers services to the RLC in the form of *logical channels*. A logical channel is defined by the *type* of information it carries and is generally classified as a *control channel*, used for transmission of control and configuration information necessary for operating an LTE system, or as a *traffic channel*, used for the user data. The set of logical-channel types specified for LTE includes:

- *Broadcast Control Channel* (BCCH), used for transmission of *system information* from the network to all mobile terminals in a cell. Prior to accessing the system, a mobile terminal needs to acquire the system information to find out how the system is configured and, in general, how to behave properly within a cell.
- *Paging Control Channel* (PCCH), used for paging of mobile terminals whose location on cell level is not known to the network. The paging message therefore needs to be transmitted in multiple cells.
- *Common Control Channel* (CCCH), used for transmission of control information in conjunction with random access.
- *Dedicated Control Channel* (DCCH), used for transmission of control information to/from a mobile terminal. This channel is used for individual configuration of mobile terminals such as different handover messages.
- *Multicast Control Channel* (MCCH), used for transmission of control information required for reception of the MTCH, see below.
- *Dedicated Traffic Channel* (DTCH), used for transmission of user data to/from a mobile terminal. This is the logical channel type used for transmission of all uplink and non-MBSFN downlink user data.
- *Multicast Traffic Channel* (MTCH), used for downlink transmission of MBMS services.

A similar logical-channel structure is used for WCDMA/HSPA. However, compared to WCDMA/HSPA, the LTE logical-channel structure is somewhat simplified, with a reduced number of logical-channel types.

From the physical layer, the MAC layer uses services in the form of *Transport Channels*. A transport channel is defined by *how* and *with what characteristics* the information is transmitted over the radio interface. Following the notation from HSPA, which has been inherited for LTE, data on a transport channel is organized into *transport blocks*. In each *Transmission Time Interval* (TTI), at most one transport block of a certain size is transmitted over the radio interface to/from a mobile terminal in absence of spatial multiplexing. In case of spatial multiplexing ('MIMO'), there can be up to two transport blocks per TTI.

Associated with each transport block is a *Transport Format* (TF), specifying *how* the transport block is to be transmitted over the radio interface. The transport format includes information about the transport-block size, the modulation scheme, and the antenna mapping. Together with the resource assignment, the resulting code rate can then be derived from the transport format. By varying the transport format, the MAC layer can thus realize different data rates. Rate control is therefore also known as *transport-format selection*.

The following transport channels are defined for LTE:

- *Broadcast Channel* (BCH) has a fixed transport format, provided by the specifications. It is used for transmission of parts of the BCCH system information, more specifically the so-called *Master Information Block* (MIB), as described in Chapter 18.
- *Paging Channel* (PCH) is used for transmission of paging information from the PCCH logical channel. The PCH supports *discontinuous reception* (DRX) to allow the mobile terminal to save battery power by waking up to receive the PCH only at predefined time instants. The LTE paging mechanism is described in Chapter 18.
- *Downlink Shared Channel* (DL-SCH) is the main transport channel used for transmission of downlink data in LTE. It supports key LTE features such as dynamic rate adaptation and channel-dependent scheduling in the time and frequency domains, hybrid ARQ with soft combining, and spatial multiplexing. It also supports DRX to reduce mobile-terminal power consumption while still providing an always-on experience. The DL-SCH is also used for transmission of the parts of the BCCH system information not mapped to the BCH and for single-cell MBMS services.
- *Multicast Channel* (MCH) is used to support MBMS. It is characterized by a semi-static transport format and semi-static scheduling. In case of multi-cell transmission using MBSFN, the scheduling and transport format configuration is coordinated among the cells involved in the MBSFN transmission.
- *Uplink Shared Channel* (UL-SCH) is the uplink counterpart to the DL-SCH, that is the uplink transport channel used for transmission of uplink data.

In addition, the *Random Access Channel* (RACH) is also defined as a transport channel although it does not carry transport blocks.

Part of the MAC functionality is multiplexing of different logical channels and mapping of the logical channels to the appropriate transport channels. The

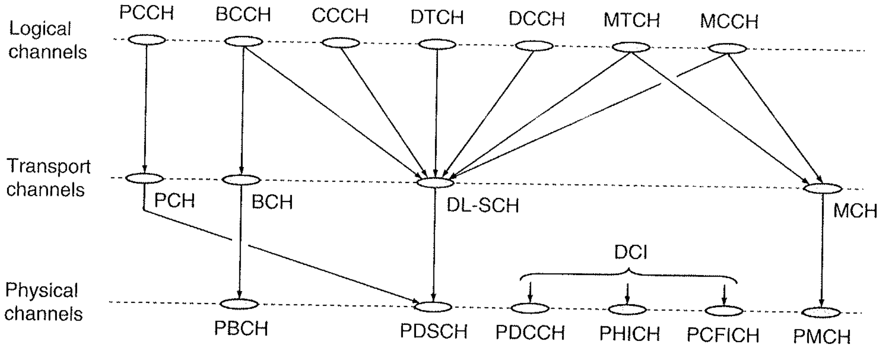

Figure 15.3 *Downlink channel mapping.*

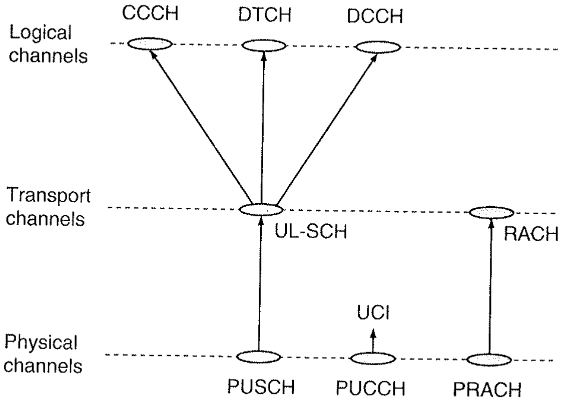

Figure 15.4 *Uplink channel mapping.*

supported mappings between logical channels and transport channels are given in Figure 15.3 for the downlink and Figure 15.4 for the uplink. The figures clearly indicate how DL-SCH and UL-SCH are the main downlink and uplink transport channels, respectively. In the figures, the corresponding physical channels, described further below, are also included and the mapping of transport channels to physical channels is illustrated.

15.2.2 Scheduling

One of the basic principles of the LTE radio access is shared-channel transmission, that is time–frequency resources are dynamically shared between users. The *scheduler* is part of the MAC layer and controls the assignment of uplink and downlink resources. The basic operation of the scheduler is so-called *dynamic* scheduling, where the eNodeB in each 1 ms TTI makes a scheduling decision and sends scheduling information to the selected set of terminals. However, there is also a possibility for semi-persistent scheduling to reduce the control-signaling overhead.

Uplink and downlink scheduling are separated in LTE and uplink and downlink scheduling decisions can be taken independently of each other (within the limits set by the uplink/downlink split in case of half-duplex FDD operation). The terminal follows scheduling commands from a single cell only, the serving cell. This is in contrast to HSPA Enhanced Uplink, where the terminal may follow scheduling information also from non-serving cells in order to control the inter-cell interference. For LTE, inter-cell coordination between different eNodeBs relies on inter-eNodeB signaling over the X2 interface.

The downlink scheduler is responsible for dynamically controlling the terminal(s) to transmit to and, for each of these terminals, the set of resource blocks upon which the terminal's DL-SCH should be transmitted. Transport-format selection (selection of transport-block size, modulation scheme, and antenna mapping) and logical-channel multiplexing for downlink transmissions are controlled by the eNodeB as illustrated in Figure 15.5a. The basic time–frequency unit in the scheduler is a so-called *resource block*. Resource blocks are described in more detail in Chapter 16 in conjunction with the mapping of data to physical resources, but in principle a resource block is a unit spanning 180 kHz in the frequency domain. In each 1 ms scheduling interval, the scheduler assigns resource blocks for DL-SCH

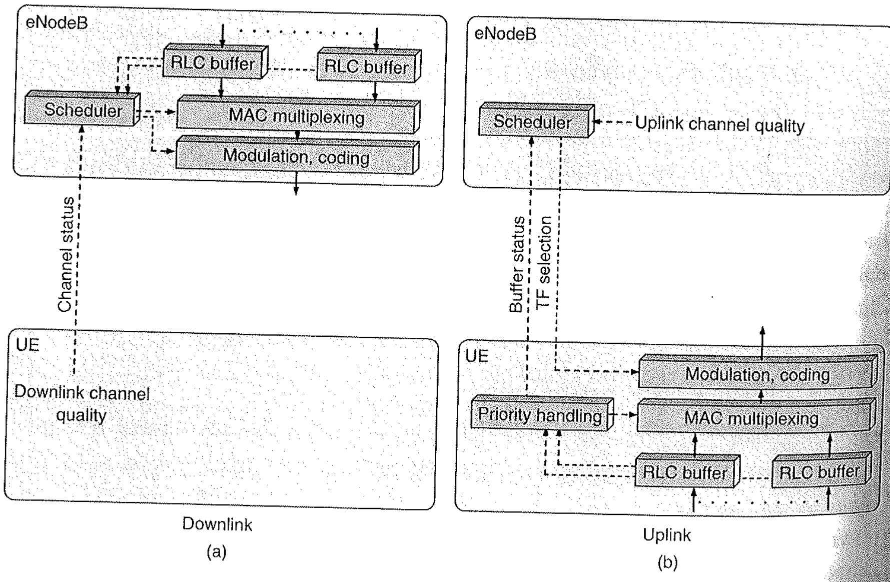

Figure 15.5 *Transport-format selection in (a) downlink and (b) uplink.*

transmission to a terminal, an assignment used by the physical-layer processing as described in Chapter 16. As a consequence of the scheduler controlling the data rate, the RLC segmentation and MAC multiplexing will also be affected by the scheduling decision. The outputs from the downlink scheduler can be seen in Figure 15.1.

The uplink scheduler serves a similar purpose, namely to dynamically control which mobile terminals are to transmit on their UL-SCH and on which uplink time/frequency resources. Despite the fact that the eNodeB scheduler determines the transport format for the mobile terminal, it is important to point out that the uplink scheduling decision is taken *per mobile terminal* and not per radio bearer. Thus, although the eNodeB scheduler controls the payload of a scheduled mobile terminal, the terminal is still responsible for selecting *from which radio bearer(s)* the data is taken. Thus, the mobile terminal autonomously handles logical-channel multiplexing. This is illustrated in Figure 15.5b, where the eNodeB scheduler controls the transport format and the mobile terminal controls the logical-channel multiplexing. The radio-bearer multiplexing in the mobile terminal is done according to rules, the parameters of which can be configured by RRC signaling from the eNodeB. Each radio bearer is assigned a priority and a prioritized data rate. The mobile terminal performs the radio-bearer multiplexing such that the radio bearers are served in priority order up to their prioritized data rate. Remaining resources, if any, after fulfilling the prioritized data rate are given to the radio bearers in priority order.

Although the scheduling strategy is implementation specific and not specified by 3GPP, the overall goal of most schedulers is to take advantage of the channel variations between mobile terminals and preferably schedule transmissions to a mobile terminal on resources with advantageous channel conditions. In this respect, operation of the LTE scheduler is in principle similar to the scheduler in HSPA. However, LTE can exploit channel variations in both frequency *and* time domains, while HSPA can only exploit time-domain variations. This was mentioned already in Chapter 14 and was illustrated in Figure 14.1. For the larger bandwidths supported by LTE, where a significant amount of frequency-selective fading often will be experienced, the possibility for the scheduler to exploit also frequency-domain channel variations becomes increasingly important compared to exploiting time-domain variations only. Especially at low speeds, where the variations in the time domain are relatively slow compared to the delay requirements set by many services, the possibility to exploit also frequency-domain variations is beneficial.

Channel-dependent scheduling is typically used for the downlink. To support this, the mobile terminal transmits *channel-status reports* reflecting the instantaneous channel quality in the time and frequency domains, in addition to information necessary to determine the appropriate antenna processing in case of spatial multiplexing. In principle, channel-dependent scheduling can be used also for the uplink. Channel-quality estimates are in this case based on a *sounding reference signal* transmitted from each mobile terminal for which the eNodeB wants to estimate the uplink channel quality. Such a sounding reference signal is supported by LTE and further described in Chapter 17, but comes at a cost in terms of overhead. Therefore, means to provide uplink diversity as an alternative to uplink channel-dependent scheduling are also supported within LTE. To aid the uplink scheduler in its decisions, the mobile terminal can transmit buffer-status information to the eNodeB using a MAC message. Obviously, this information can only be transmitted if the mobile terminal has been given a valid scheduling grant. For situations when this is not the case, an indicator that the mobile terminal needs uplink resources is provided as part of the uplink L1/L2 control-signaling structure, see further Chapter 17.

Interference coordination, which tries to control the inter-cell interference on a slow basis as mentioned in Chapter 14, is also part of the scheduler. As the scheduling strategy is not mandated by the specifications, the interference-coordination scheme (if used) is vendor specific and may range from simple higher-order reuse deployments to more advanced schemes. The mechanisms used to support inter-cell interference coordination are discussed in Chapter 19.

15.2.3 Hybrid ARQ with soft combining

Hybrid ARQ with soft combining serves a similar purpose for LTE as for HSPA – to provide robustness against transmission errors. As hybrid-ARQ retransmissions are fast, many services allow for one or multiple retransmissions, thereby forming an implicit (closed loop) rate-control mechanism. In the same way as for HSPA, the hybrid-ARQ protocol is part of the MAC layer, while the actual soft combining is handled by the physical layer.[4]

Obviously, hybrid ARQ is not applicable for all types of traffic. For example, broadcast transmissions, where the same information is intended for multiple users, typically do not rely on hybrid ARQ. Hence, hybrid ARQ is only supported for the DL-SCH and the UL-SCH.

The LTE hybrid-ARQ protocol is similar to the corresponding protocol used for HSPA, that is multiple parallel stop-and-wait processes are used. Upon reception

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[4] The soft combining is done before or as part of the channel decoding which is clearly a physical-layer functionality.

of a transport block, the receiver makes an attempt to decode the transport block and informs the transmitter about the outcome of the decoding operation through a single acknowledgement bit indicating whether the decoding was successful or if a retransmission of the transport block is required. Further details on transmission of hybrid-ARQ acknowledgements are found in Chapters 16, 17, and 19. Clearly, the receiver must know to which hybrid-ARQ process a received acknowledgement is associated. This is solved using the same approach as in HSPA, namely to use the timing of the acknowledgement for association with a certain hybrid-ARQ process. Note that, in case of TDD operation, the time relation between the reception of data in a certain hybrid-ARQ process and the transmission of the acknowledgement is also affected by the uplink/downlink allocation.

The use of multiple parallel hybrid-ARQ processes, illustrated in Figure 15.6, for each user can result in data being delivered from the hybrid-ARQ mechanism out-of-sequence. For example, transport block 5 in the figure was successfully decoded before transport block 1, which required retransmissions. In-sequence delivery of data is therefore ensured by the RLC layer. In contrast, HSPA, which is an add-on to WCDMA, handles reordering in the MAC layer as the RLC was kept unchanged for compatibility reasons as discussed in Chapter 9. For LTE, on the other hand, the protocol layers are all designed jointly, implying fewer restrictions in the design.

Similarly to HSPA, an asynchronous protocol is the basis for downlink hybrid-ARQ operation. Hence, downlink retransmissions may occur at any time after the initial transmission and an explicit hybrid-ARQ process number is used to indicate which process is being addressed. In an asynchronous hybrid-ARQ protocol, the retransmissions are in principle scheduled similarly to the initial transmissions. Uplink retransmissions, on the other hand, are based on a synchronous protocol and the retransmission occurs at a predefined time after the initial transmission and the process number can be implicitly derived. In a synchronous protocol the time instant for the retransmissions is fixed once the initial transmission has been scheduled, which must be accounted for in the scheduling operation. However, note that the scheduler knows from the hybrid-ARQ entity in the eNodeB whether a mobile terminal will do a retransmission or not.

The hybrid-ARQ mechanism will rapidly correct transmission errors due to noise or unpredictable channel variations. As discussed above, the RLC is also capable of requesting retransmissions, which at first sight may seem unnecessary. However, the reason for having two retransmission mechanisms on top of each other can be seen in the feedback signaling – hybrid ARQ provides fast retransmissions but due to errors in the feedback the residual error rate is typically too

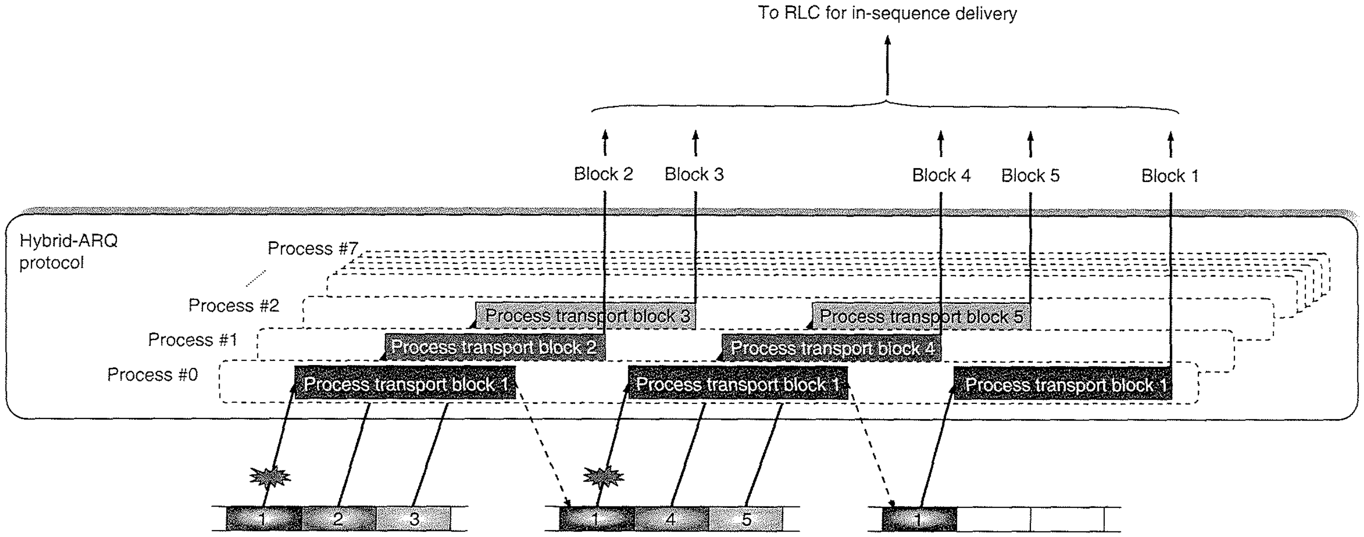

Figure 15.6 *Multiple parallel hybrid-ARQ processes.*

high for good TCP performance, while RLC ensures (almost) error-free data delivery but slower retransmissions than the hybrid-ARQ protocol. Hence, the combination of hybrid ARQ and RLC attains a good combination of small round-trip time and reliable data delivery where the two components complement each other. Furthermore, as the RLC and hybrid ARQ are located in the same node, tight interaction between the two is possible as discussed in Chapter 19.

15.3 Physical layer

The physical layer is responsible for coding, physical-layer hybrid-ARQ processing, modulation, multi-antenna processing, and mapping of the signal to the appropriate physical time–frequency resources. It also handles mapping of transport channels to physical channels as shown in Figure 15.4. A simplified overview of the processing for the DL-SCH is given in Figure 15.7.

As mentioned already in the introduction, the physical layer offers services to the MAC layer in the form of transport channels. In the downlink, the DL-SCH is the main channel for data transmission and is assumed in the description below but the processing for PCH and MCH is similar. In each TTI, there is at most one (two in case of spatial multiplexing) transport blocks.

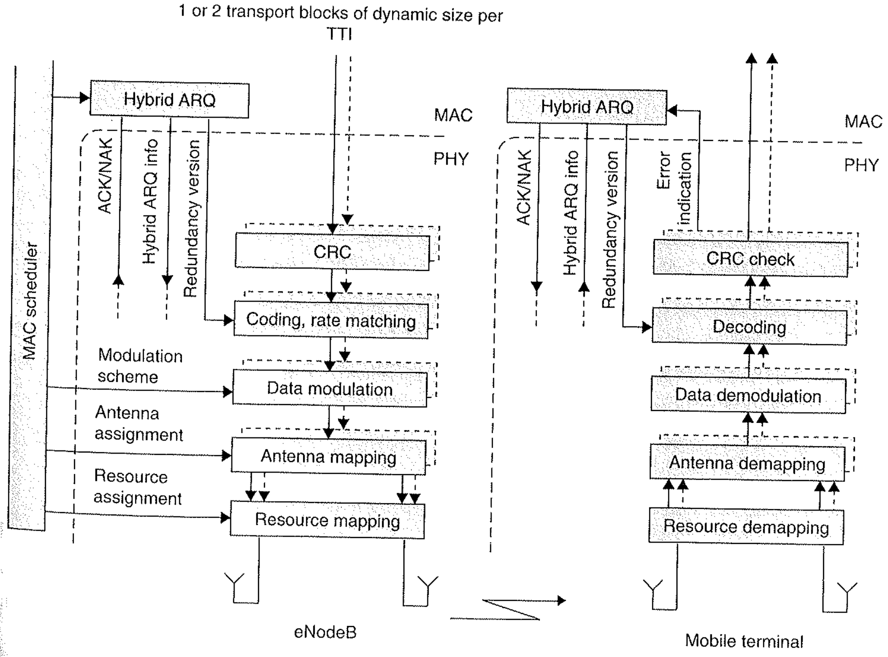

Figure 15.7 *Simplified physical-layer processing for DL-SCH.*

To the transport block(s) to transmit on the DL-SCH, a CRC, used for error detection in the receiver, is attached, followed by Turbo coding for error correction. In case of spatial multiplexing, the processing is duplicated for each of the transport blocks. Rate matching is used not only to match the number of coded bits to the amount of resources allocated for the DL-SCH transmission, but also to generate the different redundancy versions as controlled by the hybrid-ARQ protocol.

After rate matching, the coded bits are modulated using QPSK, 16QAM, or 64QAM, followed by antenna mapping. The antenna mapping can be configured to provide different multi-antenna transmission schemes including transmit diversity, beam-forming, and spatial multiplexing. Finally, the output of the antenna processing is mapped to the physical resources used for the DL-SCH. The resources, as well as the transport-block size and the modulation scheme, are under control of the scheduler.

The physical-layer processing for the UL-SCH follows closely the processing for the DL-SCH. However, note that the MAC scheduler in the eNodeB is responsible for selecting the mobile-terminal transport format and resources to be used for uplink transmission as described in Section 15.2.2. Furthermore, the uplink does not support spatial multiplexing and consequently there is no antenna mapping in the uplink.

A *physical channel* corresponds to the set of time–frequency resources used for transmission of a particular transport channel and each transport channel is mapped to a corresponding physical channel as shown in Figures 15.3 and 15.4. In addition to the physical channels with a corresponding transport channel, there are also physical channels without a corresponding transport channel. These channels, known as L1/L2 control channels, are used for downlink control information (DCI), providing the terminal with the necessary information for proper reception and decoding of the downlink data transmission, and uplink control information (UCI) used for providing the scheduler and the hybrid-ARQ protocol with information about the situation in the terminal.

The physical-channel types defined in LTE include the following:

- *Physical Downlink Shared Channel* (PDSCH) is the main physical channel used for unicast transmission, but also for transmission of paging information.
- *Physical Broadcast Channel* (PBCH) caries part of the system information, required by the terminal in order to access the network.
- *Physical Multicast Channel* (PMCH) is used for MBSFN operation.

- *Physical Downlink Control Channel* (PDCCH) is used for downlink control information, mainly scheduling decisions, required for reception of PDSCH and for scheduling grants enabling transmission on the PUSCH.
- *Physical Hybrid-ARQ Indicator Channel* (PHICH) carries the hybrid-ARQ acknowledgement to indicate to the terminal whether a transport block should be retransmitted or not.
- *Physical Control Format Indicator Channel* (PCFICH) is a channel providing the terminals with information necessary to decode the set of PDCCHs. There is only one PCFICH in each cell.
- *Physical Uplink Shared Channel* (PUSCH) is the uplink counterpart to the PDSCH. There is at most one PUSCH per terminal.
- *Physical Uplink Control Channel* (PUCCH) is used by the terminal to send hybrid-ARQ acknowledgements, indicating to the eNodeB whether the downlink transport block(s) was successfully received or not, to send channel-status reports aiding downlink channel-dependent scheduling, and for requesting resources to transmit uplink data upon. There is at most one PUCCH per terminal.
- *Physical Random Access Channel* (PRACH) is used for random access as described in Chapter 18.

The mapping between transport channels and physical channels was illustrated in Figures 15.3 and 15.4. Note that some of the physical channels, more specifically the channels used for downlink control information (PCFICH, PDCCH, PHICH) and uplink control information (PUCCH), do not have a corresponding transport channel.

The remaining downlink transport channels are based on the same general physical-layer processing as the DL-SCH, although with some restrictions in the set of features used. For the broadcast of system information on the BCH, a mobile terminal must be able to receive this information channel as one of the first steps prior to accessing the system. Consequently, the transmission format must be known to the terminals a priori and there is no dynamic control of any of the transmission parameters from the MAC layer in this case.

For transmission of paging messages on the PCH, dynamic adaptation of the transmission parameters can to some extent be used. In general, the processing in this case is similar to the generic DL-SCH processing. The MAC can control modulation, the amount of resources, and the antenna mapping. However, as an uplink has not yet been established when a mobile terminal is paged, hybrid ARQ cannot be used as there is no possibility for the mobile terminal to transmit a hybrid-ARQ acknowledgement.

The MCH is used for MBMS transmissions, typically with single-frequency network operation as described in Chapter 4 by transmitting from multiple cells on the same resources with the same format at the same time. Hence, the scheduling of MCH transmissions must be coordinated between the involved cells and dynamic selection of transmission parameters by the MAC is not possible.

15.4 Terminal states

In LTE, a mobile terminal can be in two different states as illustrated in Figure 15.8. RRC_CONNECTED is the state used when the mobile terminal is active. In this state, the mobile terminal is connected to a specific cell within the network. One or several IP addresses have been assigned to the mobile terminal, as well as an identity of the terminal, the *Cell Radio-Network Temporary Identifier* (C-RNTI), used for signaling purposes between the mobile terminal and the network. Although expressed differently in the specifications, RRC_CONNECTED can be said to have two substates, IN_SYNC and OUT_OF_SYNC, depending on whether the uplink is synchronized to the network or not. Since LTE uses an orthogonal FDMA/TDMA-based uplink, it is necessary to synchronize the uplink transmission from different mobile terminals such that they arrive at the receiver at (approximately) the same time. The procedure for obtaining and maintaining uplink synchronization is described in Chapter 19 but in short the receiver measures the arrival time of the transmissions from each actively transmitting mobile terminal and sends timing-correction commands in the downlink. As long as the uplink is synchronized, uplink transmission of user data and L1/L2 control signaling is possible. In case no uplink transmission has taken place within a given time window, timing alignment is obviously not possible and the uplink is declared to be non-synchronized. In this case, the mobile terminal needs to perform a random-access procedure to restore uplink synchronization.

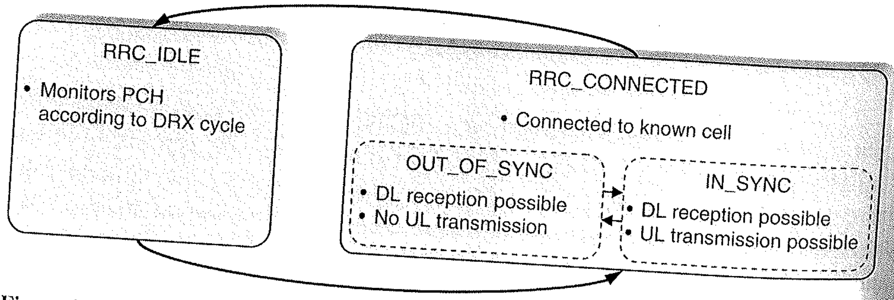

Figure 15.8 *LTE states.*

RRC_IDLE is a low activity state in which the mobile terminal sleeps most of the time in order to reduce battery consumption. Uplink synchronization is not maintained and hence the only uplink transmission activity that may take place is random access to move to RRC_CONNECTED. In the downlink, the mobile terminal can periodically wake up in order to be paged for incoming calls as described in Chapter 18. The mobile terminal keeps its IP address(es) and other internal information in order to rapidly move to RRC_CONNECTED when necessary.

15.5 Data flow

To summarize the flow of downlink data through all the protocol layers, an example illustration for a case with three IP packets, two on one radio bearer and one on another radio bearer, is given in Figure 15.9. The data flow in case of uplink transmission is similar. The PDCP performs (optional) IP header compression, followed by ciphering. A PDCP header is added, carrying information required for deciphering in the mobile terminal. The output from the PDCP is fed to the RLC.

The RLC protocol performs concatenation and/or segmentation of the PDCP SDUs and adds an RLC header. The header is used for in-sequence delivery (per logical channel) in the mobile terminal and for identification of RLC PDUs in case of retransmissions. The RLC PDUs are forwarded to the MAC layer, which takes a number of RLC PDUs, assembles those into a MAC SDU, and attaches the MAC header to form a transport block. The transport-block size depends on the instantaneous data rate selected by the link adaptation mechanism. Thus, the link adaptation affects both the MAC and RLC processing. Finally, the physical layer attaches a CRC to the transport block for error-detection purposes, performs coding and modulation, and transmits the resulting signal over the air.

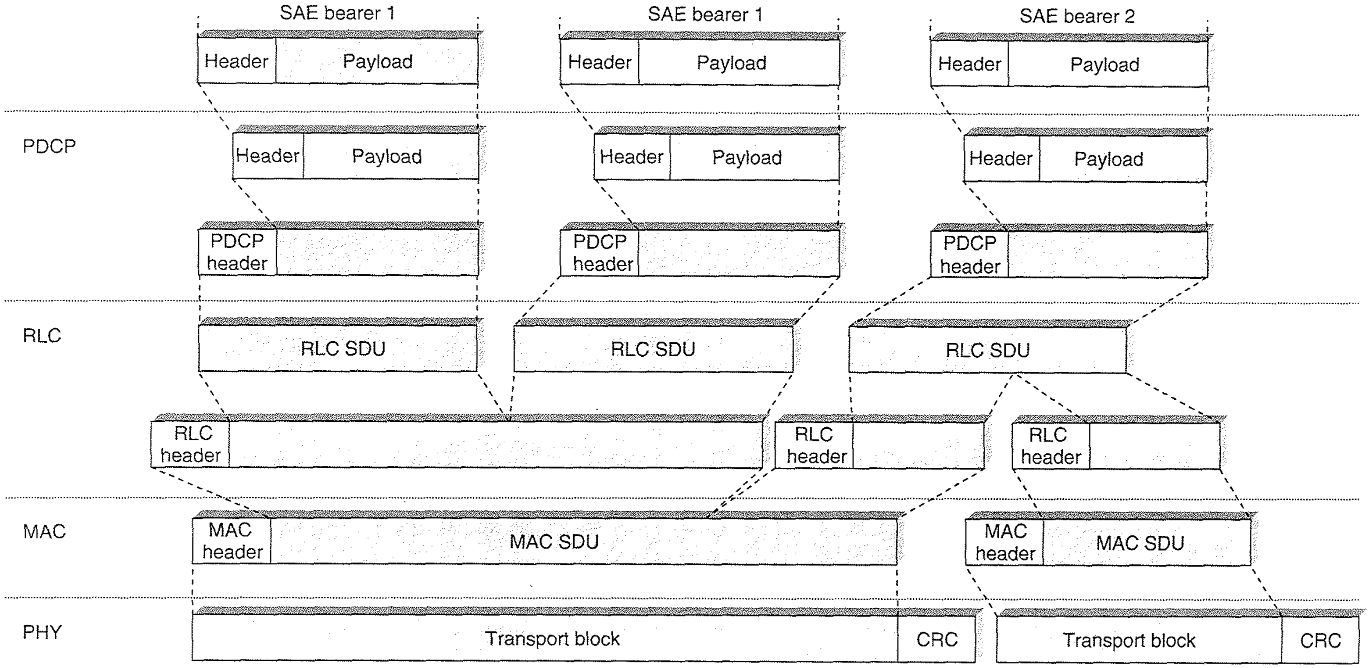

Figure 15.9 *Example of LTE data flow.*