Radio Protocols for LTE and LTE-Advanced

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Foreword

Back in 2004, 3G mobile communication systems providing high-speed Internet access were available, such as HSPA. At that time, the introduction of HSPA was considered a key enabler for 3G systems to meet market demand and remain competitive against other systems for a number of years. Looking forward into the future, however, multimedia and ubiquitous traffic were expected to grow rapidly. To support future traffic growth and maintain competitiveness, many operators shared the strong intention to evolve the 3G system with a long-term perspective. Driven by these motivations, 3GPP started specification work for Long-Term Evolution based on the 3G system and completed the work in Release 8 specifications.

The advent of high-performance smartphones opened a new era of opportunities for service providers and customers in the mobile industry. The rapid adoption of smartphones motivated customers towards the experiences of rich multimedia services including broadband mobile Internet. As a result, mobile traffic has increased explosively in an unprecedented manner, often approaching the network capacity of the existing mobile network, which has given mobile operators a strong incentive to pursue more aggressive strategies for evolution of the mobile network.

With this in mind, LTE is the central focus of the mobile industry, as LTE is the most promising technology on the market. For mobile operators running GSM/UMTS systems, LTE is a natural choice for their future networks. Even operators deploying 2G/3G CDMA systems are choosing the LTE system as their future network, because LTE is the only viable option for their survival. In this sense, LTE is a truly global mobile communication system that will cover almost all of the world. Currently, more than two hundred mobile operators are planning or are already deploying an LTE system.

The unique value of this book is that readers can gain in-depth understanding, especially on the radio protocols of the LTE system. While most other books on LTE focus on Physical layer aspects, this book distinctively focuses on providing sufficient knowledge of the radio protocols of the LTE system. The worth of this book is also found in the intensive treatment given to the technologies of LTE-Advanced. Most up-to-date issues and technologies in terms of LTE radio protocols are explained with fruitful figures and examples to aid readers' understanding.

All the authors have been actively involved in the standardization of radio protocols in 3GPP. The expertise of the authors has already been proven by their active contribution to the development of UMTS, HSPA, LTE, and LTE-Advanced systems. These experts are in a perfect position to take readers forward by explaining to them not only how the LTE system works but also why the system is designed in that way. Furthermore, the authors are currently participating in LTE-Advanced standardization; thus, readers can also ascertain the main issues, direction of enhancement, and the details of LTE-Advanced covered by this book.

The publication of this book is fortunate for those who want to understand how the LTE system really works, because the well-organized contents of this book will guide readers to reach a thorough understanding of the various aspects of LTE radio protocols such as design principles, architectures, and functions. If readers are already familiar with the Physical layer or the core network of LTE, this book will also provide a chance to bridge their knowledge of one part with knowledge of the other parts, such that those readers can reach a complete understanding of the LTE system.

Takehiro Nakamura
3GPP TSG RAN Chairman
NTT DOCOMO Inc.

Preface

It was only a few years ago that "ubiquitous connectivity" was recognized as the future of wireless communication systems. In the era of ubiquitous connectivity, it was expected that the broadband mobile Internet experience would be pervasive, and seamless connectivity on a global scale would be no surprise at all. The quality of service would be guaranteed no matter when/where/what the users wanted with the connectivity. Connectivity would even be extended to object-to-object communication, where no human intervention was required. All objects would become capable of autonomous communication.

Looking around at life today, those expectations are no longer what we imagine for the future, but what we already experience – ubiquitous connectivity is becoming reality. We are living in the era of this ongoing revolution of connectivity.

The revolution has been accelerated by the recent monumental enhancement of mobile communication technologies. At the center of the enhancement is the LTE system. It is well known that the development of the initial LTE specifications was completed within an unprecedented tight time schedule. During the course of development of the specifications, all the mobile business sectors including global mobile operators, network vendors, and terminal/chipset vendors have made tremendous efforts with regard to the standardization working process. The success of the LTE system as a truly global mobile communication standard is being proven by the mobile ecosystem whereby the LTE system is proliferating rapidly throughout the world. The success of the LTE ecosystem on a grand scale is fueling the rollout of the revolution towards ubiquitous connectivity.

The possibility of ubiquitous connectivity presents new business opportunities in terms of services. Keen-sighted readers will already recognize that the LTE system should be considered an "enabler" of the services we wish to enjoy, rather than simply a high-performance communication system. For key players in the mobile sector and associated industry, it is very important to understand the LTE system as an enabling technology.

The current design of the LTE system is the result of the 3GPP standardization working process, which comprises long courses of discussion and decision making. Often, not even a single decision meets with unanimous agreement among the companies participating in the standardization process. Many of the decisions are the result of discussions and compromises between the gains achievable and the costs and complexity incurred.

In principle, since specifications are collections of these decisions, they should be written in a neutral and ambiguity-free manner – that is, specifications only specify "minimum requirements." Specifications do not explain more than the minimum required to avoid violating neutrality. For this reason, readers often feel that specifications are rather closed and unrevealing.

A couple of books on LTE and LTE-Advanced are available on the market, offering readers information complementary to the specifications. However, when readers flick through such books, they will almost invariably notice that most of the pages in them are allocated to explaining the operations of the Physical layer. Only a small portion, if anything at all, is dedicated to giving descriptions of the radio protocols that work beyond the Physical layer. Such a treatment is insufficient for readers thirsty for a complete understanding of LTE radio protocols.

From an end-to-end communication point of view, the radio protocols contribute to the essential parts of operations and signaling that enable the user service with the LTE system. For example, connection control, mobility management, radio resource management, and user data transfer between the mobile terminal and the network are all controlled by radio protocols. Therefore, for the reader who is eager to view the complete picture of the LTE system, it is essential to obtain precise knowledge of the LTE radio protocols.

The main motivation behind this book is to quench the thirst of those readers by focusing on the LTE radio protocols. The details of each LTE Release 8 radio protocol are given in the first half of the book, by explaining how the terminal and the network interact over the radio interface in terms of both user data transfer and control signaling. Readers' understanding of LTE radio protocols can then be solidified when the enhanced technologies and services introduced in LTE Releases 9/10 are presented in the second half of the book, with useful figures to aid readers' understanding. It should be noted that this book only gives a guide to understanding the LTE radio protocols based on the authors' knowledge. Readers who want to have definitive information should also refer to the specifications published by 3GPP.

It is the authors' desire that this book will help to guide readers to a more complete understanding of the LTE system by combining the core of LTE radio protocols presented in this book with readers' knowledge of the Physical layer and the core network obtained elsewhere. As contributors to the LTE specifications, the authors are pleased with the current LTE system, which is already enabling services of which we only ever dreamed. Bearing in mind that the LTE system is still on its evolutionary path, we strongly believe that the timely publication of this book will make it possible for its readers to become the next-step enablers of services and technologies of which they only ever dreamed and that we never imagined.

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SungJun Park
SungHoon Jung

About the Authors

SeungJune Yi holds an MS degree in Electronics Engineering from Seoul National University. He joined LG Electronics in 1999, and has been actively participating in 3GPP TSG RAN Working Group 2 since 2000, contributing hundreds of papers for UMTS, HSDPA, HSUPA, MBMS, LTE, and LTE-Advanced. He has also participated in 3GPP TSG RAN Plenary as a leader of the Radio Protocol Standard team in LG Electronics. He has been the Rapporteur of the LTE PDCP specification (TS36.323) from 2008, and he has been a Vice Chairman of RAN WG2 from August 2011. He is the inventor of hundreds of patents, and won the "Inventor of the Year in LG Electronics" award in 2000, 2002, and 2008. From the Korean Intellectual Property Office, he won the "Patent Technology Award" in 2009, and was awarded "Inventor of the Year in Korea" in 2010. From 2008, he participated in the book *LTE: The UMTS Long Term Evolution* as a section author of "User Plane Protocols."

SungDuck Chun holds an MBA degree from Sloan School of Management at the Massachusetts Institute of Technology in MA, USA, and a BS degree in Electric Engineering from Seoul National University in Seoul. He studied at the Mobile Communication Laboratory at SNU for an MS degree. After joining LG Electronics in 2000, he is now Chief Research Engineer, and has been actively participating in the standardization of HSDPA, HSUPA, MBMS, LTE, and LTE-Advanced, with hundreds of contributions to 3GPP. After successfully leading the standardization activities of LG Electronics, he has been awarded "High Performance Individual" with career development opportunities. He also led several projects on the software and hardware development of mobile handsets for both the UMTS system and the CDMA system, and participated and consulted in the Bench Mark Test with telecom operators. He participated in the book *LTE: The UMTS Long Term Evolution* as a section author of "User Plane Protocols."

YoungDae Lee received an MS degree in Electronics Engineering from the Seoul National University in 1998. He joined LG Electronics (Anyang, South Korea) in 1998, and has been actively participating in 3GPP since 1999, contributing hundreds of technical documents for the standardization of W-CDMA, HSPA, MBMS, LTE, and LTE-Advanced in 3GPP TSG RAN Working Groups 1, 2, and 3, and 3GPP TSG RAN Plenary. He led the Radio Protocol Standard team in LG Electronics from 2004 to 2006, and worked in LG Electronics Mobilecomm France (Villepinte, France) as a Senior Standard Manager from 2007 to 2010. He was the Rapporteur of the "feasibility study on improvement of the MBMS in UTRAN (TS25.905)" and participated in the specification of the LTE Stage 2 as an editor of the

MBMS section (TS36.300 section 15). He was awarded “Inventor of the Year in LG Electronics” in 2000. From 2008, he participated in the book *LTE: The UMTS Long Term Evolution* as a section author of “User Plane Protocols.”

SungJun Park graduated from Hanyang University, Korea in 2003 and received an MS degree in Computer Science Engineering from the same university in 2005. He is currently a Senior Research Engineer at LG Electronics and has been participating in standardization efforts for 3GPP since 2005. He has made numerous contributions to HSUPA, LTE, and LTE- Advanced.

SungHoon Jung holds an MS degree in Electronics Engineering from the Korean Advanced Institute of Science and Technology (KAIST) and a BS degree from Yonsei University in Seoul. After joining LG Electronics in 2007, he is now a Senior Research Engineer. He has been actively participating in the standardization of radio protocols for LTE and LTE-Advanced in 3GPP TSG RAN Working Group 2. His research focus spans a variety of issues such as radio resource control, mobility management, network performance optimization, femto cells, Voice over LTE, and various technologies for heterogeneous networks.

1

Introduction

In recent years, the world has seen many changes in terms of how we experience wireless communication. A few years ago, when we talked about wireless cellular communication, we usually meant voice calls through a small handset device or text exchange called Short Message Service (SMS). However, with the wide penetration of smartphones and tablet PCs, people are starting to see possibilities beyond simple voice and text calls. Any time, anywhere, and any place, people can now connect to the Internet to receive up-to-date information such as the latest news, weather information, stock price quotes, traffic information, map data, and so on. The number of applications accessing the Internet is growing rapidly and the bandwidth that these applications require is also growing rapidly. As the use of the Internet through wireless connectivity increases explosively, wireless communication systems are required to provide not just simple connectivity to the Internet but also broadband experiences.

1.1 3GPP

3GPP is an acronym for 3rd Generation Partnership Project [1], which has its roots in the Global System for Mobile Communications (GSM). As the name suggests, the original work scope of 3GPP was to produce technical specifications for the 3G wireless system. The intended 3G wireless system was an evolutionary step from the legacy GSM system, and many functional and network elements of the intended system were to be adopted from the legacy GSM system. In the end, the scope of 3GPP was expanded to include the maintenance and development of the technical specifications for GSM.

3GPP is an entity comprising multiple Organization Partners (OPs) around the world, the goal of whom is to develop a globally adopted standard of wireless communication. GSM, which is one of the 2nd generation wireless systems, is also a collaborative outcome of multiple companies from multiple countries. However, because standardization and development activity for GSM were confined originally to Europe, GSM cannot be recognized as a truly global standard. In fact, in the timeframe of development of 2nd generation communication systems, there were several efforts to standardize and develop a wireless communication system in each geographical region, resulting in the development of multiple standards such as IS-95, GSM, PDC, and so on. To develop a wireless communication standard that would be

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adopted in most countries, it was deemed necessary to include all regional standardization entities under one roof. The motivation was that one global telecommunication standard would make it easier for people to travel anywhere with continued availability of their wireless service. It would also facilitate easy and low-cost development of wireless handsets and equipment. With these intentions in mind, 3GPP was formed to develop one unified communication standard by including as many regional Standards Development Organizations (SDOs) as possible.

The following SDOs participate in 3GPP:

- **Association of Radio Industries and Business (ARIB):** This public service corporation was chartered by the Ministry of Posts and Telecommunications of Japan in 1995. Its main role is to conduct investigation, research, and development of radio systems.
- **Alliance for Telecommunications Industry Solution (ATIS):** This standardization organization consists of more than 200 companies which have operations in North America. ATIS is accredited by the American National Standards Institute (ANSI).
- **China Communications Standard Association (CCSA):** This standardization organization was established with the approval of the Ministry of Information Industry of China and registered with the Ministry of Civil Affairs of China in 2002.
- **European Telecommunications Standards Institute (ETSI):** ETSI is a standardization organization for telecommunication industries in Europe, with more than 700 members. ETSI was created by the European Conference of Postal and Telecommunications Administrations (CEPT) in 1977 and is officially recognized by the European Commission.
- **Telecommunications Technology Association (TTA):** This organization in Korea was established in 1988 by civil law. Its major activities are planning, establishment, and certification of standards.
- **Telecommunication Technology Committee (TTC):** This standardization organization was established by the Ministry of Internal Affairs and Communication of Japan to research and develop standards for telecommunication.

In terms of structure, 3GPP consists of a Project Co-ordination Group (PCG) and Technical Specification Groups (TSGs), as shown in Figure 1.1.

The PCG is the highest decision-making body within 3GPP and its main responsibility is to ensure that the 3GPP specification is produced in a timely manner according to market requirements. In addition, the PCG approves final adoption of each TSG's work items, ratifies the election results of subordinate groups, and allocates the human and financial resources to TSGs.

The TSGs are in charge of the development of technical specifications by preparing, approving, and maintaining the specifications within each TSG's work area. Currently, there are four TSGs:

- **TSG Service and System Aspects (SA):** This TSG defines the overall architecture, requirements, and service capabilities of the systems of 3GPP. This TSG leads other TSGs. For example, this TSG decides whether support for a new service is needed or not, what is the requirement for the service, which working groups should be involved in the standardization, and what should be decided by each working group.

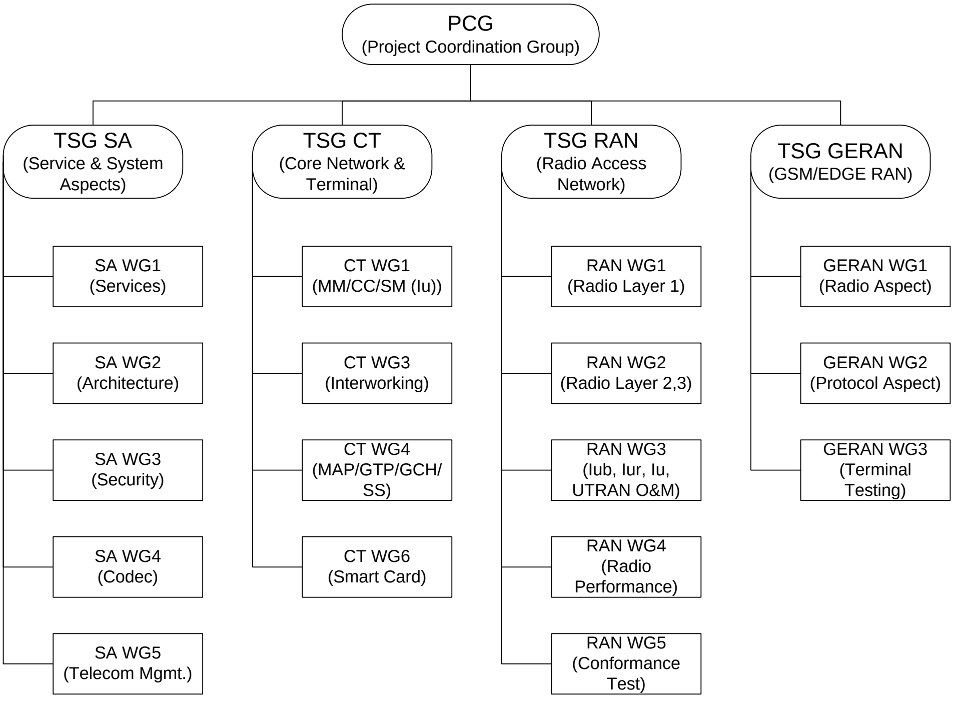

Figure 1.1 Organization chart for 3GPP [2]

- **TSG Core Network and Terminals (CT):** This TSG defines terminal interfaces, terminal capabilities, and the core network part of 3GPP. The former TSG Core Network (CN) and TSG Terminal (T) were merged into TSG CT.
- **TSG Radio Access Network (RAN):** This TSG defines functions, requirements, and interfaces of the UTRAN and the E-UTRAN in FDD and TDD modes. For example, the interface between the UE and the eNB, the interface between the eNBs, and the interface between the eNB and the MME are defined by this TSG.
- **TSG GSM/EDGE Radio Access Network (GERAN):** This TSG defines the specification of the radio access part of GSM/EDGE networks. The specification for the core network part of GSM/EDGE networks is managed within the TSG CT.

Normally, standardization work begins by creating study items or work items in the TSG plenary meeting, which is held once per quarter. Detailed work for work items or study items created in the TSG plenary meeting is undertaken by each working group of the TSG. Each working group discusses proposals submitted by individual members and tries to reach agreement on a consensus basis. For issues which fall outside each working group's expertise, the working group can consult other working groups by sending a Liaison Statement (LS). The agreements made by working groups are then sent to the TSG plenary meeting for final approval. If the agreements are approved in the TSG plenary meeting, they are included in the relevant specifications.

Table 1.1 3GPP specification series

Series	Subject
21	Requirement
22	Service Aspects (Stage 1)
23	Technical Realization (Stage 2)
24	Signaling Protocols (Stage 3) – UE to Network
25	Radio Aspect
26	CODECs
27	Data
28	Signaling Protocols (Stage 3) – RSS-CN and OAM&P and Charging
29	Signaling Protocols (Stage 3) – Intra-Fixed Network
30	Programme Management
31	SIM/USIM, IC Cards, Test Specs
32	OAM&P and Charging
33	Security Aspects
34	UE and USIM Test Specs
35	Security Algorithm
36	LTE and LTE-A Radio Technology
37	Multiple Radio Access Technology Aspects

The Mobile Competence Center (MCC) provides relevant support for making 3GPP specifications. The MCC also provides support for 3GPP meetings, such as planning meeting schedules, providing logistics, managing the IT environment of the meeting, and so on.

Each specification of 3GPP is assigned a specification number consisting of five digits. The first two digits of the specification number, called the *series*, indicate the area to which the specification belongs. A list of specification series is given in Table 1.1.

The specifications for 3GPP systems are developed in releases. Each release includes new features on top of previous releases of that specification. For example, Release 10 of the LTE specification includes support for Carrier Aggregation in addition to Release 8 of the LTE specification. Thus, though 3GPP systems are advanced with new features, backward compatibility is ensured to support UEs of old releases. Backward compatibility means that a UE of older releases can operate on a network of a later release and vice versa.

1.2 Evolutionary Path of 3GPP Systems

3GPP systems are wireless communication systems whose specifications were developed and managed by 3GPP. Examples of 3GPP systems are GSM, GPRS, EDGE, UMTS, HSPA, LTE, and LTE-Advanced. Figure 1.2 shows the evolutionary path of the 3GPP systems. Each of the 3GPP systems is explained briefly in the following sections.

1.2.1 GSM

GSM was developed originally by ETSI from 1982, and the first GSM specification was published in 1990. GSM was put into commercial use from 1991. The GSM system is one of the 2nd generation wireless communication systems and uses digital technologies (TDMA

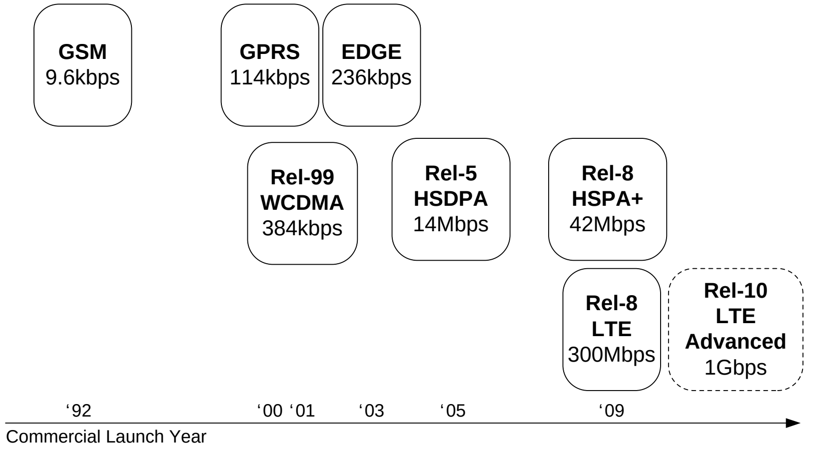

Figure 1.2 Evolution of 3GPP systems

technologies as a baseline; Figure 1.3 shows the overall network architecture of GSM), unlike the 1st generation wireless communication systems, which were based on analog technologies. By including most countries in Europe from the development phase onward, GSM could be adopted widely across Europe and eventually around the world. Now, GSM subscribers make up over 80% of the world population.

The User Equipment (UE) can be regarded as a mobile phone. The UE is composed of the Terminal Equipment (TE), which includes applications and interface to a user, the Mobile Termination (MT), which includes a module for wireless communication, and the Subscriber Identity Module (SIM), which carries information to identify each subscriber. The International Mobile Subscriber Identity (IMSI) is a unique identity that identifies a user, and is

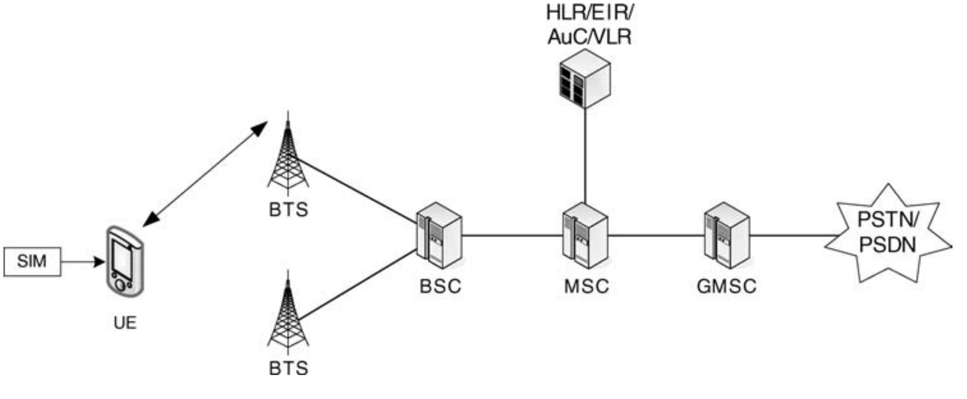

Figure 1.3 Architecture of GSM. Reproduced by permission of 3GPP, © 1998. 3GPP™ TSs and TRs are the property of ARIB, ATIS, CCSA, ETSI, TTA and TTC who jointly own the copyright in them

stored in the SIM card. The International Mobile Equipment Identity (IMEI) is a unique identity that distinguishes each TE from other TEs.

The Base Transceiver Station (BTS) is a network node that wirelessly connects wire-line networks of GSM with a mobile terminal. Thus, the BTS is the border of the radio access network and is in charge of transmitting/receiving radio signals to/from UEs. The BTS performs multiplexing/de-multiplexing, modulation/demodulation, coding/decoding, and so on. The radio interface between the UE and the BTS is called the *Um interface*.

The Base Station Controller (BSC) is a network node that controls the BTS and manages radio resource. The BSC allocates radio channels and controls the mobility of UEs. The interface between the BSC and the BTS is called the *A-bis interface*.

The Mobile Switching Center (MSC) is a network node that controls setup and release of overall connections of services such as voice calls or SMSs. It processes requests for call setup from mobile terminals as well as requests from landlines. The interface between the MSC and the BSC is called the *A interface*.

The Gateway MSC (GMSC) is the MSC that connects the MSC to the Public Switched Telephone Network (PSTN).

The Home Location Register (HLR) manages the information of its subscribers, such as MSISDN, IMSI information, the current location of the UE, and the lists of services that each UE has subscribed to.

The Equipment Identity Register (EIR) manages information related to the status of mobile phones, especially for the information related to IMEI. This status information is used to block the use of unauthorized or stolen mobile phones within the network.

The Authentication Center (AuC) manages the authentication of mobile terminals and the encryption of communication. Based on the agreed parameter between the UE and the network, the AuC generates security keys that will be used to validate the SIM card attached to the UE. The UE will be able to use services only when authentication is completed successfully.

The Visitor Location Register (VLR) manages lists of roaming users within the network. When a UE moves into another operator's network to which it does not subscribe, information about the UE is stored temporarily in the VLR of the visited operator to provide roaming services.

1.2.2 GPRS/EDGE

In terms of resource usage, a circuit-switched service requires a continued allocation of communication resource while the call is ongoing. Thus, the service over a circuit-switched network guarantees a certain level of quality but has limitations in terms of the number of concurrent users. Voice calls are one of the typical services over a circuit-switched network. On the other hand, a packet-switched network uses communication resource per demand, enabling flexible allocation and de-allocation of resource and thereby maximizing the utilization of the resource. Thus, resource to transport data may sometimes not be immediately available, depending on the amount of data generated by users. Internet packets are a typical example of data over a packet-switched network.

The first version of GSM supported only circuit-switched services such as voice calls and SMS. To support packet-switched services such as Internet services, GSM was enhanced to include the General Packet Radio Service (GPRS). Figure 1.4 shows the overall network architecture of the GPRS.

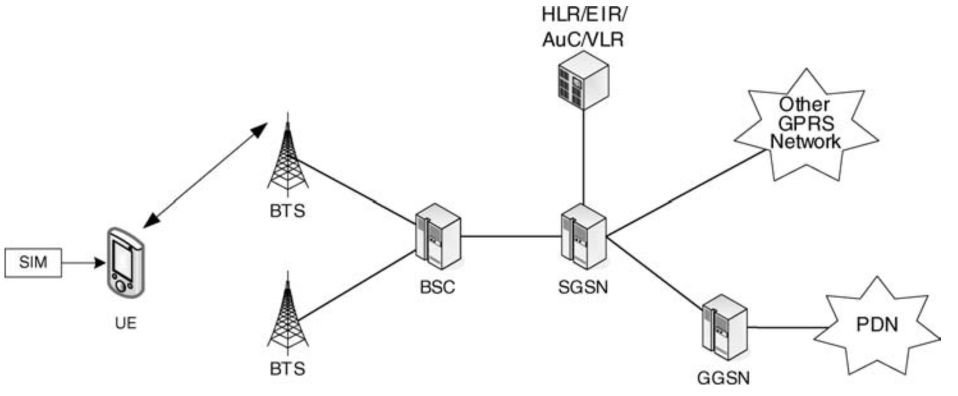

Figure 1.4 Architecture of GPRS. Reproduced by permission of 3GPP, © 2002. 3GPP™ TSs and TRs are the property of ARIB, ATIS, CCSA, ETSI, TTA and TTC who jointly own the copyright in them

To support GPRS, the GSM core network further includes the Serving GPRS Support Node (SGSN) and the Gateway GPRS Support Node (GGSN). The SGSN is in charge of packet routing, mobility management, authentication, and so on. The GGSN is in charge of connecting the GPRS network to the external network. When packets generated outside of the GPRS networks arrive at the GGSN, the GGSN captures the packets and delivers them to the UE. When packets are generated by the UE, they are delivered to the GGSN via the BSC and the SGSN, and the GGSN eventually transfers the packets outside the PDN.

Enhanced Data rates for GSM Evolution (EDGE) is an extension of the GSM/GPRS network to provide an even higher data rate service. While EDGE uses the same core network elements as GPRS, it provides a higher data rate with support for higher modulation and coding schemes enabled by upgrades in the radio access network.

1.2.3 UMTS

The Universal Mobile Telecommunication System (UMTS) is one of the 3rd generation wireless communication systems. While GSM is based on TDMA, the radio access part of UMTS is based on Wideband CDMA (WCDMA), which uses Direct Sequence CDMA (DS-CDMA) technologies. The radio access network of UMTS is called the UMTS Terrestrial Radio Access Network (UTRAN). Because UMTS shares the same core network as GSM/GPRS, major changes compared to GSM/GPRS have been made on the radio access network. In particular, the Base Station Controller (BSC) and the Base Transceiver Station (BTS) of the GSM network cannot be used in UMTS, and thus Node B and the Radio Network Controller (RNC) are deployed instead in UMTS. The architecture of UMTS is shown in Figure 1.5.

The first version of the UMTS specification, called Release 99, was published in March 2000. The commercial service of UMTS was launched in 2002, and it has been deployed successfully all around the world subsequently.

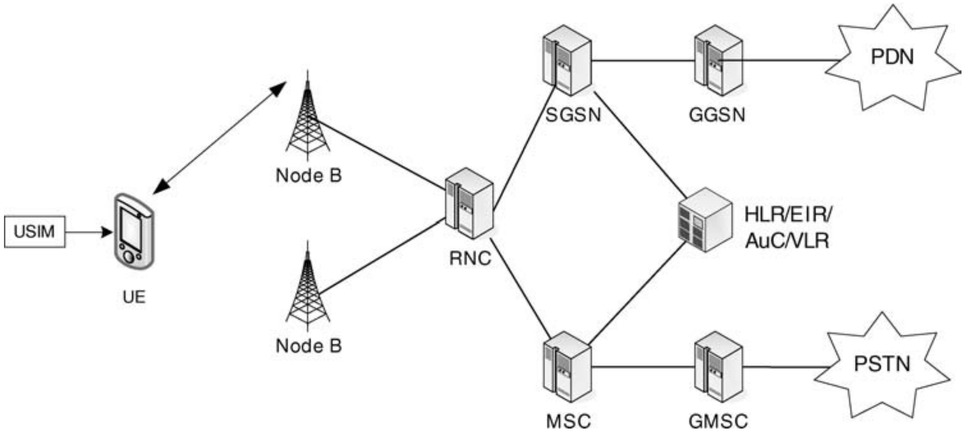

Figure 1.5 Architecture of UMTS. Reproduced by permission of 3GPP, © 2011. 3GPP™ TSs and TRs are the property of ARIB, ATIS, CCSA, ETSI, TTA and TTC who jointly own the copyright in them

The RNC is in charge of controlling radio resource and mobility of the UE. Like GSM/GPRS, the RNC is connected to the MSC for circuit-switched services, and to the SGSN for packet-switched services. The RNC is also connected to Node B to control it. Node B is in charge of transmission and reception of radio signals to/from the UE.

1.2.4 HSPA

UMTS Release 99 – that is, the first release of UMTS – provided a maximum bit rate of 384 Kbps to a single user. To support a higher data rate, High Speed Downlink Packet Access (HSDPA) was introduced in Release 5. In Release 5, a new channel called the High Speed Downlink Shared Channel (HS-DSCH) was introduced together with various techniques such as adaptive modulation, 16 QAM, and HARQ to provide a higher data rate up to 14 Mbps. In Release 6, not only the downlink direction, but also the uplink direction was enhanced via High Speed Uplink Packet Access (HSUPA). A new channel called the Enhanced DCH (E-DCH) was introduced in the uplink to support a peak data rate up to 7 Mbps. Recently, HSDPA and HSUPA have been merged into one term, High Speed Packet Access (HSPA).

From Release 5, downlink and uplink throughputs have been enhanced one by one for each release. The enhanced version of HSPA is called HSPA+. In HSPA+, further enhanced techniques such as 64 QAM, Multiple-Input Multiple-Output (MIMO), and multiple carriers support an increased data rate up to 84 Mbps.

Figure 1.6 shows the difference in protocol termination between Release 99 DCH and Release 5 HS-DSCH. Compared to Release 99 DCH, Release 5 HS-DSCH is better for fast scheduling in that a new MAC entity, called MAC-hs, is located in Node B to perform dynamic scheduling of UEs.

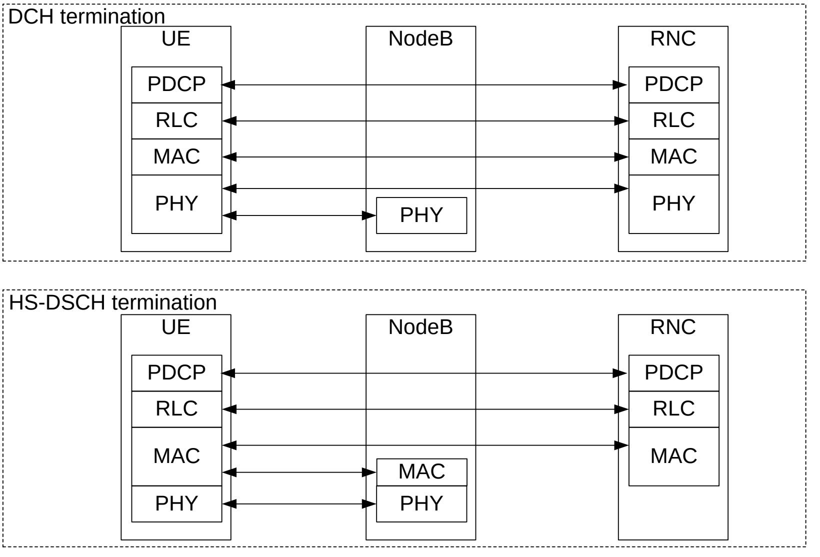

Figure 1.6 Protocol termination of DCH (Release 99) and HS-DSCH (Release 5). Reproduced by permission of 3GPP, © 2010. 3GPP^{TM} TSs and TRs are the property of ARIB, ATIS, CCSA, ETSI, TTA and TTC who jointly own the copyright in them

1.2.5 LTE

LTE, the Long-Term Evolution of UMTS, is the latest extension in the evolutionary path of 3GPP systems [3]. The study of LTE started in 2004, at which time the name LTE indicated a work item focusing on the potential evolution of UMTS. However, the simple sound of "LTE" fascinated many people, and hence it became the brand name of a new wireless communication system.

The radio access network in LTE is called Evolved UTRAN (E-UTRAN) compared with the UTRAN in UMTS. When the radio access network of 3GPP was upgraded from GSM to UMTS, there were not many changes in the core network. However, when the radio access network was enhanced from UMTS to LTE, the core network was also enhanced. The standardization work targeting enhancement of the core network architecture is called System Architecture Evolution (SAE), and the evolved core network is called the Evolved Packet Core (EPC). SAE is based on an all-IP network and supports not only 3GPP radio access networks but also non-3GPP radio access networks such as WIMAX and CDMA2000. The EPC's support for non-3GPP radio access networks enables operators with previous non-3GPP radio access networks to adopt LTE as their future radio access network. The term Evolved Packet System (EPS) is used to refer to the combination of E-UTRAN and EPC.

The LTE specification is defined from Release 8. LTE Release 8 is the first version of the LTE standard including the basic functionality that is essential to perform as a wireless system. A major addition in LTE Release 9 is the Multimedia Broadcast/Multicast Service (MBMS), which is used to provide broadcast and multicast services in LTE. Major new features in LTE Release 10 are the support of Carrier Aggregation (CA), which involves using multiple LTE carriers to provide a higher data rate; Relay, which is to increase LTE coverage; and Machine-Type Communication (MTC), which is to support access from many machine-type devices. As of January 2012, standardization for Release 11 of LTE is ongoing. Major works in LTE Release 11 are the enhancement of CA and MBMS.

1.3 Market Trend

In Korea, from mid-2009 to mid-2010, mobile data traffic over three telecommunication operators increased by 344, 232, and 114%. One of these operators forecasts that there will be a 49-fold increase in mobile data traffic. Similarly, Japanese operators have also predicted huge growth in mobile data traffic – a 15-fold increase by 2015, or 60% annual growth is expected. This is not a regional trend but also appears in other parts of the world. Thus, for today's operators, the time-critical issue is how to cope with the explosively increasing demand for mobile data traffic.

Recent research shows that smartphones represent only 13% of total global handsets, but these smartphones constitute over 78% of total global handset traffic. From this simple fact, it can be foreseen that when all existing handsets are replaced by smartphones, the demand for mobile traffic will be huge. Furthermore, as more applications are developed and become popular, the average amount of mobile traffic per capita will also increase in addition to the penetration of smartphones. The popular use of video streaming and video telephony adds another dimension to the increase in mobile traffic.

To accommodate the increased demand for mobile traffic, more dense deployment of base stations using the concept of femto or pico cells is being considered. The use of Wi-Fi to

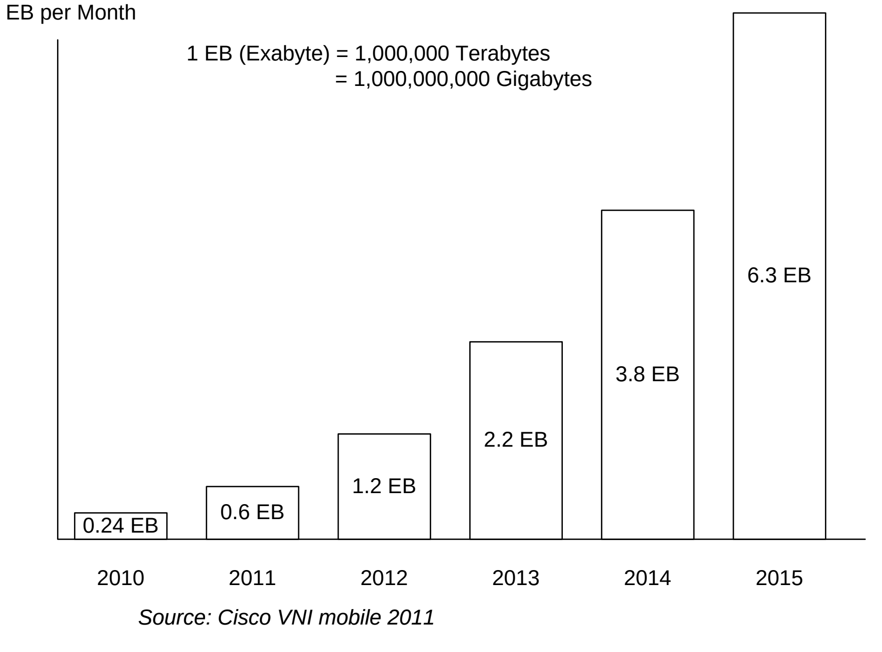

Figure 1.7 Forecast of mobile traffic [4]. Reproduced with permission from Cisco VNI Global Mobile Data Forecast, 2011–2016