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Introduction

Our first chapter puts LTE into its historical context, and lays out its requirements and key technical features. We begin by reviewing the architectures of UMTS and GSM, and by introducing some of the terminology that the two systems use. We then summarize the history of mobile telecommunication systems, discuss the issues that have driven the development of LTE and show how UMTS has evolved first into LTE and then into an enhanced version known as LTE-Advanced. The chapter closes by reviewing the standardization process for LTE.

1.1 Architectural Review of UMTS and GSM

1.1.1 High-Level Architecture

LTE was designed by a collaboration of national and regional telecommunications standards bodies known as the *Third Generation Partnership Project* (3GPP) [1] and is known in full as 3GPP *Long-Term Evolution*. LTE evolved from an earlier 3GPP system known as the *Universal Mobile Telecommunication System* (UMTS), which in turn evolved from the *Global System for Mobile Communications* (GSM). To put LTE into context, we will begin by reviewing the architectures of UMTS and GSM, and by introducing some of the important terminology.

A mobile phone network is officially known as a *public land mobile network* (PLMN), and is run by a *network operator* such as Vodafone or Verizon. UMTS and GSM share a common network architecture, which is shown in Figure 1.1. There are three main components, namely the core network, the radio access network and the mobile phone.

The *core network* contains two domains. The *circuit switched* (CS) domain transports phone calls across the geographical region that the network operator is covering, in the same way as a traditional fixed-line telecommunication system. It communicates with the *public switched telephone network* (PSTN) so that users can make calls to land lines and with the circuit switched domains of other network operators. The *packet switched* (PS) domain transports data streams, such as web pages and emails, between the user and external *packet data networks* (PDNs) such as the internet.

The two domains transport their information in very different ways. The CS domain uses a technique known as *circuit switching*, in which it sets aside a dedicated two-way connection

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Christopher Cox.

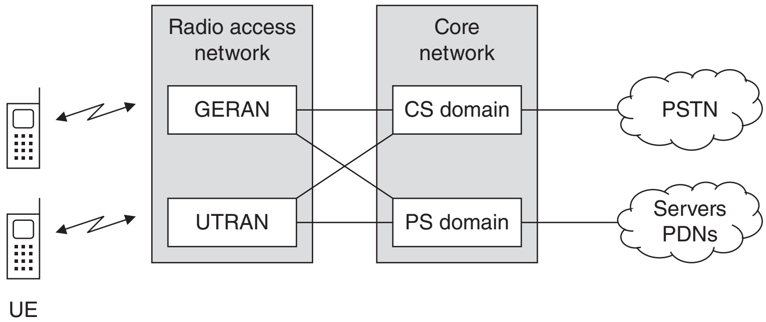

Figure 1.1 High-level architecture of UMTS and GSM

for each individual phone call so that it can transport the information with a constant data rate and minimal delay. This technique is effective, but is rather inefficient: the connection has enough capacity to handle the worst-case scenario in which both users are speaking at the same time, but is usually over-dimensioned. Furthermore, it is inappropriate for data transfers, in which the data rate can vary widely.

To deal with the problem, the PS domain uses a different technique, known as *packet switching*. In this technique, a data stream is divided into packets, each of which is labelled with the address of the required destination device. Within the network, *routers* read the address labels of the incoming data packets and forward them towards the corresponding destinations. The network's resources are shared amongst all the users, so the technique is more efficient than circuit switching. However, delays can result if too many devices try to transmit at the same time, a situation that is familiar from the operation of the internet.

The *radio access network* handles the core network's radio communications with the user. In Figure 1.1, there are actually two separate radio access networks, namely the *GSM EDGE radio access network* (GERAN) and the *UMTS terrestrial radio access network* (UTRAN). These use the different radio communication techniques of GSM and UMTS, but share a common core network between them.

The user's device is known officially as the *user equipment* (UE) and colloquially as the *mobile*. It communicates with the radio access network over the *air interface*, also known as the *radio interface*. The direction from network to mobile is known as the *downlink* (DL) or *forward link* and the direction from mobile to network is known as the *uplink* (UL) or *reverse link*.

A mobile can work outside the coverage area of its network operator by using the resources from two public land mobile networks: the *visited network*, where the mobile is located and the operator's *home network*. This situation is known as *roaming*.

1.1.2 Architecture of the Radio Access Network

Figure 1.2 shows the radio access network of UMTS. The most important component is the *base station*, which in UMTS is officially known as the *Node B*. Each base station has one or more sets of antennas, through which it communicates with the mobiles in one or more *sectors*. As shown in the diagram, a typical base station uses three sets of antennas to

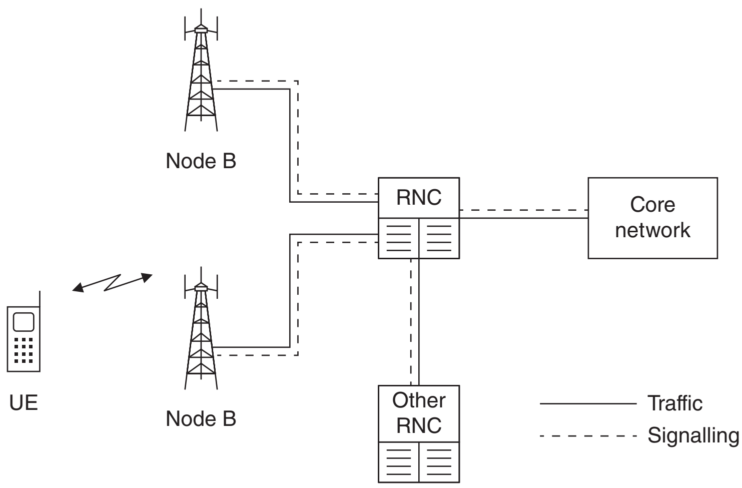

Figure 1.2 Architecture of the UMTS terrestrial radio access network

control three sectors, each of which spans an arc of 120°. In a medium-sized country like the United Kingdom, a typical mobile phone network might contain several thousand base stations altogether.

The word *cell* can be used in two different ways [2]. In Europe, a cell is usually the same thing as a sector, but in the United States, it usually means the group of sectors that a single base station controls. We will stick with the European convention throughout this book, so that the words cell and sector mean the same thing.

Each cell has a limited size, which is determined by the maximum range at which the receiver can successfully hear the transmitter. It also has a limited capacity, which is the maximum combined data rate of all the mobiles in the cell. These limits lead to the existence of several types of cell. *Macrocells* provide wide-area coverage in rural areas or suburbs and have a size of a few kilometres. *Microcells* have a size of a few hundred metres and provide a greater collective capacity that is suitable for densely populated urban areas. *Picocells* are used in large indoor environments such as offices or shopping centres and are a few tens of metres across. Finally, subscribers can buy *home base stations* to install in their own homes. These control *femtocells*, which are a few metres across.

Looking more closely at the air interface, each mobile and base station transmits on a certain radio frequency, which is known as the *carrier frequency*. Around that carrier frequency, it occupies a certain amount of frequency spectrum, known as the *bandwidth*. For example, a mobile might transmit with a carrier frequency of 1960 MHz and a bandwidth of 10 MHz, in which case its transmissions would occupy a frequency range from 1955 to 1965 MHz.

The air interface has to segregate the base stations' transmissions from those of the mobiles, to ensure that they do not interfere. UMTS can do this in two ways. When using *frequency division duplex* (FDD), the base stations transmit on one carrier frequency and the mobiles on another. When using *time division duplex* (TDD), the base stations and mobiles transmit on the same carrier frequency, but at different times. The air interface also has to segregate the different base stations and mobiles from each other. We will see the techniques that it uses in Chapters 3 and 4.

When a mobile moves from one part of the network to another, it has to stop communicating with one cell and start communicating with the next cell along. This process can be carried out using two different techniques, namely *handover* for mobiles that are actively communicating with the network and *cell reselection* for mobiles that are on standby. In UMTS, an active mobile can actually communicate with more than one cell at a time, in a state known as *soft handover*.

The base stations are grouped together by devices known as *radio network controllers* (RNCs). These have two main tasks. Firstly, they pass the user's voice information and data packets between the base stations and the core network. Secondly, they control a mobile's radio communications by means of signalling messages that are invisible to the user, for example by telling a mobile to hand over from one cell to another. A typical network might contain a few tens of radio network controllers, each of which controls a few hundred base stations.

The GSM radio access network has a similar design, although the base station is known as a *base transceiver station* (BTS) and the controller is known as a *base station controller* (BSC). If a mobile supports both GSM and UMTS, then the network can hand it over between the two radio access networks, in a process known as an *inter-system handover*. This can be invaluable if a mobile moves outside the coverage area of UMTS, and into a region that is covered by GSM alone.

In Figure 1.2, we have shown the user's traffic in solid lines and the network's signalling messages in dashed lines. We will stick with this convention throughout the book.

1.1.3 Architecture of the Core Network

Figure 1.3 shows the internal architecture of the core network. In the circuit switched domain, *media gateways* (MGWs) route phone calls from one part of the network to another, while *mobile switching centre* (MSC) *servers* handle the signalling messages that set up, manage

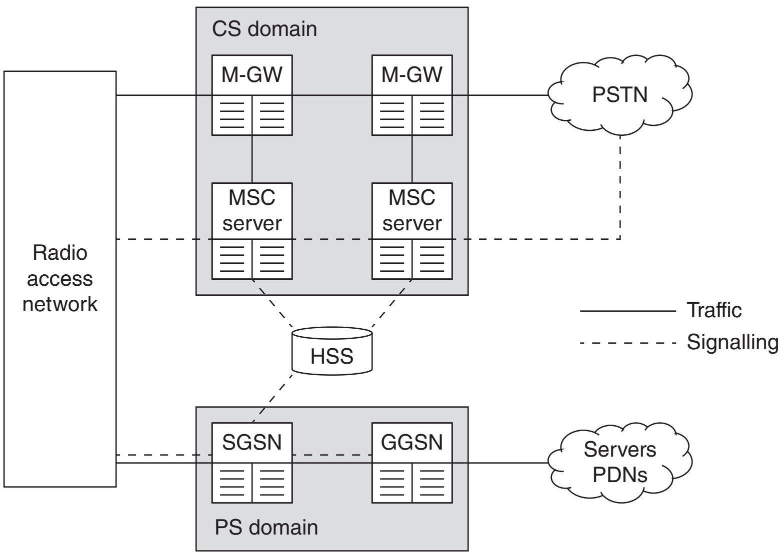

Figure 1.3 Architecture of the core networks of UMTS and GSM

and tear down the phone calls. They respectively handle the traffic and signalling functions of two earlier devices, known as the mobile switching centre and the *visitor location register* (VLR). A typical network might just contain a few of each device.

In the packet switched domain, *gateway GPRS support nodes* (GGSNs) act as interfaces to servers and packet data networks in the outside world. *Serving GPRS support nodes* (SGSNs) route data between the base stations and the GGSNs, and handle the signalling messages that set up, manage and tear down the data streams. Once again, a typical network might just contain a few of each device.

The *home subscriber server* (HSS) is a central database that contains information about all the network operator's subscribers and is shared between the two network domains. It amalgamates the functions of two earlier components, which were known as the *home location register* (HLR) and the *authentication centre* (AuC).

1.1.4 Communication Protocols

In common with other communication systems, UMTS and GSM transfer information using hardware and software *protocols*. The best way to illustrate these is actually through the protocols used by the internet. These protocols are designed by the *Internet Engineering Task Force* (IETF) and are grouped into various numbered *layers*, each of which handles one aspect of the transmission and reception process. The usual grouping follows a seven layer model known as the *Open Systems Interconnection* (OSI) model.

As an example (see Figure 1.4), let us suppose that a web server is sending information to a user's browser. In the first step, an *application layer* protocol, in this case the *hypertext transfer protocol* (HTTP), receives information from the server's application software, and passes it to the next layer down by representing it in a way that the user's application layer will eventually be able to understand. Other application layer protocols include the *simple mail transfer protocol* (SMTP) and the *file transfer protocol* (FTP).

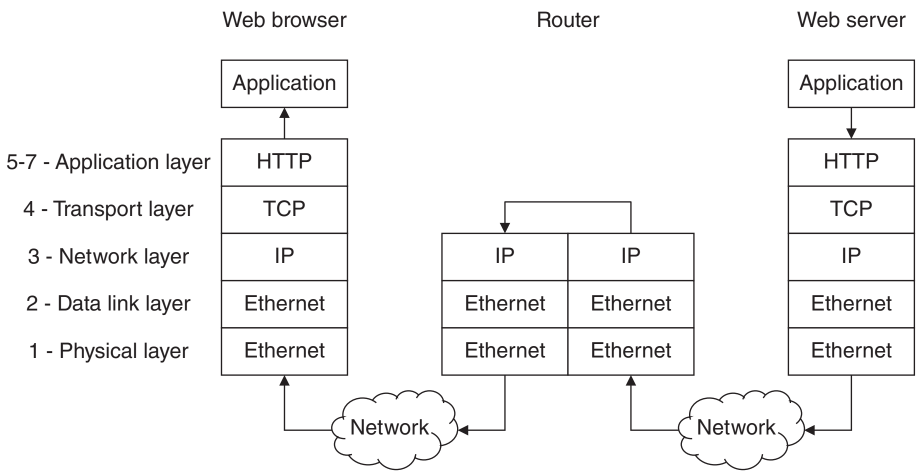

Figure 1.4 Examples of the communication protocols used by the internet, showing their mapping onto the layers of the OSI model

The *transport layer* manages the end-to-end data transmission. There are two main protocols. The *transmission control protocol* (TCP) re-transmits a packet from end to end if it does not arrive correctly, and is suitable for data such as web pages and emails that have to be received reliably. The *user datagram protocol* (UDP) sends the packet without any re-transmission and is suitable for data such as real time voice or video for which timely arrival is more important.

In the *network layer*, the *internet protocol* (IP) sends packets on the correct route from source to destination, using the IP address of the destination device. The process is handled by the intervening routers, which inspect the destination IP addresses by implementing just the lowest three layers of the protocol stack. The *data link layer* manages the transmission of packets from one device to the next, for example by re-transmitting a packet across a single interface if it does not arrive correctly. Finally, the *physical layer* deals with the actual transmission details; for example, by setting the voltage of the transmitted signal. The internet can use any suitable protocols for the data link and physical layers, such as *Ethernet*.

At each level of the transmitter's stack, a protocol receives a data packet from the protocol above in the form of a *service data unit* (SDU). It processes the packet, adds a header to describe the processing it has carried out, and outputs the result as a *protocol data unit* (PDU). This immediately becomes the incoming service data unit of the next protocol down. The process continues until the packet reaches the bottom of the protocol stack, at which point it is transmitted. The receiver reverses the process, using the headers to help it undo the effect of the transmitter's processing.

This technique is used throughout the radio access and core networks of UMTS and GSM. We will not consider their protocols in any detail at this stage; instead, we will go straight to the protocols used by LTE as part of Chapter 2.

1.2 History of Mobile Telecommunication Systems

1.2.1 From 1G to 3G

Mobile telecommunication systems were first introduced in the early 1980s. The *first generation* (1G) systems used analogue communication techniques, which were similar to those used by a traditional analogue radio. The individual cells were large and the systems did not use the available radio spectrum efficiently, so their capacity was by today's standards very small. The mobile devices were large and expensive and were marketed almost exclusively at business users.

Mobile telecommunications took off as a consumer product with the introduction of *second generation* (2G) systems in the early 1990s. These systems were the first to use digital technology, which permitted a more efficient use of the radio spectrum and the introduction of smaller, cheaper devices. They were originally designed just for voice, but were later enhanced to support instant messaging through the *Short Message Service* (SMS). The most popular 2G system was the Global System for Mobile Communications (GSM), which was originally designed as a pan-European technology, but which later became popular throughout the world. Also notable was *IS-95*, otherwise known as *cdmaOne*, which was designed by Qualcomm, and which became the dominant 2G system in the United States.

The success of 2G communication systems came at the same time as the early growth of the internet. It was natural for network operators to bring the two concepts together, by allowing users to download data onto mobile devices. To do this, so-called 2.5G systems built on the original ideas from 2G, by introducing the core network's packet switched domain and by modifying the air interface so that it could handle data as well as voice. The *General Packet Radio Service* (GPRS) incorporated these techniques into GSM, while IS-95 was developed into a system known as *IS-95B*.

At the same time, the data rates available over the internet were progressively increasing. To mirror this, designers first improved the performance of 2G systems using techniques such as *Enhanced Data Rates for GSM Evolution* (EDGE) and then introduced more powerful *third generation* (3G) systems in the years after 2000. 3G systems use different techniques for radio transmission and reception from their 2G predecessors, which increases the peak data rates that they can handle and which makes still more efficient use of the available radio spectrum.

Unfortunately, early 3G systems were excessively hyped and their performance did not at first live up to expectations. Because of this, 3G only took off properly after the introduction of 3.5G systems around 2005. In these systems, the air interface includes extra optimizations that are targeted at data applications, which increase the average rate at which a user can upload or download information, at the expense of introducing greater variability into the data rate and the arrival time.

1.2.2 Third Generation Systems

The world's dominant 3G system is the Universal Mobile Telecommunication System (UMTS). UMTS was developed from GSM by completely changing the technology used on the air interface, while keeping the core network almost unchanged. The system was later enhanced for data applications, by introducing the 3.5G technologies of *high-speed downlink packet access* (HSDPA) and *high-speed uplink packet access* (HSUPA), which are collectively known as *high-speed packet access* (HSPA).

The UMTS air interface has two slightly different implementations. *Wideband code division multiple access* (WCDMA) is the version that was originally specified, and the one that is currently used through most of the world. *Time division synchronous code division multiple access* (TD-SCDMA) is a derivative of WCDMA, which is also known as the low chip rate option of UMTS TDD mode. TD-SCDMA was developed in China, to minimize the country's dependence on Western technology and on royalty payments to Western companies. It is deployed by one of China's three 3G operators, China Mobile.

There are two main technical differences between these implementations. Firstly, WCDMA usually segregates the base stations' and mobiles' transmissions by means of frequency division duplex, while TD-SCDMA uses time division duplex. Secondly, WCDMA uses a wide bandwidth of 5 MHz, while TD-SCDMA uses a smaller value of 1.6 MHz.

cdma2000 was developed from IS-95 and is mainly used in North America. The original 3G technology was known as cdma2000 *1x radio transmission technology* (1xRTT). It was subsequently enhanced to a 3.5G system with two alternative names, cdma2000 *high-rate packet data* (HRPD) or *evolution data optimized* (EV-DO), which uses similar techniques to high-speed packet access. The specifications for IS-95 and cdma2000 are produced by a similar collaboration to 3GPP, which is known as the *Third Generation Partnership Project 2* (3GPP2) [3].

There are three main technical differences between the air interfaces of cdma2000 and UMTS. Firstly, cdma2000 uses a bandwidth of 1.25 MHz. Secondly, cdma2000 is backwards compatible with IS-95, in the sense that IS-95 mobiles can communicate with cdma2000 base stations and vice-versa, whereas UMTS is not backwards compatible with GSM. Thirdly, cdma2000 segregates voice and optimized data onto different carrier frequencies, whereas UMTS allows them to share the same one. The first two issues hindered the penetration of WCDMA into the North American market, where there were few allocations of bandwidths as wide as 5 MHz and there were a large number of legacy IS-95 devices.

The final 3G technology is *Worldwide Interoperability for Microwave Access* (WiMAX). This was developed by the *Institute of Electrical and Electronics Engineers* under IEEE standard 802.16 and has a very different history from other 3G systems. The original specification (IEEE 802.16–2001) was for a system that delivered data over point-to-point microwave links instead of fixed cables. A later revision, known as *fixed WiMAX* (IEEE 802.16–2004), supported point-to-multipoint communications between an omni-directional base station and a number of fixed devices. A further amendment, known as *mobile WiMAX* (IEEE 802.16e), allowed the devices to move and to hand over their communications from one base station to another. Once these capabilities were all in place, WiMAX started to look like any other 3G communication system, albeit one that had been optimized for data from the very beginning.

1.3 The Need for LTE

1.3.1 The Growth of Mobile Data

For many years, voice calls dominated the traffic in mobile telecommunication networks. The growth of mobile data was initially slow, but in the years leading up to 2010 its use started to increase dramatically. To illustrate this, Figure 1.5 shows measurements by Ericsson of the total traffic being handled by networks throughout the world, in petabytes (million gigabytes) per month [4]. The figure covers the period from 2007 to 2013, during which time the amount of data traffic increased by a factor of over 500.

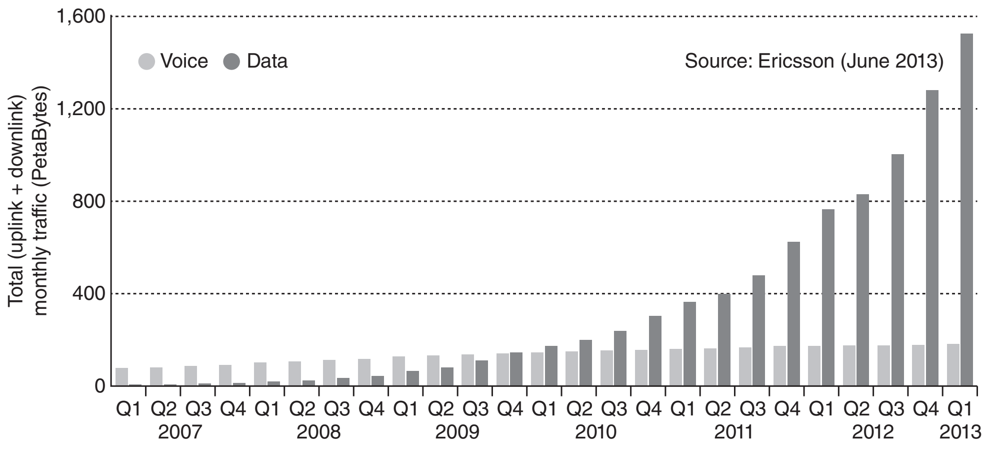

Figure 1.5 Measurements of voice and data traffic in worldwide mobile telecommunication networks, in the period from 2007 to 2013. Source: Ericsson mobility report, June 2013

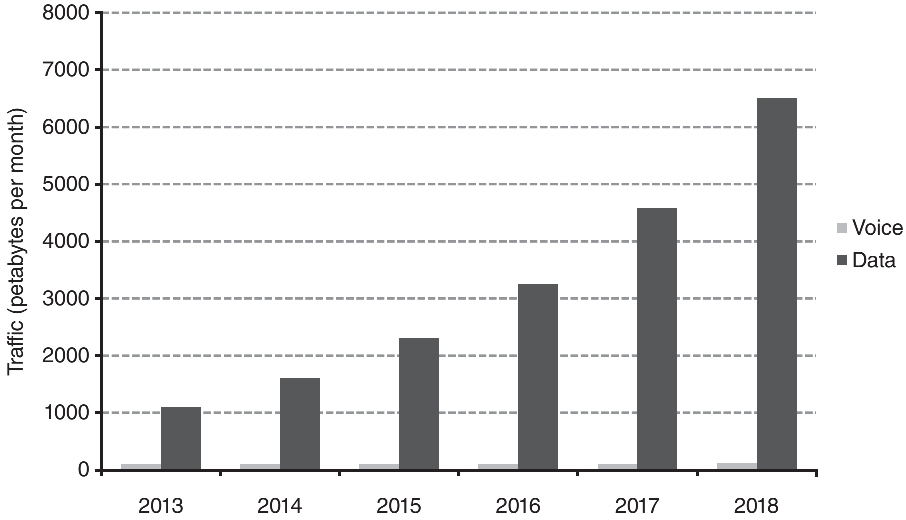

Figure 1.6 Forecasts of voice and data traffic in worldwide mobile telecommunication networks, in the period from 2013 to 2018. Data supplied by Analysys Mason

This trend is set to continue. For example, Figure 1.6 shows forecasts by Analysys Mason of the growth of mobile traffic in the period from 2013 to 2018. Note the difference in the vertical scales of the two diagrams.

In part, this growth was driven by the increased availability of 3.5G communication technologies. More important, however, was the introduction of the Apple iPhone in 2007, followed by devices based on Google's Android operating system from 2008. These smartphones were more attractive and user-friendly than their predecessors and were designed to support the creation of applications by third party developers. The result was an explosion in the number and use of mobile applications, which is reflected in the diagrams. As a contributory factor, network operators had previously tried to encourage the growth of mobile data by the introduction of flat rate charging schemes that permitted unlimited data downloads. That led to a situation where neither developers nor users were motivated to limit their data consumption.

As a result of these issues, 2G and 3G networks started to become congested in the years around 2010, leading to a requirement to increase network capacity. In the next section, we review the limits on the capacity of a mobile communication system and show how such capacity growth can be achieved.

1.3.2 Capacity of a Mobile Telecommunication System

In 1948, Claude Shannon discovered a theoretical limit on the data rate that can be achieved from any communication system [5]. We will write it in its simplest form, as follows:

$$C = B\log_2(1 + \text{SINR}) \tag{1.1}$$

Here, SINR is the *signal-to-interference plus noise ratio*, in other words the power at the receiver due to the required signal, divided by the power due to noise and interference. B is the bandwidth of the communication system in Hz, and C is the *channel capacity* in bits s^{-1}. It is theoretically possible for a communication system to send data from a transmitter to a receiver without any errors at all, provided that the data rate is less than the channel capacity. In a mobile communication system, C is the maximum data rate that one cell can handle and equals the combined data rate of all the mobiles in the cell.

The results are shown in Figure 1.7, using bandwidths of 5, 10 and 20 MHz. The vertical axis shows the channel capacity in million bits per second (Mbps), while the horizontal axis shows the signal-to-interference plus noise ratio in decibels (dB):

$$\mathrm{SINR(dB)} = 10\log_{10}(\mathrm{SINR}) \tag{1.2}$$

1.3.3 Increasing the System Capacity

There are three main ways to increase the capacity of a mobile communication system, which we can understand by inspection of Equation 1.1 and Figure 1.7. The first, and the most important, is the use of smaller cells. In a cellular network, the channel capacity is the maximum data rate that a single cell can handle. By building extra base stations and reducing the size of each cell, we can increase the capacity of a network, essentially by using many duplicate copies of Equation 1.1.

The second technique is to increase the bandwidth. Radio spectrum is managed by the *International Telecommunication Union* (ITU) and by regional and national regulators, and the increasing use of mobile telecommunications has led to the increasing allocation of spectrum to 2G and 3G systems. However, there is only a finite amount of radio spectrum available and it is also required by applications as diverse as military communications and radio astronomy. There are therefore limits as to how far this process can go.

The third technique is to improve the communication technology that we are using. This brings several benefits: it lets us approach ever closer to the theoretical channel capacity,

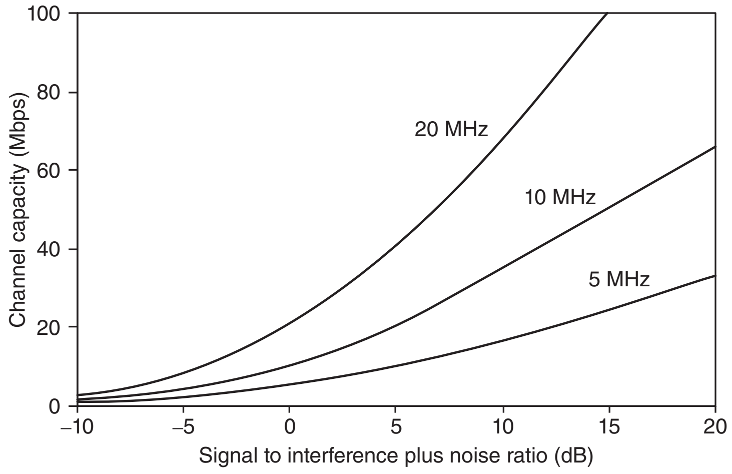

Figure 1.7 Shannon capacity of a communication system, in bandwidths of 5, 10 and 20 MHz

and it lets us exploit the higher SINR and greater bandwidth that are made available by the other changes above. This progressive improvement in communication technology has been an ongoing theme in the development of mobile telecommunications and is the main reason for the introduction of LTE.

1.3.4 Additional Motivations

Three other issues have driven the move to LTE. Firstly, a 2G or 3G operator has to maintain two core networks: the circuit switched domain for voice, and the packet switched domain for data. Provided that the network is not too congested, however, it is also possible to transport voice calls over packet switched networks using techniques such as *voice over IP* (VoIP). By doing this, operators can move everything to the packet switched domain, and can reduce both their capital and operational expenditure.

In a related issue, 3G networks introduce delays of the order of 100 ms for data applications, in transferring data packets between network elements and across the air interface. This is barely acceptable for voice and causes great difficulties for more demanding applications such as real-time interactive games. Thus a second driver is the wish to reduce the end-to-end delay, or *latency*, in the network.

Thirdly, the specifications for UMTS and GSM have become increasingly complex over the years, due to the need to add new features to the system while maintaining backwards compatibility with earlier devices. A fresh start aids the task of the designers, by letting them improve the performance of the system without the need to support legacy devices.

1.4 From UMTS to LTE

1.4.1 High-Level Architecture of LTE

In 2004, 3GPP began a study into the long term evolution of UMTS. The aim was to keep 3GPP's mobile communication systems competitive over timescales of 10 years and beyond, by delivering the high data rates and low latencies that future users would require. Figure 1.8 shows the resulting architecture and the way in which that architecture developed from that of UMTS.

In the new architecture, the *evolved packet core* (EPC) is a direct replacement for the packet switched domain of UMTS and GSM. There is no equivalent to the circuit switched domain, which allows LTE to be optimized for the delivery of data traffic, but implies that voice calls have to be handled using other techniques that are introduced below. The *evolved UMTS terrestrial radio access network* (E-UTRAN) handles the EPC's radio communications with the mobile, so is a direct replacement for the UTRAN. The mobile is still known as the user equipment, though its internal operation is very different from before.

The new architecture was designed as part of two 3GPP work items, namely *system architecture evolution* (SAE), which covered the core network, and *long-term evolution* (LTE), which covered the radio access network, air interface and mobile. Officially, the whole system is known as the *evolved packet system* (EPS), while the acronym LTE refers only to the evolution of the air interface. Despite this official usage, LTE has become a colloquial name for the whole system, and is regularly used in this way by 3GPP. We will use LTE in this colloquial way throughout the book.

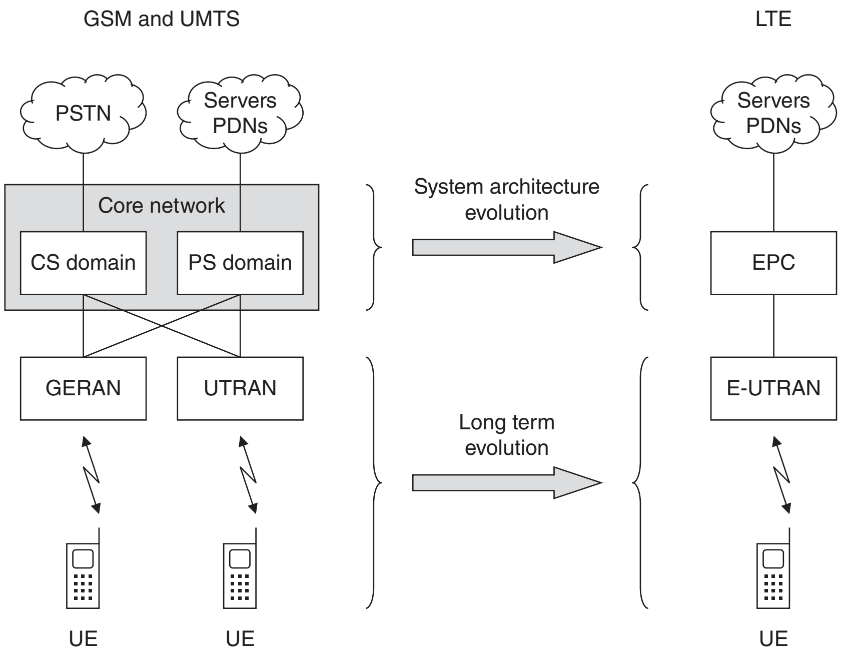

Figure 1.8 Evolution of the system architecture from GSM and UMTS to LTE

1.4.2 Long-Term Evolution

The main output of the study into long-term evolution was a requirements specification for the air interface [6], in which the most important requirements were as follows.

LTE was required to deliver a peak data rate of 100 Mbps in the downlink and 50 Mbps in the uplink. This requirement was exceeded in the eventual system, which delivers peak data rates of 300 Mbps and 75 Mbps respectively. For comparison, the peak data rate of WCDMA, in Release 6 of the 3GPP specifications, is 14 Mbps in the downlink and 5.7 Mbps in the uplink. (We will discuss the different specification releases at the end of the chapter.)

It cannot be stressed too strongly, however, that these peak data rates can only be reached in idealized conditions, and are wholly unachievable in any realistic scenario. A better measure is the *spectral efficiency*, which expresses the typical capacity of one cell per unit bandwidth. LTE was required to support a spectral efficiency three to four times greater than that of Release 6 WCDMA in the downlink and two to three times greater in the uplink.

Latency is another important issue, particularly for time-critical applications such as voice and interactive games. There are two aspects to this. Firstly, the requirements state that the time taken for data to travel between the mobile phone and the fixed network should be less than 5 ms, provided that the air interface is uncongested. Secondly, we will see in Chapter 2 that mobile phones can operate in two states: an active state in which they are communicating with the network and a low-power standby state. The requirements state that a phone should switch from standby to the active state, after an intervention from the user, in less than 100 ms.

There are also requirements on coverage and mobility. LTE is optimized for cell sizes up to 5 km, works with degraded performance up to 30 km and supports cell sizes of up to 100 km. It is also optimized for mobile speeds up to 15 km h^{-1}, works with high performance up to 120 km h^{-1} and supports speeds of up to 350 km h^{-1}. Finally, LTE is designed to work with a variety of different bandwidths, which range from 1.4 MHz up to a maximum of 20 MHz.

The requirements specification ultimately led to a detailed design for the LTE air interface, which we will cover in Chapters 3–10. For the benefit of those familiar with other systems, Table 1.1 summarizes its key technical features, and compares them with those of WCDMA.

1.4.3 System Architecture Evolution

The main output of the study into system architecture evolution was a requirements specification for the fixed network [7], in which the most important requirements were as follows.

The evolved packet core routes packets using the Internet Protocol (IP) and supports devices that are using IP version 4, IP version 6 or dual stack IP version 4/version 6. In addition, the EPC provides users with always-on connectivity to the outside world, by setting up a basic IP connection for a device when it switches on and maintaining that connection until it switches off. This is different from the behaviour of UMTS and GSM, in which the network only sets up an IP connection on request and tears that connection down when it is no longer required.

Unlike the internet, the EPC contains mechanisms to specify and control the data rate, error rate and delay that a data stream will receive. There is no explicit requirement on the maximum time required for data to travel across the EPC, but the relevant specification suggests a user plane latency of 10 ms for a non-roaming mobile, increasing to 50 ms in a typical roaming scenario [8]. To calculate the total delay, we have to add the earlier figure for the delay across the air interface, giving a typical delay in a non-roaming scenario of around 20 ms.

The EPC is also required to support inter-system handovers between LTE and earlier 2G and 3G technologies. These cover not only UMTS and GSM, but also non-3GPP systems such as cdma2000 and WiMAX.

Table 1.1 Key features of the air interfaces of WCDMA and LTE

Feature	WCDMA	LTE	Chapter
Multiple access scheme	WCDMA	OFDMA and SC-FDMA	4
Frequency re-use	100%	Flexible	4
Use of MIMO antennas	From Release 7	Yes	5
Bandwidth	5 MHz	1.4, 3, 5, 10, 15 or 20 MHz	6
Frame duration	10 ms	10 ms	6
Transmission time interval	2 or 10 ms	1 ms	6
Modes of operation	FDD and TDD	FDD and TDD	6
Uplink timing advance	Not required	Required	6
Transport channels	Dedicated and shared	Shared	6
Uplink power control	Fast	Slow	8

Table 1.2 Key features of the radio access networks of UMTS and LTE

Feature	UMTS	LTE	Chapter
Radio access network components	Node B, RNC	eNB	2
RRC protocol states	CELL_DCH, CELL_FACH, CELL_PCH, URA_PCH, RRC_IDLE	RRC_CONNECTED, RRC_IDLE	2
Handovers	Soft and hard	Hard	14
Neighbour lists	Always required	Not required	14

Table 1.3 Key features of the core networks of UMTS and LTE

Feature	UMTS	LTE	Chapter
IP version support	IPv4 and IPv6	IPv4 and IPv6	2
USIM version support	Release 99 USIM onwards	Release 99 USIM onwards	2
Transport mechanisms	Circuit & packet switching	Packet switching	2
CS domain components	MSC server, MGW	n/a	2
PS domain components	SGSN, GGSN	MME, S-GW, P-GW	2
IP connectivity	After registration	During registration	11
Voice and SMS applications	Included	External	21, 22

Tables 1.2 and 1.3 summarize the key features of the radio access network and the evolved packet core, and compare them with the corresponding features of UMTS. We will cover the architectural aspects of the fixed network in Chapter 2 and the operational aspects in Chapters 11–17.

1.4.4 LTE Voice Calls

The evolved packet core is designed as a data pipe that simply transports information to and from the user; it is not concerned with the information content or with the application. This is similar to the behaviour of the internet, which transports packets that originate from any application software, but is different from that of a traditional circuit switched network in which the voice application is an integral part of the system.

Because of this issue, voice applications do not form an integral part of LTE. However, an LTE mobile can still make a voice call using two main techniques. The first is *circuit switched fallback*, in which the network transfers the mobile to a legacy 2G or 3G cell so that the mobile can contact the 2G/3G circuit switched domain. The second is by using the *IP multimedia subsystem* (IMS), an external network that includes the signalling functions needed to set up, manage and tear down a voice over IP call. We will discuss these two techniques in Chapters 21 and 22.

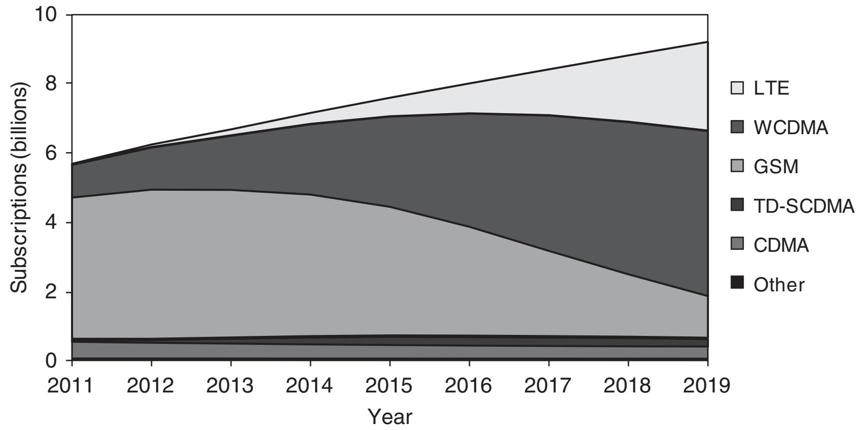

Figure 1.9 Numbers of subscriptions to different mobile communication technologies, with historical data up to 2013 and forecasts thereafter. Source: www.ericsson.com/TET

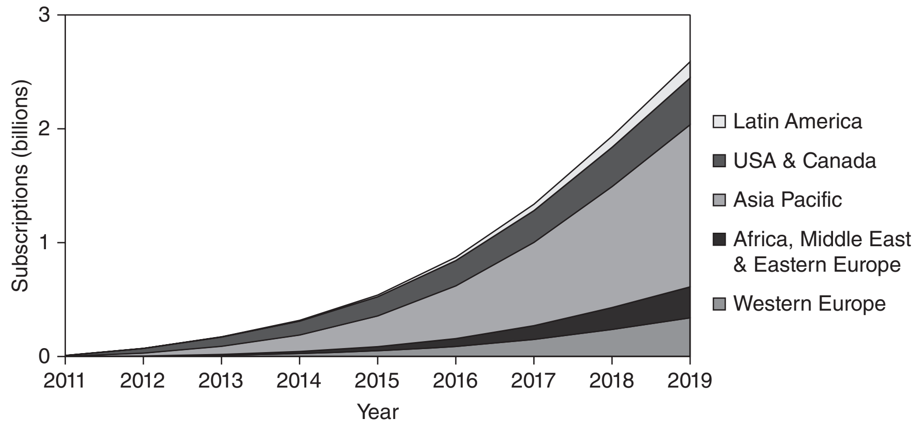

Figure 1.10 Number of subscriptions to LTE in different regions of the world, with historical data up to 2013 and forecasts thereafter. Source: www.ericsson.com/TET

1.4.5 The Growth of LTE

The first LTE networks were launched in Norway and Sweden at the end of 2009. To illustrate the subsequent growth of LTE, Figure 1.9 shows the total number of subscriptions to the most important mobile communication technologies in the period from 2011 to 2019, while Figure 1.10 shows the regional breakdown for the case of LTE. The diagrams are constructed using data published by Ericsson [9] and show historical data up to 2013 and forecasts thereafter. By the end of 2019, LTE is forecast to grow to around 2.5 billion subscribers worldwide.

1.5 From LTE to LTE-Advanced

1.5.1 The ITU Requirements for 4G

The design of LTE took place at the same time as an initiative by the International Telecommunication Union. In the late 1990s, the ITU had helped to drive the development of 3G technologies by publishing a set of requirements for a 3G mobile communication system, under the name *International Mobile Telecommunications* (IMT) *2000*. The 3G systems noted earlier are the main ones currently accepted by the ITU as meeting the requirements for IMT-2000.

The ITU launched a similar process in 2008, by publishing a set of requirements for a *fourth generation* (4G) communication system under the name *IMT-Advanced* [10–12]. According to these requirements, the peak data rate of a compatible system should be at least 600 Mbps on the downlink and 270 Mbps on the uplink, in a bandwidth of 40 MHz. We can see right away that these figures exceed the capabilities of LTE.

1.5.2 Requirements of LTE-Advanced

Driven by the ITU's requirements for IMT-Advanced, 3GPP started to study how to enhance the capabilities of LTE. The main output from the study was a specification for a system known as *LTE-Advanced* [13], in which the main requirements were as follows.

LTE-Advanced was required to deliver a peak data rate of 1000 Mbps in the downlink, and 500 Mbps in the uplink. In practice, the system has been designed so that it can eventually deliver peak data rates of 3000 and 1500 Mbps respectively, using a total bandwidth of 100 MHz that is made from five separate components of 20 MHz each. Note, as before, that these figures are unachievable in any realistic scenario.

The specification also includes targets for the spectrum efficiency in certain test scenarios. Comparison with the corresponding figures for WCDMA [14] implies a spectral efficiency 4.5–7 times greater than that of Release 6 WCDMA on the downlink, and 3.5–6 times greater on the uplink. Finally, LTE-Advanced is designed to be backwards compatible with LTE, in the sense that an LTE mobile can communicate with a base station that is operating LTE-Advanced and vice-versa.

1.5.3 4G Communication Systems

Following the submission and evaluation of proposals, the ITU announced in October 2010 that two systems met the requirements of IMT-Advanced [15]. One system was LTE-Advanced, while the other was an enhanced version of WiMAX under IEEE specification 802.16 m, known as mobile WiMAX 2.0.

Qualcomm had originally intended to develop a 4G successor to cdma2000 under the name *Ultra Mobile Broadband* (UMB). However, this system did not possess two of the advantages that its predecessor had done. Firstly, it was not backwards compatible with cdma2000, in the way that cdma2000 had been with IS-95. Secondly, it was no longer the only system that could operate in the narrow bandwidths that dominated North America, due to the flexible bandwidth support of LTE. Without any pressing reason to do so, no network operator ever announced plans to adopt the technology and the project was dropped in 2008. Instead, most cdma2000 operators decided to switch to LTE.

That left a situation where there were two remaining routes to 4G mobile communications: LTE and WiMAX. Of these, LTE has by far the greater support amongst network operators and equipment manufacturers, to the extent that several WiMAX operators have chosen to migrate their networks over to LTE. Because of this support, LTE is likely to be the world's dominant mobile communication technology for some years to come.

1.5.4 The Meaning of 4G

Originally, the ITU intended that the term 4G should only be used for systems that met the requirements of IMT-Advanced. LTE did not do so and neither did mobile WiMAX 1.0 (IEEE 802.16e). Because of this, the engineering community came to describe these systems as 3.9G. These considerations did not, however, stop the marketing community from describing LTE and mobile WiMAX 1.0 as 4G technologies. Although that description was unwarranted from a performance viewpoint, there was actually some sound logic to it: there is a clear technical transition in the move from UMTS to LTE, which does not exist in the move from LTE to LTE-Advanced.

It was not long before the ITU admitted defeat. In December 2010, the ITU gave its blessing to the use of 4G to describe not only LTE and mobile WiMAX 1.0, but also any other technology with substantially better performance than the early 3G systems [16]. They did not define the words 'substantially better', but that is not an issue for this book: we just need to know that LTE is a 4G mobile communication system.

1.6 The 3GPP Specifications for LTE

The specifications for LTE are produced by the Third Generation Partnership Project, in the same way as the specifications for UMTS and GSM. They are organized into *releases* [17], each of which contains a stable and clearly defined set of features. The use of releases allows equipment manufacturers to build devices using some or all of the features of earlier releases, while 3GPP continues to add new features to the system in a later release. Within each release, the specifications progress through a number of different versions. New functionality can be added to successive versions until the date when the release is frozen, after which the only changes involve refinement of the technical details, corrections and clarifications.

Table 1.4 lists the releases that 3GPP have used since the introduction of UMTS, together with the most important features of each release. Note that the numbering scheme was changed after Release 99, so that later releases are numbered from 4 through to 12.

LTE was first introduced in Release 8, which was frozen in December 2008. This release contains most of the important features of LTE and we will focus on it throughout the early chapters of the book. In specifying Release 8, however, 3GPP omitted some of the less important features of the system. These features were eventually included in Release 9, which we will cover in Chapter 18. Release 10 includes the extra capabilities that are required for LTE-Advanced and will be covered in Chapter 19, while the later enhancements in Releases 11 and 12 will be covered in Chapter 20. 3GPP has also continued to add new features to UMTS throughout Releases 8 to 12. This process allows network operators who stick with UMTS to remain competitive, even while other operators move over to LTE.

Table 1.4 3GPP specification releases for UMTS and LTE

Release	Date frozen	New features
R99	March 2000	WCDMA air interface
R4	March 2001	TD-SCDMA air interface
R5	June 2002	HSDPA, IP multimedia subsystem
R6	March 2005	HSUPA
R7	December 2007	Enhancements to HSPA
R8	December 2008	LTE, SAE
R9	December 2009	Enhancements to LTE and SAE
R10	June 2011	LTE-Advanced
R11	June 2013	Enhancements to LTE-Advanced
R12	September 2014	Enhancements to LTE-Advanced

The specifications are also organized into several *series*, each of which covers a particular component of the system. Table 1.5 summarizes the contents of series 21 to 37, which contain all the specifications for LTE and UMTS, as well as specifications that are common to LTE, UMTS and GSM. (Some other series numbers are used exclusively for GSM.) Within these series, the breakdown among the different systems varies widely. The 36 series is devoted to the techniques that are used for radio transmission and reception in LTE and is an important source of information for this book. In the other series, some specifications are applicable to UMTS alone, some to LTE alone and some to both, so it can be tricky to establish which

Table 1.5 3GPP specification series used by UMTS and LTE

Series	Scope
21	High-level requirements
22	Stage 1 service specifications
23	Stage 2 service and architecture specifications
24	Non-access stratum protocols
25	WCDMA and TD-SCDMA air interfaces and radio access network
26	Codecs
27	Data terminal equipment
28	Tandem free operation of speech codecs
29	Core network protocols
30	Programme management
31	UICC and USIM
32	Operations, administration, maintenance, provisioning and charging
33	Security
34	UE test specifications
35	Security algorithms
36	LTE air interface and radio access network
37	Multiple radio access technologies

specifications are the relevant ones. To help deal with this issue, the book contains references to all the important specifications that we will use.

When written out in full, an example specification number is TS 23.401 v 11.6.0. Here, TS stands for *technical specification*, 23 is the series number and 401 is the number of the specification within that series. 11 is the release number, 6 is the technical version number within that release and the final 0 is an editorial version number that is occasionally incremented for non-technical changes. 3GPP also produces *technical reports*, denoted TR, which are purely informative and have three-digit specification numbers beginning with an 8 or 9.

In a final division, each specification belongs to one of three *stages*. Stage 1 specifications define the service from the user's point of view and lie exclusively in the 22 series. Stage 2 specifications define the system's high-level architecture and operation, and lie mainly (but not exclusively) in the 23 series. Finally, stage 3 specifications define all the functional details. The stage 2 specifications are especially useful for achieving a high-level understanding of the system. The most useful ones for LTE are TS 23.401 [18] and TS 36.300 [19], which respectively cover the evolved packet core and the air interface. There is, however, an important note of caution: these specifications are superseded later on and cannot be relied upon for complete accuracy. Instead, the details should be checked if necessary in the relevant stage 3 specifications.

The individual specifications can be downloaded from 3GPP's specification numbering web page [20] or from their FTP server [21]. The 3GPP website also has summaries of the features that are covered by each individual release [22].

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