5G Deployment

Initial Startup and Long-term Migration Plan

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by

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Preface

This thesis marks the completion of my studies at Delft University of Technology, The Netherlands, for the Master of Science in Electrical Engineering in the specialization track of Wireless Communication and Sensing. For me, working on this thesis has been a very enriching and rewarding experience, as the research work on it is both challenging and academically fascinating. I would like to take this opportunity to express my gratitude to all who helped to make the research a success through their constant support and guidance.

I would like to sincerely thank Ir. Rogier Noldus, my daily supervisor for taking the time out of his busy schedule to provide me with feedback on the research project's progress and advice in writing this thesis. His professional advice and constant support has helped me in the journey of this thesis while significantly improving the quality of the research work. Additionally, I would like to thank Dr. Ir. Eric Smeitink and Dr. Ir. Stephan Wong for their valuable comments and willingness to be a part of my thesis committee.

Last but not least, I would like to extend my gratitude to all my friends and family, especially my parents for their love, moral and financial support over the years. None of my accomplishments would have been possible without their help.

Chang Ye, Dec 2022

Abstract

Since the first introduction of 4G in the early 2010s, mobile data traffic has increased significantly, mainly because 4G networks can support more devices, services and applications, as well as greater cellular network coverage. With the advent of the 5G era, the mobile communication system will be further developed. Today, most countries and regions are already implementing their own 5G plans. Compared with China, South Korea and the United States, the three leading countries in the 5G market, the EU's 5G plans are relatively slow.

The focus of this thesis is to explore various 5G deployment and migration options, as well as the current 5G status in different countries and regions. We start with current network technologies, compare and analyze various 5G deployment and migration options. Then we compare the 5G status of the EU with China, South Korea and the United States, and analyze the internal and external factors faced by the EU in the development of 5G. In these two analysis, we will consider several communication services that are currently used in the mobile network, including, but not limited to, voice/video calling and messaging, for both home usage and roaming usage. Finally, based on the above two analysis, suggestions for EU operators in 5G deployment and development are provided, along with recommendations for future research.

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Introduction

1.1. Mobile Communications Evolution Before 5G

The advent of mobile communication systems has eliminated the time and space constraints for transferring information between different places. This has evolved into an integral component of our daily lives, people can now exchange or access information anytime, anywhere. In order to better understand 5G, it is required for us to review the evolution from the ground-breaking 1G to 4G, also consider how one generation differs from the previous one. Figure 1.1 shows the evolution of mobile communications over several generations.

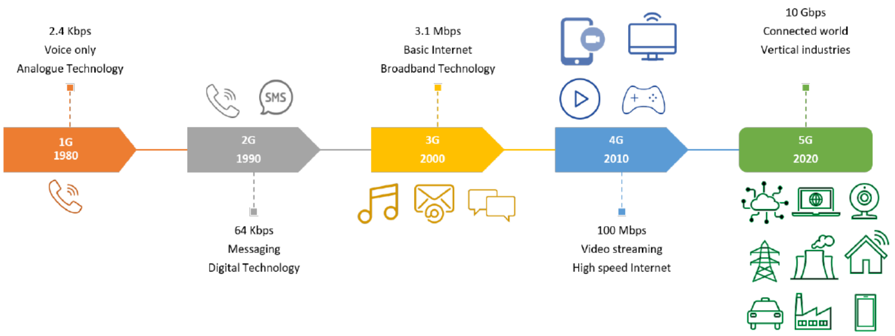

Figure 1.1: Evolution of Mobile Communications [32]

1.1.1. 1G: Analog Mobile Communication Era

The first generation (1G) started the brand new era of mobile communications, it was introduced in the early 1980s. An analog mobile communication technology with carrier frequencies of around 150 MHz was used in 1G, and 1G only supported voice calls. In addition, the Frequency Division Multiple Access (FDMA) technique was employed in 1G, which splits the frequency band into multiple channels, each channel is assigned to only one user at a time. Obviously, 1G is not perfect and has several shortcomings. Due to the inherent limitations of analog communication technology, the communication quality and the level of communication security were extremely low. Furthermore, since different countries use different mobile communication systems, there was no compatibility between them. As a result, roaming was not supported. The maximum data transmission speed on a 1G network was approximately 2.4 kbps.

1.1.2. 2G: Digital Mobile Communication Era

The second generation (2G) opened the era of digital mobile communications, it was introduced in the 1990s. The digital mobile communication technologies were adopted in 2G to improve the quality and security level of mobile communication, as well as the data rate capacity. The Global System for Mobile Communications (GSM) was a 2G digital standard, in addition to voice services, it also supported the transfer of digitally encrypted messages like Short Message Service (SMS), Multimedia Messaging Service (MMS) and picture messages. Abundant message types make the mobile communication system gradually popularized in this era. There were two schemes utilized in 2G, namely, Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). CDMA is responsible for generating a unique code for each user, TDMA is responsible for dividing signals into time slots and assigning codes to the users. In GSM, the maximum data transmission rate is 9.6 kbps per time slot. It was then evolved into General Packet Radio Service (GPRS) and Enhanced Data Rates for GSM Evolution (EDGE). The maximum data transmission rate provided by GPRS is 172 kbps [62], while the maximum data transmission rate provided by EDGE is 384 kbps [31] per cell. In addition, in 2G and 3G, a technology named Circuit Switched (CS) is used for voice and short message service traffic, while Packet Switched (PS) is used for GPRS data traffic. However, starting from 4G the whole network uses packet switched, with no support for circuit switched technology. The main difference between CS and PS is that the former needs to establish a dedicated connection[1] between the calling party and the called party, while the latter does not.

1.1.3. 3G: Mobile Internet Era

The third generation (3G) started the era of mobile internet, it was introduced in the late 2000s. The main difference between 2G and 3G is that in addition to circuit-switched communication technology, 3G also employed packet-switched communication technology. Such technology enables access to Internet applications and basic multimedia streaming. The maximum data rate supported by 3G was about 3.1 Mbps. New services such as voice over IP, fast web browsing, and video conferencing were made available as a result of the increased data rate. It was during this era that the smartphone appeared, which brought more services into mobile communications. The International Telecommunication Union (ITU) defined 3G requirements as part of the International Mobile Telephone 2000 (IMT-2000) project, also known as the Universal Mobile Telecommunications System (UMTS) as it allows for global roaming [32]. 3GPP2 standardized the CDMA 2000 system, as a family of 3G mobile technology standards, it was used especially in North America and South Korea [53].

1.1.4. 4G: Real-Time Streaming Era

The fourth generation (4G) opened the era of real-time streaming, it was introduced in the early 2010s. After that, 4G radio and 4G packet core became the industry standard. The main difference between 4G and 3G for users was the ability to provide an extraordinarily high data rate of up to 100 Mbps. New services such as real-time mobile gaming, high-definition (HD) video streaming and high-speed Internet access were made available as a result of the increased data rate. The key to improving the data rate was that 4G used two new technologies, they are Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO). Digital signals can be divided into several narrow-band channels with variable frequencies by using OFDM. In addition, the design principles of cellular networks were fundamentally changed by these two technologies, so as to overcome the interference obstacles and channel fading in wireless environments. Moreover, unlike 3G, 4G was completely based on the Internet Protocol (IP).

1.2. The Advent of 5G Era

The fifth generation (5G) is the next generation of mobile communications systems. Different from 1G-4G, 5G technology may fundamentally change the role of telecommunications technology in society. 5G will be designed with flexibility and configurability, so that mobile operators can support ultra-reliable, low latency connections as well as enhanced mobile broadband [42]. Furthermore, 5G is expected to further promote economic growth and the pervasive digitisation of hyper-connected societies, in which not only all people, but also many other devices/things can be virtually connected to the network whenever needed, that is, the Internet of Things (IoT) [41].

1.2.1. 5G Use Cases

There are three major use cases for 5G networks, they are Enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communication (URLLC) and massive Machine type communications (mMTC), as shown in Figure 1.2.

- **eMBB** - The characteristics of eMBB are its high data rate and high capacity. It aims to provide a mobile broadband experience on mobile phones and other connected devices, with a focus on high definition

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[1] Voice only. When CS is used for SMS and USSD, there is not really a "dedicated connection" between calling party and called party. SMS and USSD use CS technology through the transfer of data through a timeslot in the CS infrastructure.

video streaming, virtual meetings, augmented reality, and cloud computing. In 5G, through high-speed mobile connections supporting eMBB applications, the consumer's experience will be better.

- **URLLC** - URLLC enables services with ultra-high reliability and low latency. It will support various applications, including public safety, industrial control, autonomous driving and so on.
- **mMTC** - mMTC mainly refers to IoT services that are characterized by a massive number of devices [46]. The application examples are smart city, smart home and health care monitoring. Low device complexity, long battery life, and significant coverage extension are all important needs for such services, also compatible with a large number for devices.

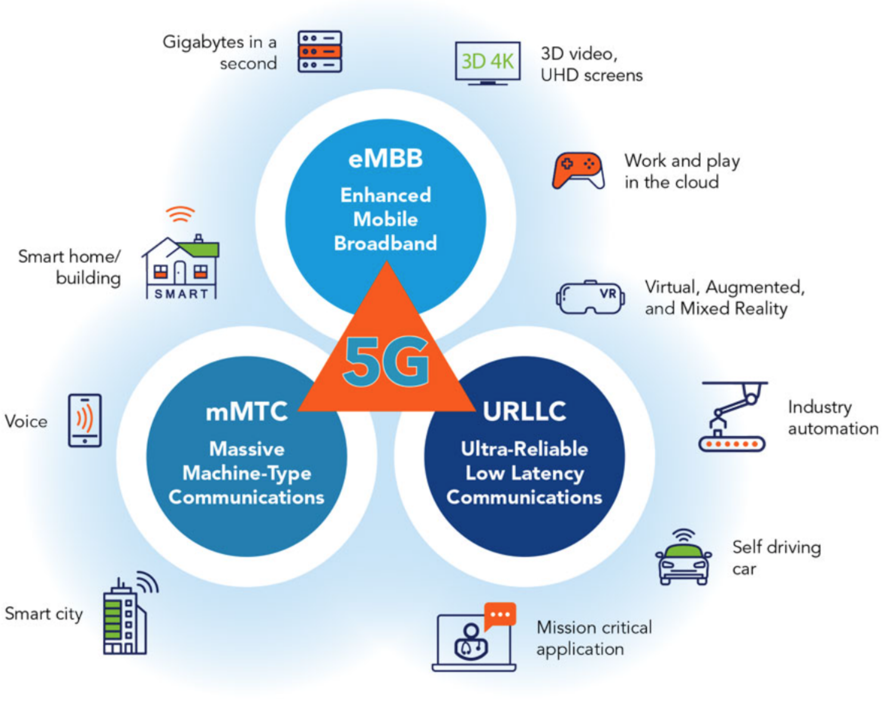


Figure 1.2: 5G Use Cases and Applications [30]

In order to support the three use cases mentioned above on the same physical infrastructure, new technologies like Network Function Virtualization (NFV), Mobile Edge Computing (MEC) and Software Defined Network (SDN) have been introduced in 5G.

1.2.2. Edge Computing

Edge computing is able to provide services at the edge of the network, help realize the localization function of 5G networks, and establish channels for some localized, close-range, and community-based network needs. In the 5G era, the business form will be transformed from the personal internet business in the 4G era to an industry-centric vertical industry (e.g. smart manufacturing and smart city) and enhanced personal business (e.g. AR and VR) , both types of services have requirements for high bandwidth, low latency, high computing power, and high security. This is why we need to introduce edge computing in 5G. The combination of the two can better meet the above needs of various businesses, and bring more flexible edge access to vertical industries and individual users. The localized large computing power and the localized edge ecosystem make edge computing a powerful tool for operators to expand vertical business and enhance personal business. By deploying edge computing platforms, operators can continuously explore vertical industries and improve the digital capabilities of the entire industry. In addition, edge computing can also solve the problems of network bandwidth and data processing brought about by the rapid growth of IoT business. The edge computing architecture is described in Appendix C.

1.2.3. 5G Spectrum

5G new radio (NR) can work across a wide frequency range; each band of the spectrum has its own properties. New frequency bands defined for 5G, as well as frequency bands re-divided from 1G to 4G, can both be utilised by NR. These spectrum bands can be divided into the following three categories:

- **Low-band (below 1 GHz)** - The propagation properties of the signal at these frequencies enable 5G to offer wide-area coverage areas and deep indoor penetration. So it enables the extension of mobile broadband coverage from urban to suburban and rural areas.
- **Mid-band (1–7 GHz)** - It offers a good compromise between coverage, capacity, data rate, and latency for 5G services. This is because, compared to high-band, the properties of wide-area and indoor coverage are better.
- **High-band (above 24 GHz)** - It is in the millimeter wave (mmWave) frequencies. The high-band is able to provide a very high data rate and significant capacity, so as to support enhanced mobile broadband applications. High band is appropriate for intensive local deployments where services require high throughput and low latency. But the shortcoming of using it is that each cell has a smaller coverage area and is more susceptible to blocking, due to the propagation properties of mmWave. Therefore, the High-band frequency may be useful in a smart factory environment.

These diverse demands and spectrum needs demonstrate that there are various choices for bringing 5G to market, and that different frequency bands will be required to cover all use cases. Therefore, in order to better use these frequency bands, operators need to consider balancing and combining the use of these three frequency bands to achieve the target quality performance.

1.2.4. Fundamental Requirements of 5G

Figure 1.3 depicts the well-known "5G Flower", which was first presented by China Mobile and later accepted by the ITU. As we can see from this diagram, the fundamental requirements for building 5G are clear: six performance requirements (petals) and three efficiency requirements (green leaves). In terms of system performance, 5G has to support massive capacity (tens of Gbps peak data rate), massive connectivity (1 million/square kilometre connection density and tens of Tbps/square kilometre traffic volume density) and high mobility (user mobility up to 500 km/h) and low latency communication (1 ms end-to-end latency). Besides, the requirements for different user services vary greatly, the data rate of the user experience ranges from 0.1 to 1 Gbps. In terms of transmission efficiency, 5G has to achieve spectrum efficiency, energy efficiency, and cost efficiency at the same time.

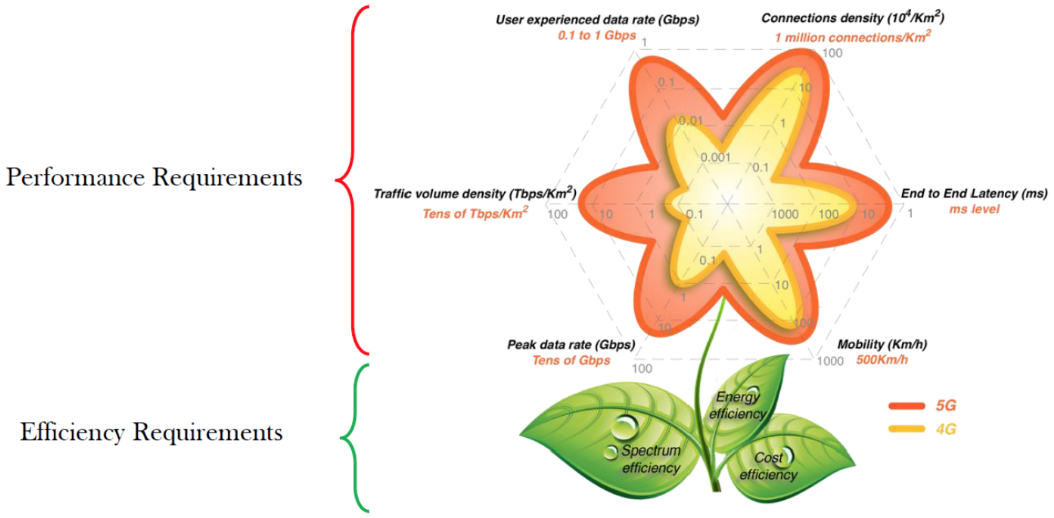


Figure 1.3: 5G Flower [33]

1.2.5. 5G Standardization

In 2015, the ITU published a worldwide 5G work schedule to promote the 5G standardization process, and 3GPP followed suit with relevant standardization work under its architecture. The 3GPP is the collective name for a number of standards organizations that develop various mobile telecommunication protocols. It is best known for developing and maintaining 2G-5G related standards. There are three technical specification groups (TSGs) in 3GPP to carry out the specification work, they are TSG RAN (Radio Access Networks), TSG SA (Services and Systems Aspects), and TSG CT (Core Network and Terminals). In February 2016, 3GPP began research on 5G vision, requirements, and technical solutions at the stage of Release 14, and published the 5G research report 10 months later. In December 2017, at the 78th plenary meeting of 3GPP, the TSG RAN published the 5G new air interface NSA standard, and the new core network architecture and process standard for 5G were published by the TSG SA. The 5G Stand Alone (SA) standard was published in June 2018, at the 80th plenary meeting of 3GPP. The last step for Release 15 was a late drop that was completed in March 2019. This represents the completion of the first complete 5G standard system, which is able to enable the deployment of 5G SA and provide new end-to-end 5G capabilities. In addition, it introduces a new business model for operators, while meeting the needs and expectations of 5G in the communications and vertical industries to a certain extent. With the maturity and near completion of Release 15, 3GPP continued to evolve the NR specification in Release 16, which can fully meet all of the ITU 5G requirements. Figure 1.4 shows the timeline for 5G standardization.

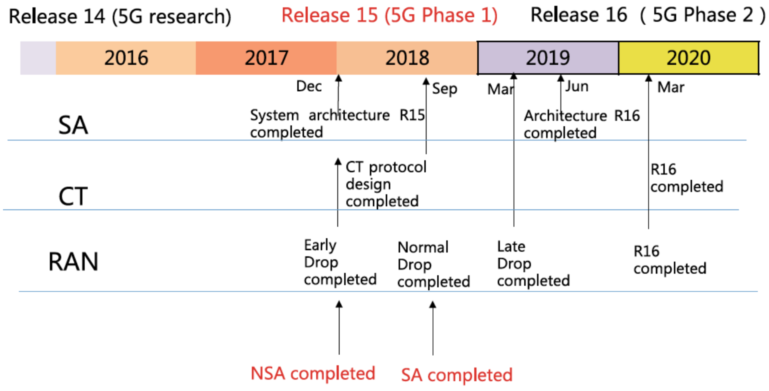


Figure 1.4: Timeline for 5G Standardization [45]

1.3. Research Motivation

Over the past few decades, mobile communication services have also continued to evolve. It is important to understand the evolution of mobile communication systems and the transition between each generation. From 1G to 3G, mobile voice telephony was the major application used to promote the development of mobile communications systems. After the introduction of 3G, mobile broadband data applications have become the driving force behind the advancement of mobile communications networks. 4G LTE is now commonly used to supply mobile broadband data services. Once 5G is introduced, the mobile communications systems will be further developed, meaning more use cases and applications will be supported.

The deployment and the migration from 4G to 5G is the main subject of this thesis. Although the evolution of LTE will be able to support a wide range of usage scenarios and applications in the 5G era, a new generation of mobile communication systems integrating more advanced technical solutions is needed to achieve higher data rates, lower latency, larger capacity and more effective spectrum utilization [47]. Today, most countries and regions are already implementing their own 5G plans. Compared with China, South Korea and the United States, the three leading countries in the 5G market, the EU's 5G plans are relatively slow. The motivation of this thesis is to explore the current status of 5G deployment in the above-mentioned countries and regions, and then draw the internal and external factors faced by the EU in the development of 5G after comparison and analysis, so as to provide recommendations for EU operators in 5G deployment. In addition, as the 5G system will support various business models and services, we will also advise EU operators on how to maintain the continuity of services migrating from 4G to 5G and how to develop new 5G services.

1.4. Research Questions

The main research purpose of the thesis is to provide reference for EU operators in 5G deployment by comparing and analysing the current state of 5G deployment in the EU with other leading countries (China, South Korea and the United States), also provide strategies for EU operators in 5G services development. To understand how to help EU operators better deploy and develop 5G according to their own conditions in the future, brings us to the following research questions:

- What are the strengths and weaknesses of the EU in developing 5G compared to other leading countries?
- What opportunities and challenges will the EU face in developing 5G?

Once these two issues have been addressed, we then need to provide appropriate 5G development advice for the EU, which brings us to the following three research questions:

- What are the pros and cons of the existing feasible 5G migration paths, and whether they are suitable for operators in the EU?
- How can EU operators deploy 5G networks and equipment?
- How can EU operators provide services during and after the migration process?

1.5. Thesis Outline

The thesis consists of seven chapters. Starting with current network technologies, we analyze and compare multiple 5G deployment and migration options. Then we compare the 5G status of the EU with China, South Korea and the United States, and analyze the internal and external factors faced by the EU in the development of 5G. Finally, based on the above two analysis results, we put forward corresponding suggestions for the development of 5G in the EU. In Chapter 2, the literature review for this thesis is provided. In Chapter 3, we describe the relevant, including the existing, network technologies in 4G and 5G. In Chapter 4, various 5G deployment options are discussed, as well as the options for communication services. Then, based on these options, we offer several paths for operators in 5G migration. In Chapter 5, we describe the 5G status/plans in different countries and regions, they are: three leading countries (China, South Korea and the United States) and the EU. Then, then compare the EU with the three leading countries, analyze the internal and external factors faced by the EU in developing 5G. In Chapter 6, we provide suggestions for EU operators in 5G deployment and 5G services development. In Chapter 7, we conclude our study and propose directions for further work.

2

Literature Review

This chapter presents the findings from prior art related to 5G deployment and migration.

2.1. 4G Network

4G LTE and 4G EPC form the EPS architecture, as described in [11][20]. The EPS in the first place responsible for providing IP address, it connects user's IP address to a public data network (PDN), allowing them to access the Internet and run applications like voice over IP (VoIP). A quality of service (QoS) is usually coupled with an EPS bearer, which can be defined as a pipe line through which data traffic flows within EPS. For a given user, multiple bearers can be created in order to provide different QoS streams or connectivity to different PDNs. A user could, for example, be on a voice (e.g. VoIP) call while also visiting the website or downloading files via FTP. A VoIP bearer would offer the required QoS for a phone call, whereas a best-effort bearer would suffice for web surfing or downloading files via File Transfer Protocol (FTP).

In 3GPP Release 9 [10], several new functions have been introduced to provide users with sufficient security and privacy, while protecting the network from fraudulent use. For example, the support of IMS, emergency calls, UE positioning and so on. All the functions mentioned above are achieved through several EPS network elements that play different roles. Inter-working and mobility (handover) with networks employing other Radio Access Technologies (RATs), such as GSM and UMTS, are also supported by EPS. Besides, LTE itself only supports VoIP using IMS services. But if IMS services have not been deployed at the outset, Circuit Switched Fallback (CSFB) is also supported by LTE. By using CSFB, the CS voice call can be processed for UE in LTE through legacy RATs. A description of the above techniques and how to implement them can be found in [4][55].

2.2. 5G Network

5G Next Generation Radio Access Network (NR RAN) and 5G Core (5GC) form the 5G System (5GS) architecture, as described in [8][9]. A new representation of the 5G network architecture, the 5G Services-Based Architecture (SBA), is also included in it, along with the reference point between any two network functions (NFs). The NFs inside the control plane that use this Service-Based representation provide authorized access to services provided by other NFs. The network becomes modular as a result of this implementation, and components in the network can be reused. And SBA supports virtual deployment, making fully scalable NFs possible. Hence, the available hardware resources can be better used while serving the growing network. Another approach to modeling interactions between architectural components is based on reference points. As a conceptual point at the intersection of two NFs that do not overlap, the reference point, is the same as one or more service-based interfaces that offer equivalent function.

Since the migration from 4G to 5G is not a one-time thing, for several years, EPC will coexist with 5GC, allowing network operators to migrate from one system to another while devices on 4G LTE can still use the legacy system. [9] explains the inter-working capabilities in various network scenarios, like roaming, non-roaming and non-3GPP access. It also includes the different ways of providing communication services when users are roaming in other networks, the roaming architecture for 5GS is described in [43]. An example architecture for inter-working with EPC is given in Chapter 3. This architecture makes it possible to move the UE between 5GC and EPC, as well as any or all the PDU sessions in the system. Furthermore, in such an architecture, the 5G user is able to roam in visited networks that do not support 5G. This is because, under this circumstance, the NFs of the 5G network only exist in the home network, while the E-UTRAN, MME and S-GW (EPC) form the visited network.

2.2.1. Deployment and Migration

With regard to 5G deployment, according to [5], operators have a variety of options to deploy 5G (as described in Chapter 4), including migration from 4G in the initial stage of 5G. First of all, it needs to be mentioned that the various 5G options can be divided into two categories: Non-Standalone (NSA) and Standalone (SA). The NSA relies on the existing LTE system to enable 5G NR deployment, whereas the SA allows 5G deployment without the LTE system. Instead, it includes a new 5G packet core architecture and uses NR as the radio access technology. Next, about the 5G migration options, Kim et al. [44] and Shetty et al. [58] presented several options available to operators for the introduction of 5G system that intend to migrate from their 4G network. For each option, they provide a high-level description of 5G introduction and subsequent migration, primarily from a technical perspective. However, it is not only technology that affects operators' choice of 5G migration path. The migration path selection can be influenced by various factors such as support for other service and industries, time to market, spectrum allocation, the current network conditions/architectures and so on. As a result, different operators will have many different concerns when choosing to roll out their own 5G plans. Also, in [44], authors did not take 5G SA as the final migration stage, the final goal of some migration paths is 5G NSA. But it is clear that the ultimate goal of 5G is to achieve 5G SA (i.e. Standalone NR under 5GC), as it does not rely on the tradition LTE system. Then the two deficiencies in these literature triggered our further thinking, that is, which operators are suitable to migrate directly from 4G to 5G SA, and which operators are suitable to start with 4G migration to 5G NSA mode, and gradually evolve to a dual-module network where SA and NSA coexist, eventually realizing SA mode. Since the topic of this thesis is the deployment and migration of 5G, it is important to understand the above contents.

In order to better understand 5G deployment, we explore the 5G deployment status in the EU and the three leading countries (China, South Korea and the United States) [15][17][18][28]. These documents mainly describe 5G availability around the world. Based on the description of [28], we can conclude that among the four countries and regions mentioned above, although China, South Korea and the United States are all leaders in the 5G market in the world today, their models of deploying 5G are different. South Korea's 5G development process makes it more like a producer country. The standard to measure their 5G success is the global sales of key 5G products such as semiconductor components and software. In addition, like China, the construction and promotion of its national 5G network is guided by national industrial policies, which is highly unified, and thus maintains its competitiveness in global competition. For China and the United States, their 5G development process makes them more like a combination of producer countries and user countries. In addition to selling their own 5G network equipment and chips across the world, they also promote technology for local broadband services in their own countries. However, due to the differences in technological levels and government functions between the two countries, their development processes in these 5G are also different. [15][17][18] mainly focused on the current state of 5G development in the EU, and also used a small part to describe the development of 5G in other countries outside the EU. From these three literature, it is not difficult to see that the EU's 5G plans are relatively slow compared to China, South Korea and the United States. However, the above four literature do not give too much information on how the EU compares with other three leading countries in terms of 5G. As the focus of the thesis is to provide reference for EU operators in 5G deployment and migration, it is important for us to compare the EU with other three leading countries and, in the process, analyse the internal and external factors that will affect the EU in the future development of 5G. Only after the results of the analysis are available, we will be able to provide useful recommendations to EU operators on different aspects.

2.2.2. Services

The telecommunications services has seen significant developments in recent decades. Each generation of mobile communication systems before 5G differed from their predecessors in several aspects, 5G is no exception. Therefore, we can roughly divide the 5G services into two parts, namely the services migrated from 4G to 5G and the newly emerging services in the 5G era.

- **Traditional Communication Services** - When it comes to voice communication technology in 4G and 5G mobile networks, Voice over LTE (VoLTE) and IP Multimedia Subsystem (IMS) are inescapable topics. In 4G networks, IMS is a network element that works with the EPC to enable VoLTE, which can be used to facilitate voice calls and SMS. And since IMS voice can be applied in both 4G and 5G networks, it is important to understand the technologies associated with it, as described in Chapter 3. It provides an overview of the IMS network, such as the definition of the IP Multimedia Core Network Subsystem, the features required to enable IMS services and how these services work in the networks.

  According to 3GPP, it is known that 5G still provides IMS-based voice/video communication services, using the voice/video communication architecture for 4G. As NR is the radio access technology in 5G, similar to the voice/video over LTE network is called VoLTE, the voice/video on 5G (NR) network is called VoNR. Several documents related to voice/video services in 5G have been published by Ericsson [23][24]. These documents provided several options for 5G voice/video services and describe how to implement them. For 5G networks, Voice over NR (VoNR) is the ultimate goal for voice/video communications, it implies that the NR Standalone Option 2 (explained in Chapter 4) is considered. A 5G core that supports voice is in charge of managing NR coverage. The 5G base station, known as NR gNodeB, will be crucial in establishing the QoS flow and may later start an inter-system handover to EPS. In most cases, in the initial phase of 5G deployment, the operator may not have NR deployed, or even if it is deployed, it may not be fully covered. It is necessary for operators to implement 5G and 4G inter-working to expand the coverage of their voice services. As a result, VoNR will not be able to represent all 5G voice/video communication solutions. The voice/video services in 5G should also include E-UTRA-NR Dual Connectivity (EN-DC) and EPS Fallback (EPS FB), which needs to be achieved by introducing NR and 5GC. The description of the above-mentioned technologies used for voice/video services is presented in Chapter 4. Unfortunately, in addition to providing several options for 5G voice/video services, Ericsson [23][24] did not build the evolution paths for 5G voice/video services with the these options. Furthermore, these two literature did not address challenges that may be encountered during network migration, such as how to maintain service continuity. To maintain the user experience, the services mentioned above must be supported at all phases of the 4G to 5G network migration for UEs and other voice-centric devices. In conclusion, it remains unanswered what voice/video service migration path operators should choose and how they should provide seamless voice support during the migration process, which are also important for other communication services such as SMS and USSD.

- **New applications in 5G** - Like previous generations of networks, 5G will give a consistent experience, access on multiple interfaces/ devices, trustworthy and dependable communications, resilient networks, responsiveness, and real-time communications, among other benefits. Compared with 4G, for users, 5G can provide higher data rates, greater capacity and lower latency; and for operators, 5G can provide more types of services for their subscribers. With the advent of 5G, applications such as Device to Device (D2D) communications, Vehicle to anything (V2X) communications, Machine to Machine (M2M) communications, augmented reality (AR), Internet of Things (IoT), etc., which are difficult to implement and sustain in 4G networks, will be developed in 5G networks. Lin et al. [46] presented a description of the above applications, but did not provide operators with suggestions on how to achieve them. For these new applications, the challenge for operators will be to better serve their subscribers and to move from a traditional communications business model to one that incorporates new 5G services. Moreover, 5G technology can also enter other areas such as transportation, healthcare, industry and so on. In general, there are still many unknown areas in the 5G industry, and there are key issues such as scale promotion and unclear business models. Operators still need to work in both the traditional services and new 5G applications.

3

Overview of Current Network Technology

In this chapter, we describe the current network technologies involved in 4G and 5G networks.

3.1. 4G Network

The Evolved Packet System (EPS) is the first place responsible for providing IP address, it connects a user's IP address to a public data network, allowing them to access the Internet and run applications like voice over IP. A quality of service is usually coupled with an EPS bearer. For a given user, multiple bearers can be created in order to provide different QoS streams or connectivity to different PDNs. A user could, for example, be on a voice (e.g. VoIP) call while also visiting the website or downloading files via FTP. A VoIP bearer would offer the required QoS for a phone call, whereas a best-effort bearer would suffice for web surfing or downloading files via File Transfer Protocol (FTP).

In order to offer users with sufficient security and privacy, and also protect the network from fraudulent use, several new functions have been introduced in LTE, Release 9. For example, the support of IP Multimedia Subsystem (IMS), emergency calls, user equipment (UE) positioning and so on. All the functions mentioned above are achieved through several EPS network elements which play different roles. The EPS network architecture, including the network elements and the standardized interfaces, is depicted in Figure 3.1.

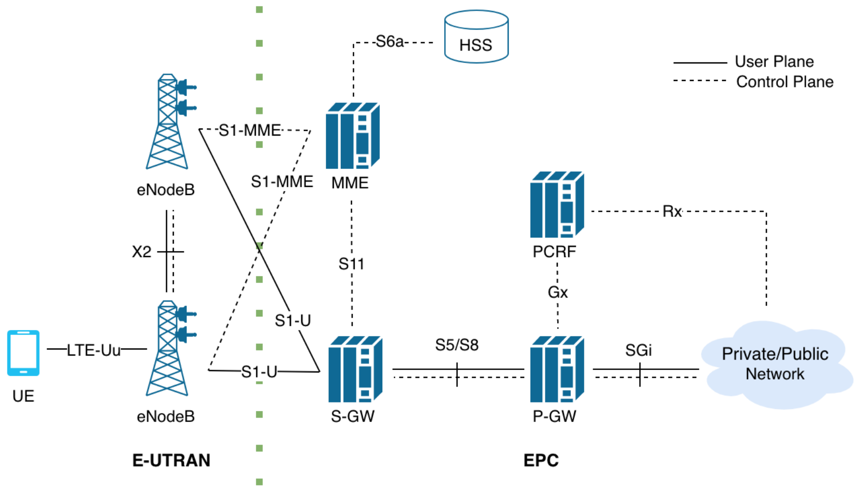


Figure 3.1: EPS Network

From Figure 3.1, we can see that the network is divided into two parts at a high level: the Evolved Packet Core (EPC),i.e., the core network, and Evolved-UMTS Terrestrial Radio Access Network (E-UTRAN), i.e., the access network. Although the core network consists of multiple logical nodes, the access network basically consists of only one node, that is, an evolved NodeB (eNodeB) links to the UE. To achieve multi-vendor interoperability, each of these network components is connected to each other through standardized interfaces. This allows network operators to source various network pieces from a variety of vendors. In fact, network operators may choose to separate or merge these logical network parts in their physical implementations based on business concerns [11].

3.1.1. Inter-working with the UMTS

3.1.1.1. 3G Network

Before discussing inter-working with UMTS, we need to introduce the 3G network first. 3GPP standardized the 3G network, which is known as Universal Mobile Telecommunication Systems (UMTS). UMTS always ensures backward compatibility, which makes the inter-operation between old and new technologies possible [26]. Figure 3.2 shows the design of a UMTS network.

UE, a set of NodeBs, and Radio Network Controllers (RNCs) make up the whole radio access network, known as the Universal Terrestrial Radio Access Network (UTRAN). In this architecture, the RNC is the aggregation point for a group of NodeB's. The Serving GPRS Support Node (SGSN) and the Gateway GPRS Support Node (GGSN) are two important components in the core network. UE's access control, security functions, and location tracking are all handled by SGSN. The home location register (HLR) is a database used to store subscription data like IMSI and MSISDN. GGSN is in charge of the billing function, as well as performing filtering and firewall protection.

And there is an important element in UMTS networks (also in GSM networks), that is, the Authentication Centre (AuC). It is associated with the HLR in a GSM/UMTS network, and is used to authenticate mobile users who want to connect to the network. Both the SIM card and the AuC store the authentication key, which cannot be read by either of the above. Authentication is done by identifying and verifying the validity of the SIM card.

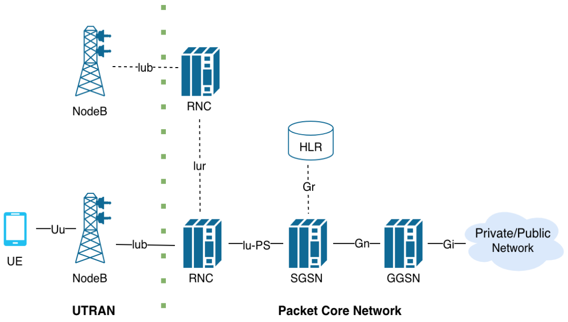


Figure 3.2: 3G Network

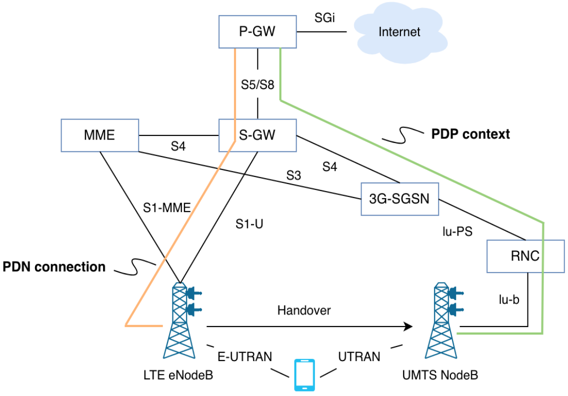


Figure 3.3: Architecture for 3G UMTS Inter-working

3.1.1.2. Inter-working Architecture

Inter-working and mobility (handover) with networks employing other Radio Access Technologies (RATs), such as Global System for Mobiles and Universal Mobile Telecommunications System, are also supported by EPS. Figure 3.3 depicts the architecture for 3G UMTS inter-working.

For users, the SGSN is the service access point to the UMTS network. It is used to handle all packet switched data within the network, such as the user's mobility management and authentication. If the authentication is completed successfully, the SGSN processes the registration of UEs with UMTS and its responsible for their mobility management. As a key element in the EPS network, the MME is used to manage UE access networks and mobility. In addition, it offers the control plane function for mobility between LTE and 2G/3G access networks, in which the S3 interface terminates from SGSN to MME.

In Figure 3.3, we can see that when the UE leaves the coverage area of an LTE network, the eNodeB is able to instruct the UE to report to the neighboring UMTS cell. Then the MME receives this report and contacts the responsible 3G-SGSN to request the handover process. The S3 interface, which is based on the protocol used for the relocation process between SGSNs, is applied here. Therefore, the process can be enabled without the changes to the software of 3G-SGSN. The MME will send a handover command to the UE through the eNodeB once the 3G radio network is ready for the handover. After the handover is completed, the user data tunnel between S-GW and eNodeB is re-routed to SGSN. The PDP Context is established over UMTS at the same P-GW as the PDN Connection in LTE. Therefore, the subscriber management tasks originally undertaken by the MME have been taken over by the SGSN. However, the S-GW stays in the user data route through the S4 interface. From the SGSN's perspective, it behaves as a 3G-GGSN, the S4 interface is thus regarded as the 3G Gn interface between SGSN and GGSN.

3.1.1.3. Circuit-Switched Fall Back (CSFB)

First of all, LTE itself only supports VoIP using IMS services. But if IMS services have not been deployed at the outset, CSFB is also supported by LTE. By using CSFB, the CS voice call can be processed for UEs in LTE through legacy RATs. Also, the UE in LTE can be handed over to a legacy RAT to initiate a CS voice call by using CSFB.

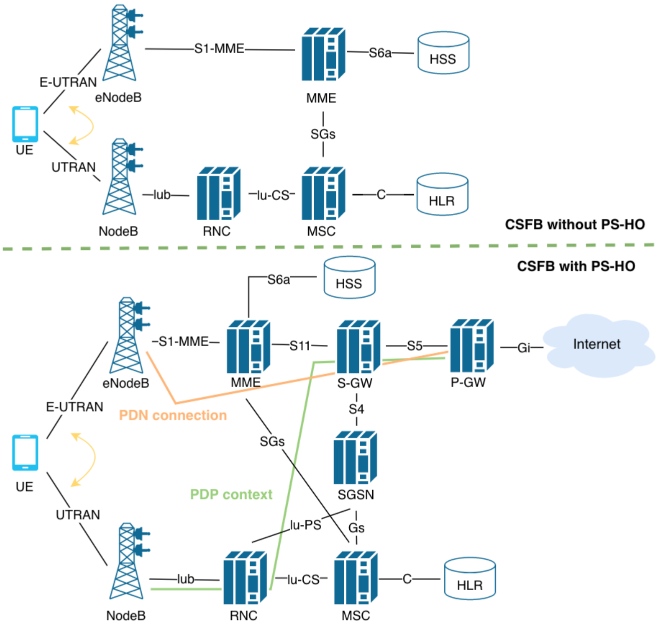


Figure 3.4: Architecture for CSFB

Figure 3.4 shows the simple architecture for CSFB and the architecture of CSFB with Packet Switched Handover (PS-HO). In Figure 3.4, we can notice that the interface between the MME and the Mobile Switching Centre (MSC) of the legacy RAT is SGs interface. By using the SGs interface, though the UE is still located in LTE, it is able to connect to MSC and register CS services. Therefor, the UE in LTE can be handed over to a legacy RAT to initiate a CS voice call by using CSFB. This interface also allows mobility management and paging procedures between the MME and the MSC. For example, in order to page UE through LTE, the paging messages from the MSC for incoming voice calls are carried by this interface. Also, in the figure of the CSFB architecture with PS-HO, we can see that after CSFB, the PDP Context established over 3G access network terminates at the same P-Gw as the PDN Connection in the 4G access network.

- **CSFB for Unstructured Supplementary Service Data (USSD)** - USSD is a communication protocol used to send short text messages on GSM networks. The format of USSD is similar to SMS. But these messages will not be saved on the operator's side or the mobile device of the subscriber, as the connection created by it during the USSD sessions is real-time. USSD can work in many cases, such as callback service and checking the usage available. Here, after sending USSD messages to the USSD gateway via IP signaling, CSFB for USSD can be alleviated through USSD over IP. For more details about CSFB, see [4].

3.2. VoLTE and IMS

As part of the vision of developing mobile networks beyond GSM, 3GPP first designed the IP Multimedia Subsystem (IMS). IMS is an architectural framework that enables any terminal to access IP multimedia services. IP Connectivity Access Networks (IP-CAN) and IM Core Network (CN) subsystems make up the IP Multimedia Subsystem. In IMS, IP-CAN means any kind of IP based access network, users reach the IMS over an IP-CAN such as LTE or 3G. All CN elements required to provide users with multimedia services form an IM CN subsystem. For both wireline and wireless users, the multimedia services mentioned above encompass voice, video, messages and so on.

IMS is capable of interacting with the legacy network and transferring calls in these two directions as needed. IMS meets two types of market needs: 1. IMS provides standardized services, allowing two users to connect without being restricted by their respective operators; 2. IMS provides users with differentiated services. Besides, when using IMS's services, the QoS can be guaranteed by IMS. These benefits are conducive to voice services. The most important signaling protocol used here is the Session Initiation Protocol (SIP), which is used in various network elements to perform various functions such as service triggering, authentication and authorisation and other basic network attributes [48].

Voice over LTE (VoLTE) is a high-speed wireless communication standard for LTE, it is suitable for mobile phones and data terminals, like Internet of Things (IoT) devices. Based on the IMS architecture framework, VoLTE has specific profiles for voice service (control and media plane). This makes VoLTE possible on the GSMA's LTE wireless broadband service, as defined in Permanent Reference Document (PRD) IR.92 [36]. The voice service is given as data flows within the LTE data bearer, eliminating the need for a circuit-switched voice network in the call path.

3.2.1. IMS Architecture

The IMS network architecture defined by 3GPP is shown in Figure 3.5. In this section, we only give an overview of the high-level IMS network architecture. Detailed descriptions of various functional entities can be found in [6].

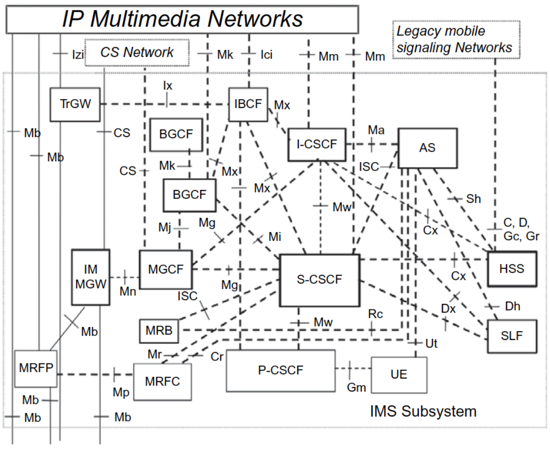


Figure 3.5: Architecture of IMS Network [6]

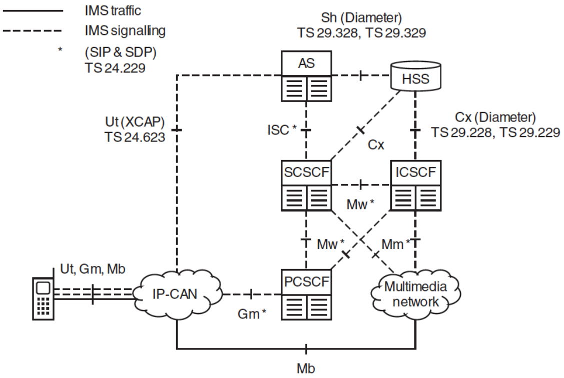


Figure 3.6: Main Architectural Components of IMS [6]

- **Core network** - Since displaying all of the functional entities will make the diagram look confusing (as shown in Figure 3.5), we will use Figure 3.6 to illustrate the main components for basic SIP session establishment. Applications deployed on the IP hosts are formed by various functional entities such as Proxy-Call Session Control Function (P-CSCF), the IP hosts connected to the IP infrastructure of the operator. More than one functional entity may reside on the same host, that is, functional entities can be co-located, such as the functional entities Serving-Call Session Control Function (S-CSCF), P-CSCF and Interrogating-Call Session Control Function (I-CSCF) shown in Figure 3.6. The signaling in the network is not affected by co-location; though IP messages between entities on the same host may choose a shorter route, we will employ the same process and signaling. Also, the functional entities shown in the figure can be deployed multiple times, which is mainly applicable to the following scenarios:

- If the number of subscribers in the network exceeds the number that one HSS can take over, multiple HSSs are needed in order to maintain the number of users in the network. Also, numerous SIP sessions established correspondingly need to be processed by multiple S-CSCFs.
- If one S-CSCF becomes temporarily inoperable or is being maintained, the registration of the subscriber can be taken over by another S-CSCF from the former one. During registration, the HSS assigns the appropriate S-CSCF to the subscriber.

The table below gives a description of the interfaces (control plane) shown in Figure 3.6.

Table 3.1: Interfaces (Control Plane) in IMS Network

Interface	**Description**
Cx	Interface used between I-CSCF/S-CSCF and HSS. The Diamater protocol is used here. By using the Cx Interface, CSCF and HSS are able to communicate with each other. Also, the procedure authentication and S-CSCF assignment need this interface.
Gm	UE connects to P-CSCF using SIP over Gm interface.
ISC	Based on SIP, the ISC links the S-CSCF to the Application Server (AS) supported in HPLMN or 3rd party network.
Mm	Interface between I-CSCF/S-CSCF and external IP networks. Based on SIP, it allows the exchange of messages between IMS and external IP networks.
Mw	Interface used to convert messages between one CSCF and another. In an IMS network, the Mw interface forms general SIP signaling between CSCFs.
Sh	Interface used to exchange user-related information between AS and HSS. The Diamater protocol is used here.
Ut	Interface between UE and AS. Based on the XML Configuration Access Protocol (XCAP), it makes the management of subscriber information related to services and settings easier.

The description of IMS in the 5G system can be found in 3GPP TS 23.228. The interfaces between IMS and 5GS are Gm (described in Table 3.1) and Rx. When UE is in 5GS, to enable IMS service, the interface between P-CSCF and PCF is Rx.

- **Access network** - The IP-CAN offers the terminal with IP connectivity and mobility. Through the IP-CAN, control plane signaling and media transfer are applied to IMS CN by the IMS terminal [48]. As shown in Figure 3.6, the UE connects to the P-CSCF via the Gm interface, which represents SIP signaling between these two functional entities. And in the user plane, the Mb interface is defined for transmission with UE. In addition, except for the entities shown in Figure 3.5, the Access Session Border Gateway (A-SBG) cannot be ignored. The Session Border Controller (SBC) on the control plane and a Session Gateway (SG) on the user plane constitute the A-SBG. It allows IMS network access from wireline terminals.

3.2.1.1. Relation with VoLTE

Through the IP network, IMS enables voice services known as VoLTE. VoLTE sessions involve different parts of the network, including UE, EPS and IMS CN. Figure 3.7 depicts the various components and how they connect with each other (for a roaming UE).
When UE is roaming, it reaches the IMS via a P-GW in the visited network [37]. By using a technique called optimal routing, this makes it possible for users to make local phone calls without the need for media all the way back to their home network. The visited network also has the P-CSCF, so IMS signaling can be seen by this network. The Application Server (AS) is responsible for offering the UE with the requested service. After the P-CSCF receives a request from UE, the data including the information about the subscriber's enabled services will be sent from the P-CSCF to AS via S-CSCF. The protocol used here is XCAP.

As we discussed in Section 3.1, UICC is used when UE accesses the EPS network. Since the USIM runs on UICC stores user-related data, by using USIM, registered users on its network can be identified. When connecting to the IMS network, UE also needs an identity, it can be done via IP Multimedia Private Identity (IMPI)/IP Multimedia Public Identity (IMPU) using keys from USIM. So by using USIM, UE can access the EPS network and then complete the registration on the IMS network. In order to guarantee that UE is able to access IMS while roaming, the VoLTE specifications require that each network operator should use the well-known access point name (APN) of IMS, i.e., "IMS", to refer to IMS. And if the IMS has not been carried out

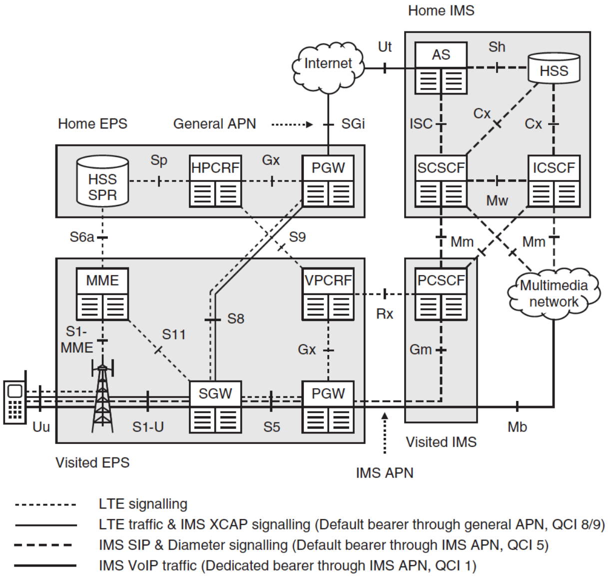


Figure 3.7: IMS in VoLTE [20]

by the operator of the visited network, then UE can use the P-GW in the home EPS to reach the P-CSCF in the home IMS. Since this does not meet the specifications of VoLTE, voice calls cannot be made on it, however, other services like SMS can be realized.

Since the SIP signaling messages sent between UE and IMS cannot be understood by the EPC, so from Figure 3.7 we can see that a default EPS bearer with QCI equals to 5 is used to transmit these messages in the user plane of LTE. This bearer was established prior to the UE's registration with the IMS, and was removed after it was de-registered. Besides, a dedicated EPS bearer with QCI equals to 1 is used to transmit voice traffic of UE. This bearer is established at the beginning of the phone call, and removed at the end. To achieve the assumption in the VoLTE specification that UE supports only one such bearer, multiple voice streams are bundled into the same bearer and given the same allocation and retention priority by the network [20]. So far, only the dedicated EPS bearer with QCI equals to 8/9 remains unexplained in the above figure. This bearer is used to process non-real-time streams.

3.2.2. SMS over IP

Figure 3.8 shows the architecture used to deliver SMS messages over the IMS, that is, SMS over IP.

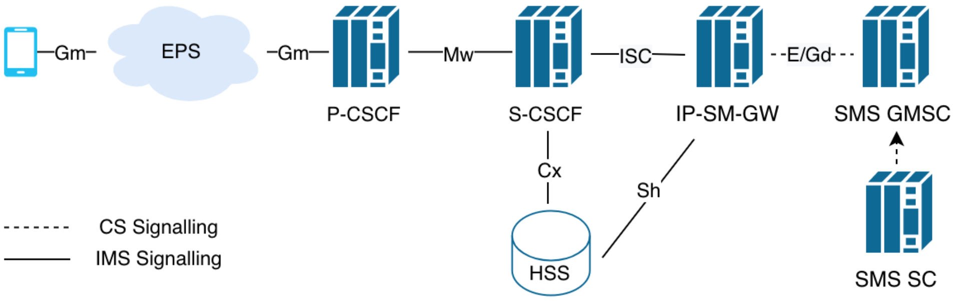


Figure 3.8: SMS over IP

The full form of the abbreviation in this diagram is as follows: ISC stands for IMS Services Control; SMS SC stands for SMS Service Center.

In Figure 3.8, the IP short message gateway (IP-SM-GW) plays the most important in the architecture, as it serves as the IMS application server, the server for mobile switching center (MSC) or SGSN for SMS interworking and gateway MSC (GMSC) [3]. SMS over IP is required for a VoLTE phone, and there are two choices for the network: SMS over IP or SMS over SGs.

The UE indicates its support for SMS during the registration process by including a media feature tag "+g.3gpp.smsip" in the REGISTER request [2]. The UE registers with the IP-SM-GW via the S-CSCF, the gateway is responsible for informing the HSS that it is ready to receive short messages from the UE. Next, similar to the method we embed SDP information as explained in Section 4.3, by embedding SMS messages in a SIP MESSAGE request, the IMS is able to transmit these messages between the UE and IP-SM-GW. A detailed description of SMS flow and the interfaces shown in the above figure can be found in [2].

3.2.3. USSD over IMS

This service supports both UE-initiated and network-initiated Man Machine Interface (MMI)-mode USSD operations, allowing for the transparent transport of MMI strings entered by the user to the IP Multimedia (IM) core network, as well as the transparent transport of text strings from the IM core network that are displayed by the UE for user information [7]. The MMI code is a cellphone code that begins with a star/hash (*/#) prefix. MMI codes are input in the same way that phone numbers are to get various information, and to enable and disable various operations.

3.2.4. Single Radio Voice Call Continuity (SRVCC)

If the LTE coverage is not available everywhere, then the UE involved in a VoIP call over LTE may be forced to exit the coverage of LTE and enter a GSM/UMTS domain that only provides CS voice services, as shown in Figure 3.9. The Single Radio Voice Call Continuity (SRVCC) process is used to handover (HO) a Packet Switched (PS) VoIP call on LTE to a CS voice call on GSM/UMTS, including transferring a PS bearer to a CS bearer [55].

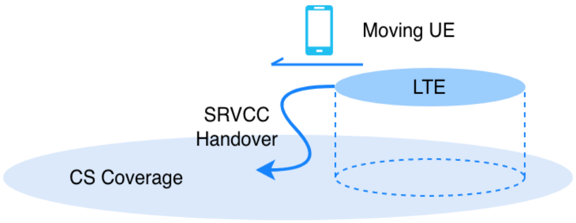


Figure 3.9: SRVCC Handover

Next, we will introduce the main procedures involved in such an SRVCC handover procedure.

First, if the UE is leaving the coverage of LTE, the eNodeB needs to be aware of this change and report it to the E-UTRAN. Next, MME gets the handover request from E-UTRAN and indicates that it is used for SRVCC processing, and then triggers the SRVCC process with the MSC Server enhanced with SRVCC if MME has the Session Transfer Number for SRVCC (STN-SR) for UE [1]. The session transfer process to the IMS is then established by the MSC Server, which is coordinated with the CS handover process to the target cell. Besides, the MME is used for transferring the PS E-UTRAN Radio Access Bearer (E-RAB) carrying VoIP to the CS bearer. After that, the MSC Server answers the request from E-UTRAN with a PS-CS HO Response, including the message of the CS HO command that is required by UE to attach UTRAN/GERAN. The UE can still make calls within the CS coverage even if the handover is completed.

3.3. 5G Network

In 5G, a new radio access technology known as New Radio is supported. As a result, equipment supporting NR and its frequency is required. Also, the 5G network architecture is different from the traditional network architecture in that it enables Service-Based Architecture. This indicates that the functional components in the 5G network architecture are used to provide services to authorized users or other functional components, which are called Network Functions (NFs). The network becomes modular as a result of this implementation, and components in the network can be reused. And SBA supports virtual deployment, making fully scalable NFs possible. Hence, the available hardware resources can be better used while serving the growing network.

3.3.1. The Core Network

There are two different representations of the 5G core network architecture, one using reference points and one using service-based interfaces, as shown in Figure 3.10 and Figure 3.11 (not all functional entities are included). By making use of the 5G core network, the UE is able to attach to one or more packet data networks (DN), such as the Internet or the IMS.

From Figure 3.10, we can see that each connection is associated with a SMF and each UE is assigned an AMF, which is known as its serving AMF [21]. These functional entities are described later. Though the representation using reference points is common from earlier generations, another approach using service-based interfaces is usually used to represent the core network in 5G.

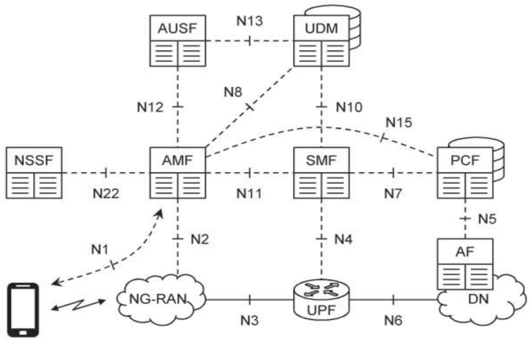


Figure 3.10: 5G Core Network Using Reference Points [9]

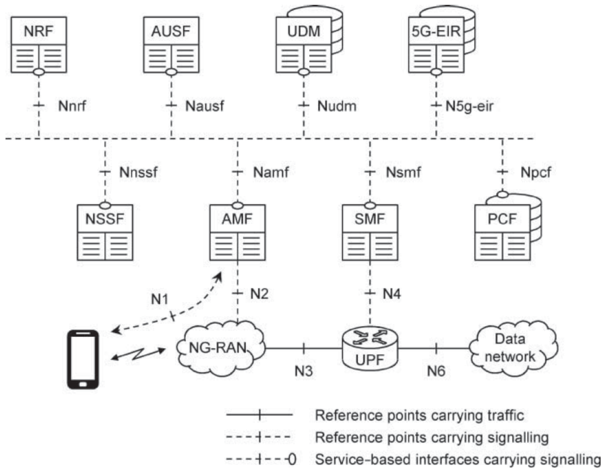


Figure 3.11: 5G Core Network Using Service-Based Interfaces [9]

From Figure 3.11, we can see two different approaches to modeling interactions between architectural components, namely, Service-Based Interfaces and Reference Points. As a conceptual point at the intersection of two NFs that do not overlap, the reference point, is the same as one or more service-based interfaces that offer equivalent functionality. In the 5GC, the great majority of signaling processes are defined through service-based interfaces. Almost every NF in Figure 3.11 is linked to a service-based interface, and through a well-defined application programming interface (API), NF is able to provide services to other NFs.

There are two kinds of NFs on the service-based interface: 1. NF producer, the one who provides services; 2. NF consumer, the one who uses the services by the NF producer. Furthermore, the producer's services are divided into two groups: a crude grouping of NF services and a finer grouping of specific service operations. The scheme Nnfname_ServiceName_ServiceOperation is used to name each operation, with the three elements identifying the service-based interface, NF service, and service operation respectively. Take UDM for example, the Nudm_SubscriberDataManagement_Get service operation in its interface allows another NF to retrieve some or all of a user's subscription data. However, the adoption of service-based interfaces is still imperfect. From Figure 3.11, we can notice that the radio access network and the UPF do not have a service-based interface. Instead, these two NFs still apply the signalling processes defined on reference points.

3.3.1.1. Difference between EPC and 5GC

To better understand the similarities and differences between the architectures of EPC and 5GC, we drew a diagram to give the mapping of EPC functions to 5GC functions, as shown in Figure 3.12.

From Figure 3.12, we can see that PCF in 5GC is equivalent to PCRF in EPC. During a session, similar to PCRF, PCF processes user plane resources and offers information related to charging. To implement a policy, the PCRF uses application server or the data of subscriber. The PCF receives data from various 5GC functional entities, including the AF, AMF, SMF and so on. Unlike the PCRF that connects directly to the P-GW, the PCF connects to the SMF, next, the SMF is connected to the UPF. Therefore, by communicating with the UPF, the SMF is able to enforce the policies created by the PCF in the user plane. In addition to managing per-session

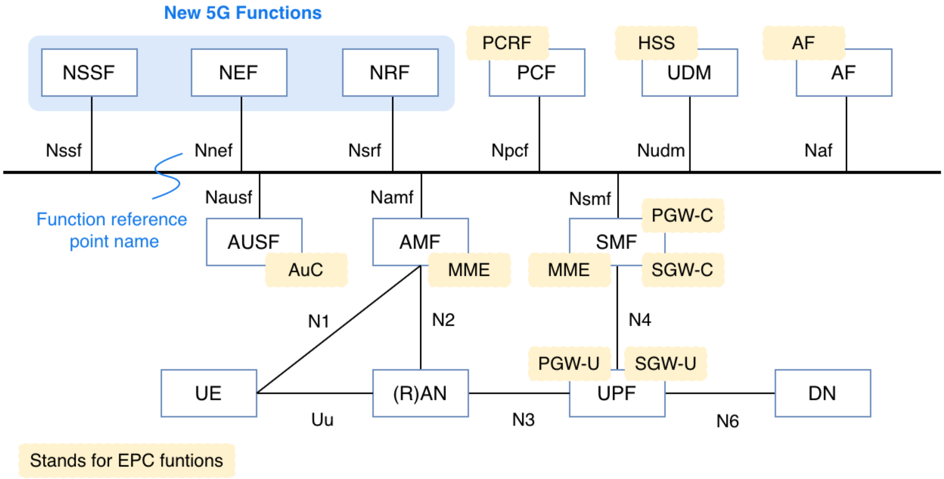


Figure 3.12: EPC vs 5GC

QoS and charging, PCF is able to validate a subscriber's right to access a particular service according to its geographic region.

And from the figure above, we can notice that the function of MME in EPC is divided into two parts in 5GC. They are 1). AMF, which is responsible for mobility management and UE authentication; 2). SMF, which is responsible for session management. The S-GW and P-GW have independent control planes and user planes in EPC. And in 5GC, the SMF manages the control plane functions of the S-GW and P-GW, whereas the UPF manages the user plane functions. In EPC, MME, HSS and AuC are responsible for managing the authentication vectors. And in 5GC, when asked by the AUSF, the UDM is able to generate the authentication vectors. Besides, through UDM, the AMF and SMF are able to access the subscription data.

3.3.1.2. Inter-working between EPC and 5GC

For several years, the EPC will coexist with the 5GC, allowing network operators to migrate from one system to another while devices on LTE are still able to use EPC. Here we give an example architecture for inter-working with the EPC, as shown in Figure 3.13. More details about migration from one system to another are discussed in Chapter 4.

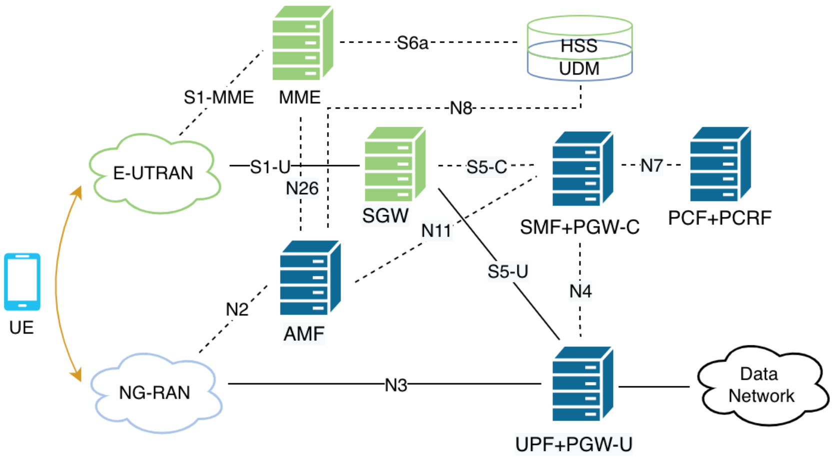


Figure 3.13: Architecture for Inter-working between EPC and 5GC

From Figure 3.13, we can see that a single subscriber database is shared by the two core networks. It acts as a UDM (5GC) and an HSS (EPC). And the base station (BS) can be located in the NG-RAN if it supports the NG backhaul to 5GC, or the E-UTRAN if it supports the S1 backhaul to EPC, or both. Apart from that, this architecture also includes three other combined NFs, namely, SMF+PGW-C, UPF+PGW-U and PCF+PCRF. Although MME and AMF are separate, the N26 interface makes the communication between these two entities possible. In addition, this architecture makes it possible to transmit the UE between 5GC and EPC, as well as any or all of the PDU sessions in the system. During the transfer process of the UE, it is able to hold the allocated DN address, while keeping the connection with the external servers. Also, in order to avoid packet loss, sometimes the N26 interface is introduced to enable the UE to pass non-transmitted data from the former network to the latter one.

This architecture is usually used for UEs roaming with home routing. Under these circumstances, the NFs of the 5G network only exist in the home network, while the E-UTRAN, MME and SGW (EPC) form the visited network. As we can see from Figure 3.13, the N26 interface is an option, that is because the communication between these two networks can be realized via LTE S6a and LTE S8 interfaces. As a result, the 5G user in such architecture is able to roam in the visited networks that do not support 5G at all. The user falls back to 4G, the UE supports 4G, and the user's HPLMN supports 4G EPC.

3.3.2. The Access Network

The overall architecture of the 5G NR radio access network (or NG-RAN) does not look very different from the E-UTRAN architecture. The main elements of NG-RAN is shown in Figure 3.14, that is, the Next Generation Node B (gNodeB/gNB). Two new interfaces with new signaling protocols have been introduced in such a network, they are the NG interface and the Xn interface. From Figure 3.14 we can see that the gNodeBs are usually connected to each other through the Xn interface and to 5GC through the NG interface (the dotted line represents interface carrying signaling and the solid line represents interface carrying traffic). The Access and Mobility Management Function (AMF) in this diagram is responsible for the management of registration and authentication of the subscriber.

Also, unlike eNodeB in LTE, which was originally designated as a single network element, the gNB can be divided into several parts, Figure 3.15 gives an example of functional splitting.

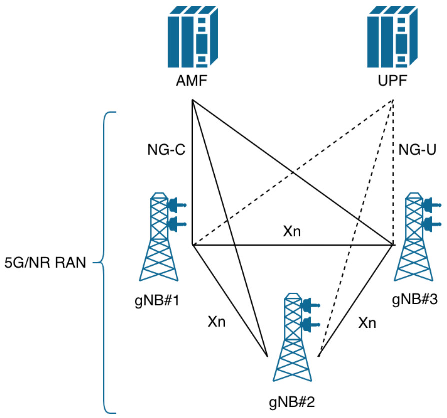


Figure 3.14: 5G/NG-RAN

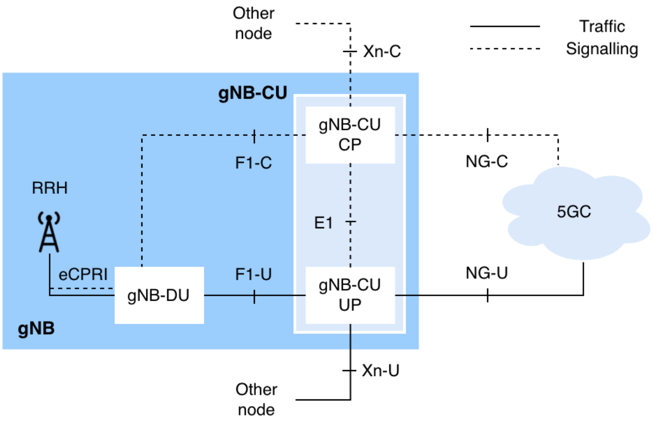


Figure 3.15: gNB: Internal Structure

- **Central Unit (CU)** - There is a single CU for each gNB. Except for those functions specially assigned to the DU, CU includes various gNB functions such as user data transmission, mobility control, radio access network sharing, positioning, session management and so on.
- **Distributed Unit (DU)** - The operation of DU is controlled by CU via a front-haul (Fs) interface. DU includes gNB functions like baseband processing and RF. Each DU is able to support one or more cells, while each cell is able to support one or more beams [13].

Each CU is in charge of one or more gNB-DUs that are meant to be installed locally. Each DU, in turn, uses low-level functions including scheduling, re-transmission and so on to manage one or more cells. The CU connects to DU through the F1 interface. Also, CU can be further split, namely, the gNB central unit control plane (gNB-CU-CP) and the gNB central unit user plane (gNB-CU-UP). The former one is used to send and receive signaling messages from the UE, 5GC, and other gNBs, also using high-level functions like encryption and decryption to handle these messages. The gNB-CU-CP connects to the gNB-CU-UP through the E1 interface and each gNB-CU-CP is able to control one or more gNB-CU-UPs, which play a similar function in user plane traffic [8]. In Figure 3.15, the Remote Radio Head (RRH) is responsible for radio transmission and reception. Here, a high-speed, low-latency digital interface is used for communication, that is, the enhanced Common Public Radio Interface (eCPRI).

3.3.3. Roaming Architecture

When a user is roaming, the UE, NG-RAN and AMF are always located in the visited network, while the AUSF and UDM are always in the home network. And the traffic within a specific PDU session can be routed in two ways. Figure 3.16 and Figure 3.17 depict these two types of 5G architecture for a roaming user.

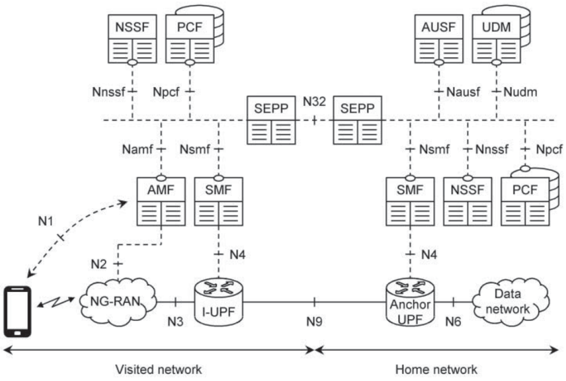


Figure 3.16: Roaming Architecture Using Home Routing [9]

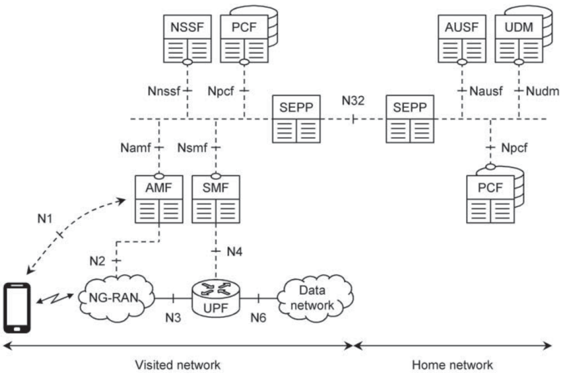


Figure 3.17: Roaming Architecture Using Local Breakout [9]

- **Home Routing** - It is commonly used for Internet data connections, as shown in Figure 3.16. Here, the home SMF is responsible for controlling the anchor UPF (anchor for data connection), which is located in the user's home network. In addition, we can notice that there is an intermediate UPF (I-UPF) in the visited network. With I-UPF, the anchor does not need to know about the base stations of the visited network, and the visited SMF is responsible for controlling them. In this architecture, since the user plane of network slicing is shared by the home network and the visited networks, both networks have a Network Slicing Selection Function (NSSF). Besides, in order to provide the appropriate network policies to the UE, PCF is included in both networks. Communications between the visited network and the home network are through a non-controllable interface, such as an inter-operator backbone called IP Packet Exchange (IPX) [35]. The NF named security edge protection proxy (SEPP) is used to protect the signaling messages on that interface.

- **Local Breakout** - It is suitable for data connections with the IMS and roaming applications that require low-latency, as shown in Figure 3.17. Here, the visited SMF is responsible for controlling the UPF, which is located in the visited network. Within it, roaming users are able to make local voice calls without returning traffic to their home network. Also, from the figure above, we can see that only one NSSF (located in the visited network as the user plane of network slicing is in the visited networks) is included in this architecture, while both networks include a PCF (same reason as in home routing).

4

5G Deployment and Migration Options

In this chapter, we first describe the various 5G deployment options which need to be enabled by the network operators, along with the options for communication services in 5G. Second, since the migration path selection can be influenced by various factors such as time to market, capital cost, operating cost, future compatibility, business trends and the current network conditions/architectures [61]. Therefore, considering the above conditions, we provide operators with several easy-to-implement 5G migration paths, and analyze the paths themselves.

4.1. Deployment Options

With regard to the deployment of 5G options, according to the releases of 3GPP, operators will have a variety of options to migrate and deploy 5G in the initial stage of 5G. First of all, it needs to be mentioned that the various 5G deployment options can be divided into two categories: Non-Standalone (NSA) and Standalone (SA). The NSA relies on the existing LTE networks to enable 5G New Radio (NR) deployment, whereas the SA is a 5G network that includes a new 5G packet core architecture and uses NR as the radio access technology. Figure 4.1 shows the six options within NSA and SA defined in 3GPP TS 23.501 and 3GPP TS 23.502, a detailed discussion can be found below.

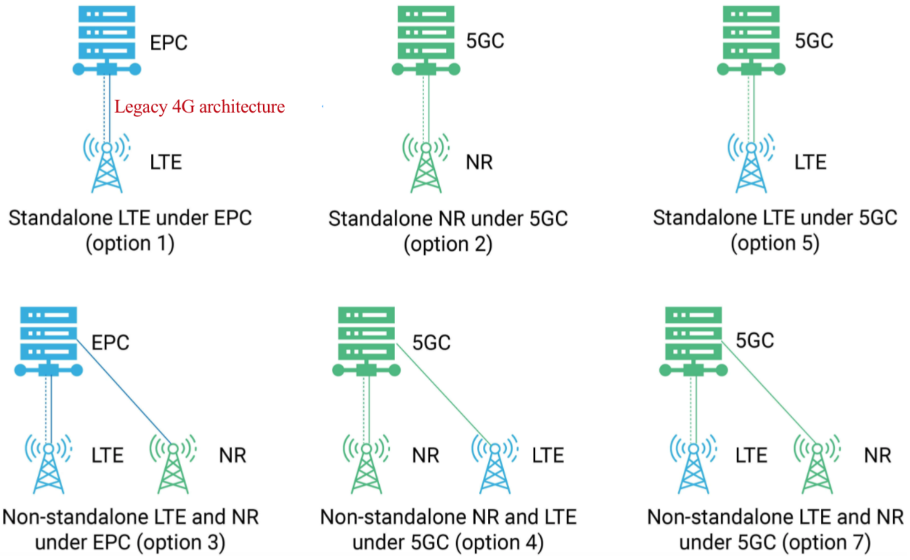


Figure 4.1: Different Deployment Options for 5G [22]

- **Standalone**
  - **Option 1**: This option stands for the legacy LTE deployment, in which the E-UTRAN NodeB (eNB) is connected to an EPC, also known as 4G Core Network. Up to now, most operators may have deployed this

option, introducing handover to achieve the continuity of services between 4G and 5G.

- **Option 2**: In this option, the next generation NodeB (gNB) of the NR access network is connected to the 5GC. The gNB is able to communicate with UE without relying on the legacy LTE system. Unlike option 1, this option introduces 5GC and radio access network (RAN) from the first step, which is the final target of 5G migration. Since the 5GS, containing option 2, is an end-to-end (E2E) system and supports new 5G services such as massive Machine-Type Communication (mMTC), enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communication (URLLC) and network slicing which obviously increases the deployment cost. Hence, it is suitable for new 5G operators with sufficient deployment funds. But fortunately, less work and evolution cost are needed when upgrading eNB for inter-working with the NR system as we don't have to make dual connectivity a mandatory requirement for this option.

- **Option 5**: In this option, the enhanced eNB (ng-eNB) is connected to the 5GC and it provides LTE radio access. It does not require a high investment cost. Unfortunately, this option has some limitations, for example, it does not support millimeter wave (mmWave) bands. Therefore, this deployment option is suitable for areas with legacy LTE networks and that need some low latency services providing 5GC coverage [61]. The rural area is an example.

- **Non-Standalone**
  - **Option 3**: This option includes both LTE and NR radio access, however, only the EPC core of LTE is utilized to route control signals and user plane. Here, E-UTRAN New Radio – Dual Connectivity (EN-DC) was introduced to deploy 5G services. The LTE (or eNB) acts as a master node and the NR (or en-gNB) acts as a secondary node. The en-gNB represents the gNB upgraded to support E-UTRAN. That is, 5GC is not necessary for operators and this option allows quick 5G migration with minimum LTE upgrade without 5GC [54]. Moreover, the deployment cost of this option is low. So it will be the preferred choice for most operators at the initial stage of 5G deployment. It is especially attractive for operators who have early deployments of 5G NR access systems in areas where legacy eNB and EPC are operational [14]. However, it also has a limit, as it relies on the legacy EPC, the scope of 5G service is limited by the capacity of the RAN. Like it does not support URLLC or network slicing. Therefore, if operators want to provide more 5G services, they have to face the long-term task of migrating from Option 3 to Option 2.

    There are three types of this option: Option 3, Option 3a and Option 3x. To better explain their respective characteristics, our description is based on Figure 4.2 below rather than Figure 4.1 at the beginning of this section. The descriptions of each are listed below.

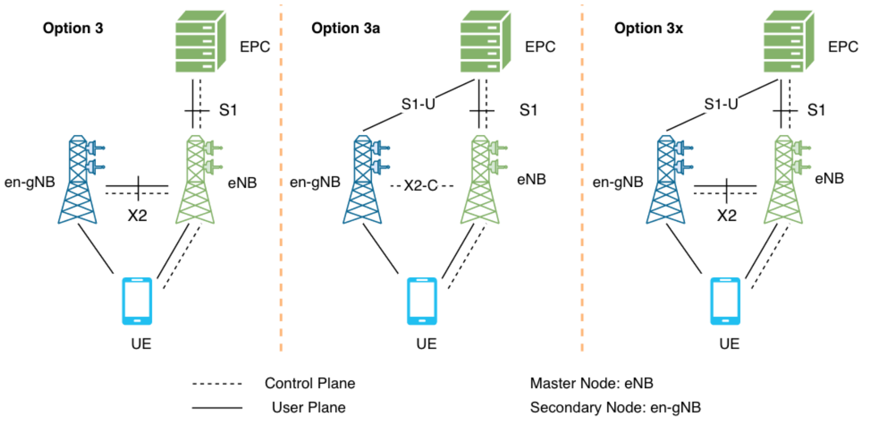


Figure 4.2: Architecture Variants of Option 3

For all Option 3 variants, what they have in common is that from the perspective of the control plane, the eNB is connected to the EPC through the S1 interface, and the en-gNB operates with the eNB through the X2 interface.

◇ **Option 3:** In this option, there is no direct connection between en-gNB and EPC. All traffic, both control plane and user plane, are to and from the intermediary eNB. Here, the traffic is split. The eNB is able to forward some user plane traffic to the en-gNB through the X2 interface or transmit most of this kind of traffic directly to the UE from the EPC via the LTE air interface. This deployment scenario allows for the reuse of EPC, also benefits users from the NR on the radio access part. But with the increase in traffic load, operators need to allocate more bandwidth for the S1 interface.

- ◇ **Option 3a:** In this option, the EPC is directly connected with both eNB and en-gNB but unfortunately they are not able to communicate with each other via the X2 interface as there is no user plane traffic through it. Therefore, compared to Option 3, there will be less traffic load on X2 and this will result in a single data bearer not being able to share the load over LTE and NR [14]. Take voice calls as an example, in Option 3a, the user's VoLTE voice traffic is processed by LTE, while the Internet traffic is processed by NR. But if the UE keeps entering and leaving the coverage of the 5G network, it would be difficult to implement the scenario mentioned above. In addition, in this variant, EPC carries the task of the traffic split. The user plane traffic from both eNB and en-gNB is transmitted or received by EPC.
- ◇ **Option 3x:** This variant is a combination of Option 3 and Option 3a. Here, the user data traffic can be transported from EPC to either eNB or en-gNB. The latter is able to directly forward one stream of data to the UE through the NR air interface. Moreover, due to the existence of an X2-U interface between eNB and en-gNB, another stream of data can also be sent indirectly to the UE through the eNB via the X2 interface. This is applicable when the speed of data flows is relatively slow, for example, VoLTE bearers with a different IP address than that used for Internet access can be directly delivered from the core network to the 4G eNB part of the 4G/5G base station [14].

  And the advantage of Option 3x is that, at the initial stage of 5G deployment, this model can provide good service continuity as it will not greatly affect the existing network. Moreover, due to the enhanced processing capability of en-gNB relative to eNB, Option 3x is a commonly used bearer splitting option for service providers, rather than using the master cell group split bearer approach, which means the data splitting is carried out by eNB [57].

– **Option 4**: For this option, 5GC has been introduced and there is a connection between gNB and 5GC. Also, gNB is connected to ng-eNB via the Xn interface, ng-eNB is the upgraded version of eNB for the purpose of interworking with 5GC or gNB. From Figure 4.3, we can see that gNB acts as the master node and the ng-eNB is the secondary node. So it supports EN-DC to aggregate NR and LTE traffic [54]. But this option is more demanding for operators because of its higher deployment investment cost and longer time to market (TTM) (compared with Option 3).

There are two types of this option: Option 4 and Option 4a. To better explain their respective characteristics, our description is based on Figure 4.3 below rather than Figure 4.1 at the beginning of this section. Actually, there are not many differences between Option 4 and Option 4a. All the control signalings are delivered via the NG RAN. The only difference between these two variants is how the user plane traffic is sent to LTE. The descriptions of each are listed below.

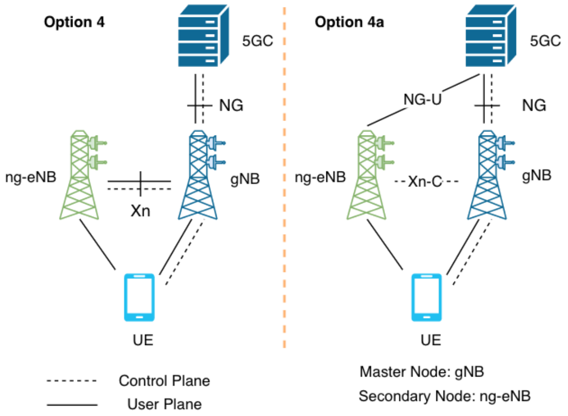


Figure 4.3: Architecture Variants of Option 4

- ◇ **Option 4:** In this variant, gNB carries out the work of traffic splitting. Here, the user plane traffic is able to be directly sent from 5GC to the UE through the NR air interface by gNB. The second approach is that some of the traffic can be indirectly sent from 5GC to the UE through ng-eNB via Xn interface by gNB. Besides, on the basis of X2 function, Xn enhances the UE context management function to adopt a new QoS flow framework and network slicing.

- ◇ **Option 4a:** In this variant, 5GC carries out the work of traffic splitting. Here, the user plane traffic is transmitted/received to/from both gNB and ng-eNB by 5GC [54]. Besides, similar to Xn for X2, on the basis of S1 function, NG enhances the bearer/session management functions and UE context management functions to adopt a new QoS flow framework and network slicing.

- **Option 7**: In this option, the CN is 5GC and there is a connection between ng-eNB and 5GC. Also, gNB is connected to ng-eNB via the Xn interface, ng-eNB is the upgraded version of eNB for the purpose of interworking with 5GC or gNB. From Figure 4.4, we can see that ng-eNB acts as the master node and the gNB is the secondary node. Option 7 supports 5G services like eMBB, network slicing and some use cases of URLLC which are decided by the capabilities of 5GC. In addition, in order to deploy this option, it is needed for operators to upgrade the eNB to support 5GC signaling and interfaces, as well as service-based 5GC with leveraging network function virtualization and software-defined networking [54]. And similar to Option 4, this option is also demanding for operators because of its higher deployment investment cost and longer TTM (compared with Option 3).

  There are three types of this option: Option 7, Option 7a and Option 7x. To better explain their respective characteristics, our description is based on Figure 4.4 below rather than Figure 4.1 at the beginning of this section. The descriptions of each are listed below.

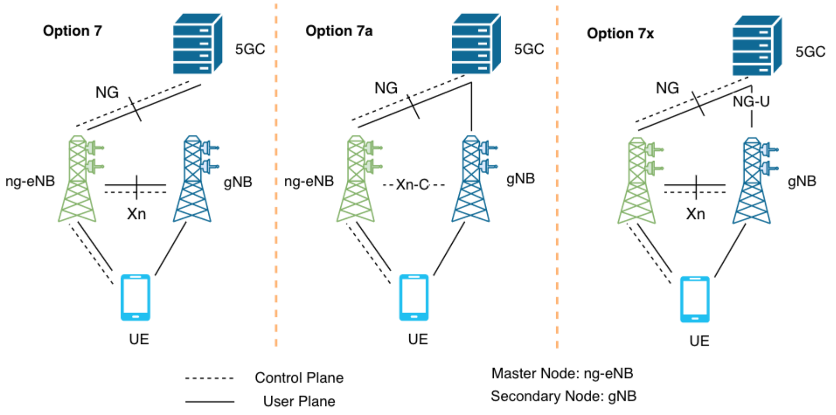


Figure 4.4: Architecture Variants of Option 7

  For all Option 7 variants, what they have in common is that from the perspective of the control plane, the ng-eNB is connected to the 5GC through the NG interface, and the gNB operates with the ng-eNB through the Xn interface.

  - ◇ **Option 7:** In this variant, ng-eNB carries out the work of traffic splitting. Here, the user plane traffic is able to be directly sent from 5GC to the UE through the LTE air interface by ng-eNB. The second approach is that some of the traffic can be indirectly sent from 5GC to the UE through gNB via Xn interface by ng-eNB.
  - ◇ **Option 7a:** In this variant, 5GC carries out the work of traffic splitting. Here, the user plane traffic is transmitted/received to/from both gNB and ng-eNB by 5GC [54].
  - ◇ **Option 7x:** This variant is a combination of Option 7 and Option 7a. Here, the user plane traffic can be transported from 5GC to either ng-eNB or gNB. Then the former is able to directly forward the traffic to the UE through the LTE air interface. The latter is able to directly forward the traffic to the UE through the NR air interface. Moreover, due to the existence of an Xn-U interface between ng-eNB or gNB, another part of the traffic can also be sent indirectly to the UE through the ng-eNB via the Xn interface.

4.2. Options for Communication Services

According to 3GPP, we know that 5G still provides IMS-based voice/video communication services, using the voice/video communication architecture for 4G. LTE is the radio access technology in 4G, NR is the radio access technology in 5G, so much like the voice/video over LTE network is called VoLTE, the voice/video on 5G (NR) network is called VoNR. Therefore, the IMS voice/video communication services have two different access modes: VoLTE and VoNR.

For 5G networks, VoNR is the ultimate goal for voice/video communications. But the operator may not have NR deployed, or even if it is deployed, it may not have full coverage. As a result, VoNR will not be able to represent all 5G voice/video communication solutions. The voice/video services in 5G should also include E-UTRA-NR Dual Connectivity (EN-DC) and EPS Fallback (EPS FB), which needs to be achieved by introducing NR and 5GC.

4.2.1. E-UTRA-NR Dual Connectivity (EN-DC)

In order to support EN-DC, the traditional LTE RAN is upgraded. In such architecture, LTE is used for voice with NR as a data booster. Figure 4.5 shows the architecture for IMS services in EPS with EN-DC (Option 3).

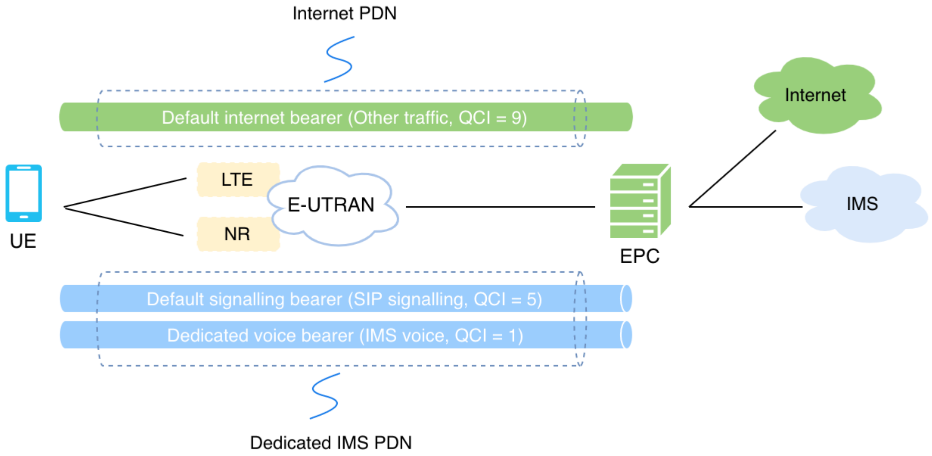


Figure 4.5: IMS Service in EPS with EN-DC

IMS services are still able to be used over E-UTRAN by operators who have implemented VoLTE for 4G, no matter the E-UTRAN is fully upgraded to EN-DC or not. The IMS will not be affected, actually, the changes that take place on the E-UTRAN are completely unknown to the IMS system. And in VoLTE, the principles of SIP signaling and user plane data remain unchanged. In Figure 4.5, the PDN connection with the IMS APN carried by the default EPS bearer is used for SIP signaling (QCI = 5), and the dedicated bearer for voice media (QCI = 1) will be set for VoLTE. And in order to use LTE and NR together, the Internet PDN default bearer (QCI = 9) is able to be mapped to a split bearer [24].

4.2.2. EPS Fallback (EPS FB)

In order to support EPS Fallback, a combination of 5GS and EPS is needed. Figure 4.6 shows the architecture for EPS fallback (Option 2). Here, NR is used for data. But during the procedure of a voice call over LTE, the establishment of QoS flow will be triggered, also, the voice and data bearer will fall back to EPS.

In such architecture, we can notice the following:

- **The SMF and UPF supporting the S5 interface replace the P-GW in 4G for voice services** - Control and user plane functions are offered by them: SMF is responsible for realizing the control plane functions of the P-GW; UPF is responsible for realizing the user plane functions of the P-GW. And no matter if the UE is camping on LTE or NR, the same UPF (controlled by the same SMF) will be utilized by the IP flow [23]. Then, the UE's IP address is able to be preserved. Besides, 5G roamers can use SMF and UPF to connect to 5GC-supported or EPC-supported networks.

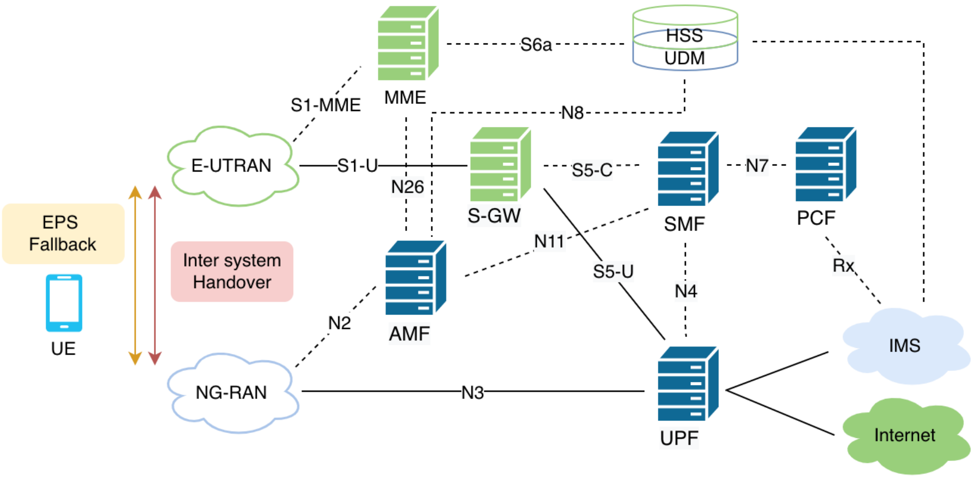


Figure 4.6: Architecture for EPS Fallback

- **Inter-working between EPC and 5GC is realized by the N26 interface used between MME and AMF** - Such a connection makes the transmission of information, as well as the handover between EPC and 5GC possible.
- In order to use the 5GS, the UE needs to be connected to 5G core network and registered to IMS over NR in NG-RAN. And to ensure that the UE remains in NR even when LTE/NR coverage overlaps, NR needs to be the preferred RAN.
- Combined HSS/UDM and PCF with Rx.

4.2.3. Voice over New Radio (VoNR)

If Option 2 is implemented, VoNR means that voice calls can be made on NR SA. In order to achieve it, all voice-related functions need to be supported by the elements in such an architecture, namely, UE, NR in NG-RAN, 5GC and IMS. NR is used for both voice and data. Figure 4.7 shows the architecture for VoNR.

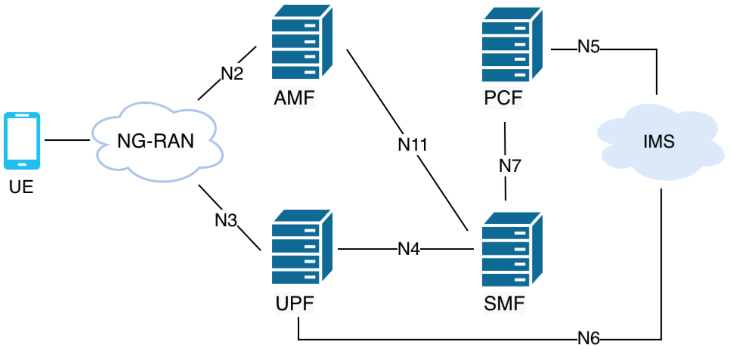


Figure 4.7: Architecture for VoNR

Below are several coverage areas and deployment scenarios for VoNR:

- A 5GC that supports voice services controls the NR coverage. Here, the NR coverage can be included or excluded from EPC's LTE coverage.
- With the support of VoLTE, the LTE coverage is controlled by EPC.
- If necessary, NR (and LTE) supports IMS emergency calls.

In such a situation, handovers might happen in either direction, from 5GS to EPS or from EPS to 5GS. The UE's measurement reports determine whether the call should be handed over to the EPS or the 5GS. This necessitates voice support on both NR and LTE. Take Voice with EPS Fallback for example, it needs the SMF and UPF to support the S5 and N26 interfaces, so as to realize close inter-working between EPS and 5GS.

4.2.4. SMS and USSD

For all the voice services that can be used in 5G networks, regardless of EPS FB or VoNR, SMS and USSD are realized through 5GC and IMS. The SMS is realized by SMS over IMS, i.e. SMS over IP (SMSoIP), and the USSD realized by USSD over IMS, i.e. USSD simulation service in IMS (USSI), as discussed in Section 3.2. And for EN-DC, SMS can be realized by SMS over SGs (SMSoSGs) or SMS over IP. The USSD can be realized by CSFB or USSI, as discussed in Section 3.1.

4.2.5. Communication Services while Roaming

One option for roaming in 5GS for voice is called N9 Home Routing (N9HR), follows the same home routing principles in EPS (Unlike the 5GS, the S8 reference point is used in EPS rather than N9 reference point). The options for voice services in 5GS are EPS FB and VoNR, the former can be realized by inter-working with 4G. When the user is roaming, it is suggested to use VoNR as the additional call setup delay in EPS FB will be greater than in non-roaming cases. In order to expand the range of compatible network capabilities with roaming partners, operators need to support EPS FB and VoNR in HPLMN simultaneously. For messaging, roaming in 5GS for SMS is known as SMS over IP/IMS, which requires the support of SMS in HPLMN. SMS over IP/IMS is based on an IMS PDU session established with HPLMN and has no impact on VPLMN [43].

- **Will Roaming Keep 2G and 3G Alive?** - From the previous discussion, we know that although operators are actively migrating to 5G, 4G networks still need to run for a long time, so what about 2G and 3G networks?

  Although the adoption rate of LTE in operators is close to 100%, VoLTE is far less popular. Today, VoLTE is quickly becoming the preferred standard for both 4G and 5G voice (also VoNR in the future), as the voice network upgrade is becoming more powerful. However, its complex standards[1] make it necessary for the CS network to remain active while roaming. In other words, the lack of simple roaming mechanisms makes it difficult for operators to implement VoLTE roaming agreements with operators in other countries, which will reduce user satisfaction with voice services. Therefore, in order to maintain the user experience, any operator without an extensive VoLTE roaming agreement must reserve spectrum resources for inbound roamers on the 2G/3G network, i.e., some operators cannot fully shutdown their CS network.

  Of course, not turning off the 2G/3G network can also cause some problems. For example, operators will not be able to re-allocate their CS spectrum until voice traffic is moved to VoLTE (or even VoNR), which could lead to spectrum bottlenecks for their LTE and 5G networks. However, the voice fallback from 5G SA to 2G/3G networks is not supported, it can only fallback to VoLTE. This is why VoLTE is needed for 5G SA as it can fallback to 2G and 3G by using CSFB, thus avoiding dropped calls in multi-generation networks. Moreover, in terms of voice call handover, VoLTE is needed when VoNR has not yet reached full coverage. When a user leaves LTE coverage and enters 2G/3G coverage, the voice call handover from VoLTE to voice over CS can be realized by SRVCC. Similarly, the voice call handover from VoNR to VoLTE can be realized by PS-HO. Although the SRVCC handover from 5G to 3G is defined in 3GPP Release 16, there are currently no mobile devices on the market that support this feature. So it is questionable whether this function can be realized.

  In addition to the above reasons, in order to provide users with faster call setup times and higher voice quality than voice over CS, operators still using 2G/3G networks must migrate their voice traffic from legacy networks to VoLTE, paving the way for them to eventually migrate to VoNR when spectrum, technology and funding allow.

4.3. Migration Paths

For LTE operators, in order to simplify deployment and control capital costs, it is reasonable to deploy 5G NR on an existing LTE network. Moreover, it is obvious that the ultimate goal of 5G is to achieve Option 2 (i.e. Standalone NR under 5GC), so in this section, we divide the migration paths into the following two categories

---

[1] First, S8HR only supports charging by data packets and not by minutes, such a significant shift in the pricing paradigm may greatly reduce operators' roaming revenue. Second, S8HR interfaces are incompatible with legacy interfaces, which might lead to legal issues when it comes to compliance with legitimate interception laws [37].

for main discussion: (i) Migrate directly to Option 2; (ii) Migrate indirectly to Option 2 through other options. This section also mentions other migration paths that are considered possible.

4.3.1. Migrate Directly to Option 2

In this case, the operator directly migrates from Option 1 (i.e. Standalone LTE under EPC) to Option 2 (i.e. Standalone NR under 5GC). As the above two options have different types of radio access technology (RAT), in order to move UE between the EPC coverage area of LTE and the 5GC coverage area of NR, an inter-RAT mobility mechanism has been introduced. Figure 4.8 shows the migration path from EPS to Option 2.

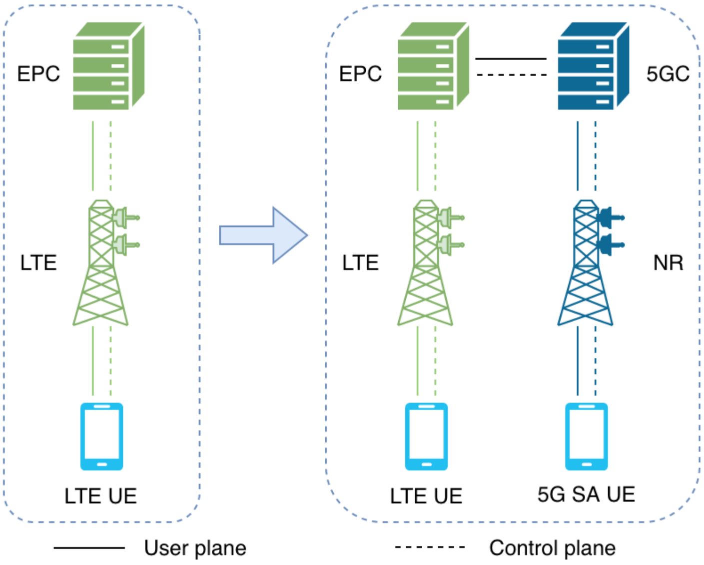


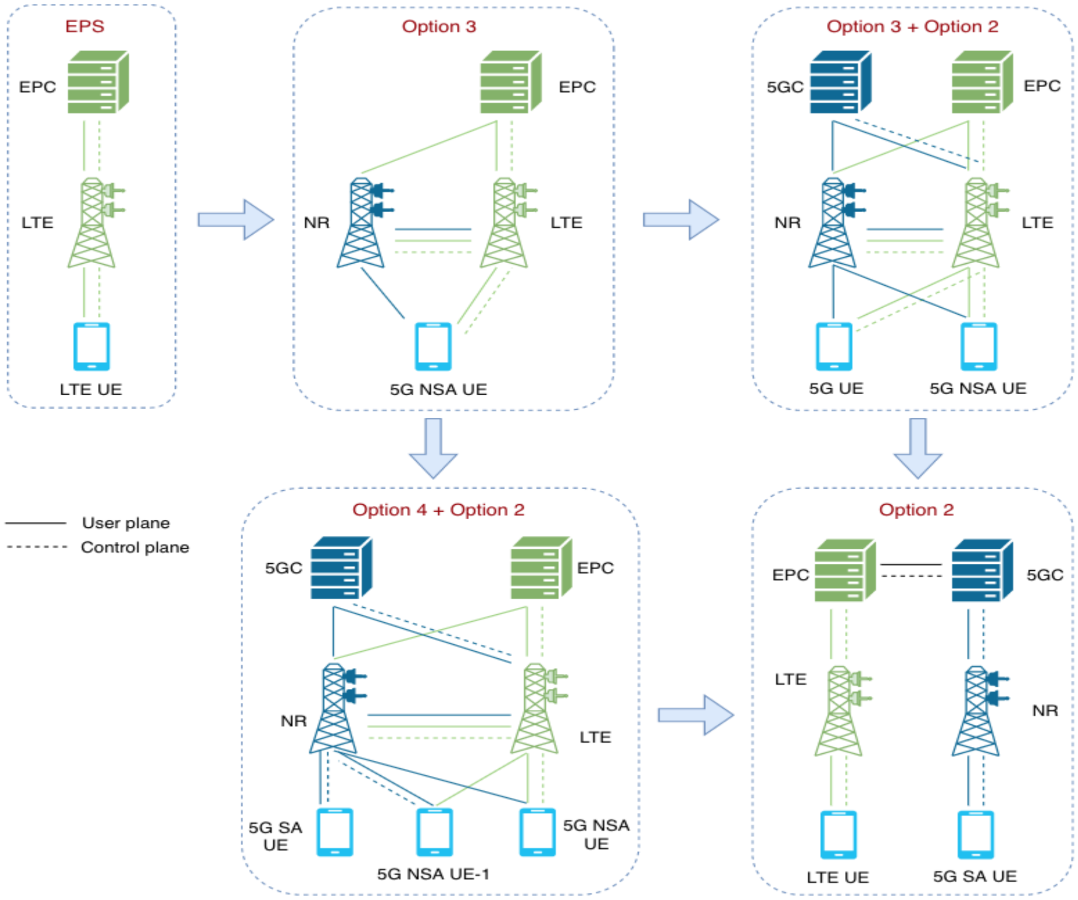
Figure 4.8: Migrate from EPS to Option 2

Table 4.1: Analysis of Migration Path Option 1 to Option 2

Pros	Unlike other deployment options based on EPC, in Option 2, the SA architecture is able to make full use of 5G end-to-end network abilities supported by NR and 5GC, allowing for the effective and efficient provision of customized services. End-to-end network slicing and service-based architecture are two examples. We can enable them based on the specific needs of each service, thereby bringing a tailored and enhanced user experience. Therefore, if the operators want to offer the complete range of 5G services from the start, Option 2 gives them an advantage over competitors who may select a different path. As a result, an operator like this has a better chance of profiting from future 5G commercial opportunities. Moreover, since no temporary NSA UE is needed, it is achievable for operators to migrate to a complete 5G SA network smoothly and quickly.
Cons	First, this migration strategy requires a large initial investment as it needs to establish a 5G network comprising of 5GC and NR without considering the legacy LTE networks. Second, before the 5G network completely replaces the 4G network, operators will also have to bear the maintenance costs of the EPC, which increases their operating expense (OPEX) burden to a certain extent.
Implement	As we discussed before, in SA Option 2, NR gNB based NG-RAN is deployed as a new radio access and 5GC is deployed as a new core. And in order to support inter-RAT mobility, new functions have been introduced on the LTE eNodeB based E-UTRAN. For devices, it is required by Option 2 to support a radio front end capable of receiving and transmitting data via NR and new 5GC procedures [44]. And since Option 2 no longer needs dual-connectivity, the workload and expense of upgrading and modifying the current 4G eNodB are relatively low, only a few upgrades are required to support inter-working with 5G.

4.3.2. Migrate Indirectly to Option 2 through Other Options

Since not all operators have the funds and capacity to deploy Option 2 at the beginning, they need to go through several transition stages before migrating to Option 2. Next, we describe some migration paths that are considered more likely to be used by operators.



NOTE 1: 5G NSA UE refers to devices that support only NSA Option 3 5G deployment option
NOTE 2: 5G NSA UE-1 refers to devices that support NSA Option 4
NOTE 3: 5G SA UE refers to devices that support SA Option 2
NOTE 4: 5G UE refers to devices that support NSA Option 3 and also other 5G deployment option(s)

Figure 4.9: Migrate from EPS to Option 2 via Other Options

For operators who already have EPS, NSA Option 3 (using EN-DC) may be a good choice. By adding en-gNB to the current LTE network, Option 3 enables a quick start to 5G under a lower initial investment. But before 5GC is incorporated into the network, this option is unable to support 5G-specific services such as network slicing. This is why operators who choose Option 3 as their migration path finally need to turn to Option 2, which can offer a full range of 5G services for subscribers. Operators can achieve Option 2 through several different migration paths, as shown in Figure 4.9.

- **Path 1: EPS → Option 3 → Option 3 and Option 2 → Option 2**
- **Path 2: EPS → Option 3 → Option 4 and Option 2 → Option 2**

Next, we discuss each step in the migration path in detail.

- **Step 1: EPS → Option 3** - Migrate from EPS (Option 1) to NSA Option 3. In order to support compatible devices that utilize dual connectivity to combine LTE and NR radio access, E-UTRA has been extended.

Table 4.2: Analysis of Migration Path Option 1 to Option 3

Pros	For Option 3, it only needs to develop the NSA access of NR specifications as part of E-UTRAN connected to EPC, rather than formulating the specifications of the whole 5GS like SA NR. And since NR is going to enhance the existing functions of the LTE radio network, Option 3 provides flexible "on demand" deployment, which requires LTE and NR capacity from the same or different suppliers. Besides, this option will be maintained in future 3GPP releases (beyond Release 15), so even with other options deployed concurrently, it will still work in the long run.
Cons	According to the EPC features defined by 3GPP in Release 15 and future releases, the EPC capabilities may provide a potential bottleneck (like latency), which restricts the performance that could have been extracted from NR [44]. And since this option does not involve 5GC, operators will not have access to any of the differentiating capabilities of the new architecture unique to 5G.
Implement	This option requires the deployment of NSA NR en-gNB in E-UTRAN as well as new LTE eNodeB capabilities to support EN-DC processes, and so has implications for E-UTRAN. The UE is also affected by it, but the EPC and HSS are affected to a limited extent, depending on the choice of the operator, and the IMS is not affected. And as we discussed before, Option 3 only needs to develop the NSA access of NR specifications as part of E-UTRAN connected to EPC. Therefore, regardless of whether the radio coverage is solely LTE or both LTE and NR, UE will use the same EPC procedures as currently available UE to communicate with the core network. But if LTE and NR radio interfaces are combined for split bearers, it may result in higher memory needs.

- **Step 2 (Path 1): Option 3 → Option 3 and Option 2** - Migrate from NSA Option 3 to NSA Option 3 and SA Option 2, as well as the inter-RAT mobility mechanism that allows UE to migrate between 5G NSA LTE + NR (EPC coverage) and 5G NR (5GC coverage).

Table 4.3: Analysis of Migration Path Option 3 to Option 3 and Option 2

Pros and Cons	In this migration step, 5GC is deployed so that users can get the full benefit of 5G end-to-end network functions. On the new architecture of 5GS, it allows operators to meet all use cases. But if 5GC provides all use cases, operators may need to consider migrating the early use cases of EPC services to 5GC. In addition, as the inter-working between 4G and 5G at the radio level is not close, this migration step is the best choice when NR is deployed to realize wide area coverage. Although the seamless handover traffic from 5GC to EPC is able to be provided by the operator, for such a transition, a change in the architecture of the core network and QoS model is needed. That's why it shouldn't be utilized too often.
Implement	In order to support NSA Option 3 and SA Option 2 simultaneously, in Option 2, 5GC needs to be deployed and NR gNB needs to be updated. The E-UTRAN connected to EPC for inter-RAT mobility, IMS for 5GS QoS management, and UE are all affected by this migration step.

- **Step 2 (Path 2): Option 3 → Option 4 and Option 2** - Migrate from NSA Option 3 to NSA Option 4 and SA Option 2. Here, the RAN is connected to the 5GC, in parallel with the EPC connection of the early 5G equipment.

Table 4.4: Analysis of Migration Path Option 3 to Option 4 and Option 2

Pros and Cons	In this migration step, 5GC is deployed so that users can get the full benefit of 5G end-to-end network functions. On the new architecture of 5GS, it allows operators to meet all use cases. But if 5GC provides all use cases, operators may need to consider migrating the early use cases of EPC services to 5GC. Besides, to connect to 5GC, LTE RAN must be upgraded; in order to enable inter-working with NR, more LTE eNodeBs may need to be upgraded. That is, close inter-working between LTE and NR is needed. In this migration step, operators can continue to selectively deploy NR only where needed [44]. And because this migration begins with Option 3, where NR and LTE have been closely inter-worked, we can continue to maintain LTE's wide-area coverage while supplementing it through selective NR deployment as needed.
Implement	In order to successfully implement this migration step, 5GC needs to be deployed, LTE eNB (only needed for Option 4a) and NR gNB need to be updated. The upgraded NR gNB is responsible for supporting 5GS session, mobility, QoS management, as well as 5GC N2/3 RAN-core interfaces. And if Option 4a is chosen, the upgraded LTE eNB is responsible for supporting the 5GC N3 RAN-Core user plane interface. Here, the interface used to connect 5G RAN and AMF is called the N2 interface, and the interface used to connect 5G RAN and UPF is called the N3 interface. Moreover, IMS for 5GS QoS management, and UE are both affected by this migration step.

- **Step 3: Option 3/4 and Option 2 → Option 2** - It is the final step in migrating to SA Option 2. As we can see from Figure 4.9, there are still many NSA UEs, so operators may need more time to reach the final stage. If two NR frequencies are available, in order to achieve higher throughput, operators can choose a technique called New Radio Dual Connectivity (NR-DC), which uses two NR frequencies for traffic aggregation. And if the number of LTE UEs is negligible, operators can then explore migrating the remaining LTE band to NR utilizing redistribution to make use of it.

From the analysis presented in this section, we can get the following observation: Migration path Option 1 → Option 2 is suitable for operators aiming to deploy full-scale 5G, and offer the complete range of 5G services from the start. Especially when they have enough capital and can wait a long time to market. Different from the previous migration path, migration path Option 1 → Option 3 → Option 3/4 and Option 2 → Option 2 is suitable for operators aiming to start 5G with leveraging 4G and then expand the coverage of 5G directly (if 5G traffic and consumer growth are rapid for operators). Especially when they want to deploy early 5G with minimal investment and wish to get to market quickly. Regarding voice services, the possibility of voice service continuity in both migration paths will vary depending on whether the operator supports voice services over IMS and the coverage it provides.

5

5G Deployment in Different Regions

In this chapter, we first describe the status of 5G deployment in three leading countries: China, South Korea and the United States. Next, we focus on EU, describe its current 5G status. Then, in the process of comparing the EU with other leading countries, we also analyze the strengths and weaknesses of the EU in the future development of 5G, as well as the opportunities and challenges it may face.

5.1. Three Leading Countries

5.1.1. China

2019 is the first year of 5G in China. On September 8th of that year, as four Chinese telecommunications companies obtained 5G commercial licenses, the construction of 5G commercial scale was started by three operators, they are China Mobile, China Telecom and China Unicom.

In 2020, although the Covid-19 has had a significant impact on China's overall national economy, the development of 5G has not stopped. As of the end of February 2022, there were more than 300 million 5G users in China. And the country expects to see the number of 5G users exceed 560 million by 2023 [60]. In response to the rapid growth of users, the three operators have accelerated the construction of base stations, and 5G coverage has gradually expanded from first-tier cities to second- and third-tier cities and rural areas, the total number of base stations is expected to exceed 1.4 million, accounting for more than 60% of the world.

Regarding the spectrum allocated for 5G in China, China Telecom and China Unicom share 3.3 GHz and 3.5 GHz bands. China Mobile has the right to use the 2.6 GHz and 4.9 GHz bands. This 2.6 GHz band, which is usually the LTE band and can also be used for 5G, has a longer range than the higher frequencies, reducing the cost of new networks.

- **China Mobile** - China Mobile is the current market leader in 5G in China. According to data released by China Mobile, since June 2019, China Mobile's 5G services have covered 50 large and medium-sized cities across the the whole country. As of January 2022, the number of users using its 5G packages has exceeded 370 million, accounting for more than half of the 5G users in China. Under the influence of vigorously constructing 5G base stations, China Mobile's planned expenditure in 2022 will be close to 185 billion yuan, of which the planned expenditure for 5G will account for 60%. This part of the expenditure is mainly used to build 5G base stations and launch 5G services in all prefecture-level cities in China, so as to achieve continuous coverage in cities, counties and towns.

  In the 5G network deployment, the 2.6 GHz frequency band owned by China Mobile has certain advantages in coverage performance. At the same time, with the help of the huge 4G base station in this frequency band, the 5G network can be quickly constructed by upgrading. Regarding the relatively lagging development of the early industrial chain in the 2.6 GHz band, as early as July 2019, China Mobile claimed that it had basically filled the development gap between 2.6 GHz and 3.5 GHz technologies. At the "2019 IMT-2020 (5G) Summit" on the 17th of that month, Wang Zhiqin, the leader of the IMT-2020 (5G) promotion group, pointed out that his group began to promote the research on the 2.6 GHz band from 2018. By using the technical characteristics of 2.6 GHz, the 5ms periodic frame structure is unified, and the test specification is formulated to carry out 2.6 GHz function, radio frequency and field networking performance tests. At present, the functions and network performance of 2.6 GHz base station equipment have reached a level comparable to that of the 3.5 GHz.

- **China Telecom** - Since 2018, China Telecom has started to deploy 5G networks in major first-tier and central cities and key areas such as Beijing and Shanghai, and exploratory 5G pilot projects. So far, a cross-provincial and cross-regional SA/NSA mixed-scale 5G trial network has been built. In April 2019, China Telecom announced as the operator to successfully conduct voice calls on the 5G SA network. At the end of 2019, the 5G coverage doubled to 40 cities by borrowing the 5G license. From 2020, it further increased cooperation with China Unicom to jointly seize the 5G market and compete with China Mobile. As of January 2022, the number of users using its 5G packages has exceeded 190 million.

  In 2022, China Telecom expects capital expenditure to be 93 billion yuan, of which 5G network investment accounts for 36.6%, reaching 34 billion yuan, a year-on-year decrease of 10.5%. Li Zhengmao, the manager of China Telecom, said it is expected that 5G deployment in the next 1-2 years will be mainly focus on improving network coverage and capacity expansion, and the scale of 5G investment will be stable compared with recent years. At the same time, in the future, they will strive to improve investment efficiency, and the proportion of capital expenditure in revenue will continue to decrease.

- **China Unicom** - After obtaining the 5G commercial license, China Unicom vigorously promoted the 5G development strategy, first targeting many first-tier key cities such as Beijing, Shanghai, Guangzhou and Shenzhen, and at the same time deploying 5G networks in nearly 40 hotspots. During the layout process, special attention was paid to the integrated development of 5G and local industries, and featured services were launched in a targeted manner to support local vertical industry applications. In February 2020, China Unicom continued to seize 5G market share, focusing on increasing investment in basic fields such as base station construction, and rapidly advancing the construction of 5G infrastructure support through strong alliances with China Telecom. Nearly 70,000 5G base stations have been shared since the end of 2019, covering 50 cities. As of January this year, the number of users using its 5G packages has exceeded 160 million. Although China Unicom has not announced the specific figures of capital expenditure in 2022, in view of the co-construction and sharing with China Telecom, the rhythm of 5G-related investment should also be a downward trend.

It can be seen from the above description that all mobile network operators in China have conducted a relatively extensive 5G test and are committed to 5G commercial use. However, the development speed of China's 5G technology will be affected by other factors, they are: 1). At the initial stage of 5G commercial use, the three operators in China choose the same deployment mode, that is, NSA mode, and then gradually transition to SA. Whether NSA or SA mode is adopted by operators, they will face the complexity of multi network integration of 2, 3, 4 and 5G and the complexity of operation and maintenance of multi network coexistence; 2). The large broadband and multi-channel of 5G will inevitably bring high energy consumption; 3). Due to the deterioration of Sino-U.S. relations, China's chip manufacturing (Huawei) has encountered a bottleneck, and the operating cost of 5G networks will be much higher than that of 4G networks, which will bring considerable financial pressure to operators. From the perspective of China's 5G status and the problems encountered, compared with previous years, China's 5G development will be slower in the next few years. However, it is still possible for operators to use their existing large user groups to rapidly develop 5G business and further maintain their leading position in the 5G market.

5.1.2. South Korea

Unlike China, the three major operators (i.e. SK Telecom, LG U+, and Korea Telecom) in South Korea jointly launched 5G and shared a public network. The three operators signed an agreement so that 5G users can have access to 5G network regardless of the operators they are subscribed to in South Korea. To support the early launch of 5G mobile services, spectrum bands in the 3.5 GHz and 28 GHz ranges were auctioned in June 2018. Since late 2018, the three major operators collaborated to bring mobile 5G to the country, however only selected customers can use 5G. In April 2019, the nation's mobile network operators started providing 5G services to the rest of its subscribers through a partnership with Samsung, which provided the terminals. The initial 5G coverage was limited, but it was expanding throughout the year. According to the information communications technology (ICT) and Broadcasting Technology Policy director at the Ministry of Science and ICT, Heo Won-seok, 90 percent of the country's mobile users will be on a 5G network by 2026 [27].

- **SK Telecom** - 2019 was the first year for SK Telecom to launch its 5G network. In that year, its 5G network covered major areas in 13 cities and counties across the country, including Seoul, Gyeonggi-do, Jeju Island and so on. Since then, the 5G coverage of SK Telecom in South Korea has been expanding, and the number of 5G users has also been rising. SK Telecom ended 2021 with a total of 9.87 million subscribers in the 5G segment, after a net addition of 4.4 million customers during the year.

  After conducting an outdoor 5G trial in Seoul in 2017, SK Telecom quickly developed 5G technology in its autonomous driving city, known as K-City. In 2018, two vehicles could communicate with each other, dozens of times per second, over SK Telecom's 5G test network. And in 2019 SK Telecom conducted their first live 5G TV broadcast, which marks the end of their 2G service. In addition to basic mobile telecommunication services, SK Telecom said it will continue to strengthen its competitiveness by expanding its AI-centric smart factory business in 28GHz, building on its solid 5G position.

- **LG U+ (plus)** - With over 7,000 5G base stations already established before 2019, the plans of LG U+ for unlimited 5G networks in Seoul and some other nearby cities are in the works, while expanding its coverage. According to the company's latest earnings statement, LG U+ ended 2021 with 4.62 million 5G subscribers. In addition, in April 2021, Nokia and LG U+ signed a contract to install small cell systems from Nokia's AirScale portfolio nationwide in order to increase 5G coverage. Therefore, Nokia will set up its small cell AirScale Interior (ASiR) systems in a series of indoor spaces, such as offices and shopping malls.

- **Korea Telecom** - Before launching 5G, Korea Telecom and Intel demonstrated 5G at the 2018 Olympic Winter Games. At this Winter Olympics, Korea Telecom demonstrated its 20 Gbps network with a delay of less than 1 millisecond and aimed for over a million devices per square kilometer. It can be used to provide autonomous vehicle for the users, while Intel, a chipset supplier, tries out its high-resolution 8K video through Korea Telecom network. With active MIMO antennas, fiber-to-the-antenna to lower base station latency, microwave line-of-site backhaul in mmWave bands with different routing for dependability, and testing of mmWave operation, 5G base stations were developed. Before 2022, they have provided 5G coverage to more than 80 cities in South Korea, with approximately 6.16 million 5G subscribers. And through 2023, they promised to invest 20 billion dollars in research into the most effective ways to use 5G.

In addition to the above three major operators, Samsung, the most well-known company in South Korea, also join in the 5G plan, e.g. its large-scale integration (LSI) business manufacture chipsets for 5G. To gain an advantage against Huawei, Samsung suggests that the 28 GHz band is more stronger than 3.5 GHz band, serve as the foundation for early 5G SA deployments. Also, Samsung hopes that they can benefit from their 5G radio modem chips and IoT sensors, so as to promote the sales of its 5G products to personal users and industries.

It can be seen from the above description that, unlike China, which prefers to focus on 5G coverage, frequency band allocation and so on, South Korea more concerned with the production and improvement of 5G equipment, especially in chipsets. Every 5G base station and 5G mobile phone may be built on those LSI substrates for software-defined radio modems, RF integrated circuits, and MIMO antenna chips. These products can be used not only for smartphone sales in its own country, but also for smartphone suppliers in other regions around the world.

5.1.3. The United States

Similar to the above two countries, the United States also began implementing its own 5G plans as early as 2018. The three major U.S. mobile network operators, i.e. T-Mobile, AT&T and Verizon, all have different ideas about 5G, such as they are diverse in terms of business models, roll-out schedules, spectrum select and so on.

Regarding the spectrum allocated for 5G in the United States, the Federal Communications Commission (FCC) has been taking action to make additional spectrum available for 5G services. In high frequency bands, the FCC completed auctions of 5G spectrum in the 24 GHz, 28 GHz bands, and the higher 37 GHz, 39 GHz, and 47 GHz bands. Through these auctions, the FCC has released nearly 5 GHz of 5G spectrum to the market. In the mid-band, the FCC provides more than 600 MHz for 5G deployment through their work in the 2.5 GHz, 3.5 GHz and 3.7-4.2 GHz bands. Additionally, the FCC is taking steps to improve the use of low-band spectrum (for wider coverage) for 5G services, with targeted changes to the 600 MHz, 800 MHz, and 900 MHz bands [19]. As of the end of October 2021, T-Mobile announced that it covered 305 million people using its 600 MHz frequency band, while AT&T revealed it covered 250 million people using the 850 MHz band. And Verizon reported that its nationwide 5G service was available for 230 million people.

- **T-Mobile** - In December 2019, T-Mobile officially launched its countrywide 5G network, and it is constantly expanding its service area. Compared with high frequency band, T-Mobile prefers 600 MHz spectrum because it does not want to waste its huge investment on this band. Also, low-band waves can spread 5G coverage over hundreds of square miles from only a cellular tower, in contrast to millimeter waves, which only cover a very narrow region. Users can expect to achieve 450 Mbps download rates on average in the near future. By 2024, the maximum 5G speed will reach about 4 Gbps. Of course, T-Mobile does not ignore the mid and high frequency band, they also hope to provide 5G services to users in the 2.5 GHz, 28 GHz and 39 GHz bands. In December 2021, T-Mobile announced that it is aiming to cover 300 million people with its 2.5 GHz spectrum by end-2023, and to double its spectrum position from 100 MHz of mid-band to 200 MHz. And for 28 GHz and 39 GHz bands, i.e. millimeter waves, T-Mobile continues to selectively deploy the network, focusing on other high-traffic locations such as stadiums and airports.

  In terms of 5G devices, T-Mobile signed two 3.5 billion dollars contracts with Ericsson and Nokia in August 2018 to facilitate the roll-out of a countrywide 5G NR network. According to the contract, Ericsson needs to provide T-Mobile with its 5G NR hardware, software, as well as Ericsson's digital service software for management.

- **AT&T** - In December 2018, AT&T took the lead in announcing the launch of a mobile 5G commercial network based on the 3GPP standard in the United States. It has provided 5G services to 31 cities by 2020. Some well-known companies, such as Ericsson, Samsung, Nokia and Intel, are its technology partners. So far, they have cooperated to carry out multiple mobile 5G tests throughout the city, demonstrating their first mobile 5G device using millimeter wave spectrum. In recent years, AT&T has been building small cellular networks in medium-sized and large cities to better expand AT&T's 5G coverage. As plants and rain can absorb millimeter waves, buildings are difficult for them to get through, thus AT&T is strategically putting these tiny cells across the city to maximize reception effect. These little cells can be mounted on utility poles and other places. AT&T claims it would use its own mid- and low-band spectrum (e.g. 850 MHz band) for urban, suburban, and rural areas, but the corporation gives no further details.

  In 2020, AT&T declared that 5G was available across the whole country. But in fact, some people doubt whether AT&T provides a real 5G network. They think that AT&T just names the upgraded version of its LTE network 5G Evolution (5G E). This suspicion is not groundless, because in late December 2019, AT&T began to use 4G hardware under the 5G E label to promote its 5G Evolution network improvement. In short, if you use AT&T and see the 5G E label on your screen, know you are not connected to a 5G network tower — it's just a faster 4G LTE cell network. However, AT&T gave a reasonable explanation for these doubts. They acknowledged that this is not the real 5G network of AT&T, instead serving as a foundation for the AT&T's true 5G service, which will come later. AT&T suggested that we regard it as a "developing" 4.5G platform, which will eventually become a comprehensive AT&T 5G service. In addition, with the emergence of devices and the increasing demand of customers for 5G connections, AT&T said more spectrum will be allocated from its 4G services to 5G.

- **Verizon** - In order to densify its 4G LTE network in densely populated areas, Verizon started its 5G preparations years ago. Verizon's dispersed millimeter 5G small cell sites across the country will receive data from the company's current fiber-based network. Verizon 5G uses the 28GHz and 39GHz bands, both of which are high-band millimeter wave frequencies. These band suit rapid data downloads but not coverage of large areas. In August 2018, using spectrum in the 28 GHz band in a New Jersey trial, Verizon and Nokia were successful in delivering a 5G NR signal to a moving car. Additionally, it used its 5G NR network's prototype user devices to transmit 5G signals successfully during commercial trials in Minneapolis and Washington, DC.

  The 5G deployment plan of Verizon is as follows: First, sell a fixed in-home 5G service, after that, introduce a mobile 5G service. For 5G home service, it began in October 2018, currently offers this service in hundreds of cities, with speeds range from 300 Mbps to 1 Gbps. The initial hardware of Verizon 5G home service is provided by Samsung. The professional installation may include a compact 5G home and outdoor router, a 5G radio and virtualized radio options, depending on the customer's locations [50]. The 5G mobile service started in April 2019 and is currently available in more than 2,000 cities in the United States. Verizon expects to expand the 5G mobile service nationwide by 2024.

It can be seen from the above analysis that, unlike the above two Asian countries, the initial 5G deployment model in the United States has a hint of deception. For example, AT&T is simply renaming the existing LTE in the early stages of deployment, rather than offering a new network. However, because the United States has large rural spaces and high-density urban centers along the coast, reuse of LTE spectrum in the ultra high frequency range (300 MHz to 3 GHz) becomes important. So sticking to 5G on mmWave bands may not make as much sense as the dense metropolises of China and South Korea.

5.2. European Union (EU)

5.2.1. 5G Action Plan

In 2013, the European Commission created the 5G Infrastructure Public Private Partnership (5G PPP), a joint initiative between the European Commission and the European ICT industry, to provide 5G with solutions, architectures, technologies and standards. Its objective is to ensure the leadership of EU in particular fields like autonomous vehicles, where 5G will have a significant impact on its development. In the following years, the 5G PPP continued to reiterate the impact 5G will have on society, emphasizing the need for the EU ICT industry to be prepared and seize this new opportunity. In September 2016, the European Commission launched the 5G Action Plan for Europe. This plan brings together all 5G stakeholders and aims to bring 5G to EU citizens and businesses by 2020. In order to take full advantage of 5G technology, the European Commission believes that a coordinated approach is needed when deploying 5G, such as only EU member states being able to share the same standards, spectrum and regulations. In addition, since the required investment may be large, if operators cannot see European compatibility in the region, they will not participate in this plan. To fully enjoy some technologies, such as autonomous vehicles, a certain level of compatibility within the EU is needed. Therefore, the 5G Action Plan for Europe aims to address these issues and challenges, with the following objectives [15]:

- Align road-maps and priorities for a coordinated 5G deployment within the EU
- Make provisional spectrum bands available and suggest a strategy for authorising above 6GHz bands
- Promote early deployment in urban areas and along transportation infrastructure. Following this, it suggests a rapid build-up to ensure uninterrupted 5G coverage by 2025
- Promote pan-European multi-stakeholder trials
- Promote an industry-led environment for 5G innovation
- Unite leading actors to ensure the promotion of global standards

5.2.2. Current Status

According to the European 5G Observatory [17], since January 2022, all EU countries have commercial 5G service available at least in a part of the country, with a total of 112,000 5G base stations currently active. The overview of commercial 5G launches across the EU is in Appendix B. And based on data collected by the European Commission in 2021, the population coverage in the EU is estimated at 49%, as shown in Figure 5.1.

Regarding the spectrum, 5G spectrum auctions have resumed after the pandemic slowdown, but as of January 2022, five member states have still have not been able to allocate any spectrum from the 5G Pioneer band (700 MHz, 3.6 GHz and 26 GHz) [1]. Figure 5.2 shows the spectrum allocation across the EU. The most popular band is the 3.6 GHz band, 21 of the 27 EU member states have assigned this band. The 700 MHz band, which has been allocated to 19 of the 27 EU member states, is the second most popular band. The 26 GHz band is the least popular band, it has only been allotted in 7 EU member states. Also, in recent times, some member states have tended to offer parts of the C-band to private enterprises, with vertical industries in countries like the Netherlands being able to use the dedicated 100 MHz part, enabling spectrum sharing to support local network deployments.

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[1] In 2016, with the release of the 5G Action Plan, the EU Commission recommended creating a list of pioneer spectrum bands for the initial launch of 5G services. It proposed bands in three categories: below 1 GHz, between 1 GHz and 6 GHz and above 6 GHz. The following are the 5G pioneer bands designated at the EU level: 700 MHz (703-733 MHz and 758-788 MHz), 3.6 GHz (3.4-3.8 GHz), 26 GHz (at least 1000 MHz within 24.25-27.5 MHz).

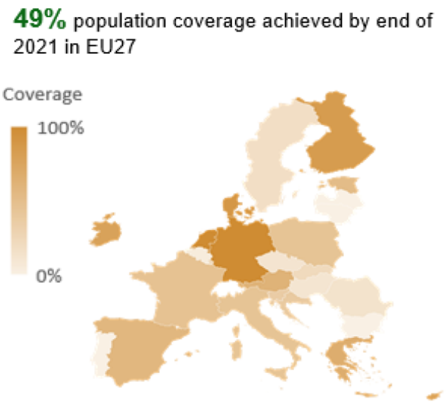

Figure 5.1: 5G Coverage in EU [17]

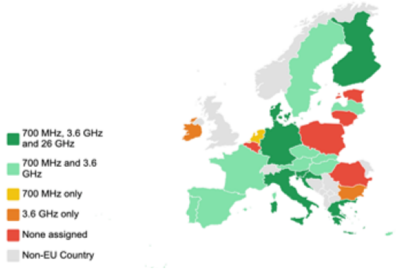

Figure 5.2: 5G Spectrum Assignments in EU [17]

As for the "pan-European multi-stakeholder trials" mentioned in the 5G Action Plan, before 2022, 12 "digital cross-border corridors" have been set up to stimulate the use of 5G in transport services, in particular to pave the way for Cooperative Connected and Automated Mobility (17 of 27 EU member states are involved in this project).

5.2.3. Analysis

From the performance of 5G in different countries and regions, it can be seen that the promotion of 5G in South Korea is dominated by 5G products, and its standard to measure the success of 5G is the global sales of its 5G products such as semiconductor components. The launch of the national 5G network is guided by the national industrial policy as an early testing ground for products against global competition. China, the United States and the European Union are different from South Korea. They are not only producers of 5G products, but also consumers of 5G technologies. The goal of their deployment of 5G is to develop network devices and chipsets for global sales, and to launch the technology internally for local broadband services. In addition, due to the differences in 5G deployment policies or 5G technology mastered by different countries and regions, China, the United States and the European Union have different 5G performance. Next, in the process of comparing the EU with other three leading countries, we will analyze the development prospects of 5G in the EU in detail.

5.2.3.1. Strengths

1. **Equipment Production** - First of all, EU is home to two well-known manufacturers of network equipment, Nokia and Ericsson, who hold about 30% of the global market for telecom equipment[2] and possess several key patents. Second, some important semiconductor suppliers are based in the EU, for example, NXP Semiconductors and ASML (Even if they are currently owned by investors from China, South Korea, or the United States).

2. **5G-Related Organization** - The key organization for 5G standards, ETSI/3GPP is located in the EU.

3. **5G Corridors** - Europe is leading the way in developing 5G industrial ecosystems, providing many trial investments to create market opportunities. One of the high potential areas of this leading market is 5G based Connected and Automated Mobility (CAM), especially the introduction of CAM 5G corridors. It is designed to provide seamless 5G connectivity for cross-border vehicles, thus paving the way for autonomous driving of major roads, trains and sea routes. So far, there are 12 "digital cross-border corridors" in the EU, which will help the EU to establish a 5G leading market in the future, because the funds are often transferred to more developed markets.

4. **Experience in Network Deployment and Operation** - Most operators in the EU were established earlier (such as Orange and Vadofane). They have their own 2, 3 and 4G wireless networks and fixed broadband

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[2] According to a report by Dell'Oro [52], a Silicon Valley-based telecom information and service provide, Huawei continue to take the first place with revenue accounting for 28.7% of global share n telecom equipment in 2021, followed by Ericsson (15%), Nokia (14.9%), ZTE (10.5%) and Cisco (5.6%). Excluding the Chinese market, the competition between the big three kit vendors is more even, with Ericsson and Nokia at 20%, and Huawei at around 18% of the market.

networks, provide multiple communication services, hold 5G licenses, and have rich experience in network construction and maintenance.

After years of development and accumulation, most operators have accumulated rich resources in various channels such as online and offline. From a large number of telecom business halls at the beginning, to gradually developed mobile phone stores, to gradually moving from offline to online (e.g. mobile phone applications), the tentacles of operators have penetrated into every aspect of people's lives. Even at the airport, people can receive SIM cards that the operators distribute free of charge. In recent years, with the rapid development of Internet services and the invasion of Covid-19, operators have gradually shifted the focus of services from offline to online, such as customer service hot-lines, portals, etc., giving more choices to user groups who are gradually accustomed to mobile Internet access. This continuous development process allows traditional operators to continuously learn development and management experience, thus forming a unique development model, creating favorable conditions for the development of 5G. In addition, with the development of mobile terminal technology, people tend to spend more time on electronic devices. The behavior analysis of these groups can help operators to better accumulate user data, so as to formulate effective strategies after analysis.

5.2.3.2. Weaknesses

1. **Deployment of Infrastructure** - EU countries have lagged behind their global counterparts (China, South Korea and the United States) in the deployment of 5G infrastructure. This is reflected not only in the migration of 4G to 5G access infrastructure, but also in the construction of an 5G SA access infrastructure, as shown in Figure 5.3.

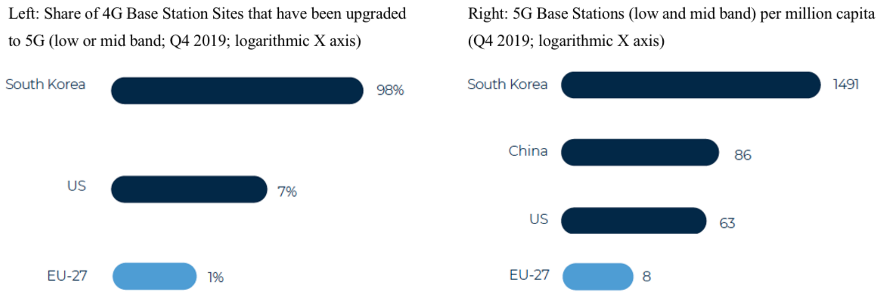

Figure 5.3: Deployment of Infrastructure [29]

As of May 2022, the ranking of 5G base station deployment has not changed compared to the above figure (right part). South Korea is still the leader in the deployment of 5G, the nation has 162,000 5G base stations, according to its communication agency. Considering the population of the country, this means that each 5G base station can be shared by 319 people. China has deployed 916,000 base stations, ranking second behind South Korea. Although China has a large population, each base station can accommodate 1531 people. The US and EU each have 500,000 and 147,308 base stations, each of which can accommodate up to 6,590 and 3,039 people, respectively.

2. **Market** - Although the EU has formulated a unified 5G development plan, the market structure of 5G in the EU is relatively fragmented. This restricts business expansion across borders and increases costs to handle regional variations. Compared with companies operating in single market countries (China, South Korea and the United States), this puts the EU operators at a disadvantage. In addition, even though fierce competition among different operators has resulted in certain advantages such as lower consumer prices and service innovation, it has also resulted in declining revenues and rising investment costs by preventing rational market consolidation, which has negatively impacted investor and commercial viability.

3. **Content Services** - In order to build the completed industrial chain system, some operators have already established their own content business bases. Taking China Mobile as an example, it has captured various content markets early. Including video content, such as the Mobile Phone Video Base established in Shanghai, which specializes in video content production; Music content, such as the wireless music base in Chengdu, Sichuan province; It also includes reading, games, animation bases, etc. South Korea, the

United States and the European Union are relatively backward in this regard. Compared with establishing their own content service bases, they prefer to cooperate with OTT service providers (such as YouTube, Netflix, etc.) that provide content services based on the network. And this involves the distribution of network costs.

Today, the world has entered an era of large traffic outbreaks, especially the continuation of the Covid-19 has caused a surge in traffic, and one of the main sources of the surge in traffic is large-scale streaming media platforms such as Netflix. The growth of data traffic is a key determinant of network size and capacity. To this end, operators have invested heavily to upgrade network infrastructure and increase capacity. In February 2022, four operators in the EU (Orange, Deutsche Telekom, Vodafone and Telefónica) issued a joint statement [34] calling for EU-level legislation to force OTT service providers such as large technology companies and large-scale providers to pay for their "own" network investment. The statement cited the Global Internet Phenomenon Report released by Sandvine in January 2022, which said that video stream, game and social media traffic brought by a few digital content platforms accounted for more than 70% of all traffic on the network. "The burden of investment must be shared in a more appropriate way." insisted the CEOs of the four operators. "Digital platforms benefit from the super large-scale business model at a small cost, while the investment required for connectivity is made by the operators. At the same time, the profitability of operators in the retail market is declining." In addition, due to reasons such as strong market positions, unequal bargaining power and fair regulatory competition environment, network operators could not negotiate fair terms with giant digital platforms. It is undeniable that if the contradiction between operators and OTT service providers is further intensified, it may lead to problems such as reduced network carrying and reduced consumer experience, thus making the EU lag behind the rest of the world.

4. **Funding** - According to the research conducted by the research company Analysys Mason, despite the investment of 52.2 billion euros in optical cable network and high-speed 5G in 2020, a four-year high, the European telecommunications industry still lags behind its competitors globally. Also, the EU spends 96.3 euros per person in capital expenditure compared to 191.9 euros in the United States and 115.4 euros in South Korea.

5.2.3.3. Opportunities

1. **Base Station Deployment** - A key factor in 5G deployment is the the ease with which a large number of small base stations can be deployed in order to densify the network. China and South Korea have an advantage in this aspect, because of the way their political structures and cultures allow them to mandate deployment without getting approval from the general populace. But in the United States, due to the light-touch regulation proposed by FCC, the deployment of small base stations will face legal obstacles at the municipal and state levels. There are similarities between the EU and the US, but starting in 2019, the EU has been developing a Small-Area Wireless Access Points (SAWAPs) deployment regime aimed at permit-free installations within the EU [16]. Specifically, the release of this regime means that the EU wants to facilitate the deployment of ultra-high-capacity networks by reducing administrative barriers and costs. It also intends to provide more legal certainty and create incentives for co-investment in these networks.

   - **What is SAWAPs deployment regime?** - First, SAWAPs are small radio transceivers with an antenna that has a low visual impact. SAWAPs can be utilized for both cellular and non-cellular technologies that operate in a small range (e.g. 100m), such as 5G and WiFi. Hence, SAWAPs require dense deployment in cities because they have a limited operating range. Also, in order to provide good connectivity, the equipment should use the 26GHz frequency band, which means it needs to be installed close to people. The SAWAPs deployment regime contains measures that make it easier to deploy SAWAPs in public areas. The regime's supporting measures in particular grant rights to the authorized telecom operators, for example, a right to access all public infrastructures and street furniture such as light poles.

2. **Young Consumers** - In the consumer group, young people are more "happy with the new and tired of the old", and they tend to show more curiosity and pursuit of new things. These young people are already in the 3G or even 4G era when they were born. They are accustomed to surfing the Internet with their smartphones, connecting to the cellular network anytime and anywhere. They are willing to spend more time, energy and money on the mobile network and are accustomed to this digital age lifestyle. The 5G technological revolution will bring a new way of life, consumption and entertainment. The young people will soon be attracted by high-definition video, interactive games, VR and so on, thus quickly becoming the most loyal users of 5G.

3. **Industry Digital Transformation** - Although the concept of 5G was proposed as early as 10 years ago, it seems that 5G is still an emerging development issue, and the actual role in promoting future economic development is still unknown. The existence of 5G can bring more possibilities and imagination to the transformation of traditional economies. The EU can use 5G as a digital medium to optimize the current economic structure, for example, to make the traditional economy originally linked by human beings realize the connection between things, improve the digitalization of various industries, so as to have a positive impact on the economy.

   Since the commercial use of 5G, the 5G business model has shown new vitality in some traditional industries, such as smart agriculture and so on; also because of the high-speed and smooth interconnection of things, new business models have emerged, creating conditions for the transformation of traditional agriculture to modern agriculture and the establishment of a new energy growth mode that meets modern requirements. Also, in the traditional automobile industry, because of the emergence of 5G high-speed interconnection, a series of intelligent transportation ideas such as autonomous driving have become possible. Therefore, a number of research and development achievements have been generated around the traditional automobile industry and new energy industry, and constantly explored some new business model in the traditional industry. For example, with the continuous development of 5G, there will likely be more and more unmanned workshops and fully intelligent workshops. Through the 5G high-speed wireless network, the direct interconnection between devices will greatly accelerate the production efficiency of vehicles and reduce labor costs manual error rate.

4. **Policy in Sustainability** - In 2019, the European Commission emphasizes digital technologies as a crucial enabler for achieving the sustainability targets set by the Green deal in various areas. It also announced the aim to investigate ways to make sure the digital technologies like AI, 5G and IoT can accelerate and maximize the policy impact of addressing climate change and protecting the environment [18]. In terms of the energy saving, the improved operational efficiency of 5G and its architecture, which emphasizes infrastructure sharing as a way to cut costs, both help to explain improvements in energy efficiency associated with 5G installations. This involves several practical energy efficiency initiatives include deploying more energy-efficient network equipment (decommissioning old equipment), gradually shutting down the legacy network (i.e. 2G/3G), which is less energy-efficient. In terms of environmental protection, the EU suggests that the the telecom industry help other economic sectors reduce carbon emissions through digitalization. Based on Ericsson's analysis of Europe's decarbonization scenarios [25], connectivity is required for climate solutions amounting to over 550 million tons of CO2 (equivalent to 15% of the EU's total yearly emissions in 2017). By 2030, it is anticipated that the adoption of 5G technology in four high-emission sectors (i.e. transportation, power, industry and buildings) will result in extra yearly emissions savings of 55-170 million tons of CO2, which is equivalent to one seventh of EU cars off road (more than 35 million cars).

5.2.3.4. Challenges

1. **The High Cost of 5G** - From the perspective of the development trend of 5G, almost all EU countries that deploy 5G are NSA first, and then gradually transition to dual-module network on this basis, and finally realize SA. Due to the high cost of Massive MIMO equipment and the construction density of 5G sites is much higher than that of 4G, the investment in 5G network equipment will bring a huge cost to operators. In addition, the large broadband and multi-channel of 5G will inevitably bring high energy consumption, and the operating cost of 5G network will also be much higher than that of 4G network, which will bring considerable pressure to the financial affairs of operators.

2. **Spectrum Management in 5G Verticals** - 5G is highly adapted to enter the so-called "vertical" including industrial, the automobile industry and healthcare because it has low latency and high speeds. Trials of 5G verticals have been promoted in Europe thanks to the 5G Public Private Partnership initiative (5G PPP), which is supported by research grants from the EU for 700 million euro. A group called the 5G-PPP Vertical Engagement Task Force (VTF) has also been created to organize and keep track of operations involving the vertical sector. However, in the field of spectrum management, there is now a discussion on the licensing model (or models) required for 5G verticals. Some opponents believe that there is a serious risk in doing so, which may damage the already scarce 5G spectrum, as well as reduced speed and quality of service. Besides, due to its inability to be flexibly reassigned to suit changes in traffic, 5G frequencies may not be fully utilized if spectrum is dedicated to verticals.

3. **Coexistence of Multiple Networks** - Regardless of whether the operator adopts the NSA or SA networking mode, it will face the complexity of multi-network integration of 2, 3, 4, and 5G, as well as the complexity of operation and maintenance of multi-network coexistence.
4. **Lack of a Convincing Business Model** - Although the operators within the EU have gained millions of 5G users, the traffic policy in the 4G era has made users accustomed to low cost traffic, resulting in weak growth of 5G user traffic revenue. In addition, in terms of industrial application, scale effect has not yet appeared. The traditional traffic operation model of operators cannot adapt to the comprehensive business innovation brought by 5G, and the traditional "To Customer" business model cannot be copied to the "To Business" model. Smart transportation, smart factories, etc. have bright prospects, but how to balance the investment and return of industrial applications, how to choose valuable customers in value industries, what major functions can 5G use to impress customers, and how operators build the core capabilities of 5G enabling and their brand status in industrial applications are unknown. As a result, the business model of operators is still unclear.
5. **Multi-Service Performance** - How to meet both reliability and efficiency, so as to provide end-to-end network slice guarantee for services with high network requirements; how to balance the economy of private and public networks in the industry, and how to ensure the experience of low latency and high bandwidth services, all pose significant challenges to the performance of 5G networks.

5.2.4. Analysis Result

From the analysis in this section, we can get table below:

Table 5.1: Analysis of EU Operators in Developing 5G

Internal Factors	**Strengths:** 1. A number of well-known network equipment manufacturers and chip manufacturing companies 2. Key organization that develops the 5G standard 3. Favorable environment for developing the 5G industrial ecosystem 4. Rich experience in network deployment and operation **Weaknesses:** 1. 5G infrastructure deployment is slow 2. The 5G market structure is relatively fragmented 3. Unable to provide their own content services and difficult to reach fair agreements with other OTT service providers 4. Low capital investment
External Factors	**Opportunities:** 1. The release of Small-Area Wireless Access Points (SWAPS) deployment regime (aimed at permit-free installations within the EU) 2. The potential of young consumers 3. Industry digital transformation needs 4. Sustainability Strategy **Challenges:** 1. High costs to deploy and operate 5G 2. Controversy in 5G vertical industry spectrum allocation 3. Multi-network coexistence is complicated in operation and maintenance 4. Lack of a convincing business model 5. Hard operation of multiple-service

From the content in the table, we can see that on the one hand, EU operators are facing huge network construction expenditures, on the other hand, traditional business growth is weak, and performance pressure is increasing sharply, so exploring new business models has become a must. In addition to maintaining traditional ordinary consumer connection services, operators must fully recognize their own advantages, integrate existing resources, expand revenue channels, and actively enter other industry markets. The first step for EU operators is to improve the construction of 5G networks and gradually improve network performance. At the same time, in order to better bring 5G technology into vertical industries, they need to further strengthen the edge computing capabilities of the network and continuously improve network slicing capabilities, so as to meet the network connection service requirements of various types of services. Next, after the completion of 5G network construction, EU operators need to focus their attention on how to provide/develop their 5G services, that is, how to explore a set of their own business models. For example, they can use their own spectrum resources and 4G network operation experience to maintain existing user groups, and then add new 5G applications such as VR/AR to the original traditional communication service packages, so as to rapidly develop the individual user market and increase their operating revenue. Besides, they also need to pay attention to the development of other industries, study the market needs of enterprises, use their advantages in 5G deployment, migration and operation to seek cooperation with enterprises, and provide enterprises with 5G solutions, which will also helps meet the needs of enterprises' industrial digital transformation.

In addition to the efforts of operators, the EU will need to make corresponding efforts to support the development of 5G. First, in terms of funding, the EU needs to increase its investment in 5G, which should encompass the construction of the entire supply chain from basic technology research to experimental development to trials, pilots and large-scale deployments, thus creating a better 5G ecosystem for operators. Secondly, regarding the fragmentation of the 5G market structure in the EU, in order to reduce the impact of this factor on operators, the EU can consider formulating a relatively unified 5G development plan, but it is not easy to operate.

The above operator-related recommendations are described in detail in Chapter 6.

6

Recommendations for EU Operators in Developing 5G

Based on the analysis in the previous chapters, in this chapter, we provide recommendation on 5G deployment and service development for EU operators. In Section 6.1, we provide operators with the process of deploying 5G networks and 5G equipment. Network deployment can help operators grab a part of the 5G market share and not fall too far behind other leading countries; the deployment of 5G devices such as edge computing sites can provide the possibility of 5G applications in various vertical industries, such as smart factories and VR/AR. In Section 6.2, we analyze the two key areas of 5G commercial, namely, the individual user market and the industrial field, also provide several commercial operation suggestions for operators in these two areas.

6.1. 5G Deployment

6.1.1. Network

Network deployment strategies are critical to an operator's 5G market share. Operators should only begin the first phase of 5G networks when they are ready to move quickly to the next phase. Lessons learned from 4G network deployments suggest that operators that expand network coverage rapidly after the launch phase can outpace operators that preemptively roll out 4G without rapidly expanding coverage.

- **NSA or SA mode** - In Chapter 4, we describe various 5G deployment and migration options, including the migration from 5G NSA to 5G SA. From the 5G deployment status in Chapter 5, the leading countries have built 5G networks start from the NSA mode, and gradually evolve to a dual-module network in which SA and NSA coexist, and finally achieve SA mode. This is also a migration step that EU operators should learn from, and the reasons why they should gradually evolve to the SA mode are given below.
  - **Deployment** - Through the analysis in Chapter 4, we we have come to the insight that compared to the NSA deployment mode, the SA deployment mode has certain advantages. First of all, in terms of the transformation of LTE base stations, SA networking has fewer requirements for the transformation of LTE base stations, and only needs software configuration. Secondly, in terms of network evolution, under the NSA network, 5G and 4G are tightly coupled and restrict each other in the process of operation and evolution; while under the SA network, 5G and 4G are independent of each other and evolve independently. As a result, when purchasing 5G equipment, operators in the SA network are more flexible in selecting 5G manufacturers, reducing the requirements for interoperability between 5G equipment and LTE equipment.
  - **Investment** - Compared with SA, the initial investment cost of NSA will be much lower. The operator's financial strength and resource investment determine the deployment mode of its own 5G network. From the perspective of network investment, although the initial investment cost of the NSA deployment model will be lower, it will face the upgrade of LTE network equipment and the evolution of NSA to SA architecture in a later stage. After comprehensive calculation, the overall investment cost of the NSA architecture deployment mode is higher than that of the SA deployment mode. Mainly, four additional

  costs are added: NR upgrade, 4G eNB upgrade and capacity expansion, EPC upgrade and capacity expansion, and transmission reconfiguration. In this regard, operators can consider promoting the potential and role of 5G through various communication channels, thereby promoting public understanding of 5G. As the public's acceptance of 5G increases, investors will also be more willing to join operators' 5G deployment plans.

  - **Services** - Through 5GC, SA mode can better enhance the 5G service experience and better handle various 5G services; through SBA, it can help achieve more refined control under the 5G large network. Because of its simple architecture, SA mode has become a good platform for smooth transition of new services, enabling operators to develop a variety of services for users and industries as soon as possible. In addition, with the introduction of edge computing, operators are able to enter vertical industries to create new ecosystems.

6.1.2. Device

6.1.2.1. Mobile Device

When the operators plan to implement 5G voice, their device ecosystems also have to consider emergency services, roaming and backward compatibility with existing technologies.

- **Deployment**
  - **5G NSA Phase and 5G SA Initial Phase** - In the 5G NSA phase (or 5G EN-DC), the device with voice and emergency services should include: VoLTE with EN-DC split-bearer, VoLTE without the EN-DC split bearer, and CSFB mode utilizing CS voice (2G/3G). At early stages, operators should expect the device to enable emergency service+ without EN-DC split bearer [12]. EPS FB and VoNR should also be included in this device. And for emergency service, it should contain domain re-selection and emergency service fallback (ESFB). At the 5G SA initial phase, the device is able to send signals to the 5G SA network, however it does not enable enough VoNR features to satisfy voice coverage since the UE VoNR capability bit is missing. This lack results in the device needing to trigger the service provider to supply EPS FB voice.
  - **5G SA Mature Phase** - When operators choose to deploy 5G SA and multiple 5G voice options through more than one phase, that early deployment advantage will become the challenge of the 5G SA mature phase. For example, how to maintain support for the device with EPS FB voice when the VoNR upgrade path is not available/upgrade to VoNR is difficult. Besides, it is important to keep devices that only support EPS FB from connecting to VoNR-only networks.
- **Cost** - In the development process of the 5G business model, operators have to rely on 5G terminals such as mobile phones, and are limited by the allocated spectrum resources, their own network models and investment funds, which also leads to different operators choosing different 5G network deployments and migration options. Because NSA standards were formulated earlier, technical standards are relatively mature, and supporting products are abundant, most operators have completed the testing of 5G NSA. More importantly, the NSA networking is carried out on the basis of the existing network equipment of the operator. In order to maintain the consistency of network interoperability, the operator still needs to purchase the 5G network equipment of the original network manufacturer, which makes it difficult for the operators to adjust their investment direction. For example, once an operator adopts Ericsson's equipment on the 4G network, it still needs to continue to use the equipment of these manufacturers when deploying 5G NSA, which makes it difficult for the operator to negotiate with the supplier on the price of 5G devices.

6.1.2.2. Edge Computing Sites

The deployment of edge computing is a relatively long-term process. Like the deployment of 5G networks, it will go through three stages: pilot, small and medium-scale commercial use, and large-scale commercial use in mature stages. For operators, the whole network is theirs, so the location of deploying MEC is very flexible. The common solution is to add MEC functions to the edge UPF to form an edge-integrated enhanced UPF. Following the deployment of 5G networks and the acceptance of vertical industries, we provide operators with the following edge computing deployment processes:

- **Phase 1** - In this phase, the 5G network is still in the early stage of deployment. Edge computing is mainly based on the joint exploration of operators, equipment suppliers and vertical industries. Small-scale testing can be considered.

- **Phase 2** - In this phase, as operators deploy 5G networks on a large scale, the deployment of edge computing can also gradually increase. Therefore, edge computing sites can be deployed more flexibly in site computer rooms, integrated access computer rooms, aggregation computer rooms, and regional data centers [51]. The application can also be tried in scenarios such as ultra-high-definition sports events.

- **Phase 3** - In this phase, the maturity of 5G, the reduction in the cost of 5G equipment, and the establishment of wider collaboration between operators and enterprises are driving the scale of edge deployments. At this stage, edge computing sites are able to be deployed on a large scale, and deployment efficiency and market acceptance have been continuously improved. Through edge computing, technologies such as autonomous driving and smart manufacturing can be further developed.

Regarding the choice of the deployment location of the edge computing site, generally speaking, the closer it is to the end user, the lower the service latency. Operators can match the delay of the service to be deployed according to the service delay that can be satisfied by their own computer room location (site computer room, integrated access computer room, aggregation computer room, regional center computer room, etc.), so as to roughly select the location of the edge computing site. And operators also need to consider the requirements of covered users when choosing a deployment location.

6.1.3. Timeline

For operators in the EU, the past few years have been the initial stage of their 5G deployment. At this stage, the 4G service is still in the heavy load period, and the 5G service is still in the exploratory trial stage. Most operators choose NSA network deployment, and the 5G services provided are only traditional mobile communication services. Based on this, next we give the recommended timeline for EU operators to develop 5G in the next few years: 1). From November 2022 to 2023, this will be a period of rapid growth of 5G services, 4G services will be gradually diverted, 5G personal services will trigger new applications like AR, VR, etc. Other services such as URLLC should be in the preliminary testing stage. In terms of network deployment, it is recommended to re-allocate part of the 2/3G spectrum to 4G or 5G through software upgrades or replacements, also gradually expand 5G coverage. In addition, it is recommended that operators migrate to the NSA SA hybrid network to achieve 5GC deployment; 2). From 2024 to 2027, after several years of exploration, 5G industry applications should be gradually formed (URLLC and other services should been maturely used), the business model should be mature, and it will gradually entered the 5G era, that is, 5G provides main services. In addition, the digital transformation of the industry also needs to be in progress. In terms of network deployment, it is recommended to completely close the 2/3G spectrum, re-allocate part of the spectrum to 5G, and 4G only provides basic coverage and services. In addition, it is recommended that EU operators migrate to SA mode and realize 5GC capacity expansion at the same time.

6.2. 5G Services

6.2.1. Communication Services Migrating from 4G to 5G

6.2.1.1. Migration to VoNR

As we discussed before, for 5G networks, VoNR is the target solution for voice/video communications. Other technologies like EN-DC and EPS FB are also included. Here we give two paths to migrate the voice/video communication options chosen in the initial 5G stage to VoNR, as shown in Figure 6.1.

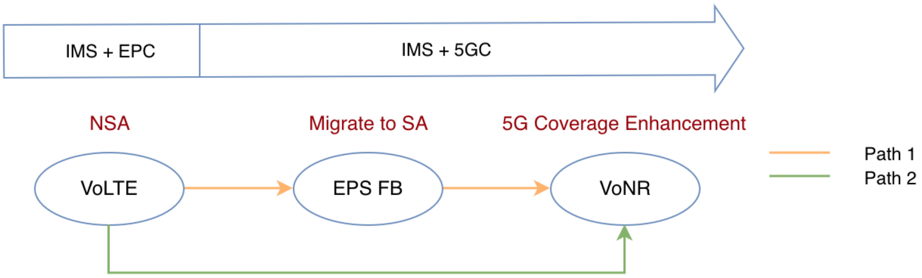

Figure 6.1: Migration to VoNR

As EN-DC still uses EPC, so in this diagram, EN-DC is included in VoLTE.

Voice/video communications and data networks are segregated at the beginning of 5G. The EPC and LTE offer voice/video communication services, with VoLTE serving as the solution for voice/video communications. After the advent of 5GC, the EPC and LTE continued to provide voice/video communication services, EPS FB was introduced as a solution for voice/video communications. With the further development of 5G networks, operators can achieve VoNR through the following migration methods:

- **Path 1: VoLTE → EPS FB → VoNR** - 4G → 5G Option 3/3a/3x → 5G Option 2
- **Path 2: VoLTE → VoNR** - 4G → 5G Option 2

To better understand these migration paths, we next describe how voice solutions should be selected for the three different phases of 5G shown in Figure 6.1.

- **5G NSA Phase** - Due to the limitations of funds or existing network architecture, most operators are expected to start by releasing 5G services in NSA mode. These operators will offer voice services to 4G users via CSFB or VoLTE before introducing 5G services, while still offering voice services to 2G/3G users over the CS network. With the launch of 5G services, operators should activate VoLTE services for 5G NSA users by default. Otherwise, users will have to fallback to 3G to make and answer calls, which results in increased call setup time due to reduced speed from 5G to 3G. Therefore, users would not be able to fully experience the exceptional experience that 5G may provide in this case. In other words, for 5G NSA users, if their operator does not offer VoLTE service or if they do not subscribe to VoLTE service, their 5G experience will be degraded.
- **Initial Phase of 5G SA** - When establishing a voice call, the 5G SA network should use EPS FB to fallback the voice to the LTE network, connection is done via VoLTE. This is because CS fallback from 5G to 2G/3G is not supported according to 3GPP Release 15. So for 5G SA users, if they do not subscribe to VoLTE services, the situation will get worse, i.e. they will not be able to make or answer calls.
- **Mature Phase of 5G SA** - In this phase, the coverage of NR has expanded compared to the previous one, but full coverage has not yet been achieved. The communication industry needs to become mature, particularly in terms of terminals. Support for 5G SA terminals will need to become mainstream, with VoNR by default (set to ON by default), that is, the main voice service provider at that time [40]. When a user leaves the coverage of 5G during a call, a technology named PS-HO (introduced in section 3.5) can help to switch the session from NR to LTE seamlessly, thus making VoLTE responsible for voice services. Since the session control on 4G and 5G networks is integrated into IMS for processing, a complex cross-system SRVCC handover process can be avoided, for example, from 4G to 2G/3G. In order to prevent the perception of the upper control layer, a simple PS-HO only performs transmission switching in the access domain. As a result, in this phase, operators need to build VoLTE into a basic, full-coverage network everywhere. This allows 2G/3G networks to be retired, which not only saves operation costs, but also frees up spectrum.

6.2.1.2. SMS and USSD

In the 5G NSA phase, SMS can be realized by SMS over SGs or SMS over IP (SMSoIP), and USSD can be realized by CSFB or USSD over IMS (USSI). In the 5G SA phase (initial and mature), both SMS and USSD are realized through 5GC and IMS. The SMS is realized by SMS over IMS, and the USSD is realized by USSD over IMS. (SMS and USSD have been discussed in Sections 3.5 and 4.2).

According to the survey done by the GSMA [38], there is an interesting point in the evolution of technology for SMS services. Operators who participated in this survey indicate that this evolution is based on the type of user, rather than an overall trend for all users. Users can be roughly divided into the following three categories:

- **Legacy User** - Still use 2G/3G. Changes to SMS delivery technology for legacy users do not appear to be necessary. If these users want to migrate to 4G/5G, they should change their devices.
- **IMS User** - Benefiting from the maturity of VoLTE technology and the introduction of 5G networks, for IMS users, the migration of SMS to IP/IMS (SIP enabled) has become mainstream.
- **MIoT User** - In the context of the Mobile Internet of Things (MIoT), operators believe SMS to be a critical technical enabler. Aside from regular Mobile Originated-SMS (MO-SMS) and Mobile Terminated-SMS (MT-SMS), the "Wake Up IP session" and Over the Air (OTA) are the most common use cases [38]. In addition, in

order to minimize non future-oriented capacity expansion on legacy networks, users should only connect to the PS network rather than the dual attachment on CS and PS networks. By using MIoT, migrating SMS services on Diameter appears to be a good idea, and it also complies with the Diameter's ecosystem for connecting Service Capability Exposure Function (SCEF).

In summary, the types of subscribers operators currently have and the types of subscribers they target in the future will affect the technology they choose to support SMS services.

6.2.2. New Applications in 5G

Due to changes in network architecture, the arrival of 5G will give rise to more personalized services to meet the needs of users at different levels. At this time, operators can consider shifting their focus to network services, such as providing combined services (basic network service plus value-added services) for different individual users with different traffic, network speed, delay, connection, etc.; also provides corresponding edge computing and other services for customers in different industries.

6.2.2.1. To Individual Customer

Although compared with 4G, the role of 5G is mainly reflected in vertical industries, but operators should not ignore the individual user market. Below we make suggestions on several aspects that will affect individual users market.

- **OTT Services** - When analyzing the status quo of 5G development in the EU in Chapter 5, we mentioned that the EU has a disadvantage compared to China in terms of content services. Operators in the EU cannot provide their own content services and have difficulty reaching fair agreements with other OTT service providers. In recent years, although China's three major operators have tried to develop their own OTT services, such as China Mobile's MIGU Video/Music, the subscriber scale has not seen a jump due to capital investment and operation mode. So we don't recommend EU operators to create their own video content services because it is difficult to attract users and make profits, and it is more realistic to cooperate with OTT services providers. Then how to bundle OTT video and other content services, how to improve the attractiveness of the package and the stickiness of the user base, thus bringing revenue to the operator is the current problem that needs to be solved. For example, operators could seek cooperation with OTT service providers such as Netflix and YouTube, where subscribers could avoid subscription fees for the above video sites by purchasing the operator's 5G package. This scheme could be effective in improving subscriber stickiness, but would not change the operator's revenue structure. In order to bring higher revenue to themselves, operators can consider investing more in OTT content services with larger market size, such as live streaming of sports events. Since live sports events have high requirements for timeliness, clarity, and detailed presentation, the 5G's large bandwidth and low latency characteristics can come into play. As cameras continue to be upgraded and live streaming forms are enriched, 5G can support more functional features, such as free choice of viewpoint and simultaneous multi-shot live broadcast. Then the operator can invest a part of the funds to purchase the live broadcast rights of some important events (such as this year's World Cup); services should be sold in a bundled package, and high-level package users are bundled for free (free to watch various sports events), ordinary package users can enjoy discounts, while other network users need to pay in full, which can be a good way to expand the revenue of operators.
- **VR (Virtual Reality)/AR (Augmented Reality)** - At present, the mainstream terminals in the VR/AR field are head-mounted devices, such as helmets and glasses, and the leading enterprise is Meta [1]. Games and videos will be the main market for VR/AR content in the future, but unfortunately, due to technical constraints, the current VR/AR fails to achieve full immersion, and there is still a gap between partial immersion and the VR experience that consumers desire. In addition, at this stage, VR/AR devices have two more obvious disadvantages, namely their higher hardware costs and the content experience that cannot be continuously enhanced after the novelty. We can take games as an example, what determines whether a game is popular or not is not the improvement in picture quality or latency brought by 5G technology, but the play-ability and interactivity of the game. The emergence of VR/AR can greatly improve the sense of interaction, but the play-ability of the game is still determined by the game itself, which leads to not all users will pursue VR/AR devices. Since it is difficult for operators to produce their own VR/AR devices, they can only cooperate with other manufacturers to make bundled packages (for example, if you purchase the operator's

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[1] The global VR headset market saw growth by 241.6% in Q1 this year, with Meta owning 90% of the market with its Quest headsets, per Internet Data Center (IDC) [56].

5G package, you can get a discount when purchasing VR/AR devices) to obtain terminal agent revenue. In addition, operators will be important players in the operation of video, games and other content services, here, they can refer to the points we put forward in the OTT service part.

6.2.2.2. To Industry Customer

With the advent of 5G and the maturity of 5G technologies such as network slicing, operators are no longer satisfied with providing telecommunication services to individual users. They expect to enter the industrial Internet market and create new revenue streams in the industrial sector through 5G technologies, thus establishing a suitable 5G business model of their own. This is because operators have the spectrum and network resources and the advantage of integrating connectivity capabilities into industrial manufacturing and services.

Despite the above advantages for operators, the industrial sector is still a relatively new market for them. There are bound to be some problems and challenges when expanding its industrial Internet. The industrial sector, for example, is currently faced with the challenge of running multiple different networks simultaneously in a single factory, such as Wi-Fi for a wide range of IT applications, short-range technologies like Zigbee for connecting sensors, Ethernet for connecting fixed machines, and mobile networks for connecting mobile objects such as robotic arms [59]. The flexibility of 5G networks can meet these different needs, thereby bringing new business opportunities to operators. In addition, operators can customize networks for enterprises so that different applications run on different slices of the 5G network. But this raises a question, how can operators seek cooperation with these factories? After all, the 5G solution mentioned above can also be completed by equipment suppliers (e.g. Ericsson) or by the factories themselves. Based on this, our advice to operators is that they need to analyze the industrial user groups they may attract based on their own positioning, and at the same time, when cooperating with these customers, they should continuously improve their capabilities in network construction and service provision. Only in this way can operators make full use of their advantages in spectrum and network connectivity to provide 5G solutions for industrial companies and attract more partners, thereby enhancing their industry experience and operational revenue. It can also facilitate the formation of operators' 5G business models and the digital transformation of the industry.

7

Conclusion and Future Work

In this chapter, we conclude the work done in this thesis, and based on the analysis from Chapter 4 to Chapter 6, we draw some general conclusions, thus solving the research questions we defined in Chapter 1. And the recommendations and directions for future research are also provided.

7.1. Conclusion

The research conducted in this thesis aims to provide reference for EU operators in 5G deployment and migration by comparing and analysing the current state of 5G deployment in the EU with other leading countries (China, South Korea and the United States), also provide strategies for EU operators in 5G services development. Through the analysis in Chapter 5, we solve the first two research questions we defined in Chapter 1, namely the internal and external factors faced by EU operators in deploying 5G, as shown in Table 5.1. Integrating the content of this table with the analysis results in Chapter 4 helps us to make more appropriate recommendations for EU operators on the future development strategy of 5G, i.e. solving the last three research questions we defined in Chapter 1. Next, we describe the conclusions obtained in this thesis in detail.

By looking at the analysis results presented in Chapter 4, it can be generally concluded that migration path Option 1 → Option 2 is suitable for operators aiming to deploy full-scale 5G, and offer the complete range of 5G services from the start. Especially when they have enough capital and can wait a long time to market. Migration path Option 1 → Option 3 → Option 3/4 and Option 2 → Option 2 is suitable for operators aiming to start 5G with leveraging 4G and then expand the coverage of 5G directly (if 5G traffic and consumer growth are rapid for operators). Especially when they want to deploy early 5G with minimal investment and wish to get to market quickly. Then after we analyze the current state of 5G in the EU and the factors they face in developing 5G, we give a recommended timeline for EU operators in 5G deployment and migration: 1). From November 2022 to 2023, it is recommended to re-allocate part of the 2/3G spectrum to 4G or 5G through software upgrades or replacements, also gradually expand 5G coverage. In addition, it is recommended that operators migrate to the NSA SA hybrid network to achieve 5GC deployment; 2). From 2024 to 2027, it is recommended to completely close the 2/3G spectrum, re-allocate part of the spectrum to 5G, and 4G only provides basic coverage and services. In addition, it is recommended that EU operators migrate to SA mode and realize 5GC capacity expansion at the same time.

In addition, in the process of deploying and migrating to 5G networks, the services that operators can provide are also an important part. First, for traditional communication services, the following observations are noted from the analysis presented in Chapter 6: 1). At the beginning of 5G, the EPC and LTE offer voice/video communication services, with VoLTE serving as the solution for voice/video communications. After the advent of 5GC, the EPC and LTE continued to provide voice/video communication services, EPS FB was introduced as a solution for voice/video communications. With the further development of 5G networks, operators can choose to migrate to VoNR; 2). The evolution of technology for SMS services is based on the types of subscribers operators currently have and the types of subscribers they target in the future, rather than an overall trend for all users. For legacy users who still use 2G/3G, changes to SMS delivery technology for legacy users do not appear to be necessary. If these users want to migrate to 4G/5G, they should change their devices. For

IMS users, the migration of SMS to IP/IMS (SIP enabled) has become mainstream. For users who want to experience mobile IoT, migrating SMS services on Diameter appears to be a good idea.

Second, for the newly emerging applications in 5G, we divide it into two parts, which are applied to the individual user market and applied to the industrial field. For individual user market, we suggest the EU operators to seek cooperation with OTT service providers such as Netflix and YouTube, where subscribers could waive subscription fees for the above video sites by purchasing the operator's 5G package. This scheme could be effective in improving subscriber stickiness, but would not change the operator's revenue structure. In order to bring higher revenue to themselves, operators can consider investing more in OTT content services with larger market size, such as live streaming of sports events. Such service should be sold in a bundled package, high-level package users are bundled for free (free to watch various sports events), ordinary package users can enjoy discounts, while other network users need to pay in full. In addition , in the field of VR/AR, since it is difficult for the EU operators to produce their own VR/AR devices, so we suggest they to cooperate with other manufacturers to make bundled packages (for example, if you purchase the operator's 5G package, you can get a discount when purchasing VR/AR devices) to obtain terminal agent revenue. For industrial field, our advice to operators is that they need to analyze the industrial user groups they may attract based on their own positioning, and at the same time, when cooperating with these customers, they should continuously improve their capabilities in network construction and service provision. Only in this way can operators make full use of their advantages in spectrum and network connectivity to provide 5G solutions for industrial companies and attract more partners, thereby enhancing their industry experience and operational revenue. It can also facilitate the formation of operators' 5G business models and the digital transformation of the industry.

Based on this, we give a recommended timeline for the EU operators to develop 5G services in the next few years: 1). From November 2022 to 2023, this will be a period of rapid growth of 5G services, 4G services will be gradually diverted, 5G personal services will trigger new applications like AR, VR, etc. Other services such as URLLC should be in the preliminary testing stage. 2). From 2024 to 2027, after several years of exploration, 5G industry applications should be gradually formed (URLLC and other services should been maturely used), the business model should be mature, and it will gradually entered the 5G era, that is, 5G provides main services. In addition, the digital transformation of the industry also needs to be in progress.

7.2. Future Work

As the 5G deployment and migration strategies (including the services provided by operators) given in this thesis are based on theory, we do not have a practical test platform to verify the feasibility of these strategies. That is, the suggested deployment and migration approaches and their implementation strategies still need to be further improved, so as to be successfully implemented on networks provided by EU operators. It would be helpful if operators are willing to help us. Therefore, in the future, we can try to find operators willing to test the strategies we provided to verify their feasibility. Also, we will try to adjust our plans according to the conditions of the operators.

A

Quality of Service (QoS)

As the name suggests, QoS is the quality of service. EPS uses a series of parameters to describe user expectations, such as bit rate (e.g. guaranteed bit rate (GBR), Maximum bit rate (MBR)), delay and allocation and retention priority (ARP). Whether the expectations can be realized depends on the specific implementation of the network. The QoS we expect is end-to-end, that is, the QoS from UE to server, but the QoS of EPS can only be responsible for the interior of EPS, that is, the QoS from UE to P-GW.

3GPP TS 23.203 divides QoS into multiple classes according to different expected combinations, represented by quality class identity (QCI). Nine QCIs are defined in Release 8, and different QCIs represent different service categories. QCI 1-4 belong to the GBR type and QCI 5-9 belong to the non-GBR type. The dedicated bearer can be of GBR type or non-GBR type, while the default bearer can only be non-GBR type. The table of OCIs (R8 version) can be found below.

Table A.1: QCIs for LTE [55]

QCI	**Resource type**	**Priority**	**Packet delay budge (ms)**	**Packet error loss rate**	**Example services**
1	GBR	2	100	10^{-2}	Conversational voice
2	GBR	4	150	10^{-3}	Conversational video (live streaming)
3	GBR	5	300	10^{-6}	Non-conversational video (buffered streaming)
4	GBR	3	50	10^{-3}	Real time gaming
5	Non-GBR	1	100	10^{-6}	IMS signalling
6	Non-GBR	7	100	10^{-3}	Voice, video (live streaming), interactive gaming
7	Non-GBR	6	300	10^{-6}	Video (buffered streaming)
8	Non-GBR	8	300	10^{-6}	TCP-based (e.g.WWW, e-mail), chat, FTP, p2p file sharing, progress video, etc.
9	Non-GBR	9	300	10^{-6}	

B

Overview of Commercial 5G Launches in EU

The table below provides an overview of commercial launches per operators offering 5G services across the EU [49].

Table B.1: Overview of commercial 5G launches

Country	**Summary**
Austria	**T-Mobile** - In March 2019, the operator announced commercial launch using the 3.7 GHz band deploying 25 base stations in rural areas. The operator declared its implementation of Dynamic Spectrum Sharing technology. In May 2021, the operator announced the roll-out of the 700 MHz band for 5G services in rural areas. By using also the 2100 MHz and 3.7 GHz bands, its 5G service covered more than a third of the Austrian population. **Three** - On May 2022, Three Austria announced that, along with Qualcomm Technologies and ZTE, had successfully executed a 5G network demonstration using a SA coverage layer based on 700MHz and the world's first supplemental downlink (SDL) band 1400MHz. **A1 Telekom** - In January 2020, A1 Telecom launched its 5G network using the 3.5 GHz band. In April 2021, the operator announced that its 5G network covered 3.8 million people in both urban and rural parts of the country.
Belgium	**Proximus** - In April 2020, Proximus launched Belgium's first commercial 5G services using spectrum in its existing spectrum holdings (2.1 GHz) and within current EMF norms specified per region. **Telenet** - Belgian telecom operator Telenet has announced plans to deploy its 5G mobile network in the country starting on December 6 using provisional spectrum in the 3.6 GHz band.
Bulgaria	**Orange** - On February 2022, Orange Belgium announced the activation in Antwerp of the operator's first 5G sites. Using temporary spectrum provided by the regulator, Orange Belgium plans to extend coverage to the cities of Ghent, Bruges, Leuven and coastal areas in the Flanders region over the coming months as part of a phased deployment, before activating the service in other areas of the country once the spectrum allocation and EMF standards have been determined. **Vivacom** - In September 2020, Vivacom launched the first commercial 5G network in Bulgaria in via Dynamic Spectrum Sharing (DSS) technology on the existing 1800 MHz and 2100 MHz bands. **A1** - In November 2020, the operator A1 launched its 5G network using 3.6 GHz in Sofia. **Telenor** - Telenor launched in early June 2021 in the bigger cities in Bulgaria on the 3.6 GHz band.

Croatia	**Hrvatski Telekom** - Hrvatski Telekom‘s 5G network is based on the use of Dynamic Spectrum Sharing (DSS) technology to make use of the 2100 MHz band, and the newly acquired 700 MHz and 3600 MHz bands. Its 5G network currently covers 45 Croatian cities and a population of 1.7 million.
Cyprus	**Cytamobile-Vodafone** - Cyta, the first operator in Cyprus to launch commercial 5G services, claimed to cover 70% of Cyprus's population in February 2021 using its assignments in the 700 MHz and 3.6 GHz bands. The operator is aiming to reach 98% of the population in 2022.
Czechia	**Vodafone** - Vodafone is in the process of rolling out 5G netwrok using the 3.7 GHz band. **O2 (Telefonica)** - O2 is in the process of rolling out 5G netwrok using the 3.7 GHz band. O2 is expected to use its newly acquired 700 MHz frequencies for national roaming as well as public protection and disaster relief services for public emergency and security bodies. **T-Mobile** - T-mobile is in the process of rolling out 5G netwrok using the 3.7 GHz band. The above three operators secured spectrum in the 3400-3600 MHz bands, would have to lease the frequencies to support "Industry 4.0" services.
Denmark	**TDC** - In September 2020, TDC launched commercial 5G services in the 3.5 GHz band in Copenhagen, Odense, Tand Helsingør. In September 2020, they have achieve nationwide (80%) population coverage. **Telenor** - In November 2020, Telenor Denmark activated its 5G network using the 3.5 GHz band. **Telia Denmark** - In November 2020, Telia launched commercial 5G services using the 3.5 GHz band. Telia planned to provide 5G coverage to 75% of the population by the end of 2022. **Hi3G Access** - In December 2020, Hi3g Access announced the official switch-on of its new 5G network using frequencies in the 700 MHz and 1800 MHz bands. In addition, the operator acquired spectrum in the 2100 MHz band, 3.5 GHz band and 26 GHz band.
Estonia	**Telia** - In November 2020, Telia launched a commercial 5G network using Ericsson's Dynamic Spectrum Sharing technology, enabling Telia to use its existing frequencies since the government has not yet auctioned off the 3.6 GHz licences for 5G. **Elisa Estonia** - Elisa Estonia introduced its first 5G services by its newly awarded 3.5GHz band. By the end of 2022, the operator aims to cover half of Estonia's population with its 5G network.
Finland	**Elisa Oyj** - The telecom operator Elisa Oyj claims to be the first in the world to launch a commercial 5G network and to have the most comprehensive network in Finland today. The first 5G licences were made available in the 3.6 GHz band frequencies in autumn 2018. Elisa's 5G network is continuing to expand in southern Finland. In total, its 5G network is now available in 158 locations in Finland, covering more than 70% of Finns. **Telia** - At the end of 2019, Telia Finland launched 5G services using its 3.5 GHz spectrum. In March 2021, its 5G network reached circa 40% of the population. **DNA** - In January 2020, the operator started selling mobile 5G subscriptions using its 3.5 GHz band. In June 2021, the operator said its 5G network covered 42% of the population.
France	**Bouygues Telecom** - The operator confirmed the goal of achieving nationwide coverage by the end of 2021, while the current roll-out phase relies on the 3.5 GHz and 2.1 GHz bands. In 2023, Bouygues plans to switch on its 5G core network, paving the way for standalone 5G. **Orange** - By March 2021, about 200 municipalities were covered with the operator's 3.5 GHz 5G network. Orange France has planned to launch Standalone 5G network for enterprise customers in 2022 and for the retail customers in 2023. **SFR** - In November 2020, SFR announced the launch of its 5G service using the 2.6 GHz and 3.5 GHz in the city of Nice. On February 2022, SFR revealed that coverage of its 5G network currently reaches 52% of the population, with SFR's 5G services present in the 32 largest cities of France. **Free** - In December 2020, Free launched its commercial 5G services thanks to its cell sites equipped with 700 MHz and 3.5 GHz frequencies. Accessible in more than 9,648 municipalities, Free's 5G network covers 79% of the population in France.

Germany	**Deutsche Telekom** - On February 2022, Telekom Deutschland, the domestic fixed and mobile unit of Deutsche Telekom, announced the addition of 159 new 5G locations last month, bringing the 5G antenna total to more than 63,000 to provide coverage to 90% of the population. The total includes 4,000 antennas in over 180 cities and municipalities in the 3.7 GHz band. Dynamic Spectrum Sharing is also being deployed. Telekom revealed that it plans to use its 700 MHz spectrum for 5G SA this year. **Vodafone** - Vodafone is using the 1800 MHz band to provide 5G in densely populated cities, while the 700 MHz range is being deployed in rural areas. The 3.5 GHz band is being rolled out in high traffic areas. With a total of 18,000 5G antennas at 6,000 locations, on January 2022, Vodafone declared its 5G network is available for around 45 million people in Germany. Moreover, the company stated that 5G SA will be activated at each 5G station with the goal of achieving almost nationwide coverage by 2025. **Telefonica** - Telefonica's 5G network covers more than 30% of the population by the end of 2021 in the 3.6 GHz band. The operator also plans to use the 700 MHz and 1800 MHz bands to expand its coverage. In rural areas, the company will use Dynamic Spectrum Sharing. The operator expects to reach around 50% of the population by the end of 2022 and the whole country by 2025.
Greece	**Wind Hellas** - In December 2020, the operator announced it switched on its 5G mobile network a few days after winning frequencies in the country's multi-band 5G spectrum auction. 5G-capable frequencies have been assigned in the 700 MHz, 3.7 GHz and 26 GHz bands were sold, alongside permits for the 2100 MHz range. The operator said its 5G population coverage is expected to exceed 60% by 2023. **Cosmote** - Cosmote launched its commercial 5G services in December 2020 in Athens Thessaloniki and other Greek cities. Before 2022, it has coverd over 50% of the population in Greece. **Vodafone** - In January 2021, Vodafone Greece became the third mobile operator to switch on its 5G network. The operator plans to cover 40% of the population by March 2022.
Hungary	**Magyar Telekom** - In April 2020, the operator launched commercial 5G mobile network services in partnership with Ericsson. It uses the 3.6 GHz , 2100 and 700 MHz bands. **Telenor** - The most recent operator to launch commercial 5G, Telenor used its 700 MHz and 3600 MHz bands acquired in 2020. **Vodafone** - In October 2019, Vodafone Hungary launched a commercial 5G service limited to Budapest, using its existing 3.5 GHz spectrum and ahead of Hungary's March 2020 license auction where it won additional 3.5 GHz frequencies plus a 700 MHz license.
Ireland	**Vodafone** - In August 2019, Vodafone Ireland launched 5G services in selected areas of five Irish cities using the 3.5 GHz band. **Three** - In September 2020, Three Ireland launched commercial 5G services with Ericsson's equipment using the 3.7 GHz band. **Eir** - In December 2019, Eir launched its 5G service using the 3.5 GHz band. The operator declares its 5G network covers over 70% of the population.
Italy	**Vodafone** - In 2021, Vodafone and TIM announced an agreement for network/ infrastructure sharing. **Telecom Italia (TIM)** - TIM published the latest update on its 5G coverage list, with services now available in 20 cities across the country. In addition, TIM stated that speeds of up to 2 Gbps are attainable on its 5G network. **Windtre** - In Sep 2022, WindTre announced that has implemented 5G technology nationwide with a current overall coverage of more than 95.7% of the population. More specifically, 95.7% of the population coverage is carried out in 5G Frequency Division Duplex (FDD) Dynamic Spectrum Sharing (DSS) mode in the 1800 MHz and 2600 MHz bands , and 58.9% in 5G Time Division Duplex (TDD) mode in the 3600 MHz band. **Fastweb** - In 2021, Fastweb and Windtree announced an agreement for network/ infrastructure sharing.
Latvia	**LMT** - For its initial 5G deployment, LMT relied on 3.5GHz spectrum. **Tele2** - For its initial 5G deployment, Tele2 relied on 3.5GHz spectrum. Tele2 announced it will accelerate rollout to achieve 99% of the country's population within 3 years.

Lithuania	**Telia** - The first commercial 5G service has been launched by Telia. Using commercial 2100 MHz (DSS) and 3.5 GHz test frequencies, the operator's 5G connection has been activated at 110 base stations. Following the ruling of the Lithuanian regulator allowing operators to use existing spectrum holdings for 5G, Telia will be able to roll out 5G services in other bands, including the 2.1 GHz and 2.5 GHz bands.
Luxembourg	**Orange** - Orange uses the 700 MHz and 3.6 Ghz frequencies to operate their 5G networks. **Tango** - Tango uses the 700 MHz and 3.6 Ghz frequencies to operate their 5G networks. **Post** - Post Luxembourg uses the 700 MHz and 3.6 Ghz bands to operate their 5G networks.
Malta	**Melita** - In May 2021, Melita launched Malta's first 5G network nationwide. Melita 5G uses Band 1 and Band 78. **Epic** - Epic has become the second telecoms company in the country to launch 5G services with Ericsson selected as its exclusive 5G radio access network (RAN) provider.
Netherlands	**VodafoneZiggo** - In April 2020 launched its 5G network. In partnership with Ericsson, the operator implemented 5G services via its antennas and Dynamic Spectrum Sharing technology, using 800/1800/2100/2600 MHz bands. **T-Mobile** - In July 2020, the operator launched its initial 5G network based on its new 700 MHz spectrum band. The operator declares that 90% of the inhabitants of the Netherlands live in T-Mobile's 5G coverage area. **KPN** - In July 2020, the KPN launched its initial 5G network based on its new 700 MHz spectrum.
Poland	**Polkomtel** - In May 2020, the operator launched the country's first commercial 5G mobile network in the 2.6 GHz band. It covers over 13 million people and is available in each of the provinces in almost 400 cities. **T-Mobile** - The last operator to launch commercial service was T-Mobile using the 2100 MHz band. **Orange** - In July 2020, the operator launched its 5G services using the 2.1 GHz band. **Play** - In June 2020, the operator launched its 5G services using the 2.1 GHz band.
Portugal	**NOS** - NOS is first operator in Portugal to launch 5G, following the country's spectrum auction in October 2021. to operate its 5G service, the operator secured 100MHz in the 3.6GHz band and 2x10MHz in the 700MHz band.
Romania	**Vodafone** - Vodafone launched its commercial 5G services between June and November 2019. ANCOM reports that commercial 5G services available today in Romania use the bands 3400 – 3800 MHz and, starting with 2021, the band 2100 MHz also. **Digi** - Digi launched its commercial 5G services between June and November 2019. ANCOM reports that commercial 5G services available today in Romania use the bands 3400 – 3800 MHz and, starting with 2021, the band 2100 MHz also. **Orange** - Orange launched its commercial 5G services between June and November 2019. ANCOM reports that commercial 5G services available today in Romania use the bands 3400 – 3800 MHz and, starting with 2021, the band 2100 MHz also.
Slovakia	**Slovak Telecom** - In December 2020, Slovak Telecom launched commercial 5G services utilising 15 MHz of frequencies in the 2.1 GHz band, in combination with LTE spectrum. **Orange** - In May 2021, Orange launched its 5G network using 3.5 GHz spectrum and Massive MIMO equipment. **O2** - In September 2021, the operator announced 15 new sites with 5G signal availability in the west of the country. Before 2022, it has coverd 20% of Slovakia's population with 5G services, with the network relied on Ericsson's 5G technology.
Slovenia	**Telekom Slovenije** - In July 2020, Telekom Slovenije launched the first commercial 5G network in Slovenia. Ericsson announced that Telekom Slovenije is using its Radio Access Network (RAN) and Cloud Core solutions for its 5G commercial rollout. Ericsson also assisted with a software installation to existing Ericsson Radio System and packet core equipment, enabling spectrum sharing between 4G and 5G on 2.6 GHz FDD spectrum. At the moment, Telekom Slovenije's 5G network covers 33% of mobile users nationwide.

Spain	**Vodafone** - Vodafone Spain declared it is targeting 46% population coverage (983 municipalities) by end-2022. **Telefonica** - In September 2020, the operator announced the switch-on of its 5G network, which uses 3.5 GHz spectrum, alongside with reframed 1800 MHz and 2.1 GHz frequencies. On February 2022, Telefonica switched on 5G in the 700 MHz band complementing its population coverage, which now reaches more than 80% of population. **Orange** - Orange Spain announced it is currently offering 5G services through frequencies in the 3.5 GHz and 700 MHz bands in 1,222 towns and cities in 51 provinces across the country. According to the European operator, its 5G network infrastructure currently reaches 65% of the Spanish population. The operator announced it plans to reach 1,500 localities by the end of 2022. The Ericsson Radio System, delivering Massive MIMO, powers the 3.6 GHz 5G network in Madrid and Barcelona. Ericsson also supplies Orange Spain with a 5G evolved Packet Core to support the 5G New Radio non-standalone 5G network. **MasMovil** - In September 2020, Grupo MasMovil became the fourth Spanish operator to launch 5G services. Besides its 80 MHz of spectrum in the 3.5 GHz band, the operator entered into an agreement with Orange Spain which gives Masmovil access to Orange Spain's entire 5G network thanks to a "virtual active sharing mode" until 2028. The operator says it has expanded its 5G coverage to almost 900 towns and cities covering 57% of the country's population. Its 5G service is being offered via a combination of its own infrastructure and an agreement with Orange operator. The 5G deal between Masmovil and Orange will be valid until 2028 and is extendable for 5 additional years. Masmovil currently has 80 megahertz of spectrum in the 3.5 GHz band for the provision of 5G.
Sweden	**Tele2** - In May 2020, Tele2 launched its 5G network using 80 MHz of the 3.6 GHz spectrum band. **Telia Sweden** - In May 2020, Telia Sweden announced the activation of its 5G network in Stockholm, using its existing 700 MHz spectrum. **Tre** - In June 2020, Tre Sweden announced the commercial launch of 5G services using frequencies in the 2.6 GHz band. On April 2022, Tre Sweden announced full 5G coverage in the centres of seven cities: Stockholm, Gothenburg, Malmo, Norrkoping, Linkoping, Jonkoping and Helsingborg. The operator is also continuing to deploy 5G infrastructure in cities with more than 20,000 inhabitants, using 2100MHz spectrum and faster 3.5GHz frequencies. **Telenor** - In October 2020, Telenor Sweden launched commercial 5G service with 80 MHz of spectrum in the 3.7 GHz band. The operator expects to cover with its 5G network 99% of Sweden's population by 2023 as part of its network sharing agreement with Telenor ("Net4Mobility" joint venture).

C

Edge Computing Architecture

Edge computing is a distributed computing paradigm that brings computation and data storage closer to the data source. In order to move the burden closer to the location where data is created and to enable actions to be performed in response to an analysis of that data, edge computing technologies make use of computing resources that are available outside of traditional and cloud data centers. Developers can create applications that significantly reduce latency, lower demands on network bandwidth, increase privacy of sensitive information, and enable operations even when networks are disrupted by utilizing and managing the compute power that is available on remote premises, such as factories, retail stores, warehouses, hotels, distribution centers, or vehicles. To move the application workload out to the edge, multiple edge are needed.

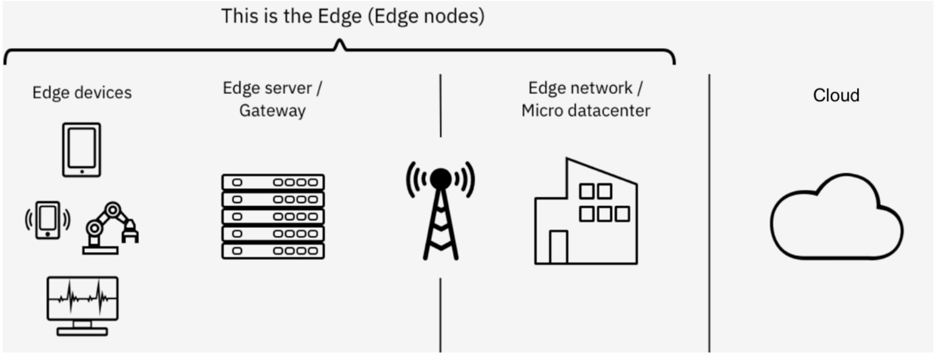

Figure C.1: Architecture of Edge Computing [39]

These are some of the key components that form the edge architecture, as shown in Figure C.1.

- **Edge devices** - In order to support operations at the edge, the edge and IoT devices are designed to do analytics, apply AI rules, and even some certain data locally. Without the assistance of the edge server or the cloud region, the devices could undertake analysis and real-time inferencing.
- **Edge server/gateway** - Apps are distributed to the devices using edge servers. Using agents that are placed on each of the devices, they are in continual communication with one another. Millions of devices are monitored by thousands of edge servers. Data from the devices is forwarded to the edge server for further analysis if something other than inferencing is required.
- **Edge network/micro data center** - The edge network or micro data center, which may be thought of as a local cloud for devices to communicate with, is the outcome of new networking technology. With the arrival of 5G, the edge network reduces latency and bandwidth difficulties by shortening the distance that data from the devices must travel. Additionally, this region provides extra model storage space and an increased capacity for analysis.

- **Cloud** - A repository for container-based workloads like applications and machine learning models may be found in this public or private cloud. Additionally, these clouds house and operate the software necessary to coordinate and control the various edge nodes. Workloads on these clouds will communicate with workloads at the edge, including local and device workloads. Any data that the other nodes need can also be a source or destination in the cloud.

D

List of Abbreviations

5GS	5G System
5GC	5G Core
5G-EIR	5G Equipment Identity Register
API	Application Programming Interface
APN	Access Point Name
AR	Augmented Reality
AMF	Access and Mobility Management Function
AuC	Authentication Centre
AUSF	Authentication Server Function
CDMA	Code Division Multiple Access
CSFB	Circuit-Switched Fall Back
CU	Control Plane
D2D	Device to Device
E2E	End-to-End
EDGE	Enhanced Data rates for GSM Evolution
EPC	Enhanced Packet Core
EPS FB	EPS Fallback
eMBB	Enhanced Mobile Broadband
EMM	EPS Mobility Management
EN-DC	E-UTRA-NR Dual Connectivity
ESM	EPS Session Management
E-UTRAN	Evolved-UMTS Terrestrial Radio Access Network
FDMA	Frequency Division Multiple Access
FTP	File Transfer Protocol
GGSN	Gateway GPRS Support Node
GPRS	General Packet Radio Service
GMSC	Gateway MSC
gNodeB/gNB	Next Generation Node B
GRX	GPRS Roaming Exchange
GSM	Global System for Mobiles
HLR	Home Location Register
HR	Home Routing
HSS	Home Subscriber Server
ICS	IMS Centralized Services
I-CSCF	Interrogating-Call State Control Function
IoT	Internet of Things
IP	Internet Protocol
IPX	IP Exchange
IMEI	International Mobile Equipment Identifier
IMS	IP Multimedia Subsystem
IMSI	International Mobile Subscriber Identity
LB	Local Breakout
LRF	Location Retrieval Function
LTE	Long-Term Evolution
M2M	Machine to Machine
MEC	Mobile Edge Computing
MIMO	Multiple Input Multiple Output

MMS	Multimedia Messaging Service
mmWave	millimeter Wave
mMTC	massive Machine Type Communications
MME	Mobility Management Entity
MSC	Mobile Switching Centre
MSISDN	Mobile Subscriber Integrated services Digital Network (ISDN) Number
NAS	Non-Access Stratum
NFV	Network Function Virtualization
NR-DC	New Radio Dual Connectivity
NSA	Non-Standalone
NSSF	Network Slice Selection Function
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operating Expense
PCEF	Policy Control Execution Function
PCF	Policy Charging Function
PCRF	Policy and Charging Rules Function
P-CSCF	Proxy-Call State Control Function
PDU	Protocol Data Unit
P-GW	Packet Data Network (PDN) Gateway
PS-HO	Packet Switched Han-dover
QCI	Quality Class Identity
QoS	Quality of Service
RAN	Radio Access Network
RATs	Radio Access Technologies
RDF	Route Determination Function
RRC	Radio Resource Control
SA	Standalone
SBA	Services-Based Architecture
SCC-SA	Service Centralization and Continuity Application Server
S-CSCF	Serving-Call State Control Function
SDN	Software Defined Network
SGSN	Serving GPRS Support Node
S-GW	Serving GateWay
SIP	Session Initiation Protocol
SIM	Subscriber Identity Module
SPR	Subscription Profile Repository
SMF	Session Management Function
SMS	Short Message Service
SRVCC	Single Radio Voice Call Continuity
TCP	Transmission Control Protocol
TDF	Traffic Detection Function
TDMA	Time Division Multiple Access
UDP	User Datagram Protocol
UDM	Unified Data Management
UICC	Universal Integrated Circuit Card
UMTS	Universal Mobile Telecommunications System
URLCC	Ultra Reliable Low Latency Communication
UP	User Plane
USIM	Universal Subscriber Identity Module
USSD	Unstructured Supplementary Service Data
V2X	Vehicle to Anything
VoIP	Voice over IP
VoLTE	Voice over LTE
VoNR	Voice over New Radio

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