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Foreword

This Group Report (GR) has been produced by ETSI Industry Specification Group (ISG) Fifth Generation Fixed Network (F5G).

Modal verbs terminology

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Introduction

The present document investigates the historical evolution path of fixed networks, including aggregation, access and customer on-premises networks. Their main characteristics are identified, including technology basis and performance levels. These can be used to demarcate different generations of fixed networks. Typical examples for each generation (relevant standards and deployments, relevant use cases) are provided.

1 Scope

In the past, the lack of a clear fixed network generation definition has prevented a wider technology standards adoption and prevented the creation and use of global mass markets. The success of the mobile and cable networks deployments, supported by clear specifications related to particular technological generations, has shown how important this generation definition is.

The focus of the 5th generation fixed networks (F5G) specifications is on telecommunication networks which consist fully of optical fibre elements up to the connection serving locations (user, home, office, base station, etc.). That being said, the connection to some terminals can still be assisted with wireless technologies (for instance, Wi-Fi®).

The main assumption behind the present document foresees that, in the near future, all the fixed networks will adopt end-to-end fibre architectures: Fibre to Everywhere.

The present document addresses the history of fixed networks and summarizes their development paths and driving forces. The factors that influence the definition of fixed, cable and mobile network generations will be analysed. Based upon this, the business and technology characteristics of F5G will be considered.

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

NOTE: While any hyperlinks included in this clause were valid at the time of publication, ETSI cannot guarantee their long term validity.

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] IEEE 802.11™ series: "Wireless Local Area Networks (WLAN)".

[i.2] Recommendation ITU-T I.100-I.699 series: "ISDN".

[i.3] Recommendation ITU-T G.992.x series: "Asymmetric digital subscriber (ADSL) transceivers".

[i.4] Recommendation ITU-T G.993.x series: "Very high speed digital subscriber line transceivers 2 (VDSL2)".

[i.5] Recommendation ITU-T G.984.x series: "Gigabit-capable passive optical networks (GPON)".

[i.6] Recommendation ITU-T G.9701: "Fast access to subscriber terminals (G.fast) - Physical layer specification".

[i.7] Recommendation ITU-T G.987.x series: "10-Gigabit-capable passive optical networks (XG-PON)".

[i.8] Recommendation ITU-T G.9807.x series: "10-Gigabit-capable symmetric passive optical network (XGS-PON)".

[i.9] Recommendation ITU-T J.112 series: "Transmission systems for interactive cable television services".

[i.10] Recommendation ITU-T J.122 series: "Second-generation transmission systems for interactive cable television services - IP cable modems".

[i.11] Recommendation ITU-T J.222 series: "Third-generation transmission systems for interactive cable television services - IP cable modems".

[i.12] Recommendation ITU-T J.225 series: "Fourth-generation transmission systems for interactive cable television services - IP cable modems".

[i.13] Recommendation ITU-T J.224 series: "Fifth-generation transmission systems for interactive cable television services - IP cable modems".

[i.14] 3GPP TS 45 series: "GSM radio specifications series".

[i.15] 3GPP TS 25 series: "UMTS radio specifications series".

[i.16] 3GPP TS 36 series: "LTE radio specifications series" (if only LTE radio access technology is covered).

[i.17] 3GPP TS 37 series: "LTE radio specifications series" (if UMTS or GERAN radio access technologies are also covered).

[i.18] 3GPP TS 38 series: "5G new radio specifications series".

[i.19] Recommendation ITU-T G.702: "Digital hierarchy bit rates".

[i.20] Recommendation ITU-T G.707: "Network node interface for the synchronous digital hierarchy (SDH)".

[i.21] Recommendation ITU-T Y.1731: "OAM functions and mechanisms for Ethernet based networks".

[i.22] Recommendation ITU-T G.996.x series: "Unified high-speed wireline-based home networking transceivers)".

[i.23] IEEE 802.1ag™: "Connectivity Fault Management".

[i.24] IEEE 1901™ series: "Power Line Communications for Smart Grid Applications".

3 Definition of terms, symbols and abbreviations

3.1 Terms

For the purposes of the present document, the following terms apply:

Aggregation Network (AggN): telecommunication network segment that connects the Optical Access Network (OAN) and the Core Network or Data Centres, which comprises the IP Network (IPN) and/or the Optical Transport Network (OTN)

auto-healing: ability of systems or environments to detect and resolve problems automatically

NOTE: Sometimes also known as self-healing.

C-band: optical "Conventional wavelength-band" (1 530-1 565 nm)

closed-loop: refers to network automation and management capabilities that use (big) data and analytics to monitor and access network events (such as faults and congestion) and act appropriately to correct any issues

NOTE: Usually known as closed-loop automation.

Continuous Integration/Continuous Delivery (CI/CD): set of operating principles and a collection of practices that enable application development teams to deliver code changes more frequently and reliably

NOTE: Also known as CI/CD pipeline, it is an agile methodology best practice for DevOps teams to implement.

Customer Premises Network (CPN): telecommunication network segment that comprises the customer on-premises locations and its equipment and infrastructureswhere the network terminal equipment and the end-user customer premises equipment are connected via the CPN

digital twin: digital replica of a living or a non-living physical entity, i.e. a virtual model

NOTE: Digital twins integrate artificial intelligence, machine learning and software analytics with spatial network graphs. This integration creates a living digital simulation model that updates as their physical counterparts change. Digital twins are being used to optimize the operation and maintenance of physical assets and systems.

End-to-End (E2E) slicing: refers to running multiple virtualized and independent logical networks on the same physical network infrastructure where each network slice is an isolated end-to-end network tailored to fulfil the diverse requirements of a particular application

IP Network (IPN): telecommunication network segment that uses the Internet Protocol (IP) for network layer communication between network nodes/equipment

L-band: optical "Long wavelength-band" (1 565-1 625 nm)

Optical Access Network (OAN): optical telecommunication network segment that gives the end-user access to the telecommunications service and connects the Customer Premises Network (CPN) to the Aggregation and Transport Network (ATN)

Optical Transport Network (OTN): optical telecommunication network segment comprised by a set of optical network nodes/equipment connected through optical fibres that provide the functionality of transport, multiplexing, switching, management, supervision and survivability of the optical channels carrying the end-user's client signals

NOTE: Also known as Optical Transportation Network.

3.2 Symbols

Void.

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

ADM	Add-Drop Multiplexer
ADSL	Asymmetric Digital Subscriber Line
AggN	Aggregation Network
AI	Artificial Intelligence
AMPS	Advanced Mobile Phone System
API	Application Programming Interface
ATM	Asynchronous Transfer Mode
C450	C-Netz 450 MHz analog cellular network
CAT	Category
CATV	Community Antenna Television
CCAP	Converged Cable Access Platform
CCTV	Closed-Circuit Television
CDMA	Code Division Multiple Access
CMTS	Cable Modem Termination System
CO	Central Office
CPN	Customer Premises Network
CRAN	Cloud-RAN (sometimes referred also as Centralized-RAN)
CS	Circuit Switching
CSFB	CS Fall Back
DC	Data Centre
D-CCAP	Distributed-CCAP
DOCSIS	Data Over Cable Service Interface Specification
DRAN	Distributed-RAN
DSL	Digital Subscriber Line

DSLAM	Digital Subscriber Line Access Multiplexer
DWDM	Dense WDM
E2E	End-to-End
EDGE	Enhanced Data rates for GSM Evolution
eFBB	enhanced Fixed Broadband
F4G	Fixed Fourth Generation
F5G	Fixed Fifth Generation
FDD	Frequency-Division Duplexing
FDM	Frequency Division Multiplexing
FFC	Full-Fibre Connection
FOADM	Fixed Optical ADM
FTTB	Fibre To The Building
FTTC	Fibre To The Curb
FTTD	Fibre To The Desk
FTTdp	Fibre To The distribution point
FTTH	Fibre To The Home
FTTLA	Fibre To The Last Amplifier/Active
FTTM	Fibre To The Machine
FTTO	Fibre To The Office
FTTR	Fibre To The Room
FTTx	Fibre To The x
G.fast	Gigabit fast access to subscriber terminals
GERAN	GSM Edge RAN
GPON	Gigabit Passive Optical Network
GPRS	General Packet Radio Service
GRE	Guaranteed Reliable Experience
GSM	Global System for Mobile communications
HD	High-Definition (video) - resolution of 1 366 x 768 pixels
HFC	Hybrid Fibre-Coaxial
HPNA	Home Phoneline Network Alliance
HSI	High-Speed Internet
HSPA	High-Speed Packet Access
HW	Hardware
IMT	International Mobile Telecommunications
IP	Internet Protocol
IPTV	Internet Protocol Television
IS	Interim Standard
ISDN	Integrated Services Digital Network
IT	Information Technology
LAN	Local Area Network
LTE	Long Term Evolution
MIMO	Multiple-Input Multiple-Output
MMS	Multimedia Messaging Service
MoCA	Multimedia over Coax Alliance
MPLS	Multiprotocol Label Switching
MS-OTN	Multi-Service OTN
MSTP	MultiService Transport Platform
MU-MIMO	Multi-User MIMO
NFV	Network Functions Virtualisation
NGA	Next-Generation Access network
NG-PON	Next-Generation PON
NMT	Nordic Mobile Telephone
NR	New Radio
O&M	Operation & Management
OAN	Optical Access Network
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OLT	Optical Line Termination
OTN	Optical Transport Network
OXC	Optical Cross-Connect
PaaS	Platform as a Service

PDH	Plesiochronous Digital Hierarchy
PON	Passive Optical Network
PS	Packet Switching
PSTN	Public Switched Telephone Network
QoE	Quality of Experience
QoS	Quality of Service
R	Release
RAN	Radio Access Network
RF	Radio Frequency
ROADM	Reconfigurable Optical ADM
ROI	Return On Investment
SDH	Synchronous Digital Hierarchy
SDN	Software-Defined Networking
SD-WAN	Software-Defined networking WAN
SLA	Service Level Agreement
SME	Small and Medium-sized Enterprise
SMS	Short Messaging Service
SOHO	Small Office Home Office
SONET	Synchronous Optical Networking
SW	Software
TACS	Total Access Communication System
TDD	Time-Division Duplexing
TSN	Time-Sensitive Networking
TV	Television
UHD	Ultra-High Definition (video) - resolution of 3 840 x 160 pixels
UMTS	Universal Mobile Telecommunications System
VDSL	Very high-speed Digital Subscriber Line
VPN	Virtual Private Network
VR	Virtual Reality
WAN	Wide Area Network
WCDMA	Wideband CDMA
WDM	Wavelength Division Multiplexing
Wi-Fi®	Wireless Fidelity
XG-PON	10-Gigabit-capable PON (also known as asymmetric 10G-PON)
XGS-PON	10-Gigabit-capable Symmetric PON (also known as symmetric 10G-PON)

4 Overview

At the time of publication, half of the world's 2 billion households have been connected to at least one fixed broadband network, and a lot of companies, enterprises, vertical industries and institutions rely on broadband networks to conduct operations and services. Broadband development has become a strong indicator of national economic progress. Being the cornerstone of global economic and technological development, fixed networks have become an indispensable part of political and economic life worldwide. The introduction of optical fibre communication technology has transformed the communications network. Since then, the global network has been exponentially expanding. It can be observed that the network has experienced five generations of technologies and capabilities: voice, broadband, ultra-broadband, 100 Mbit/s optical fibre broadband, and 1 000 Mbit/s optical fibre broadband, and is increasingly vigorous and changing. The present document will explore the historical evolution path of fixed network and define details of the 5th generation.

5 Generations definition

5.1 Historical fixed networks evolution

5.1.1 Introduction

Since the 19th century, the fixed network has developed for more than 100 years, from dedicated networks to each kind of service (voice, data, text) to the era of digital that enabled convergence of many services in the same network. Fibre technologies played an essential role in this evolution expanding network capacity and capabilities. This evolution can be mapped in five generations and more are yet to come in a flourishing ecosystem.

5.1.2 The first generation

The first generation of fixed networks were telephone networks. This period was from the birth of the telephone network until the end of the 20th century, and lasted for more than a century. The services were mainly audio services, while the application experience was no more than a dial-up call. Global communications experts worked together to establish a complete telephone network infrastructure, with a network architecture and control signaling suitable for a global network. The era of globalized telecommunication started. During this period, data services had their initial first steps using dial-up access and ISDN [i.2]; however, the technology was still voice band carrier, and progress was very slow in general.

5.1.3 The second generation

The fixed network entered the broadband era from the second generation. From the 1990's to the 2000's, the fixed network entered the second generation, which was the prelude of the broadband era and the high-speed development period of the fixed network. The Internet rapidly and globally developed in this era, with the wide adoption of personal computers and web browsers. Web browsing, email, and search engine became important applications of the fixed network. ADSL [i.3] technology also revitalized the 100-year-old copper line network and provided access rates of 2-20 Mbit/s via a system that was data-oriented. The global mainstream ADSL broadband network construction lasted for ten years from 1998 to 2008.

5.1.4 The third generation

Internet applications and broadband networks led to the third generation of fixed networks. Since 2005, leading operators had started to provide triple-play services that integrated telephone, Internet access, and video applications based on broadband networks. Carrier-class video services had become an important driving force for the development of broadband networks. Due to bandwidth restrictions, the ADSL network in the early stage supported only video services with standard resolution.

In 2008, the Federal Communications Commission (FCC) officially redefined the "broadband" as 25 Mbit/s or higher. In 2010, Europe announced the EU2020 and Digital Europe Plan, which defined the goal of 30 Mbit/s full coverage for the broadband network in Europe. The world had officially entered the third generation of fixed networks, that was called NGA (Next Generation Access network) era.

In this era, both fixed network services and network architecture were undergoing significant changes. IPTV became a powerful tool for carriers to improve market share and service differentiation. In terms of network architecture, the traditional ADSL technology carried over the original telephone network could not support the "new broadband" service of over 25 Mbit/s. Therefore, operators had to adopt the "fibre-deep" network architecture and introduce the new VDSL [i.4] technology on the twisted pair cable to achieve higher speed. The optical fibre communication technology, born in the 1970s, was applied to the access network for the first time to implement the FTTx network architecture, e.g. FTTC (Fibre To The Curb) and FTTB (Fibre To The Building). The original Central Office for copper line access was gradually reconstructed as the Central Office for optical fibre access. Based on the FTTC and FTTB architecture, operators also introduced enhanced copper-based technologies like VDSL2 and VDSL vectoring to reuse the twisted pair wire on the last mile and provide access bandwidths up to 100 Mbit/s. This provided the balance between higher bandwidth demand and the cost of implementing full fibre-based network architecture.

5.1.5 The fourth generation

4K HD and fibre broadband signaled the arrival of the fourth generation of fixed networks. Around 2010, copper cables were being replaced by optical fibres through the continuous efforts of global broadband operators. The optical broadband access technology represented by GPON [i.5] had made great progress (over 100 million lines deployed). The FTTH (Fibre To The Home) network construction and business operation of leading operators in Europe, US and Eastern Asia, are good examples for this development.

The continuous development of broadband services had once again become an important driving force for the development of broadband networks. For example, in 2012, the BBC officially broadcasted the London Olympic Games in 4K HD signal format. In 2014, the world's first 4K HD channel was officially launched in South Korea, representing the beginning of the 4K HD era. 4K HD brought unprecedented viewing experience to global broadband users and also posed new challenges to broadband networks. Carrier-grade broadband networks were required to provide stable access capabilities of 100 Mbit/s or higher.

The optical access network, with its advantages of high bandwidth, stability, simplified architecture, and long-term development, had become the most competitive target network in the eyes of global operators. The fourth generation fixed networks construction had also been fully carried out. A series of national broadband plans in Asia Pacific, Middle East, Europe and North America have been released with the goal of building national fibre broadband networks, and promoting the development of global fibre networks. By 2014, the number of global FTTH users has reached 200 million.

Meanwhile, as a supplement to FTTH, twisted pair wire technology made another step forward. Super-vectoring and G.fast [i.6] can provide access bandwidth up to 500 Mbit/s over the twisted pair wire, with the usual trade-off of speed and distance.

5.1.6 The fifth generation

With the continuous expansion of optical broadband deployment, the entire industry has ushered in the fifth-generation fixed network, which is marked by ultra-high bandwidth (~1 Gb/s), extensive optical connections (all-fibre), and in-depth service experience.

FTTH networks are booming worldwide. According to OVUM, by the first half of 2020, 650 million FTTH users, accounting for over half of all fixed broadband users, have been registered worldwide. In the next few years, with the continuous development of global information technology, optical broadband networks will continue to develop rapidly. It is estimated that 750 million households will have implemented optical access by 2023. The development of optical broadband networks is increasing not only the number of users but also their access speed. In these FTTH networks, more than 200 operators in nearly 60 countries have launched commercial gigabit home broadband services. The world has entered the 5^{th} generation fibre broadband era.

F5G was introduced into the home market first. HD video services have become an irresistible trend. As an indicator of video service quality, live sports have been leading the development of video services. With the changes brought by the video referees of the 2018 World Cup in Russia, the first 8K HD live broadcast has also set a new standard for live sports. The high resolution, high color gamut, high frame rate, and large dynamic range of 8K videos will refresh the video experience and increase service expectations once again. The price of an 8K TV set is close to 15 000 $ currently, but will decline very rapidly. This will bring a new round of consumption upgrade for mass market customers. The gigabit, low-latency, and high reliable broadband network is the basis for fully deploying 8K HD video services.

At the same time, Virtual Reality (VR) services figure very prominently in carriers' business plans. Different from screen-based video services, VR services bring a brand-new video experience with full-view and immersive features, and a breakthrough of content interactivity. Leading carriers expect VR services to be regarded as the next-generation IPTV services. South Korean carriers have released carrier-class VR services based on gigabit networks in 2018. China's three major operators are also actively planning to launch VR services and develop millions of VR users by 2020. The gigabit network-based HD video communication will also interface with voice control and smart home systems.

The gigabit access capability of the fifth-generation fixed broadband network not only serves home users, but will be extended to the entire telecom market, bringing transformation to every facet of society. Fibre broadband will be extended from large enterprises to small and medium enterprises and companies to provide them with fast private line interconnection and cloud access. Fibre broadband will be extended from dedicated education networks to offices, classrooms, laboratories, teachers' offices, student dormitories, and even desks. This will cover all levels of education, from colleges and universities to secondary schools, primary schools, and professional education institutions. Teachers and students will be able to use various teaching methods, such as cloud-based education, online learning, offline learning, cloud-based textbooks, cloud-based notes, and multimedia teaching to implement book-free education. Fibre broadband will be available in many hotels, providing business travelers with anytime, anywhere office experience when traveling. Fibre broadband will be deployed cross industries, like in factories, mines, docks, and oilfields to implement industrial automation. Automation machinery and robots with precise control will replace manual labor, achieving efficient and automated unmanned factories.

In summary, compared with the fourth-generation's 100 Mbit/s fibre broadband, the fifth-generation fibre broadband will provide 10 times more bandwidth and 100 times more connection from people to things. It will create an ultra-broadband application experience featuring high reliability and near zero wait time, fully realizing the digital transformation of the entire industry.

5.2 Networks generations landscape

5.2.1 Introduction

This clause will analyse and characterize the different technology generations in the major network types: fixed telecom (copper and fibre), mobile and cable.

In figure 1, the proposed approach is illustrated. The objective is to represent the technology evolution cycles for at least the last 30/40 years. A special emphasis will be placed on standards.

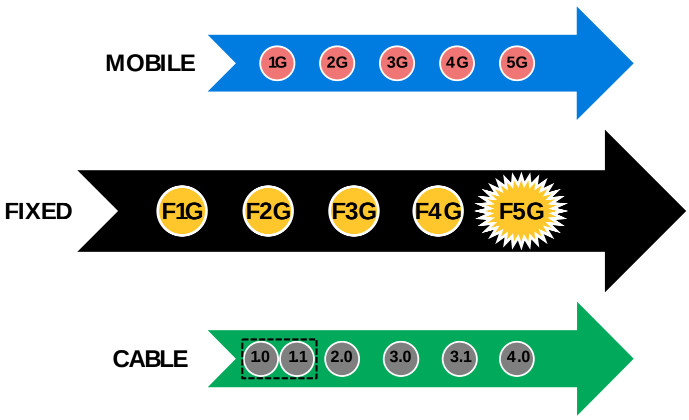

Figure 1: Networks generations

As it can be seen, the current large scale adoption and last stage of technology evolution is the fifth one, in all the major three types of networks (the sixth one is just starting to be prepared). But, this said, the technology implementation landscape over the world in general and, even Europe in particular, is not quite homogeneous.

The access technologies play an important role in the definition of generations since its characteristics are a key enabler to the services that can be delivered to the end customer. Networks tend to use similar infrastructures and technologies in the bearer networks and even progressively share common service platforms, but in the end, it is the access network capabilities that end users can recognize make the difference in the availability and quality of services to users.

In the next clauses, the characterization of the different technology types will be detailed and structured.

5.2.2 Fixed networks

Fixed telecom networks comprise solutions either for copper cables and fibre cables technologies, where the end users remain at the same location to use the delivered services.

In the beginning, fixed networks were designed for delivering voice services to consumers via copper networks.

Copper networks evolved throughout the 20th century to deliver also video and broadband content as well, supported mainly on DSL (Digital Subscriber Line) technologies and later on G.fast.

In the beginning of the 21st century, fibre networks started to be deployed on the access network, especially with PON (Passive Optical Networks) point-to-multipoint technologies, initially with GPON and later with 10G-PON technologies ([i.7], [i.8]).

Meanwhile, Next Generation PON technologies (NG-PON) began to be researched and developed.

All these technologies can be mapped to a certain generation.

The five generations of fixed broadband have not developed at a constant pace. The infrastructure and its deployment have become an important constraint to broadband development. The first generation with voice services lasted for more than a century, for example, while ADSL lasted only a decade.

Based on the international copper line telephone network infrastructure established in the first-generation, the second-generation fixed network could realize the transition from narrowband to broadband by replacing only network equipment at the network and customer premises, which was every economical and quick. In the early 20th century, global major operators have implemented fixed broadband networks in just four or five years.

The original copper line telephone network could not support the 3rd generation of systems. Both the third generation, "fibre-deep", and the fourth generation, "all-optical broadband," required major adjustment of the infrastructure. A large number of access optical fibres needed to be laid out in the existing infrastructure, replacing the copper cables. These two generations of fixed networks had been developing for 8 to 10 years. Over time, 3rd generation networks fiberized the feeder portions of the network, while 4th generation networks fiberized the distribution and drop portions. Global carriers faced many economic challenges and the Return On Investment (ROI) was insufficient and the payback period was too long. Therefore, the development of fixed networks around the world has happened at a deliberate pace. The good news is that once the network is fiberrized, one can look forward to another century of use of this infrastructure.

The 5th generation fixed network is based on the 4th generation's 100 Mbit/s optical fibre broadband. At this time, optical fibres have been largely extended to homes, broadband applications are continuously enriched, and content quality is continuously increasing. The information technology development requirements of various industries have been increasing sharply. The infrastructure is either in place or needs minor extension. Especially for home broadband, only network device upgrade is needed to improve service experience significantly. Operators are facing the "singularity" of fixed network investment and the golden age of fixed network development will come again.

- Aggregation network technology evolution.

The evolution of the fixed access network technologies was running in parallel with the evolution of the aggregation network, that being a fixed network asset, also supported the evolution of mobile and cable networks.

This aggregation network evolved from FDM (Frequency Division Multiplexing) in the very beginning to PDH, introduced by Recommendation ITU-T G.702 [i.19] in the 1970s and designed to support digital voice channels running at 64 kbps. Different country/regions adopted PDH with different hierarchy schemes like T-1 and E-1. The maximum transmission speed supported by PDH was 564 Mbps and was used for many years.

With the common deployment of optical technologies, SDH is standardized as Recommendation ITU-T G.707 [i.20] in the 1990s to meet the interoperability and bandwidth requirements from telecom operators. Still, SDH was not the only optical technology. SONET was adopted by North America. The typical line speeds of SDH/SONET were 155 Mbps/622 Mbps/2,5 Gbps/10 Gbps at that time.

The first WDM system was launched in 1992. There were up to 32λ (lambdas) supported in a single fibre. FOADM was later developed to add/drop optical signals.

OTN was designed as an international standard in early 2000s. But it was not widely deployed at that time. On the contrary, SDH was reborn with MSTP which supports the transportation of Ethernet, ATM and other data traffic types. The optical transmission speed was up to 40 Gbps. WDM could support up to 80λ (lambdas) and ROADM was introduced.

From the 2010s, the 100 Gbps line speed was commercially deployed. MS-OTN started to emerge. Meanwhile, telecom operators started to abandon SDH/SONET networks.

To support high volumes of data traffic, 200 Gbps and 400 Gbps DWDM started to be deployed from operators' backbone network down to the metro network. Optical switching architecture started to evolve from ROADM to OXC.

Earlier on, there were no specific aggregation networking technologies being deployed, but the technologies used were the transport network technologies. See clause 5.2.1 for more details. Later, several operators have moved towards a specific aggregation network segment using different kinds of packet network technologies including IP, Carrier Ethernet and MPLS. The reason for going packet was the possibility to have easier multiplexing gains in the aggregation segment and operators were able to choose their aggregation capacity and therefore their service quality for subscribers more freely. Also the end-user services were packet based anyway, therefore such a packet based aggregation network was adopted to save some of the conversions required otherwise.

Over the years, several generations of different interface capacities have been deployed running over different types of optical communication channels. Different carrier specific functionalities for the aggregation networks have been developed, for example, the provider backbone bridges (IEEE 802.1ad™ and IEEE 802.1ah™ [i.1]), link aggregation (IEEE 802.1ax™ [i.1]) and operations features (see IEEE 802.1ag™ [i.23]/Recommendation ITU-T Y.1731 [i.21]).

Also note that Ethernet has been offered as a business service to enterprise customers having Ethernet over MPLS for different Ethernet as a service models (E-Line, E-LAN and E-Tree by the Metro Ethernet Forum).

Anyway, the evolution of the aggregation network segment for a F5G architecture still needs some further study.

- Customer premises network technology evolution.

The concept of Customer Premise Network (CPN) originated from the demand of access network and CPN which shares an indoor copper wiring since the appearance of broadband access technologies. Before mobile computing (2003) and smartphone (2007) being widely used, wireline technologies were used in CPN, such as HomePNA (HPNA) over phone line, MoCA over coaxial cable, IEEE P1901™ [i.24] over power line and G.hn [i.22] (Recommendation ITU-T G.996.x series) (for both phone line, coaxial cable and power line), which provided speeds from several Mbit/s to multiple Gbit/s (now).

Since 2007, the demand for wireless connection rapidly expanded from computers to smart terminals such as smartphones and tablets, and WiFi® technology quickly became the mainstream technology for CPN. Till now WiFi® has gone through six generations from WiFi1 to WiFi6, and new unlicensed spectrum was marked, including 2,41~2,48 GHz, 5,125-5,925 GHz. The corresponding capability of these technologies ranges from several megabits of WiFi1 to a maximum of 10 Gbit/s of WiFi 6, and support more and more applications.

The path to F5G will require not only changes in the access technologies but also in the aggregation network and customer premises network. The fact that this evolution will be based on a full optical communication, end-to-end, opens new opportunities for increasing the synergies between access and aggregation networks.

Table 1: Fixed networks generations

Fixed Network Generation	F1G	F2G	F3G	F4G	F5G
Reference Wave	Kilobits	Megabits			**Gigabits**
Reference Downstream Bandwidth per User	<2 Mbps	2-30 Mbps	30-100 Mbps	100-1000 Mbps	**1-10 Gbps**
Reference Upstream Bandwidth per User	<2 Mbps	1/2 Mbps	15-100 Mbps	50-500 Mbps	**1-10 Gbps**
Reference Services	Voice (PSTN/ISDN) Dial Internet	High Speed Internet (HSI) SD Video	HD Video	UHD 4K Video	**VR Video Cloud Gaming Smart City**
Reference Characterization	Narrowband (NB)	Basic Broadband (BBB)	Fast Broadband (FBB)	Ultra Fast Broadband (UFBB)	**Gigabit Broadband (GBB)**
Reference Architecture	CO LE	CO DSLAM	FTTC/FTTB	FTTH/FTTdp	**FTTH/FTTR**
Access Network Technology Reference	PSTN/ISDN	ADSL/ADSL2+	VDSL2	GPON/G.fast	**10GPON**
Technical Specifications Reference	I.100-I.699	G.992.x	G.993.x	G.984.x G.9701	**G.987.x (XG-PON) G.9807.x (XGS-PON)**
On-Premise Network Technology Reference	RJ11/RJ45	FE+ WiFi1/WiFi2 (802.11b/802.11a)	FE+ WiFi3 (802.11g)	FE/GE+WiFi4/WiFi5 (802.11n/802.11ac)	**GE/10G+WiFi6 (802.11ax)**
Radio Frequency (RF) Video over Fibre (LAN Coaxial) Reference	No	No	No	Yes	**Yes**
Specification Timeline Reference	1988-1993	1999 (ADSL) 2003 (ADSL2+)	2006	2006 (GPON) 2014 (G.fast)	**2017**
Production Timeline Reference	1990	2000	2007	2010-2012 (GPON) 2016 (G.fast)	**2018**

5.2.3 Cable networks

Cable networks were originally designed for delivering television content to consumers via Radio Frequency (RF) signals transmitted through coaxial cables. These were typically built in mountainous regions where a single tall antenna mast could be shared by a community. Hence, they were originally known as Community Antenna Television (CATV).

Today, however, the majority of today's systems use Hybrid Fibre-Coaxial (HFC) access distribution for delivering superfast broadband, interactive television and digital telephony.

Modern cable technology is based on an open technical specification (DOCSIS - Data Over Cable Service Interface Specification) developed by CableLabs®, in the United States. This work is then translated into a European Standard inside ETSI (Technical Committee of Cable). The cable industry participates in various standardization bodies like ETSI and CENELEC and, in Europe, the active trade association is Cable Europe, of course in collaboration with CableLabs®.

Table 2: Cable networks generations

Cable Network Generation	1G	2G	3G	4G	5G
Reference Wave	Megabits			Gigabits	
Reference Total Downstream Capacity	40 Mbps	40 Mbps	1 Gbps	5 Gbps	**10 Gbps**
Reference Total Upstream Capacity	10 Mbps	30 Mbps	200 Mbps	1-2 Gbps	**6 Gbps**
Reference Highlights	Best Effort Data QoS Data VoIP	Higher Upstream Speed	High Capacity Enhancement Channel bonding	Capacity and Efficiency Progression	**Full-Duplex Increased upload speeds**
Reference Spectrum (UP/DW)	5-42/65 MHz* (UP) 88/108-860 MHz (DW) *EuroDOCSIS	5-42/65 MHz* (UP) 88/108-860 MHz (DW) *EuroDOCSIS	5-42/65 MHz* (UP) 88/108-860 MHz (DW) *EuroDOCSIS	5-204 MHz (UP) 258-1218 MHz (DW)	**5-85 MHz & 108-684 MHz (UP) 108-1218 MHz (DW)**
Reference Architecture	HFC/I-CMTS	HFC/I-CMTS	HFC/CCAP	HFC/DCCAP/M-CMTS	**HFC/FTTLA**
Access Network Technology Reference	DOCSIS 1.0/1.1	DOCSIS 2.0	DOCSIS 3.0	DOCSIS 3.1	**DOCSIS 4.0**
Technical Specifications Reference	J.112	J.122	J.222	J.225	**J.224**
Specification Timeline Reference	1996/99	2001	2006	2013	**2019**
Production Timeline Reference	1997	2002	2008	2016	**2022/23**

NOTE: Refer to [i.9], [i.10], [i.11], [i.12] and [i.13].

5.2.4 Mobile networks

Mobile networks were originally designed for voice services with mobility. The first systems were proprietary and analog in nature, presenting several limitations regarding capacity, geography and services, and were not very well subscribed.

The second generation promoted the wide spread use and success of mobile services, and came with the first European standard digital system GSM (Global System for Mobile communications) allowing a true global use with open interfaces, allowing roaming and interoperability between vendors.

With the 3rd Generation, data services and IP services were introduced, but these were provided over the existing voice transport systems, resulting in fairly narrow bandwidth. It was only with the 4G that broadband services truly reached their full potential, as a result of the system being designed for data transport from the ground up. As a consequence, there was a large demand for high bandwidth connections from the mobile radio sites to the core sites. These demands have been addressed by the fibre access and transport networks.

5G mobile is anticipated to provide enhancements to all the major service metrics. The density of radio sites will be increased, data rates will be higher, new low latency requirements will be met, and the massive number of IoT connections will be supported. All these requirements will be a challenge to the fibre access and transport networks. The F5G should address these new requirements and architectures for the coming 5G deployment.

Table 3: Mobile networks generations

Mobile Network Generation	1G	2G	3G	4G	5G
Reference Wave	Kilobits		Megabits		**Gigabits**
Reference Downstream Bandwidth per User	2 kbps	28-64 kbps	14-42,5 Mbps	1-300 Mbps	**1-10 Gbps**
Reference Upstream Bandwidth per User	2 kbps	14-42 kbps	5,7-11,5 Mbps	1-150 Mbps	**40 Mbps-10 Gbps**
Reference Services	Voice	SMS Basic Internet	Multimedia (MMS, video)	IP-based protocols Broadband	**VR Video Cloud Gaming Network Slicing**
Reference Characterization	Circuit Switching (CS)	Digital Circuit Switching (CS)	PS for Data CS for Voice	PS only VoLTE & CSFB	**PS only VoNR/VoLTE_FB & CSFB**
Reference Architecture	C450, NMT, AMPS, TACS	GSM/ GPRS/EDGE IS95/CDMA	UMTS/ HSPA	IMT-Advanced/ LTE/LTE-A	**IMT-2020**
Access Network Technology Reference	FDMA	TDMA	WCDMA CDMA2000	LTE TDD/FDD	**NR TDD/FDD**
Technical Specifications Reference (3GPP Release)	(Pre-standard)	GSM (3GPP TS 45 series)	>=R99 (3GPP TS 25 series)	>=R8 (3GPP TS 36/37 series)	**>=R15 (3GPP TS 38 series)**
Production Timeline Reference	1979	1991	2001	2009	**2019**

NOTE: Refer to [i.14], [i.15], [i.16], [i.17] and [i.18].

5.3 Fixed networks characterization/requirements

5.3.1 General

In the previous clause, an analysis of the historical fixed networks evolution and the networks generations landscape driving forces was done, including the classification of the cable and mobile networks generation's definition. In this clause, it will be analysed and identified the business and technology characteristics, and their requirements, in the context of the fixed fifth generation networks, in order to enable a gap analysis that will define the developments needed as well as the qualitative and quantitative metrics.

5.3.2 Principles of intergenerational division

5.3.2.0 Introduction

By analysing the evolution history and driving forces of the fixed network and referring to the generation division methods of other networks, a proposal for the generation demarcation principles of the fixed network, including typical services, technology characteristics and representative key technologies in each generation, can be attained.

5.3.2.1 Services

Service applications are the fundamental driving force of network development. From the evolution history of the fixed network, it can be seen that each generation of network evolution is driven by the need to meet the challenge of new services. When the existing network cannot meet the requirements of new services, a new generation of network emerges.

Fixed network services have directly changed people's sensory experience. In the past few decades, people's network application experience has changed from audibility to visuality, from static images to dynamic videos, and from low-definition videos to high-definition videos. In the future it is expected to see a shift from the 2D screen-based visuals to 3D fully special vision.

Fixed network services have also undergone a transformation from a single service to diversified services. From the initial single service to multi-play at home, from home to enterprises, base stations, machines, sensors, and points beyond.

The increase of service application bandwidth, the increase of the number of connections, and the ever increasing demand of service application experience will drive the constant evolution of fixed networks. Therefore services are the first principle for generation demarcation.

5.3.2.2 Technology characteristics

To meet the requirements of service application development, bearer network technologies will have to improve and evolve continuously. The development of fixed network technologies is directly reflected in three aspects: bandwidth, connection, and experience. These aspects are reflected in representative technologies in each generation.

Firstly, upgrade of each generation of fixed access network technology is the upgrade of bandwidth. The access bandwidth has grown in generations: 64 kbit/s, 2 Mbit/s, 10 Mbit/s, 100 Mbit/s, and 1 000 Mbit/s. The bandwidth upgrade for each generation access technology is increased by an order of magnitude compared with that of the previous generation. Along with the development of access technologies, transport technologies are also developing to improve the bandwidth of bearer networks. It has been seen these networks grow from 2 Mbit/s, 155 Mbit/s, 622 Mbit/s, 2,5 Gbit/s, 10 Gbit/s, 100 Gbit/s, and 200/400 Gbit/s. Currently, the single-wavelength bandwidth has reached 800 Gbit/s, and the single-fibre transmission capacity exceeds 40 Tbit/s. It is also a 4 to 10 times increase between generations.

Secondly, the number of connections is increasing. With the development of fixed network services, there are more and more broadband users, and the access devices are gradually expanded from a singular device such as telephones and computers to various devices, such as televisions, mobile phones, game players, video terminals, sensors, office devices, and industrial devices. With the continuous growth of device connections, the connectivity density and connection efficiency of bearer networks needs to be increased, and the level of integration and capacity of fixed network devices needs to be improved. The connection media of fixed networks is also changing. At first, users used twisted pairs for access. With the development of Internet applications, technologies such as coaxial cables, Ethernet cables, power cables, fibre cables, and wireless networks emerged and developed.

Thirdly, the user experience requirements have expanded. New services bring rich experiences to users and raise new requirements for bearer networks that go beyond increasing bandwidth. Requirements on network latency and jitter are becoming more and more stringent, going from seconds to milliseconds to microseconds, to meet the deployment requirements of applications such as Cloud VR, Cloud gaming, Big Data, Artificial Intelligence, and 5G xhauling. The connection reliability requirement is increasing from 99,99 % to 99,9999 %, meeting the demands of high-value services such as finance, education, healthcare, energy, and transportation, etc. The automation level of network Operation and Maintenance (O&M) is continuously improved, which helps service provisioning, network diagnosis and maintenance. O&M is moving from specific processes driven by operators to full domain policy driven autonomous networks.

5.3.3 Definition of F5G

5.3.3.1 F5G services and business drivers

New services are the driving force for networks evolving to F5G. F5G services are classified into three scenarios: residential, business, and vertical industries.

In residential scenarios, for services like Cloud VR and 8K HD videos, good customer experience (QoE) can be achieved only when the home access bandwidth reaches 1 Gbit/s and E2E network indicators can be guaranteed. To improve the bandwidth and service quality of home networks, optical fibres are extended into rooms to directly connect to user terminals or function as the backhaul for Wi-Fi APs. In addition, FTTR and access networks should be mostly managed by operators in a unified manner.

In business scenarios, SOHO is more and more popular. Similar to campus customers, they have higher requirements on broadband network bandwidth, service quality and security. Therefore, the network operators will require the provision of high-quality broadband access and private line premium services. With the rapid adoption of public Cloud services, e.g. PaaS, carriers need to provide high-bandwidth and high-quality broadband network to more and more enterprises so that they can access the Cloud. Mobile xHaul is another type of business service, which is provided to the integrated operators internally or as a wholesale service to other mobile operators.

In vertical industries scenario, it may be found several demanding scenarios. For example, Smart Cities will have a multitude of devices such as smart cameras and smart lamp poles, and each needs a broadband connection. The network will have to provide access capabilities for these devices and meet the requirements for bandwidth and latency. Another example is smart manufacturing (e.g. Industry 4.0). A unified physical network may be used to support three isolated services with different requirements: the production line for manufacturing (production network), the office system (office network) and campus devices including CCTV and Access control (campus network). The production network requires ultra-reliable and ultra-low latency connections, the office network needs symmetric high bandwidth, and the campus network will have to provide massive connections and easy maintenance.

All services need to be interpreted into business requirements. The business requirements are a high-level characterization of the main distinguishing features that enable the support of specific applications and use cases.

The main business challenges towards the development of F5G networks and the existing gaps in relation to the previous network generation need to be determined. To do so, it is first necessary to identify and characterize the main requirements to be addressed to reach the fifth generation.

After that, it is then possible to identify and quantify the requirements needed to address the present and future applications and use cases of F5G networks. This process might need to be updated in case new future applications and use cases requirements are identified.

The main business requirements identified are outlined below, considering that not all the requirements need to be met at the same time and that each application and use case may require a different combination of requirements. The requirements are classified into three groups: networks, services and operations.

Networks	Services	Operations
a) High Speed and Capacity (Bandwidth)	e) High Reliability	h) High Operational Efficiency
b) High Coverage (Connectivity)	f) High Availability	i) High Energy Efficiency
c) High Responsivity (Latency)	g) High Security	j) High Spectral Efficiency
d) High (Connection) Density		

Figure 2: Business requirements for F5G

Below a short description of each of the requirements that are attached to applications and use cases qualitative and quantitative metrics.

a) High speed and high capacity communications

Communication speed and capacity will be increased in fixed Access Networks and LANs from about 1 Gbps to at least 10 Gbps. The requirements for symmetric bandwidth use cases will also increase.

b) High coverage connectivity extension

Coverage expansions will allow service available everywhere and to everything (every smart object and machine) and new coverage areas.

c) High responsivity (low latency)

For mobile 5G xHaul, approximately 1 ms or less E2E latency will be necessary. The human reaction time differs depending on the involved task. Human real-time interaction is characterized by very low latency and ultra-high reliability. Visual interaction can tolerate a delay of 10 ms, while audio can tolerate 100 ms.

d) High number of dense connections

Networks will have to cope with massively and densely connected devices, requiring an increase in the number of connections by approximately 10 ~ 100 times: From Fibre to the Home/Fibre to the Office to Fibre to the Room/Fibre to the Desk, Fibre to Everywhere.

e) High reliability communication

Guaranteed quality of service and error-free communication will be required for certain mission critical services. Communication will require not only best-effort services but also quality assured services.

f) High availability communication

Network availability will be essential for mission critical services and its importance will also increase with the increasing number of devices and services supported. Network resilience and protection are essential to maintain the required network and service availabilities, by reducing or eliminating the outage time.

g) High security communication

One can also identify security as an essential enabling future requirement in all its dimensions: safety, privacy & confidentiality and integrity of the communications.

h) High operational efficiency

The efficiency of network operations will still be very important, because it will continue to drive the operational costs. Achieving high efficiency implies the network is managed E2E and support automatic service deployment and O&M.

i) High energy and cost efficiency

Low power consumption and cost reduction for network and terminal devices will still be important requirements for F5G.

j) High spectral utilization and efficiency

The spectral (wavelengths) utilization and efficiency in optical networks will be also an important issue for the capacity requirements of F5G networks, which will exceed 10 times the current values.

Figure 3 identifies and represents the major measurable and quantifiable gaps and challenges towards F5G.

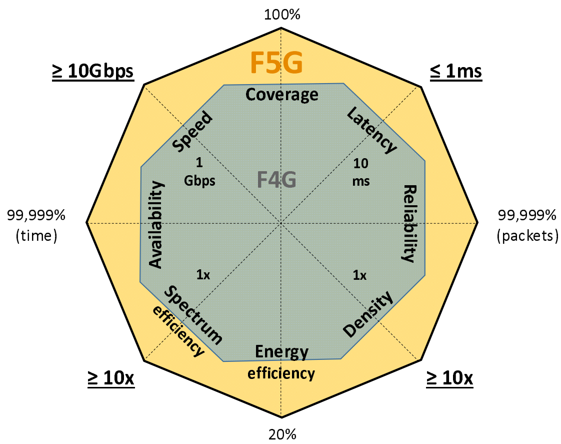

Figure 3: Gaps and challenges for F5G

It can be seen that the main commercial drivers for F5G are essentially composed by three dimensions: Speed, Density and Latency. These dimensions are implemented based on three technical characteristics, eFBB, FFC and GRE.

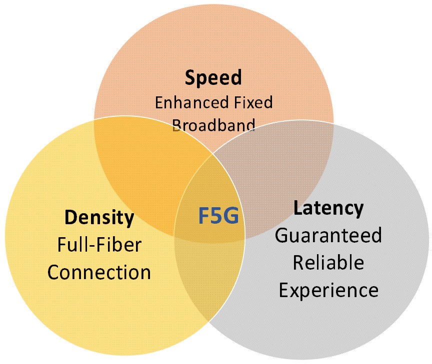

Figure 4: Commercial drivers for F5G

5.3.3.2 F5G technology characteristics and representative technologies

Compared with previous generations of fixed access technologies, 10G-PON networks bring a quantum leap of bandwidth, user experience, and connection capacity. The upstream and downstream rates are up to 10 Gbit/s symmetric, and the latency is reduced to the level of 100 µs. These changes will push the fibre network to break through the traditional industry boundaries and provide connections everywhere, including every room in the home, every office building, and every factory.

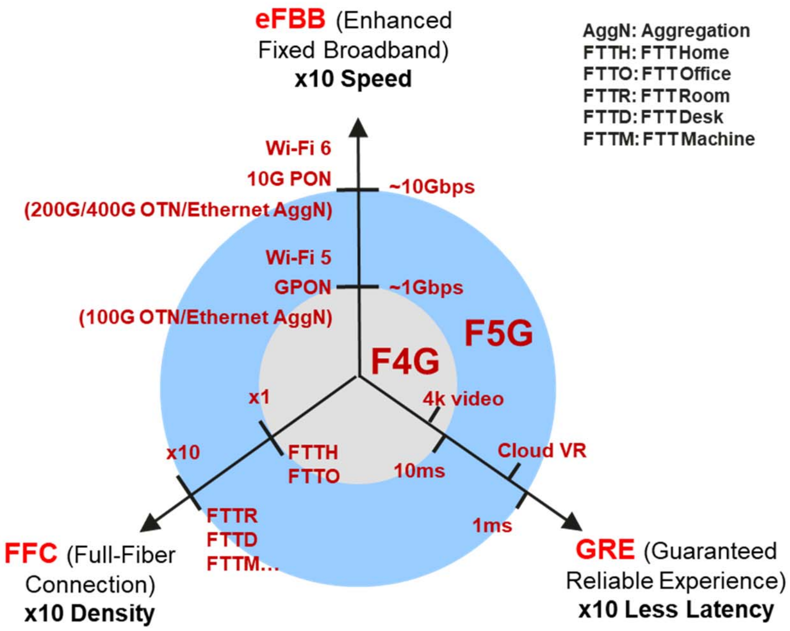

Figure 5: Technical characteristics for F5G

The above mentioned business requirements can be categorized into three key technical characteristics, i.e. eFBB, FFC and GRE.

1) **Enhanced Fixed BroadBand (eFBB)**

In order to support the business demand of high speed and high capacity communications and high spectral efficiency, the first characteristic of F5G is eFBB.

Compared to F4G fibre broadband, F5G further increases the bandwidth by more than 10 times. The fibre access technology represented by 10G-PON delivers this improvement. The per-subscriber network bandwidth has symmetric gigabit upstream and downstream bandwidth capability. The Wi-Fi 6 technology is used to break the bottleneck of the last 10 meters of gigabit connections. Users can be efficiently connected to Data Centres and enjoy high bandwidth experience.

In CPN, Wi-Fi 6 can be used to continuously improve performance, stability, and coverage. Combined with FTTR, both residential and business users can experience gigabit seamless broadband access.

For the Access Network, 10G-PON has become the dominant broadband access technology and has been continuously optimized. It achieves full coverage of gigabit access to the customer premises. Coexistence with GPON enables smooth network migration.

High-bandwidth technologies, such as 100GE and OTN, are deployed at access sites to implement large-bandwidth backhaul for access networks and ensure E2E gigabit bandwidth capabilities. WDM nodes are moved from the Backbone Network down to the Access Network Central Offices, and are directly interconnected with OLTs to implement E2E all-optical connections.

The capacity of OTN is continuously improved. 200 Gbit/s and 400 Gbit/s single-wavelength OTN are fully deployed, and the C-band and L-band are widely used, achieving high-performance transmission of more than 40 Tbit/s per fibre.

OTN is responsible for Data Centre interconnection and even provides high speed connections between servers inside DC.

2) Full-Fibre Connection (FFC)

In order to support the business demand of high coverage connectivity extension and high massive and dense communications, the second characteristic of F5G is FFC.

Converged Network

The F4G optical access network mainly solved the problem of fibre-based home access. On this basis, F5G uses the fully-covered fibre infrastructure to support ubiquitous connections, including home connections, machine connections, and connections between each room, supporting the development of vertical industry applications. Service scenarios are expanded, and the number of connections is increased by more than 100 times, enabling the era of full-fibre connectivity. F4G optical access was the first step to reach the user's premises with fibre, while F5G is the second step to push the fibre into the home to the user's devices. This second step will include potentially the concept of cascading PON systems to achieve the closest fibre connectivity to the user based on new fibre infrastructures. In the home access domain, F5G further extends traditional FTTH by deploying fibre into each room (FTTR), and provides complete infrastructure for smart home and family life. Rules for cabling new buildings with fibre would help F5G expansion if they can be developed and embedded in the appropriate legislation of each country. When combined with Wi-Fi 6 and its enhanced technologies, FTTR can cover the home environment with gigabit broadband access without dead spots.

High-quality Enterprise private Lines

In the business services domain, OTN technology will provide high-quality private line services for global business users. Based on the traditional technology with high-quality, high-reliability, and low-latency features, OTN reduces the container granularity and provides as small as 2 Mbit/s connection, which guides the migration direction of MSTP services and resolves the quality weakness of traditional Ethernet, VPN, and SD-WAN private line services. The OTN technology can further collaborate with PON to implement wide coverage of OTN private lines through point-to-multipoint access fibres, providing high-quality private line premium services for SMEs and SOHO with fast provisioning.

5G mobile network xHaul

Optical fibres are the optimal connection medium for 5G base stations. 5G networks require large bandwidth, wide coverage, and low latency, which can be maximized only through optical fibre access and transport. Full-scale 5G deployment will increase the number of mobile sites (base stations and small cells) by an order of magnitude. The deployment scenarios will become more complex and closer to end users. The distribution of 5G mobile sites will overlap with the ODN distribution of FTTH. Therefore, the DRAN and CRAN architectures of 5G networks and the deployment of macro, micro, and pole sites can leverage ODN for fronthaul or backhaul. Access Network and Aggregation Networks may need some upgrade with new features and capabilities to meet 5G xHaul requirements.

Optical Industrial/Campus Networks

In the enterprise access domain, F5G will replace the traditional Ethernet network that dominates the campus network with PON. Implementing LAN with PON can save the cost of cable and maintenance, because ODN is cheaper and maintenance free compared with traditional Ethernet network comprised of switches and CAT6 copper cables.

Fibre access further penetrates into the production systems of industrial enterprises, connecting machines (FTTMachine) and industrial robots. Based on the high bandwidth, high reliability, low latency, anti-interference and high confidentiality features of fibre networks, TSNs (Time Sensitive Networks) can be established to implement industrial digital transformation.

Optical fibres can be connected to each smart camera to provide high-bandwidth and low-latency transmission channels, implementing high-speed connection between cameras and Data Centres and facilitating the application of machine vision and AI technologies.

Efficient and Flexible Deployment Models

The massive extension of optical fibres requires more flexible and efficient construction of optical transmission and access networks. The traditional telecom CO network construction mode will also face changes in a multi-scenario network construction.

The capacity of backbone and aggregation networks is increasing, and the increasing of device integration should follow Moore's Law. Therefore, a large-capacity all-optical switching architecture is required to implement efficient convergence of the optical and electrical layers of transmission and efficient network construction.

The network construction modes of carriers and IT infrastructure construction may gradually converge. The Backbone Network and Data Centre equipment room of carriers are becoming one and the same. The OTN technology is used for Data Centre interconnection or internal networking of Data Centres. Therefore, the OTN device, network construction mode, and O&M mode need to be gradually transformed to be compatible with DC.

The access optical network is evolving from traditional carrier access equipment rooms to various industries, and the construction scenarios are becoming increasingly diversified. On one hand, the capacity of the traditional access equipment room increases by 10 times. On the other hand, the access network sites with medium or small capacity may be placed remotely. With the application of various industries and the characteristics of the user premises, new construction mode including Access Network clustering and cascading are considered.

The evolution to a full fibre network will also allow for a significant reduction on the required number of network aggregation points paving the way for operator to reduce the number of their actual CO and greatly simplify their networks. Moving towards a full fibre connection in many different scenarios, the frontier between access and transport will tend to blur and a closer coordination between these two layers is expected in F5G.

3) Guaranteed Reliable Experience (GRE)

In order to support the business demand of highly sensitive services (low latency), high reliability and high availability communication, and high operational efficiency, the third characteristic of F5G is GRE.

Depending on the unique high-quality transmission capability of optical fibres, the network supports almost-zero packet loss, microsecond-level delay and jitter, and works with intelligent O&M enabled by AI and big data to meet users' requirements for the ultimate service experience.

In residential broadband scenarios, 8K video, Cloud VR, gaming, video conferencing, and home security protection services are provided. Especially for high-bandwidth, delay-sensitive, and packet loss-sensitive services such as HD video, Cloud VR, and large-scale cloud gaming, millisecond-level low-latency transmission over OTN, PON, and Wi-Fi is required. Intelligent real-time service identification and allocation of high-quality network resources are required. The broadband network assurance policy needs to be automatically identified and adjusted to adapt to changes in user service applications.

Private line services and other industry application services require constant and reliable bandwidth, millisecond-level latency, and high availability to support SLA commitments. Therefore, the network needs to be flexible E2E capacity reservation and isolation capabilities.

Mobile bearer services also require high bandwidth, millisecond-level low latency, high-reliability networking, and high-precision clock synchronization technologies to ensure the quality of various mobile broadband services.

In the F5G era, software and hardware technologies need to be continuously optimized to ensure high service experience including:

a) Programmability

As a first step to achieve the desired flexibility and agility in the telco networks, it is essential to implement SDN/NFV as the main basic technologies to enable software and hardware separation and programmable networking. ETSI NFV framework provides a standard architecture for network functions virtualisation that enables more flexibility and quick response to scale in/out or move/deploy network functions whenever and wherever needed. To complete the desired NFV agility it is essential to have software defined networking. SDN provides a decoupling of the control plane and the user plane on the switching elements of the network. This makes it possible to provide software defined networking to the virtualized functions.

b) Agility

Automation/Orchestration

The implementation path and technological evolution to virtualization/cloudification in telco networks has proven difficult to manage and operate using the legacy operation and management systems and existing processes/workflows.

Most services need to pass through multiple network segments from the server to user terminals, such as the Backbone Network, Aggregation Network, Access Network, and CPN. E2E management, maintenance, and service provisioning enable fast automatic service provisioning, real-time service ordering and online, and E2E QoS and QoE assurance. This requires unified management and O&M of Transport, IP, Access, and CPN network segments.

In networks that are becoming more disaggregated (HW and SW, or mix suppliers), more dynamic and more complex (network slicing), the job of managing the network becomes more difficult. This requires automation at all network layers:

- Infrastructure layer: Dynamic orchestration with scale in/out and High Availability
- Domain Layer: Orchestration dealing with the specifics of each domain
- Network Layer: E2E orchestration - Service provision, fulfilment and global operation

Service Assurance

Considering the need to provide service assurance in more complex networks like F5G, increased intelligence and new procedures are required for the automation/orchestration systems to be able to guarantee the quality of experience for the customer. Some of these procedures/tools are:

- Auto-Healing/Closed-Loop
- Analytics - Fault correlation, root cause analysis, service impact analysis
- Big Data Analytics (business data and network data)
- Digital Twin
- Telemetry streaming
- SLA management
- Security management

Artificial Intelligence is a very powerful tool for service assurance both for O&M and also for data transportation. The AI technology automatically identifies multiple services and provides intelligent service assurance based on the built-in capability of the network. It can automatically detect services and allocate differentiated network resources to ensure differentiated application experience of different services for end users. Network intelligence is also reflected in the following aspects: collecting and analysing network status based on service application changes, detecting service experience risks in real time and adjusting network resources, diagnosis and isolation of network faults, and automatic repair of network faults in a timely manner.

E2E slicing

Full service applications on the unified fibre bearer network require differentiated experience assurance. Thanks to Wi-Fi OFDM/OFDMA, Beamforming, and MU-MIMO technologies, Wi-Fi air interfaces support carrier- and space-based slicing. PON ports support slicing based on service types. The OLT provides Ethernet/OTN networking ports in the upstream direction and supports slicing based on service types.

c) Interoperability

The key for the success of a faster deployment lays on the interoperability between different suppliers and vendors, meaning standardization compliance and open APIs. The success of F5G adoption depends on the integration and/or migration from legacy networks in the smoothest possible way.

Open networks and interfaces, together with reference service models and open APIs, will provide a faster and easier integration and interoperation between all elements of the fixed network.

d) Low-latency

Some high-value services require E2E millisecond-level latency. PON technology has to be optimized and achieve microsecond-level latency, and the Wi-Fi technology needs to reduce the delay to less than 1 ms. For some high-value services, such as high-quality private lines, small-granularity OTN channels can be directly applied to achieve even lower latency.

History

Document history		
V1.1.1	December 2020	Publication