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Fifth Generation Fixed Network (F5G); F5G Advanced Generation Definition

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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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1 Scope

The present document studies the driving forces and the characteristics of the fixed network evolution from F5G to F5G Advanced. It includes all segments of E2E connectivity between on-premises networks and data centres, and extends the F5G concepts and characteristics initially described in ETSI GR F5G 001 [i.12].

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] Cisco Annual Internet Report, 2018-2023.

[i.2] G.fgOTN project in ITU (in progress).

[i.3] Wikipedia: "Software as a Service".

[i.4] TM Forum: "Autonomous Networks: Empowering Digital Transformation for Smart Societies and Industries".

[i.5] Recommendation ITU-T Series G Supplement 51 (05/2012).

[i.6] ETSI GR F5G 008 (V1.1.1): "Fifth Generation Fixed Network (F5G); F5G Use Cases Release #2".

[i.7] TM Forum IG1218 (V2.2.0): "Autonomous Networks - Business requirements & architecture".

[i.8] TM Forum IG1230 (V1.1.1): "Autonomous Networks Technical Architecture".

[i.9] ETSI GR ZSM 011 (V1.1.1): "Zero-touch network and Service Management (ZSM); Intent-driven autonomous networks; Generic aspects".

[i.10] Introducing the Knowledge Graph: things, not strings.

[i.11] Wikipedia: "Large language model".

[i.12] ETSI GR F5G 001: "Fifth Generation Fixed Network (F5G); F5G Generation Definition Release #1".

[i.13] ETSI GS F5G 006: "Fifth Generation Fixed Network (F5G); End-to-End Management and Control; Release #1".

[i.14] ETSI GS F5G 011: "Fifth Generation Fixed Network (F5G); Telemetry Framework and Requirements for Access Networks".

[i.15] ETSI GS F5G 005: "Fifth Generation Fixed Network (F5G) F5G High-Quality Service Experience Factors Release #1".

[i.16] ETSI GR F5G 007 (V1.1.1): "Fifth Generation Fixed Network (F5G); F5G Industrial PON".

[i.17] Europe's Digital Decade: digital targets for 2030.

[i.18] Recommendation ITU-T Y.2501: "Computing power network - Framework and architecture".

[i.19] ETSI TR 103 775: "Access, Terminals, Transmission and Multiplexing (ATTM); Optical Distribution Network (ODN) Quick Construction and Digitalization".

[i.20] IEEE 802.11ax™: "IEEE Standard for Information Technology - Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks - Specific Requirementsv Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 1: Enhancements for High-Efficiency WLAN".

[i.21] IEEE 802.11be™: "IEEE Draft Standard for Information technology - Telecommunications and information exchange between systems Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment: Enhancements for Extremely High Throughput (EHT)".

[i.22] IEEE 802.11bf™: "IEEE Draft Standard for Information Technology -- Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks -- Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Enhancements for Wireless LAN Sensing".

[i.23] Recommendation ITU-T G.9804 series: "Higher speed passive optical networks".

[i.24] Recommendation ITU-T G.984.series: " Gigabit-capable passive optical networks (GPON)".

[i.25] Recommendation ITU-T G.9701: " Fast access to subscriber terminals (G.fast) - Physical layer specification".

[i.26] Recommendation ITU-T G.987 series: "10-Gigabit-capable passive optical network (XG-PON) systems: Definitions, abbreviations and acronyms".

[i.27] Recommendation ITU-T G.9807 series: "10-Gigabit-capable symmetric passive optical network (XGS-PON)".

[i.28] Fifth Generation Fixed Network (F5G); F5G Advanced Release Documentation (Release 3 and 4).

[i.29] Fifth Generation Fixed Network (F5G); F5G Release Documentation Release 1 and 2.

3 Definition of terms, symbols and abbreviations

3.1 Terms

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

Artificial intelligence as a Service (AIaaS): service that outsources AI-related computing to enable individuals and companies to explore and scale AI techniques at a minimal cost

NOTE: The motivation for AIaaS is because developing in-house AI-based solutions is a complex process that requires huge capital investment, outsourcing and getting it as service is beneficial

computing power networks: type of network that realizes optimized resource allocation, by distributing computing, storage, network and other resource information of service nodes through a network control plane (such as a centralized controller, distributed routing protocol, etc.)

NOTE: It combines network context and user requirements to provide optimal distribution, association, transaction and scheduling of computing, storage and network resources (see Recommendation ITU-T Y.2501 [i.18] for the definition).

digital twin: virtual representation of a physical object or system across its lifecycle, using real-time data to enable the understanding, learning and reasoning

Fibre to the thing (FTTThing): integrated technology scheme to provide connection to end devices in a communication system, in which the fibre is directly connected to end device instead of a network terminal

metaverse: proposed network of immersive online worlds experienced typically through virtual reality or augmented reality in which users would interact with each other and purchase goods and services, some of which would exist only in the online world

3.2 Symbols

Void.

3.3 Abbreviations

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

50G-PON	50 gigabit Passive Optical Network
AI	Artificial Intelligence
AIaaS	Artificial Intelligence as a Service
ANL	Autonomous Network Level
API	Application Programming Interface
AR	Augmented Reality
CIaaS	Compute Infrastructure as a Service
CO	Central Office
DAS	Distributed Acoustic Sensing
DSP	Digital Signal Processing
DU	Distributed Unit
E2E	End to End
EC	Edge Computing
EMI	Electro-Magnetic Interference
F5G	Fifth Generation Fixed Network
F5G-A	F5G Advanced
FEC	Forward Error Correction
fgOTN	fine-grain OTN
FTTD	Fibre To The Desk
FTTM	Fibre To The Machine
FTTO	Fibre To The Office
FTTThing	Fibre To The Thing
FTTR	Fibre To The Room
GPON	Gigabit PON
HD	High Definition
HMD	Head-Mounted Display
IaaS	Infrastructure as a Service
ICT	Information & Communication Technology
IEEE	Institute of Electrical and Electronic Engineers
IoT	Internet of Things
IP	Internet Protocol
IT	Information Technology
LAN	Local Area Network
LDPC	Low Density Parity Check
NETCONF	Network Configuration protocol
NFV	Network Functions Virtualisation
NRZ	Non Return to Zero
O&M	Operation & Management
OAM	Operation Administration and Maintenance
ODN	Optical Distribution Network
ODU	Optical channel Data Unit
OLT	Optical Line Termination
ONU	Optical Network Unit
OT	Operational Technology
OXC	Optical Cross-Connects

PON	Passive Optical Network
QoE	Quality of Experience
QoS	Quality of Service
SDH	Synchronous Data Hierarchy
SNMP	Simple Network Management Protocol
SaaS	Software as a Service
SOHO	Small Office and Home Office
SONET	Synchronous Optical NETwork
TDM	Time-Division-Multiplex
TDMA	Time-Division-Multiple Access
UHD	Ultra-High Definition
VNF	Virtualized Network Function
VoIP	Voice over IP
VPN	Virtual Private Network
VR	Virtual Reality
WDM-PON	Wavelength Division Multiplexing Passive Optical Network
Wi-Fi®	Wireless Fidelity
XG	10 Gbps
XG-PON	10-Gigabit-capable Passive Optical Network
XGS	10 Gbps Symmetrical
XGS-PON	10-Gigabit-capable Symmetric Passive Optical Network
XR	Extended Reality
YANG	Yet Another Next Generation.

4 Overview

The ETSI Industry Specification Group (ISG) F5G has established a continuous evolutional approach to the fixed network defining generations that may direct the industry toward a consistent E2E network vision.

ETSI GR F5G 001 [i.12] defines the Fifth Generation Fixed Network generation, to enable a wider technological standards adoption and boost the creation of a global market. There are many drivers that motivate the advancement of F5G networks towards their next evolutionary step, such as the digitization or cloudification of various services or application domains, new emerging technologies and improvements to the network infrastructure, the growing density and applicability of the network for various purposes and environments. The evolution of F5G needs to be considered and the next steps to F5G Advanced are defined.

The present document explores the evolution path from F5G to F5G Advanced and details the six dimensions of F5G Advanced. Three of the dimensions were already specified for F5G [i.12], and F5G Advanced introduces enhancements for those. In addition, F5G Advanced introduces three new dimensions that will allow to meet the requirements of emerging services. The key enabling technologies for these six dimensions are addressed. Looking forward, the outlook of F5G Advanced and beyond is described in clause 8 of the present document.

5 From F5G to F5G Advanced

5.1 Application requirements for F5G Advanced

5.1.1 F5G Advanced - an enabler for emerging applications

In the ETSI GR F5G 001 [i.12], some major emerging application requirements are discussed. These requirements are mainly from residential, business and vertical industries. Several typical applications are analysed as Cloud VR, 8K HD videos, SOHO, as well as smart cities and smart manufacturing. These applications impose requirements such as network bandwidth, E2E quality assurance, security and network coverage based on FTTR and Wi-Fi®.

F5G Advanced supports the next generation of emerging digital services such as digital twins and metaverses, to name two, and continues to accelerate the popularization of fibre services and meet people's needs for personalized and higher-quality services. These emerging digital services impose more stringent requirements on the communication network technologies.

At the same time, the scientific, technological and industrial evolution are accelerating worldwide. Digital development has become an important growth engine for the world economy. Industrial digitalization has promoted the transformation of production methods achieving more intelligent infrastructure and higher quality.

The current F5G network technology, compared to the previous generations such as F4G, improved not only the network performance, but also the energy efficiency by expanding fibre to everywhere and replacing power hungry traditional copper networks. With the common global goal of reducing carbon emissions and achieving carbon neutrality, it is necessary to promote further advances in F5G network technology to meet the future green transition and low-carbon trends, e.g. achieving lower power per bit. At the same time, the low-carbon transformation of various high-energy- industries can be supported by further enhancing F5G network technology to provide a more intelligent network infrastructure to meet these needs.

5.1.2 Emerging applications

5.1.2.1 Digital Twin

The digital twin is an integration approach and an innovative application of multiple digital technologies, based on advanced modelling tools to define accurate digital models of the physical objects, based on the collection of real-time data for improved operation. The digital twin achieves the integration of physical objects and digital models, and thereby builds a comprehensive decision-making capability, and supports the optimization of the operation of physical objects.

The digital twin can be used to improve management decisions and outcomes via the visualization and support of individual objects, like a car or a robot and up to the complexity of smart robotic fleets, complex manufacturing operations and smart cities.

For the digital twins to achieve accurate real-time information capture and real-time interaction with the physical world, improvements to the existing architecture and capabilities of networks need to be accomplished. F5G Advanced aims at providing the needed key performances such as the connection of a large number of devices, high data throughput, and deterministic transmission capabilities.

5.1.2.2 Metaverse

The Metaverse is a persistent and immersive digital environment of independent but interconnected networks. It enables persistent, decentralized, collaborative, interoperable digital content that intersects with the physical world's objects.

The Metaverse needs the combined use of multiple technologies like Augmented Reality (AR), eXtended Reality (XR) or Mixed Reality (MR), Internet of Things (IoT), Artificial Intelligence (AI) and cloud computing technologies. These technologies combined, form a complete metaverse solution.

The Metaverse needs that the network supports the wide-scale interconnection of a large number of users, supporting flexible and elastic networking, and imposes more extreme requirements for network performance. In terms of network service interaction and collaboration, the network needs to change from capability-oriented to service-oriented, enhancing the integration of network service applications, establishing a collaboration model, and better supporting the needs of highly interactive services.

It is necessary to implement fine grain QoS assurance for multi-stream services, and coordinate transmission of various data streams such as video, audio, network control signalling, and performance monitoring. This ensures the respective QoS of all streams to achieve an excellent overall service experience.

Due to the high metaverse service requirements for network bandwidth and deterministic performance, serving concurrent user poses greater challenges to the dynamic real-time optimization and adjustment of network resources.

5.1.2.3 Deterministic networking for vertical industries

The Internet technologies reached global coverage and are more and more used in industrial production. It is becoming more difficult for the traditional best effort network architecture and capabilities to support future vertical industry service requirements for differentiated networking, low latency and low jitter transmission capabilities.

Deterministic network technologies, which optimize network latency, packet jitter, packet loss and other key parameters that define the service quality metrics, can provide reliable and guaranteed transmission capabilities. The needs of smart factories, smart grids, remote industrial control, traffic safety control, telemedicine, unmanned driving and other applications can therefore be met, greatly improving real-world productivity and creativity.

Deterministic network technology can be combined with network virtualization and network slicing technology to partition application scenarios, separate deterministic capabilities for different business needs, and realize differentiated deterministic performances for different customers.

Deterministic network technology can also be employed to optimize the QoS of the computing power networks [i.18], improving the support of the stringent network performance requirements. Thereby ensure the coordination of end-to-end computing and networking, and assign tasks to the appropriate computing nodes in real-time. In addition, it can meet the requirements of massive data processing, transmission, and storage access, providing customers with an improved service experience of computing and networking convergence.

5.1.2.4 Digitization and cloudification of applications

The move to cloud environments is spreading in all market segments, adding network requirements on bandwidth, availability, low latency and jitter. In addition, an efficient balance between computing, storage and networking in an edge cloud architecture enables the optimisation of total energy consumption.

These factors largely influence the success of enterprise and campus digitization and cloudification. For network operators, this creates the opportunity to develop premium computing power networks-based services in an "as a Service" model, adding more intelligence for services creation and the improvement of customer interaction. Through appropriate frontend portals, users are able to select and customize the needed services. F5G Advanced networks enable this evolution, expanding the scope of Fibre To The Office (FTTO) solutions.

Another emerging area, either for business and or residential users, are the Ultra-High Definition (UHD) immersive experience applications that frequently need cloud resources, and large bandwidth and low latency.

5.2 Trends and demands on network infrastructures

5.2.1 The quest for higher bandwidth and Quality of Experience (QoE)

Services and bandwidth evolution make up a virtuous cycle, where new services demand more bandwidth and more bandwidth favours the creation of new services.

The digitization and cloudification is a trend in all segments including residential users, public services, health or industry. The evolution to UHD video, extended reality or remote work generate an increase in the number of users and endpoints and drive the quest for higher and improved broadband capacity and functionality.

F5G Advanced is the next step in the fixed network evolution, providing an ecosystem that integrates higher bandwidth technologies with the appropriate architecture and E2E management, enabling the required flexibility and agility to address a wide range of services and deployment environments.

This evolution can take different paces depending on specific services, applications and market segments. However, as stated in the EU digital targets for 2030 [i.17], a next step is to ensure Gbit network access for everyone in 2030.

The vision of "fibre to everything and everywhere" set forward by ETSI ISG F5G is becoming a trend, extending fibre deeper into several environment as FTTR, FTTD or FTTM.

Along with the growth of the number of end-points and diversity of applications, there is a growing demand for quality of the network infrastructure, where the focus on speed is complemented by specific requirements on latency, jitter and functionalities such as E2E slicing, providing premium Quality of Experience (QoE). The resources need to be available and guaranteed for all services using the infrastructure. The rich service functionality needs the infrastructure to be able to meet a variety of requirements along multiple dimensions of those represented in Figure 1.

An initial QoE framework was specified in ETSI GR F5G 005 [i.15] and is embedded in the evolution to F5G Advanced.

5.2.2 Digitization and automation of network operations

Optical networks are expanding fast in number of users, number of connected devices and diversity of service requirements, covering different segments that may share the network resources. To address this growing dimension and complexity, the digitization and automation of network operations is a key requirement. A holistic perspective on the network management is needed. For the F5G generation these aspects are addressed in ETSI GS F5G 006 [i.13] and ETSI GS F5G 011 [i.14]; an evolution will be required in F5G Advanced.

Furthermore, the adoption of autonomous network approaches adds intelligence and simplicity to Operation Administration and Maintenance (OAM) increasing the ease of operation and reducing operational costs. This trend has already started in ISG F5G and is expanded in further evolutions. Core technologies, such as service intent, multi-dimensional experience awareness, and adaptive network adjustment, can be used to upgrade the network management system to a higher Autonomous Network Level (ANL), as defined by the TMF. It includes achieving close to zero wait for services, zero touch for network maintenance, and zero trouble in services.

5.2.3 Optical fibre networks becoming ubiquitous

Optical networks, either in access, aggregation or core, are a key infrastructure for broadband development, addressing a growing number of applications and requirements from a wide range of segments such as residential, enterprise, campus or industry. They are also fundamental to support many other networks such as offloading of mobile and wireless networks (e.g. Wi-Fi®) or Data Centres interconnection.

This key role of optical networks, becoming ubiquitous, also leads to the massive and fast deployment of optical fibre cable infrastructures, that being passive, face several management challenges such as the accumulation of a large number of passive resources, assets location mapping, reliable real-time occupancy status and performance monitoring. To address these challenges, new technologies and architectures need to be introduced, aiming to facilitate the visualization of passive fibre resources, topologies, and connection status of the Optical Distribution Network (ODN). ETSI TR 103 775 [i.19] addresses some of these questions. F5G Advanced improves the overall O&M efficiency of the optical fibre infrastructure and the automation capability of upper-layer service networks.

Furthermore, optical fibre cables have "sensing" capabilities that are be exploited for the improvement of the optical fibre infrastructure management. The optical fibre sensing technology, represented by Distributed Acoustic Sensing (DAS), can capture and collect environmental information such as vibration, stress, and temperature changes. It has been applied in oil and gas pipeline intrusion monitoring and coal mine conveyor belt monitoring, opening a new dimension to optical networks.

5.2.4 Green and Digital for a Sustainable Society

The digital transformation is crossing all areas of the society, requiring capable and flexible networks that can adapt to the needs of the various stakeholders. This transformation contributes to meet the challenges of a greener society and reduction of CO_2 emissions.

Optical networks are a key infrastructure to achieve the green and digital objectives.

Productivity gains, adoption of virtual meetings or remote work are just some examples of the energy savings brought by the digital transformation supported by efficient networks. But the energy consumption of the network itself needs also to be managed and reduced whenever possible, and optical networks have a key role also in this.

In access, the passive structure of PON networks makes it very energy efficient when compared with other options. In aggregation and core networks, the development of optical switching and AI assisted enhanced routing intelligence, ensuring the traffic paths with the highest energy efficiency.

Improvements in the optical fibre infrastructure management contributes to the reduction of carbon emissions. The field operations require to perform maintenance and fix network faults, demanding for travel and human resources; they are the major sources of cost and carbon emission in network operation. That leading to self-operating networks and, ultimately, to self-healing networks is therefore an important trend.

5.2.5 Integration of computing in the network

The digital transformation implies the implementation of computing power networks, where Artificial Intelligence (AI) is an enabler for flexibility, adaptability, and efficiency in infrastructure operations.

The integration of computing, storage, and communication requires orchestration of the various resources and infrastructure components. In this scenario, more intelligence and autonomous network features are added to the network infrastructure to enable the dynamic scaling of each component and to provide the resource functionality needed to react to changes in demand and location of the services. The basic functionality for combining computing, storage, and networking is the intelligent provisioning of the applications and services and the self-adaptation of the infrastructure to meet the requirements in terms of performance and functionality.

Embedding computing capabilities in the network is expected to enable new service offers. New combined IT, media, or communication-oriented services can arise from the integration of computing in networks where a high degree of flexibility in the infrastructure is needed to enable such services. New standardized interfaces between computing and network are needed. In the case of a computing power network [i.18] infrastructure, common optimization of computing and network resources and combined management of the service quality can be achieved. The services can be easily guaranteed by doing this. The service provider infrastructure needs to migrate to a platform approach allowing for a plethora of different services being produced on the same infrastructure.

5.2.6 Industrial Optical Networks

Industries are on the path to digitization, to become more efficient, sustainable and agile. The investment in adequate communication networks and computing infrastructures is key to achieve that goal. The high bandwidth, low latency, high reliability and immunity to Electro-Magnetic Interference (EMI) of the Optical networks makes them very suitable to be applicable in the industry.

However, the industry ecosystem presents some challenges on environmental conditions, specific interfaces and stringent QoS requirements that need some adaptation of existing standards. The use of optical networks in industry environments was considered in several F5G use cases and a first evaluation was published in ETSI GR F5G 007 [i.16].

On top of existing studies, F5G Advanced addresses the requirements of a native industry optical networks that enable an efficient E2E solution for Industrial environments.

6 F5G Advanced dimensions

6.1 F5G Advanced characteristic dimensions

Figure 1 shows the six dimensions that characterize F5G Advanced. Each dimension is showing some major technologies used to enable it and the key indicators for those characteristics in the functional or performance domain. Finally, Figure 1 visualizes the evolution from F5G to F5G Advanced. Each dimension is described in clause 6.

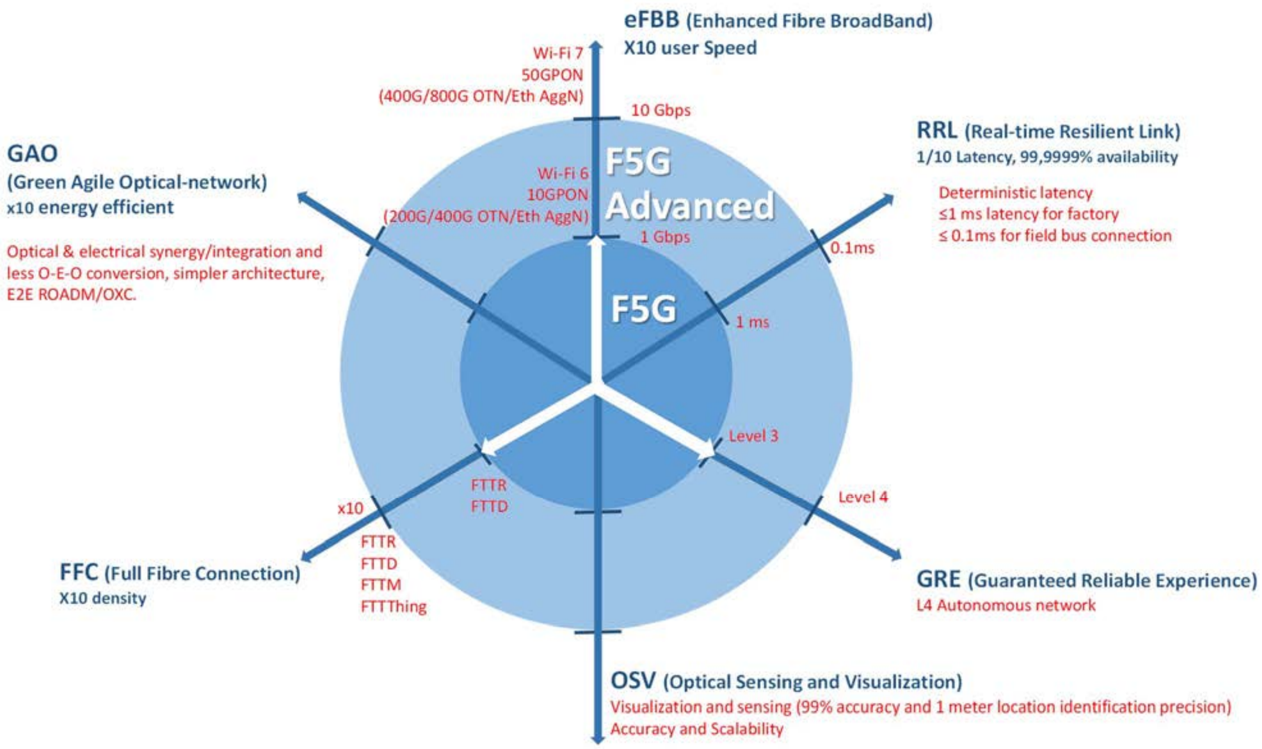

Figure 1: Six Dimensions of F5G Advanced with enabling technologies characteristics

6.2 F5G Advanced dimensions definition

6.2.1 Enhanced Fibre Broadband (eFBB)

Application bandwidth has been growing at a rate of about 40 % per year, and this is expected to continue [i.1]. The sources of this growth include the increase of the number of endpoints, the proliferation of more and more applications (metaverse and immersive services), and the expansion of usage in existing applications. The fixed network needs to keep up with this growth, and that implies modernization of the transport, aggregation, access, and customer premises networks. The assumption for F5G is the need for up to 1 Gbit/s per subscriber depending on the user profile and subscription chosen. For F5G Advanced, the assumption is that users start to use up to 10 Gbit/s per subscriber.

In the optical transport and aggregation network, the predominant technologies in the F5G era provide 200G and 400G per lambda (OTN or Ethernet). Bandwidth growth in the F5G Advanced increases this to 800G per lambda, coupled with increasing the number of wavelengths over a wider optical spectrum per fibre. See clause 7.6 also on the aspects and usage of optical cross-connects in the edge of the network enabling lower energy consumption and high bandwidth.

The F5G optical access system is XG(S)-PON and is currently in deployment. The PON based systems, with its architecture, is kept in F5G Advanced and upgrades to 50G-PON for increasing the bandwidth in the Access Network. For certain more business-oriented scenarios, OTN is extended to the edge using fine-grain OTN (fgOTN) [i.2] allowing for sub-1G connections with hard isolation and hard guaranteed characteristics.

For the in-premises network, there are several means to improve bandwidth, including Fibre To The Room (FTTR) and upgrading from Wi-Fi® 6 to Wi-Fi® 7. With FTTR and its evolution to a higher bandwidth version, the benefits of fibre technologies are extended to home networks.

6.2.2 Real-time Resilient Link (RLL)

The emergence of interactive immersive experience services and digitization of the industry, are the major drivers for the dimension of Real-time Resilient Link (RRL) in F5G Advanced.

Interactive immersive experience services, including Cloud VR, AR, XR, etc., beside huge bandwidth requirements, the end-to-end latency, jitter and availability of the connections are also key performance issues for smooth user experiences. The network provides end-to-end high-quality links between the content servers in the datacentres and the end users across broad geographic areas.

The digitization of the industry is realized by novel industrial applications, as real-time data flows among machines and platforms with very strict requirements on deterministic transmission and nearly zero packet loss. The fibre-based network of F5G Advanced can provide real-time resilient links with PON and Wi-Fi® technologies. Novel fibre based optical buses can be deployed, which has the merits of higher bandwidth, immunity to electromagnetic interferences and longer life span comparing to conventional copper-based fieldbus connections. Interactive immersive services are needed in the industrial environment as well, since co-operations with remote technicians for machine installation and maintenance based on AR and XR technologies are used.

These emerging applications call for Real-time Resilient Link (RRL) to be part of F5G Advanced. The transport network, access network with PON-based fibre network and Wi-Fi® based wireless network, allow achieving RRL capabilities.

6.2.3 Guaranteed Reliable Experience (GRE)

Several aspects need to be taken into consideration when speaking of Guaranteed Reliable Experience (GRE). One aspect is that user experience is linked to subjective perception, and is also environment dependent. Besides that, in order to reliably guarantee a certain quality, mechanisms for appropriate resource management, allocation, control and isolation have to be implemented. Finally, as a basis for GRE, AI-based mechanisms with dedicated computing resources are needed.

The integration of computing into the network has several advantages. Computing can be used for better operation of the network including the capability to run AI-based training and decision algorithms. Computing can also be used to provide Compute Infrastructure as a Service (CIaaS), AI as a Service (AIaaS) or Software as a Service (SaaS) [i.3] to customers. From an operational perspective in-network compute capabilities are used to enhance the services for a better experience. The model to provide computing and storage as a service to customers allows for additional value-added services in any combination.

The integration of computing is a necessity when using Artificial Intelligence (AI) to make operation of networks and services smarter. In addition, AI in the network can be provided as a service to customers. Due to the amount of data for training and decision making the increase of computing power in the network is required and the amount of data distributed and gathered increases so that the network itself needs to be able to cope with that additional traffic.

In order to operate a more complex F5G Advanced network it is necessary to increase the autonomous network level. This targets the level 4 "high autonomy" in the TM Forum Autonomous Network definition [i.4]. This includes self-configuration, self-healing, and self-optimization in network operation. This in turn improves the user experience and service quality in several dimensions including:

- Automatic provisioning reducing the fulfilment time.
- Reliability guarantees by increased fault handling efficiency.
- Smart diagnosis of the network quality, enabling fast fault localization and predictive maintenance.
- Optimization of roll-out and capacity through intelligent predictive network planning.

Another aspect of a computing power network in GRE is the capability to increase the service richness. There is much more freedom to create attractive services beyond pure communication. Since the infrastructure can create or operate that plethora of services, smart management of those service is a pre-requisite.

6.2.4 Optical Sensing and Visualization (OSV)

Multi-modal sensing technologies enabled in optical networks and Wi-Fi® can be used to collect environmental data, such as vibration, temperature, pressure, strain and others, that combined with digital twin technologies can leverage the new awareness capabilities for networks and services (residential, enterprise, and industrial).

These sensing capabilities leverage a new wide range of applications for the F5G-A generation that is further explored, either as an enabler for services that need to gather information using optical and Wi-Fi® sensing or as a valuable tool to enhance network operations.

Optical networks are becoming ubiquitous, with a rapid deployment of optical fibre infrastructures that, being a passive resource, face several management challenges. Fibre sensing capabilities, using multiple optical signal detection technologies, collect information about the fibre topology and the insertion loss of each optical path. With the information a digital model (digital twin) of the optical network is created and accurately visualized. As consequence it is possible to detect real-time optical cable degradation, to predict the fibre health status, and to provide advance warning of a potential failures.

Another important area is the use of optical sensing technologies to identify shared route situations where the same cable and same duct are being used for the working and protection route, creating higher risk for service outages or degradation.

Some use cases addressing these topics were already approved by ETSI ISG F5G (see ETSI GR F5G 008 [i.6], use cases on "Intelligent Optical Cable management" and "AI-based PON optical path diagnosis", complemented with the "Digitalized ODN/FTTX").

There are other applications, not related to network management, which also leverage the use of optical sensing. Some examples are:

a) the oil and gas industry, where optical sensing can detect and localize intrusion and sabotage events around the clock and implement unattended inspection to improve pipeline reliability;

b) enhancing digital 3D map generation, and indoor robot navigation in smart factories;

c) early earthquake prediction using optical submarine cables.

The above-mentioned applications are not limited to the optical fibre used in communication networks, they can run over dedicated fibre if they have particular requirements on the type of fibre.

The sensing and visualization scenarios of F5G-A also includes Wi-Fi® sensing, specifically indoors, that is capable of capturing environmental parameters and enable the tracking of humans and animals.

Therefore, there is a wide application space for sensing technologies that leverages the importance of this new dimension for F5G-A.

The development of these sensing technologies aims for improved accuracy and scalability, setting visualization and sensing targets of 99 % accuracy and location identification precision within one meter.

6.2.5 Full Fibre Connection (FFC)

In F5G Advanced, both the network scope and number of endpoints are expected to increase. More services and a larger coverage with fibre and all-optical technologies are supported. The network scope is the area where fibre is deployed, which increases from the core of the networks more and more towards the edge and finally to the end-systems. The extension of the scope implies that the higher number of fibre end-points have impacts on other dimensions and the overall network architecture.

F5G Advanced aims to serve as the cornerstone of the cloud and digital transformation by providing ubiquitous high-capacity, high-performance, and high-reliability. Fibre optics can extend into the home, campuses and factories. To fit all these scenarios, the ease of deployment, environmental adaptability, high networking reliability, and accelerate the copper-to-optical transformation of many industries need be enhanced.

Scenarios driving this dimension include Fibre To The Room (FTTR), Fibre To the Desk (FTTD), Fibre To The Machine (FTTM) and Fibre To The Thing (FTTThing).

FTTR is improved with features for smart homes in F5G Advanced. FTTR integrates home/small office networking (intelligent connection of smart devices throughout the house) and edge computing (for example, Network Attached Storage (NAS)) to implement building-wide connections, control, storage, and computing capabilities This builds an all-optical foundation for smart homes and small/micro enterprises.

Fibre To The Machine (FTTM) provides fibre connectivity for the digitalization of industries integrating IT and OT technologies; it can be considered the foundation of the digital factory. Fibre has the advantages of large bandwidth, long distance, and anti-electromagnetic interference. FTTM needs to be supported by high network reliability and guarantee industrial explosion-proof, dust-proof, shock-proof, and anti-corrosion capabilities.

Fibre To The Desk (FTTD) is bringing fibre to many devices on campuses or offices. Services such as wireless projection (beamers with wireless connection to laptops), cloud desktop, and UHD video conferencing are to be supported. The up to 100-meter copper cable in the legacy office network cannot support the required bandwidth. Network architecture innovation is urgently needed to implement one-to-one optical fibre connections for campuses and offices. Using FTTD also allows to have a smaller footprint for cables and less need for Ethernet switches saving space in the buildings.

Fibre To The Thing (FTTThing) is to connect things with fibre. Things include devices such as cameras, machines, sensors, actuators, etc. The superior fibre connections are improving applications to provide various types of services. Devices connected directly by fibre serve as basis for intelligent systems. The use is very application and scenario dependent. The FTTThing is suitable for residential, enterprise, or vertical industry-oriented use cases.

NOTE: The assumption is that FTTThing is used in scenarios where connecting devices by fibre is suitable, in other scenarios a wireless connection of the things might be more appropriate.

6.2.6 Green Agile Optical-network (GAO)

Sustainability is a major global challenge raising the quest for a greener and agile optical network, which is a new dimension for F5G Advanced. Several countries and enterprises set specific objectives to become climate neutral in the near future. For example, the European Union (EU) approved in 2020 the European Green Deal that sets several policy initiatives to achieve climate neutrality in 2050.

ICT plays an important role to achieve the sustainability objectives improving energy efficiency in several sectors by automating processes in business and industry, by enhancements to a digital life enabling efficient remote work, education, e-health or e-government, reducing the need for user mobility. The evolution to more energy efficient F5G Advanced optical networks contributes significantly to those goals.

In the access networks, the replacement of legacy copper-based networks (like xDSL and coaxial-based networks) by Passive Optical Networks (PON) brings significant energy savings that goes beyond 50 % energy reduction. In transport networks, the adoption of all-optical E2E networking, with simpler architectures, Optical Cross-Connects (OXC), minimizing optical-electrical-optical conversions will allow achieving a greener network infrastructure.

The objective proposed for F5G Advanced is to be 10 times more energy efficient than F5G. In order to achieve this objective, it is essential to develop an E2E high level design for energy efficiency, exploring novel network architectures and improve the energy efficiency of equipment. For example, energy usage can be reduced by F5G Advanced technologies such as energy aware switching and routing, power saving modes, optical networks integration with mobile and wireless access points, dynamical allocation of processing power and others.

Finally, F5G Advanced considers mechanisms and migration capabilities that minimizes the carbon footprint for the overall life-cycle of the network infrastructure elements.

6.2.7 Key Cross-dimensional Aspects

6.2.7.1 Latency

Latency is an aspect needed along various dimensions. RRL together with eFBB (Enhanced Fibre Broadband), can provide ultra-high bandwidth and reliable transmission capability for the target applications. The latency aspects of GRE, defined in ETSI GR F5G 001 [i.12], are also addressed by RRL, supporting more stringent latency requirements. RRL is therefore an important aspect to help achieving GRE in F5G Advanced.

6.2.7.2 Artificial Intelligence

Since AI, computing, and autonomous networks are relevant to the other dimensions in F5G Advanced, care need to be taken to have a holistic perspective on the overall system. As shown above, AI application in networks requires computing for learning and decision making and it requires high-speed networking for transporting data to the AI computing. This needs the enhanced Fixed Broadband (eFBB) capabilities. When decisions need to be taken in a very short time, latency of the network and computing matter and therefore, the Real-time Resilient Link (RRL) capability is relevant for the operations on networks and services. For the Full-Fibre Connectivity (FFC), the operation of networks needs to be automatic, otherwise scaling up the number of fibres, service session, and end-points cannot be managed properly and cost efficiently. With regard to energy usage, a trade-off needs to be found in terms of where compute is placed and what is computed.

Computing resources use additional energy, but they might be located where energy is produced without emissions. By centralizing computing resources, multiplexing gains can be achieved and therefore decrease the overall energy usage. The Optical Sensing and Visualization (OSV) capability interacts with the GRE dimension because sensed information can be a primary input to AI for applications and for an improved operational efficiency. Visualization of the results of AI and guaranteed experience improve the credibility and operation of the network and services. The GRE capability dimension interacts with and relies on many other aspects of F5G Advanced. Only a high-level relationship between them is shown here.

6.2.7.3 Fibre to Everywhere and Everything

All of the Full-Fibre Connection (FFC) aspects described above interact naturally with all other dimensions. Many of applications need high bandwidth, low latency and jitter, reliability, sensing, and autonomous networking. Fibre is the primary technology addressing those needs.

6.2.7.4 Sensing for Operational Excellence

The sensing capabilities of optical fibre as can be used manifold, but also as a mean to improve operational excellence in networks. It includes the use of sensing technologies on various levels, and the use of AI to make decisions based on the sensed information.

7 Key enabling technologies

7.1 Key Enabling Technologies for eFBB

7.1.1 The components of eFBB

Enhanced Fibre Broadband (eFBB) is about improving the network capabilities and performance and improving the quality perceived by the user. This can be broken down into three major divisions of technology. The first is supporting more capacity from end-to-end in the network data plane. The second is exploiting the pure communication capacity to deliver useful services leveraging the signalling plane. The third is providing multiple control schemes in the management plane to enable a rich ecosystem of various types of services.

The most fundamental enhancement is to increase the capacity of the network. This upgrade needs to happen in all segments of the network: transport, access, and customer premises. The transport network is growing in multiple ways: by increasing the number of fibres and wavelengths in use, but also by increasing the capacity per wavelength to 800 Gb/s. The access network expands from 10G-PON to 50G-PON, while maintaining the same ODN and overall design concept to promote early and economic upgrades. The customer premises network upgrades to Wi-Fi® 7, which provides higher peak rates and total capacity, as well as other advanced features.

Raw capacity is not enough unless it can be harnessed into efficient and useful services. Most networks are based on the TCP/IP protocol stack. Alternatively, OTN technology can be used to avoid the routing and processing overhead and provide guaranteed low latency. In particular, fine grain OTN (fgOTN) has the capability of making many thousands of micro connections over the OTN infrastructure. In this way, OTN can be transformed from a long-distance inter-router transport technology into a user service platform. Services such as wireless front-haul are special, in that they need their own physical layer connections using dedicated wavelengths.

Management and control systems are another important aspect. They use cloud-native orchestrator and controller systems. These avoid the need for dedicated computing resources, instead profit from cloud technologies. The technique of network slicing enables competitive service providers to work alongside each other on the same basic infrastructure. Savvy users who want a lot of control the network services directly. In contrast, many users would like to avoid management and its complexity, for these data-driven AI-based management is the right approach by observing the users' traffic and determining the optimal configuration.

7.1.2 The segments of the network (data plane)

Transport: 800G OTN

800G OTN (Optical Transport Network) refers to the utilization of OTN technology to achieve a data transmission rate of 800 Gigabits per second (Gbps). OTN is a standardized optical networking protocol that enables efficient and flexible transport of data over fibre optic networks. The key aspects and benefits of 800G OTN include:

- Higher Bandwidth: 800G OTN provides a significantly increased data transmission rate compared to previous OTN generations. This caters to the growing demand for bandwidth-intensive applications, cloud services, and emerging technologies.
- Multiplexing and Aggregation: 800G OTN employs advanced multiplexing. This aggregation optimizes the utilization of network capacity and enables efficient transport of multiple services and traffic types over a single optical wavelength.
- Forward Error Correction (FEC): 800G OTN incorporates FEC mechanisms to enhance transmission reliability caused by optical impairments.
- Network Flexibility and Scalability: 800G OTN offers network operators the flexibility to allocate and manage bandwidth in a granular manner. It supports dynamic provisioning of bandwidth to adapt to changing traffic demands.
- Compatibility and Interoperability: 800G OTN is designed to be backward compatible with previous OTN generations, ensuring smooth coexistence and seamless integration with existing network infrastructure, avoiding a complete overhaul of the network.
- Network Resiliency and Protection: 800G OTN incorporates protection mechanisms, such as 1+1 linear and ring protection, to ensure network resiliency and minimize service disruptions.
- Standardization and Interoperability: 800G OTN is based on standardized protocols and interfaces, enabling interoperability between different vendors' equipment and network elements, promoting a competitive market and network operator choice.

800G OTN represents a significant advancement in optical networking technology, addressing the escalating demand for higher bandwidth and more efficient transport networks. It offers increased capacity, flexibility, and reliability, empowering service providers to deliver high-speed and high-quality data transport services to meet the requirements of data-intensive applications, services, and emerging technologies in a rapidly evolving digital landscape.

Access: 50G-PON

GPON and its successor XG(S)-PON are largely deployed in the world, approaching 1 billion homes served by the technology. Simply put, PON technology is kept also for the next generation of fixed ultra-broadband. PON systems use an Optical Distribution Network (ODN) that is single fibre (working bidirectionally), using passive splitters to connect a shared Optical Line Terminal (OLT) to many Optical Network Units (ONUs) located at the customer's premises. Each piece of equipment has a single transmitter and a single receiver to minimize its cost and to permit the maximum sharing of the bandwidth.

The next generation of PON equipment is 50G-PON. This system leverages many of the proven design concepts of the XG(S)-PON system. Some of these are:

- Increased capacity: 50G-PON provides 50G bps downlink and 12,5G/25G/50G bps uplink capacities, which support various applications including residential scenarios (mainly asymmetric in downlink/uplink) and business scenarios (mainly symmetric) which need 10 Gbps connectivity.
- Reuse existing ODN infrastructure: 50G-PON defined PMD specifications to support same ODN which is used in GPON and XG(S)-PON to protect the capital expenditure of infrastructure.
- Smooth evolution: 50G-PON wavelength plan enables its coexistence with either GPON or XG(S)-GPON(Either/Or), or coexistence with both (GPON/XG(S)-PON/50G-PON three generation coexist), also the capability of coexistence with IEEE symmetrical 10G-EPON, this gives operators flexibility during upgrading their access network with minimum needs of touching ODN and end users.

- Latency optimization and reliability: 50G-PON introduced latency control schemes to meet requirements of industrial scenarios. Same as GPON and XGS-PON, 50G-PON supports Type-B/Type-C protection to meet reliability requirements.

Customer premises: Fibre-fed Wi-Fi® 7

Currently, Wi-Fi® 6, also known as IEEE 802.11ax [i.20], is the newest widely deployed Wi-Fi® technology. Wi-Fi® 7, also referred to as IEEE 802.11be [i.21] is the next standard that is expected to succeed Wi-Fi® 6. This system provides the following advancements over previous Wi-Fi® generations:

- Higher data rates: Wi-Fi® 7 offers even higher data rates compared to Wi-Fi® 6. This would enable faster wireless communication, supporting applications such as 8K video streaming, virtual reality, augmented reality, and other data-intensive tasks.

- Increased capacity: Wi-Fi® 7 introduces techniques to enhance network capacity, allowing more devices to connect simultaneously without experiencing performance degradation. This can be achieved through multiple-access technologies and improved interference management.

- Lower latency: This improvement would be beneficial for real-time applications like online gaming, video conferencing, and IoT (Internet of Things) devices that need immediate responses.

- Enhanced security: Wi-Fi® 7 ensures the integrity of wireless connections. This includes stronger encryption protocols, improved authentication methods, and enhanced safeguards against various types of attacks.

- Improved power efficiency: Energy efficiency is an important consideration for wireless devices. Wi-Fi® 7 aims to optimize power consumption, enabling devices to operate for longer periods on battery power and reducing the overall energy consumption of Wi-Fi® networks.

Wi-Fi® 7 faces some fundamental hurdles to achieve these performance goals. Most important is the lack of accessible spectrum. Sub-6 GHz spectrum is very difficult to obtain, partly because it is very useful, being the highest frequencies that still penetrate most construction materials. Millimetre wave spectrum is available, but it cannot penetrate walls in many buildings. Hence, to enable the use of mm-waves, an access point needs to be placed in almost every room. These distributed AP's need to have a backhaul solution to interconnect them back to the main access point in the building. Fibre to the room systems as well as other LAN technologies provide this.

7.1.3 End-to-end services

IP-based connectivity: conventional and otherwise

Internet Connectivity is the most fundamental IP service and provides access to the world-wide data network. The current IP infrastructure has evolved over time from a very basic computer inter-working system to the most prevalent networking technology in the world. Currently it allows users to access a wide range of applications, such as the following:

- Web-based Services: search engines, social media platforms, video streaming, online shopping, cloud storage, and collaborative tools, etc.

- Voice over IP (VoIP)

- Messaging and Communication

- Cloud Computing

- Virtual Private Networks (VPNs)

The evolution process continues, with new features added and new services supported:

- Internet of Things (IoT): IoT devices are different compared to traditional end-systems. Most obviously is their huge number, expecting 10 to 100 times more endpoints than traditional applications. They also tend to be power limited such that sleep-modes and remote powering techniques need to be supported.

- Mobile 5G and Beyond: Connecting wireless endpoints to the fixed network requires solving mobility in a way that is highly efficient and quickly adaptive to movement and network conditions.

- Data-centric networking: The vast majority of Internet traffic is data being accessed by users from a repository. stored anywhere in the network.
- Cloud Computing: A fast growing sector of networking is supporting cloud computing.

These are just a few examples of the current and future IP services and features. As technology advances and new innovations emerge, IP continues to be the underlying protocol that enables a wide range of services, connecting people, devices, and systems in increasingly sophisticated and transformative ways.

Fine-grain Layer1/2 services: fgOTN

Fine-grain OTN (Optical Transport Network) refers to a specific implementation of the OTN technology that provides enhanced flexibility and granularity in allocating bandwidth and managing optical network resources. It is designed to meet the increasing demands for high-capacity and highly flexible transport networks. In traditional OTN networks, the bandwidth allocation is based on fixed-size containers called Optical Channel Data Units (ODUs). These containers have predefined sizes, such as ODU0, ODU1, ODU2, etc. However, fine-grain OTN introduces smaller-sized containers, enabling more granular and efficient use of the network resources. The key features of fine-grain OTN include:

- Flexible Container Sizes: Fine-grain OTN introduces smaller container sizes, leveraging ODUflex techniques. Unlike the fixed-size ODUs, ODUflex allows network operators to dynamically allocate bandwidth in smaller increments, ranging from ten Mb/s to several Gb/s. This flexibility enables more efficient utilization of network capacity and allows for better adaptation to varying service requirements.
- Bandwidth-on-Demand: Fine-grain OTN enables the concept of "Bandwidth-on-Demand" by allowing dynamic adjustment of the container size based on real-time bandwidth needs. It provides the ability to allocate or deallocate bandwidth as needed, enabling service providers to deliver more flexible and elastic services to their customers.
- Efficient Multiplexing: Fine-grain OTN supports the efficient multiplexing of different-sized containers within the same wavelength, allowing for optimal utilization of the available network capacity. It enables the aggregation of various services and traffic types, including Ethernet, storage traffic, and legacy SDH/SONET, simplifying management and reducing equipment costs.
- Sub-Wavelength Level Protection: Fine-grain OTN enhances network resiliency by providing sub-wavelength level protection mechanisms. It allows for the independent protection of individual containers within a wavelength, ensuring that the failure of one is isolated.
- Service Differentiation: Fine-grain OTN enables service differentiation by offering varying levels of quality of service (QoS) guarantees for different containers. This allows for optimized resource allocation and improved service performance.

Fine-grain OTN provides greater flexibility, scalability, and efficiency in managing optical network resources compared to traditional fixed-size OTN containers. It enables service providers to meet the diverse requirements of different applications and services while maximizing the utilization of their network infrastructure.

Special services, e.g. fronthaul

While IP or OTN network provide a versatile service framework, there are inevitably those services that cannot tolerate any 'middleman' between themselves and the medium. The archetypical example is wireless front-haul, which connects the remote radio units to the distributed units that process the data. These links are both high speed and ultra-low latency and jitter. While it is possible to carry these over IP, Ethernet, or OTN systems, it is often more economical to just provide dedicated wavelength links. There are several types of access systems that can be used for this purpose:

- Point to point fibre: The simplest scheme uses traditional two fibre links between duplex optical modules. This leverages the large volume of Ethernet optics which are very cost effective. However, it does consume a large amount of fibre which can become prohibitive.
- Bidirectional fibre links: The next step is to use single fibre links between bidirectional optical modules. This cuts the fibre requirement by 50 %. Bidirectional optics also have the feature that the transmission delay is nearly the same in either direction. This permits accurate time of day distribution, which is often needed in wireless systems.

- WDM-PON: This type of system multiplexes many bidirectional links onto a single common fibre. There are several system standards for a WDM-PON style network: some operate in the C-band, while others operate in the O-band. Some employ tuneable ONU optics, while others need the correct colour optics installed in each ONU.

In most front-haul systems, the DU is located in the central office which is at the junction of the access and transport network. This means that the front-haul links terminate at the office, and the transport network is not required. In the rare case that it is needed, the optical transport network can certainly provide end-to-end wavelength services.

7.1.4 Management and administration

Conventional integrated OAM

Legacy systems with separately hosted network and element management systems are deployed in many networks and infrastructures. These systems typically involve the use of traditional Simple Network Management Protocol (SNMP)-based interfaces or more recent NETCONF/YANG interfaces for managing and controlling network elements.

In parallel with these legacy systems, newer cloud-native orchestrator and controller systems are gaining traction. These systems leverage cloud computing technologies, such as virtualization and containerization, to provide network orchestration and control functionalities. They eliminate the need for dedicated computing resources and enable more scalable and flexible network management. Cloud-native orchestrator and controller systems often utilize modern Software-Defined Networking (SDN) and Network Functions Virtualisation (NFV) principles. They allow for dynamic provisioning of network resources, policy-based management, and efficient deployment and scaling of network services. These systems also open up the development space to a broader range of entities, including third-party vendors and developers, who can build and deploy applications and services on top of the infrastructure.

Network slicing

Network slicing allows the partitioning of a physical network into multiple virtual networks. Each network slice is an isolated, end-to-end virtual network instance that can be customized to meet specific requirements of different applications, services, or tenants. With network slicing, the management problem can be split up into arbitrary pieces, allowing different entities, including competitive service providers, to coexist and operate independently within the same underlying physical infrastructure. Here's how network slicing enables competitive service providers to work alongside each other:

- Resource Isolation: Each network slice operates as a separate, virtualized network instance with dedicated resources. This isolation ensures that the performance, security, and quality of service for one slice are independent of other slices. Competitive service providers can have their own dedicated network slices, enabling them to deliver their services without interference.

- Customization and Service Differentiation: Network slicing allows service providers to tailor the network characteristics, such as latency, bandwidth, reliability, and security, to the specific requirements of their services. This customization enables service differentiation, allowing providers to offer unique and specialized services that cater to their target market segments.

- Independent Management and Control: Network slices have their own management and control functions, enabling service providers to have autonomy over their slice operations. This independence fosters healthy competition and enables multiple service providers to coexist on the same infrastructure.

- Efficient Resource Utilization: Network slicing enables the efficient sharing of physical resources among multiple service providers. By dynamically allocating and reallocating resources based on demand, the underlying physical infrastructure can be utilized more effectively, leading to cost savings and optimized resource utilization for each provider.

Overall, network slicing allows for the virtual partitioning of a network infrastructure, enabling competitive service providers to operate independently and offer differentiated services. It promotes collaboration, competition, and innovation within the same underlying infrastructure, making it an attractive concept in the context of modern networking ecosystems.

User-driven management

Enabling users to manage their network services directly can revolutionize the customer-provider relationship and empower the user to make their own choices regarding upgrading their services and experience. Ultimately, only the users know what they want, and self-service schemes can permit them to get what they want when they want it. Implementing self-service portals or dashboards allows users to access and manage their network services directly. These portals provide user-friendly interfaces that enable users to perform tasks such as provisioning, configuration changes, monitoring, and troubleshooting. By providing intuitive tools and controls, users can have more control over their network services without relying on intermediaries.

Enabling technologies for user-driven management includes SDN and NFV. With SDN, users can have programmable interfaces or APIs that allow them to directly interact with the network infrastructure. Through these interfaces, users can define and manage their network services, set policies, and make real-time changes to adapt to their specific needs. NFV decouples network functions from proprietary hardware and implements them as virtualized software instances. This virtualization allows users to manage their network services through software-based interfaces. Users can select, deploy, and manage Virtual Network Functions (VNFs) according to their requirements, scaling them as needed and potentially reducing reliance on physical equipment.

An important aspect is the provision of Application Programming Interfaces (APIs). By exposing well-defined APIs, network service providers can enable users to directly interact with and manage their services. APIs provide a standardized way for users to automate network management tasks, integrate their services with other systems, and customize their network configurations as desired. Network service orchestrators also play a role here because they provide higher-level abstraction and automation of network services. These orchestrators allow users to define, deploy, and manage complex network service chains, comprising multiple interconnected components. Users can leverage these platforms to directly control their service orchestration and adapt the network behaviour to meet their specific requirements.

It is important to note that the level of direct management control provided to users may vary depending on factors such as the user's sophistication level, the service provider's policies, security considerations, and the complexity of the underlying network infrastructure. However, these approaches can provide varying degrees of empowerment to users, allowing them to manage their network services more directly and flexibly.

Data-driven control

Many users may prefer to avoid the complexities of network management and would rather have automated systems handle the task for them. In such cases, data-driven AI-based management can play a crucial role in observing users' traffic patterns and determining optimal network configurations. The potential steps in this process include:

- Traffic Analysis: AI management systems can analyse network traffic data to gain insights into users' behaviour, application requirements, and network performance. By collecting and processing data from various sources, including network devices, logs, and monitoring tools, the AI system can build a comprehensive understanding of the network environment.

- Anomaly Detection: AI algorithms can continuously monitor network traffic patterns and identify any anomalies or deviations from normal behaviour. By comparing current traffic patterns with historical data or predefined thresholds, the AI system can detect unusual or suspicious activities that may need attention.

- Performance Optimization: Based on the analysis of traffic patterns and performance metrics, AI management systems can determine the optimal configuration settings for network devices, such as routers, switches, and load balancers. By dynamically adjusting parameters like bandwidth allocation, routing policies, and Quality of Service (QoS) settings, the AI system can optimize network performance and ensure efficient resource utilization.

- Predictive Maintenance: AI algorithms can analyse network performance data and detect potential issues or bottlenecks before they cause service disruptions. By identifying patterns that lead to performance degradation or failures, the AI management system can proactively recommend maintenance actions, upgrades, or repairs to prevent service outages.

- Automated Remediation: In the event of network issues or service disruptions, AI management systems can automatically initiate remediation actions. By leveraging predefined policies or learned patterns, the system can take corrective actions, such as rerouting traffic, applying traffic prioritization, or reallocating resources, to restore service levels and minimize the impact on users.

- Continuous Learning: AI management systems can continually learn from new data and adapt their decision-making processes accordingly. By applying machine learning techniques, the system can improve its accuracy and effectiveness over time, enhancing its ability to make optimal network configuration decisions based on evolving traffic patterns and user requirements.

By leveraging data-driven AI-based management, users can benefit from automated network configuration and optimization, reducing the need for manual intervention and expertise. This approach can improve network performance, reliability, and responsiveness while freeing users from the complexities of network management. However, it is important to ensure that AI management systems are properly trained, validated, and regularly monitored to maintain accurate and reliable results.

7.2 Key Enabling Technologies for RRL

7.2.1 Latency control technologies

7.2.1.1 Deterministic Networking for home/campus scenarios

Latency and jitter of Wi-Fi® interfaces are key bottlenecks in home/campus office scenarios. Wi-Fi® 7 uses OFDMA technology, multi-user resource allocation, and multi-link coordination algorithms to implement RU slicing over the air interface. This effectively reduces conflicts over the Wi-Fi® air interface, improving service forwarding delay and jitter, and achieving a deterministic low latency of milliseconds to meet service requirements such as Cloud VR, AR, XR, etc.

The optical access network introduces several new technologies for optimizing latency and jitter performance, and provide deterministic networking capabilities. These technologies including single-frame multi-burst (frame-based dense burst allocation) technology, optimization of quiet window opening, dual-plane forwarding, and collaborative Dynamic Bandwidth Allocation (DBA), etc.

Single-frame multi-burst (frame-based dense burst allocation) technology: in a traditional BWmap, one T-CONT is allocated only one time slot to transmit one burst in one 125 µs frame, thus, the maximum latency for a user data packet can be as large as 125 µs. To reduce the maximum latency, the number of bursts of one T-CONT in one frame can be increased, thus cut short the time cycle, and the latency can be reduced accordingly.

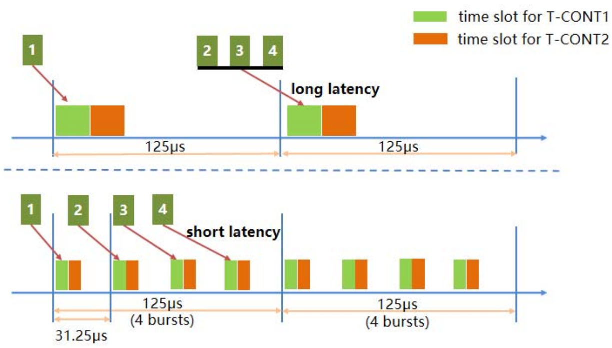

Figure 2: Illustration of the single-frame multi-burst (frame-based dense burst allocation) technology

- Optimization of quiet window opening: the quiet window opening in the upstream direction of the PON system, introduced a 250 µs latency for the user data packets, it can be optimized with configurable variable opening length, and further an independent wavelength pair can be used to eliminate these additional latency and jitter.

- Dual-plane forwarding architecture: it adds the TDM forwarding plane to the existing packet forwarding plane. The traffic that is handled by the TDM-plane can be easily handed over to an OTN/fgOTN system, reducing latency even further.

On an optical transport network, the intrinsic fibre latency per kilometre is 5 μs. The fibre latency is a major contribution to the end-to-end link delay. Selecting the optimal (shortest) physical path based on the network service direction or traffic ownership can greatly reduce the latency. In network planning, multi-path mesh or mesh structure can be considered. The network architecture supports all-optical grooming and small-granularity electrical grooming capabilities, improving the low-latency grooming capability of the network to meet service requirements. The next-generation OTN container technology for small-granularity bearer greatly reduces the latency of a single-node devices by reducing multiplexing layers based on virtual channel technology. Connections that meet deterministic low-latency requirements can be based on hard segregated traffic pipes.

7.2.1.2 Deterministic Networking for industrial scenarios

In industrial scenarios, the requirements of latency and jitter are much stricter than home/campus scenarios, and resilience of network is also crucial. Industrial scenarios can even be divided to two sub-scenarios:

1) **Manufacture line field bus (FTTM)**

   In this scenario, short reach manufacture line field bus which carries real-time signals, e.g. signals between controller and actuator, with a range from hundreds of metres up to less than 1 km. In this case, network delay can be below 0,1ms and jitter needs 0,01ms, with reliability in the order of 99,9999 %.

   To meet strict latency and jitter requirements, PON with the combination of single-frame multi-burst (Figure 2) and a dedicated wavelength or an auxiliary management and control channel (AMCC) is used. Type-C protection defined in [i.5], is used to improve the link resilience of the network (also see use case #24 in [i.4]). Furthermore, schemes to deal with the link outage caused by rogue ONUs can be adopted to improve reliability.

   Current PON technology is TDMA based, causing uplink latency, jitter and potential rogue ONUs (even the probability is extremely low), which limits the performance. Other schemes, for example, FDMA-PON is based on a P2MP (point-to-multi-point) ODN and can provide high resilience and a real-time link with latency down to tens of microseconds in both uplink and downlink, nearly zero jitter, and rogue-ONU free connectivity.

2) **Network for large area factory**

   Large factories, e.g. petrochemical works, mines, transportation, often have one headquarter and multiple branches, with distance between branch and headquarter that can be up to 20 to 40 km. In this case, latency between field devices to the headquarter might be not more than 1ms, with reliability in the order of 99,9999 %.

   To meet such strict latency and jitter requirements, similar technologies mentioned in previous 'Manufacture line field bus (FTTM)' part can be also deployed.

   ITU-T OTN/fgOTN can be used to connect branches to headquarter. which are based on ODUk over synchronous TDM bit stream, this "hard" pipe makes the delay of traffic is low and stable, hence almost zero jitter. OTN/fgOTN also provide isolation of service traffics which carried in different pipes. ODUk container is packed at start point and unpacked at end point, it is transparent to interim devices and is of high security.

7.3 Enabling technologies for GRE

7.3.1 Overview

The GRE dimension includes the improvement of service experience for users, and the improvement of operational efficiency for network operators.

To achieve this improvement, the capabilities of the holistic F5G Advanced network system, including the network equipment and the network management and control in different network segments, need to be enhanced. Many key enabling technologies for other dimensions in F5G Advanced also apply to the GRE dimension. To avoid overlap, the present clause mainly focuses on the technologies used for improving the service life-cycle management, and the network operation, management and control.

7.3.2 Improving the efficiency of network operation

7.3.2.1 Autonomous Network

Artificial Intelligence (AI) technology has been continuously and rapidly developed, and has been successfully applied in many technical areas including the communication network, greatly advancing the network intelligence and improving the network operation experience.

The TM Forum IG1218 [i.7] defines the general Autonomous Network framework, which positions the intelligent systems across the resource operation layer, service operation layer and business operation layer. It also defines the closed control loops within the Autonomous Domains, and the cross-layer control loops using intent-driven interfaces.

To provide a common understanding of intelligent network, TM Forum IG1230 [i.8] defines the Autonomous Network levels framework (from Level 0 to Level 5), based on the participation of the human and systems in the general network management workflow.

In order to enable self-configuration, self-healing, and self-optimization in the F5G Advanced fixed network operation, it is necessary to reach the Autonomous Network Level 4 - "High Autonomous Networks". The key distinguishing technologies of Level 4, compared with Level 3, are the introduction of AI in the network for intelligent network status analysis, and based on the result of the analysis automatic decision-making enabling the intent-driven network operation.

7.3.2.2 Network digitalization

Optical networks are complex analogue systems. They cannot be accurately visualized and modelled, which makes network performance monitoring, network capacity improvement, and fault locating and recovery difficult.

Therefore, optical network digitization plays a key role for the improvement of the operational excellence in F5G Advanced.

It involves the setting up of a sensor system at four different parts of the optical network: optical fibre link, optical component, optical channel, and the service layer observed at the optical channel. The goal is to setup a comprehensive, precise, and real-time mass data collection system.

Autonomous networking requires the digitization of optical networks, including the conversion of analogue signals of the original optical system into digital signals. Based on the data, NEs integrate intelligent prediction and awareness algorithms to further build autonomous capabilities such as proactive fault prediction, automatic recovery, self-optimization of transmission performance, and automatic power consumption control.

The core of optical communication network digitization are the sensors. With digital signal processing, various optical link impairments can be detected, calculated and even compensated for. One typical example of an optical sensor is an Optical Time Domain Reflectometer (OTDR). Using the OTDRs, network management systems can obtain information of the connection properties of the fibre, such as insertion loss and ageing status. Another example is an Optical Channel Monitor (OCM) which can detect optical power and centre frequencies of signals of each wavelength, used for channel planning or power balancing in a WDM system.

The digital ODN in access networks is an example for improving operational excellence. It supports image recognition and QR code scanning, helping carriers to automatically restore the ODN network topology and achieve 100 % accuracy of ODN port resources, greatly improving installation and O&M efficiency. Besides, with the continuous development of digital ODN technologies, the solution uses the coherent optical signal analysis technology to automatically detect and analyse ODN link loading, implement dynamic real-time ODN topology restoration, minute-level fault diagnosis, and meter-level fault localization, greatly improving the network O&M efficiency.

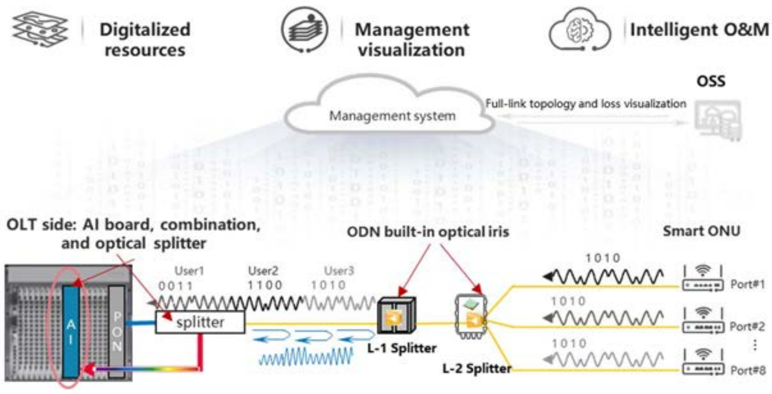

Figure 3: Example of Digitalized ODN in Access Networks

7.3.2.3 Intent-driven management

The intent is defined a "formal specification of the expectations, including requirements, goals, and constraints, given to a technical system" (ETSI GR ZSM 011 [i.9]). In an intent-driven network, an intent describes operational objectives that the network needs to meet and the results the network delivers, rather than specifying how they are achieved or implemented.

The intent-driven network provides a natural and efficient way of interacting between humans and machines, and interaction between machines. It shields the technical complexity of the underlying network, enables O&M personnel to focus on the value of the network, and simplifies the interaction between service domains. It also gives the network management and control system the flexibility to explore various solution options and determine the optimal one.

As a typical application, the intent-driven approach can be used for the service provisioning (e.g. high-value private line services or home broadband services). The customer can express their service expectations (e.g. the target SLA requirements including service type, bandwidth, latency and availability) through an intent-driven interface to the network controller. The network controller can translate the customer's intent into detailed network configuration, and trigger the detailed network provisioning and maintenance processes, for example, intelligent path computation based on multiple path computation factors, real-time precise location of network bottlenecks, and adaptive optimisation of optical and Wi-Fi® networks. In this way, it can improve the service time to market by providing automatic service provisioning without or with less manual intervention, and can ensure the user-level service experience in real-time.

7.3.2.4 Intelligent fault management

Fault management is one of the most critical processes in the network operation and maintenance procedure. To reach Autonomous Network Level 4 in the fault management process, the F5G Advanced network needs to perform network status analysis to identify the network faults or risk of faults, to determine the root causes and the suggested recovery procedure. In the most ideal situation, network faults can be detected and rectified before service interruptions occur, without being noticed by the users. In this way, the network O&M efficiency is greatly improved.

In an optical network, a single fault may cause a large number of alarms in multiple network elements in multiple network layers, increasing the difficulty identifying the root cause. Manual process on root cause analysis requires technician's expertise, which is not real-time and not very efficient. Another way is to build up a rule-based system, which includes as many pre-defined alarm correlation rules as possible, and uses these rules to perform root cause inference. The difficulty lies in that there are too many variations of alarm correlation rules to be pre-defined and included in the system, due to the heterogeneity of different network compositions or domains.

Knowledge graph [i.10] and Large Language Model (LLM) [i.11] are two enabling technologies for the root cause inference. Take Knowledge graph as an example, once the knowledge graph is established, it can use a variety of relational inference technologies such as graph-based AI algorithm to learn new inference rules, and then to update itself. With such a self-learning system, real-time fault identification and root cause analysis can be determined by the inference rules, greatly improving the efficiency and accuracy of fault management.

7.3.3 Improving the user experience of network services

7.3.3.1 Overview

The key point to improve the users' service experience is to ensure the quality of the services, namely for premium services with more stringent requirements.

In F5G Advanced, premium services are typically deployed in the Cloud DCs, to take full advantage of shared cloud infrastructure, and to make full use of high-performance cloud computing resources. Different types of high-performance computing resources are normally distributed in different Data Centres, so there is a need to build a high-quality computing interworking network to interconnect the users and the distributed computing resources, which could possibly include CPN, access, aggregation, core, and Data Centre networks.

The computing resources are used in a task-based manner, driven by the users' services. This requires the high-quality computing power network [i.18] to enhance the system capabilities in terms of elasticity, flexibility, and intelligent scheduling to provide network resources on demand. In this way, the network resources can be obtained when used and released when no longer needed.

Another import factor for the user experience of network services relies on the quality and consistency of the "last meter" connection. This connection is often provided by using Wi-Fi®, requiring good control and coordination mechanisms for the surrounding APs, where FTTR can be an important enabler.

7.3.3.2 Awareness of optical network information

The F5G Advanced system needs to obtain the optical network topology and resource information, so that it can perform optimal path computation based on multiple factors such as bandwidth, latency, reliability, and packet loss rate.

Optical networks provide deterministic and ultra-low network latency both at the optical wavelength layer and electrical layer. With the latency information from the optical networks, the F5G Advanced network can identify the different hierarchical physical segments, and in each segment the network latency can be guaranteed to be below a given value. In this way, a "latency map" can be built up on the physical optical networks. The computing resources can be deployed in different physical segments (e.g. metro, regional, and cross-regional network), to meet different latency requirements of differentiated computing services.

7.3.3.3 Elastic resource scaling

One of the most well-known and used function of today's cloud technologies is elastic scaling, which enables the "as a service" model. In a centralized cloud, scaling -up, -down, -in, and -out are well-known and implemented. The scaling mechanisms need to take the resource usage and workload placement of resources into account. In a distributed computing scenario, the workload placement and required resources needs to be considered for intelligent decisions on what workload to place at what location needing a certain number of resources.

To support the transmission of such elastic scaling cloud computing services, the network resources need to be dynamically scheduled and adjusted on demand. In this way, resources can be reused by multiple services in a time division manner, achieving efficient utilization.

The optical network has the characteristics of ultra-large capacity, ultra-low latency and packet jitter that best fit for the high-quality cloud computing services. In F5G Advanced, the optical network needs to be further developed the elasticity and flexibility aspects, and therefore could be used as a service network for the distributed computing services. The key enabling technologies include:

- The optical network needs to quickly respond to the service transmission requirements, and has the capability of rapidly establishing connections at an optical level (e.g. wavelength connections) or at an electrical level (e.g. Optical Data Unit (ODU) connections), with the appropriate bandwidth that fits to the service request. In a typical example, the wavelength connections can be created within several minutes, while the ODU connections can be created within several seconds.

- The optical network needs to support different granularities of connection bandwidth, to best fit for different cloud computing requests. Furthermore, lossless bandwidth adjustment (e.g. from tens of Mbps to Gbps-level) of the electrical connections needs to be supported based on the changing service requirements.

- To enable the task-based mode, the optical network needs to be aware of the identification information of different cloud computing services, as well as the associated network requirements (such as destination cloud DC, bandwidth requirements and priority). In this way, it can provide correct optical connections (such as wavelength or ODU connections) on demand, driven by the computing tasks. In addition, the service traffic can be automatically identified and steered into its corresponding optical connection by the edge node of the optical network. This provides the assurance of an agile and effective computing task scheduling process.
- To protect the cloud computing services against network failures, the optical network needs to ensure the high availability (≥ 99,999 %) of the optical connections, and to provide mechanisms to enable the deterministic recovery time and recovery route.
- To support the increasing number of users, DCs and distributed computing applications, the optical network expands, and the number of connections per port increase in orders of magnitude, to carry massive number of distributed computing services. New control plane technologies need to be developed to support the expanding optical network.

7.3.3.4 Joint optimization of optical network and cloud computing resources

Cloud computing services are becoming increasingly important. Coordination of network and cloud computing resources on the management plane, control plane and data plane is necessary, which is beneficial for the joint optimization of the optical network and cloud computing resources.

In such case, the service capability information, such as computing resource deployment location, computing power type, remaining computing power, and computing power level, needs to be periodically collected, to generate the visualized computing resource map. Together with the resource map / latency map of the optical network, the joint optimization of optical network resources and cloud computing resources can be implemented.

Various optimization strategies are possible and allow service providers and users to make trade-offs between resource usage and service quality. The process dispatching (or workload placement) algorithms need to be multi-dimensional optimization oriented.

7.3.3.5 Guaranteed QoS of network transmission over on-premises Wi-Fi®

The "last meter" connection in fixed network (i.e. Wi-Fi®) is the key for user experience. The quality of Wi-Fi® connections is essential. In a multi-AP network, the coordination between the different APs are needed to avoid potential collision, thereby enabling a stable and reliable high-quality Wi-Fi® connection. This leads to achieving continuity in network performance to provide consistent user experience of a dedicated service. The stable and reliable Wi-Fi® connection could provide a number of benefit for on-premises scenarios, such as support for Gigabit/multi-Gigabit coverage everywhere for a comprehensive network service, to provide continuous good experience in latency sensitive service (e.g. on-line game), to support seamless hand-over for service continuity, to provide robust control for IoT service, etc. See clause 7.5 for further details.

The E2E coordination in the optical network provides a means to assure the QoS guaranteeing the user experience.

7.4 Enabling technologies for OSV

7.4.1 Overview

The Optical Sensing and visualization dimension address three main areas of application:

1) Using fibre optical infrastructure as sensor to capture and collect environmental parameters, such as temperature, stress, vibration, etc. Which can be deployed to monitoring bridges, tunnels, roadmaps and railways for strain and increased vibrations and strain which could indicate an imminent failure. Similarly, Fibre optical Sensor can also be deployed along with pipelines which carry oil, gas, water and other flow for leakage, temperature variations detection.
2) As FTTR + Wi-Fi® is an essential part of F5G Advanced network, it is good to leverage Wi-Fi® sensing technologies, e.g. Channel State Information (CSI) to provide enhanced sensing capabilities in some use cases.

3) Detect fibre optical communication network infrastructure in terms of network topology, insertion loss of each branch and segment, monitor degradation or detect/locate broken points in fibre optical network infrastructure, such information enables the managements to visualize optical network infrastructure for digitized operation, management and diagnostic purposes.

Artificial Intelligent technologies may be used in the OSV system to improve the accuracy of sensing and visualization results.

7.4.2 Distributed Fibre optical sensing

Rayleigh scattering, Brillouin scattering and Raman scattering mechanisms all cause backscattering when light propagates through optical fibres (Figure 4). When vibration, temperature, and strain change in the environment of a certain point of the fibre, the intensity, phase and frequency of the backscattered light signal generated at that point of the fibre changes accordingly. The variation of Rayleigh scattering phase is related to the variation of temperature, strain and vibration. The variation of Brillouin scattering frequency position is related to the variation of temperature and strain. The intensity variation of Raman scattering is related to the temperature variation. This effectiveness is able to be used in Optical fibre sensing system.

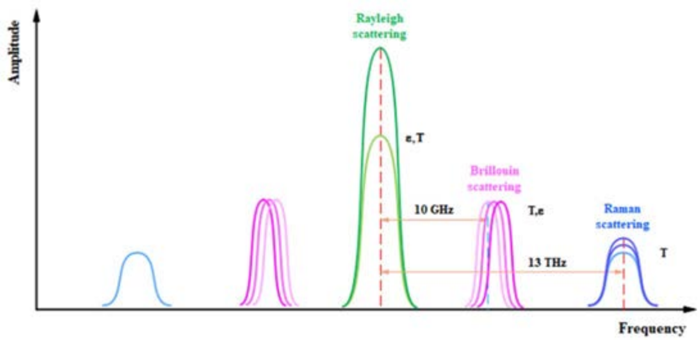

Figure 4: Illustration of Rayleigh/ Brillouin/Raman Scattering effectiveness

A typical optical sensor function diagram is shown in Figure 5.

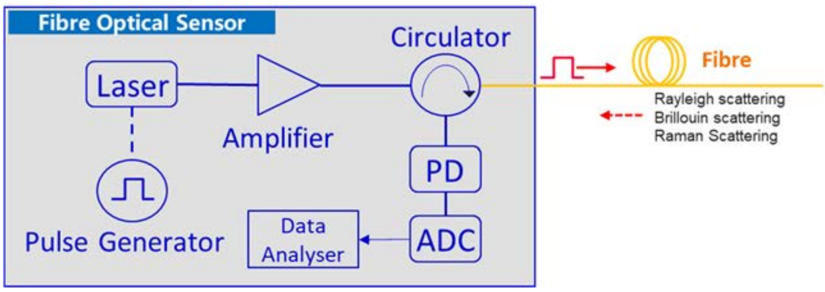

Figure 5: Fibre optical Sensor diagram

The distributed optical fibre sensor uses optical fibre as a sensor, which is connected to a laser. The laser is driven by a pulse generator and periodically injects short pulses of detection light into the optical fibre, to measure, monitor and analyse the spatial distribution and time-varying information of the backscattered signal (intensity, frequency, phase, etc.) from the fibre. By using technologies such as coherent demodulation algorithm, the backscattered signal is processed and spatial position of the current scattered light can be located according to the time difference between the sampling time and the light sending time.

The distributed optical fibre sensing technology may have sufficient linear perception capability for detecting environmental acoustic frequency signals. A data analyser is located at each side of a fibre and handles the processing of sensing signals. Supported by AI technologies, the data analyser extracts useful features, classifies and identifies signals, and builds perception models for various perception scenarios.

Outputs of data analysers are collected by data collector and sent to management/supervisory system. The management/supervisory system then triggers alarms and dispatches on-site visual inspection or repair assignments, in case of faults or risks are detected.

7.4.3 Wi-Fi® Sensing

Although the communications provided by indoor Wireless Access Network support high quality of experience and high throughput data rate with IEEE 802.11.ax [i.20] (< 6 GHz) or 802.11.be [i.21] (< 7,125 GHz), the coverage extension to the entire home and Wi-Fi® coordinated services to all users remain challenging.

The Wi-Fi® network additionally enables wireless devices to function as sensors to act as part of the network to synthesis received signals and determine the locations of objects and humans, under IEEE 802.11bf [i.22] with Wi-Fi®. It can provide approximate sensing features to identify the movements based on Channel State Information (CSI) measurements, while it is also approximate and less accurate due to limited coverage and lack of a central management of Wi-Fi® repeaters and relays.

The communications and sensing features of Wi-Fi® system can degrade from the nominal performance due to diffraction of the waves and instable Wi-Fi® signals in complex indoor environments. The use of Wi-Fi® repeaters and extension of Access Point nodes with no central management and with Point-to-Point architectures may not solve the issues, mainly due to uncontrollable electromagnetic interferences.

Based on the characteristics of Wi-Fi® signal propagation, future Wi-Fi® perception can be further explored from different angles. To build a centrally-managed multiple Access Point system to provide Point-to-Multi-Point Wi-Fi® coverage everywhere in the home, such as FTTR, and exploit the multi-beam smart antennas to improve the accuracy and precision of localization and sensing.

7.4.4 Fibre optical cable network digitization and visualization

In ETSI GR F5G 008 [i.6], use case #14 introduced ODN infrastructure digitalization based labels attached to each fibre and connector, to identify the connection relationship and status of each fibre, which needs a technician to scan the labels manually, use case #31 introduced AI based algorithms to identify co-cable Shared Risk Link Group (SLRG), use case #32 introduced AI based PON optical path diagnosis. However, each of them has limitations and does not meet the requirement of improved network visualization.

Optical fibre cable visualization targets to provide the digital profile of the ODN topology with information connecting relationship of fibre, insertion loss of each optical path, which enables reconstruction of a digital twins of the ODN topology in management system, hence support autonomous network management.

An implementation to achieve abovementioned goal is showed in Figure 6.

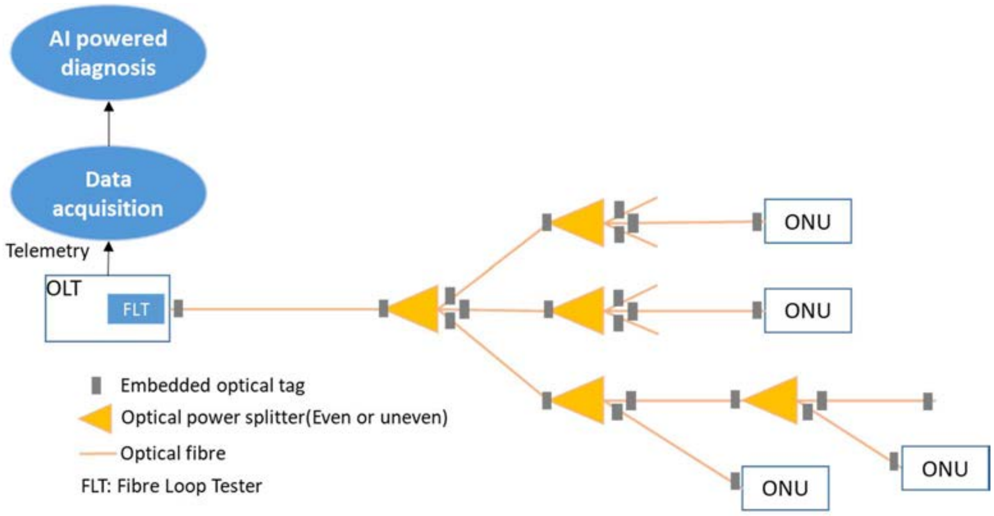

Figure 6: Optical fibre cable visualization implementation

7.5 Enabling technologies for FFC

7.5.1 Overview

Fibre optics can extend into the home, campuses and factories. To fit all these scenarios, it is needed to continuously enhance the ease of deployment, environmental adaptability, high networking reliability, and accelerate the copper to optical transformation of networks in many industries.

The evolution to10 Gbps from 2,5 Gbps for FTTR targets to fulfil the requirements of new network services. The C-WAN architecture of FTTRs solves the traditional Wi-Fi® collision problem, providing centralized resource optimization, coordinated Wi-Fi® transmission, seamless roaming, and energy efficient transmission. Stability and reliability are crucial for FTTM, ring topology with main and backup link are important link protection mechanism for FTTM. Fibre diagnostics needs the digitalized ODN technology to quickly identify the problem and confine the risk in industrial applications. Higher throughput like 50G-PON technology is necessary for FTTO scenario to provide 10 Gbps everywhere link in a dedicated region. Moreover, FTTThing needs flexible fibre communication technologies to adapt the diverging demand of different end user devices.

7.5.2 Fibre To The Room (FTTR)

To meet the evolved network requirements of residential and SME applications (such as immersive VR, 3D naked eye display, etc.), F5G-A FTTR evolves to 10 Gbps. In addition, stability and reliability are important for FTTR to enable best Quality of Experience (QoE) for end users. The network KQI includes throughput, connection, latency, handover, green & security, and smart O&M. For F5G-A FTTR, the following technologies are needed:

1) Centralized optical and Wi-Fi® coordination:

   - The optical and wireless coordination mechanism focuses on the centralized optical and Wi-Fi® synergy mechanism. That is, the MFU controls the SFU in real-time through the controller of the MFU, ensuring objectives such as orderly coordination of the Wi-Fi® air interface on the FTTR network and insensible roaming handovers and maximizing the air interface performance. This is based on a low latency assurance technology, which is the key to tune the Wi-Fi® behaviour in packet to packet level. The MFU collects the service data status and air interface status of the SFUs in real-time. Air interface transmission resources (such as time, frequency, and space) of the MFU and SFUs are scheduled in real-time, ensuring that no packet conflict occurs on the Wi-Fi® air interface between different devices.

2) Seamless handover:

   - Seamless handover leverages the mechanism of centralized optical and Wi-Fi® collaboration. The MFU senses and maintains the entire network topology, configures the air interface connection status and data forwarding path in a unified manner, and controls all terminal connections in a unified manner. The switching is one-hop to the SFUs. The interaction between the MFU and SFUs is simplified. The switching of data forwarding and connection can be performed simultaneously, significantly reducing the handover switching time and ensuring the continuity of data transmission.

3) Energy-saving technology:

   - To facilitate higher efficient utilization of energy, FTTR needs to provide adaptive communication scheme to save energy.

7.5.3 Fibre To The Machine (FTTM)

Fibre has the advantages of large bandwidth, long distance, and anti-electromagnetic interference. It is suitable for industrial applications. FTTM maximizes the advantages of optical fibres and needs to support high network reliability and introduce industrial explosion-proof, shock-proof, and anti-corrosion capabilities. The typical technical architecture of FTTM is shown in Figure 7. Ring network protection and zero-interruption protection for hitless service switching is to be supported.

There are three main categories for FTTM applications, needing distinct technologies:

1) Real-time control scenarios, such as production line control, ship container operation in ports, visual inspection, intelligent scheduling, TOS automation, etc.

   In this category, some important requirements are: high-bandwidth transmission to provide up to 10 Gbps real-time transmission of 4K images (e.g. for visual inspection), deterministic low latency within microseconds for fibre up to 100 km long, high availability and zero service interruption, fast switchover within 30 ms upon network faults. The passive networks create an environment with zero electromagnetic interference.

2) Production environment monitoring and inspection scenarios, such as the dispatch automation system, IoT access platform, and analysis platform.

   In this category, some important requirements are: Support of wide temperature ranges from -40 °C to +70 °C, full coverage to ultra-long distance (40 km long-distance coverage, twice that of industry average), high security requiring devices with explosion-proof certification.

3) Data backhaul scenarios in public places, such as highway video backhaul, tunnel sensing data backhaul, metro security protection, PIS, and IoT.

   In this category some important requirements are: Simplified architecture with fewer network layers and high-density access to massive IoT devices, high split ratio of 1:128 for scalability, cost effective technology to provide long-term evolution with continuous bandwidth upgrade and network evolution without cable replacement. Easy management needs efficient management of the 2-layer network architecture, plug-and-play ONUs, and a unified NMS platform.

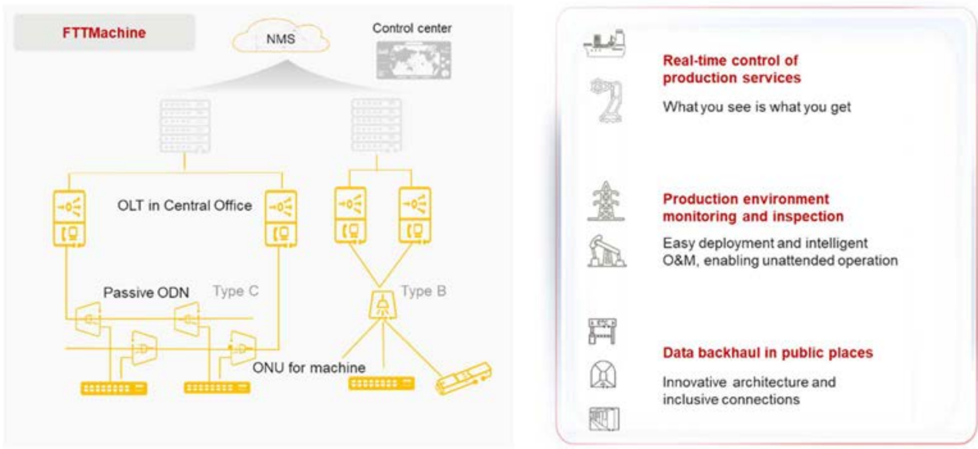

Figure 7: Technical architecture of FTTM

7.5.4 Fibre to the Office

Data centre and wireless campus networks are evolving to use Wi-Fi® 7. Services such as wireless projection, cloud desktop, and UHD video conferencing are to be supported. The todays up-to 100-meter copper cable in the legacy office network cannot support the needed bandwidth. Network architecture innovation is urgently needed to implement one-to-one optical fibre connections for campus/office fibre-to-desktop networks. FTTO and FTTD scenario's optical fibre needs to support 50G-PON symmetric high-bandwidth communication to support the backhaul of Wi-Fi® 6e/7 access points. Network hard slicing/hard isolation enables the integration of multiple campus networks into one.

Currently, the typical office network lacks management features and uses manual interventions to configure, find and fix faults, and monitor the network status. In the future, it is important to support intent-based deployment, poor-QoE identification, automatic optimization, fault prediction, and self-healing for autonomic network management in a smart all-optical campus. In this way, fibre-to-desktop brings advantages such as high bandwidth, easy evolution, hard isolation, and easy O&M to help smart all-optical campuses.

Symmetric 50G-PON for FTTO

50G-PON for FTTO, as specified in the published recommendations of 50G-PON (G.9804 series), provides ultra-high bandwidth and more than 10 Gbit/s for each access point. In addition, 50G-PON is upgraded in terms of service experience assurance. Therefore, 50G-PON can carry multiple services in FTTO scenarios. For example, enterprise high-speed Internet access, cloud services, campus Wi-Fi® 7 backhaul, and industrial Internet. It greatly improves the value of optical networks and enables to large scale digitalization of enterprises.

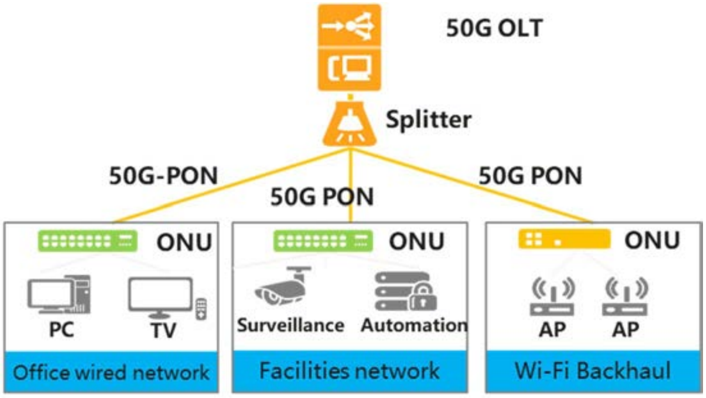

Figure 8: 50G-PON for FTTO

7.5.5 FTTThing

The applications of optical communication technologies are network device oriented in FTTx, such as FTTH, FTTR, FTTM, FTTO, etc., the optical network is traditionally terminated in a network terminal (i.e. ONU). Additional interfaces like Ethernet point (e.g. GE, 2.5GE, 10GE, etc.), Wi-Fi®, HDMI, etc. are used to connect the end devices (e.g. IoT device, camera, machine, etc.).

Fibre to the thing (FTTThing) describes an integrated technologies scheme to provide a connection to an end device over the communication system, in which the fibre is directly connected to end systems instead of a network terminal (e.g. ONU, AP, etc.). This may need new innovation of the traditional technology:

1) Support dense connections up to thousands of devices. The data rate for each connection might not be high but still need to maintain enough aggregated throughput. Other modulation scheme may need to reduce the complexity for simple devices. A hybrid mode of different modulation methodology for different throughput demands is needed.

2) Dynamic scheduling for a fibre sharing topology like P2MP provides efficient usage of communication resource, achieving a highly efficient usage of the energy.

3) Flexible fibre infrastructure, like multiple layers, is indispensable to support scalable extension of new plug-in devices. Easy construction of fibre components (like fibre connectors) need to be developed to support quick establishment of the fibre connection. In extreme cases, the fibre infrastructure may need to support a device with mobility like AGV.

4) Quick fibre diagnostic methodology is on demand since large amount of fibre are expected to be deployed under FTTThing. A robust fibre connection is important to avoid frequent fibre breaks.

7.6 Green Agile Optical-network (GAO)

7.6.1 Overview

With the rapid development of the digital economy, an all-optical network has advantages such as green and low-carbon emission, high bandwidth, high reliability, and low deterministic latency. An all-optical network can support advanced services and applications for users, enterprises, and industries, as shown in Figure 9. An all-optical network is a key strategy for the green and digital transformation worldwide.

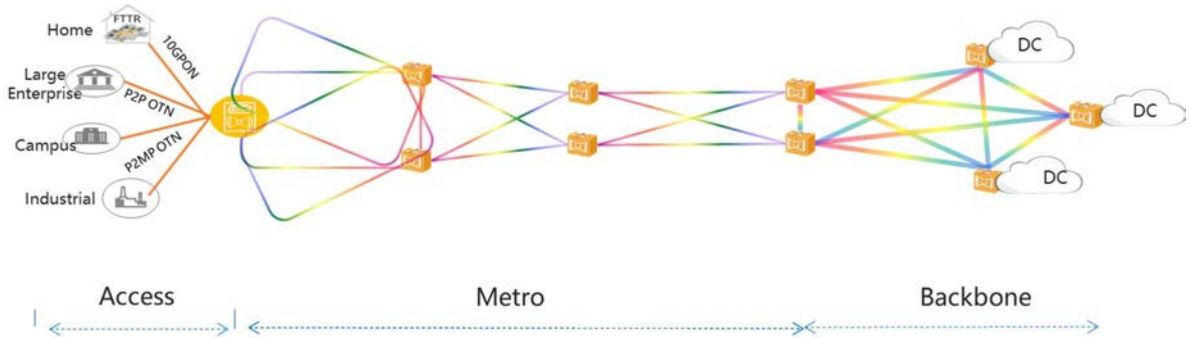

Figure 9: Overview of green agile all-optical network

In the 2H scenario, optical fibres are extended to the end user devices to replace copper and cable transmission, greatly reducing the energy consumption and satisfying digital home experience. In the 2B scenario, optical fibre connections are extending to offices and factories, greatly reducing the energy consumption and improving user experience with high bandwidth and low latency. In the entire network, network equipment switches from electrical switching technology to the optical switching technology, reducing the energy consumption at the electrical layer and enhancing coverage at the optical layer. This optical technology extension, provides end to end network energy efficiency improvements. With the all-optical shift, the energy efficiency of a hardware device can be improved by up to two to three times, and the energy efficiency of a single network node can be improved by up to two times. The energy efficiency of the network energy saving technology can be improved by up to 2,5 times. The energy efficiency of the architecture can be improved by up to two times, and more spectrum bandwidth can improve the energy efficiency by up to two times. Therefore, the energy efficiency of the entire network can be improved by more than 10 times.

To evolve from F5G to F5G Advanced, the Green Agile Optical-network (GAO) can be achieved by the introduction of new technologies:

1) Greener sites: To reduce the energy consumption per bit, for example, replacing legacy SDH equipment with the higher bandwidth efficient fine-grain OTN (fgOTN) technology in a transmission network, migrating 1G/10G PON to 50G-PON in an access network. At the chip-level, higher integration can reduce chip power consumption, on-chip optics can also reduce chip interface power consumption. At the module-level, technologies such as high-performance algorithms, innovative materials and processes can improve the module energy efficiency. At the equipment-level technologies such as DC-powered equipment and liquid cooling.

2) Greener architecture: To manage the rapid traffic growth, reducing the energy consumption per-bit by improving the single-fibre capacity such as higher performance FEC and super C+L technologies, optimising the architecture by replacing electrical components with optical ones such as Optical Cross-Connects (OXCs) technologies, and extending WDM to the aggregation and access network by sharing optical-layer system resources such as wavelength-shared WDM. All-optical network management can dynamically force part or all of the network to enter or exit power saving mode based on real-time traffic conditions. In the access network examples, based on the usage and other conditions, ONUs can go into a power-shedding, doze, deep sleep, fast (cyclic) sleep or dynamic power save state.

3) Agile Operation: Provide agile service connection by introducing one-hop connection from the access network to the cloud, optical-layer route configured in minutes and electrical-layer route configured in seconds, and millisecond level hitless bandwidth adjustment.

7.6.2 Fine-grain OTN for replacing legacy SDH

Historically, SDH networks based on the TDM approach was used to transport PDH and Packet traffic from 2 Mbps to 40 Gbps. With the evolution of digitalization, these SDH networks are not fit to support the emerging needs of small-granularity private line services and are no longer capable of supporting the higher bandwidth requirement of today's networks. They need to be replaced by new technologies that also optimize the equipment space and energy consumption. Operators are finding it difficult to source SDH vendor support for this legacy technology, so faults are becoming more difficult to repair. The SDH rates above 10 Gbps are efficiently supported by OTN, however STM1 and STM4 and VCn type signals are not efficiently supported by existing OTN. An enhancement to the existing OTN technology, is a new fine grain OTN technology which is being defined as an alternative to carry these low rate services. The fine grain OTN technology can provide hard-isolation, low deterministic latency, end to end synchronisation, secure and reliable transport capabilities.

The fgOTN technology is a TDM-based path layer network, which is based on traditional OTN technology that supports both large-scale and small-granularity private line scenarios in aggregation networks. It uses a finer timeslot granularity (10 Mbit/s level) than traditional OTN. It supports massive number of flexible hard pipe connections, and provides guaranteed deterministic low latency, as well as a comprehensive E2E OAM functions, satisfying the high-quality private line requirements in aggregation networks.

As shown in Figure 10, the fgOTN layer network is a client of the OTN ODUk (k = 0, 1, 2, flex) layer network.

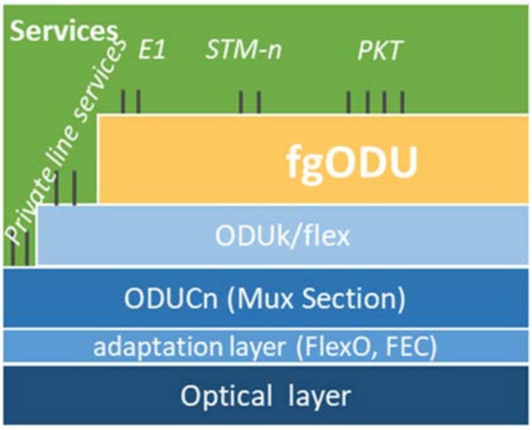

Figure 10: Overview of fgOTN path layer network architecture

The fgOTN key technologies are as follows:

- Large scale connections: 10 000 connections per 100G are supported; therefore 100 000 connections can be achieved on an aggregation network.
- Service awareness and mapping: Service awareness is supported to encapsulate and map service flows to fgOTN pipes.
- Simplified multiplexing: Simplified multiplexing mechanism is used for rate adapting the fgODU into the ODU server layer.
- Timing transparent: Timing transparency is needed for CBR services to meet the clock performance requirements of customer services. It is not needed and difficult or not at all possible to achieve for packet services.
- Hitless bandwidth adjustment: Bandwidth adjustment is supported to hitlessly increase or decrease the bandwidth of an fgODU connection in the OTN network.
- Deterministic low latency: The end-to-end latency of a fgOTN connection is deterministic. The latency during electrical layer pass-through processing of large-granularity server layer is lower.

7.6.3 OXC for green, agile and flexible optical network

Compared to optical-electrical network, that uses optical-electrical conversions and electrical switching, end-to-end all-optical network, employing OXCs, has the advantages of low energy consumption and low latency. Currently, high-dimensional OXCs have been deployed in backbone and aggregation-core networks, and cost-effective low-dimensional OXCs are used in F5G-A aggregation and access nodes for more economical and high energy efficient network deployment. All-optical networks provide a one-hop service transmission at the wavelength level, reducing complex electrical-optical conversions. Similar to direct trips between high-speed railway stations, all-optical networks feature non-blocking transmission with ultra-low latency. In addition, all-optical grooming enabled by OXCs-functioning as a "high-speed overpass" - efficiently grooms service traffic, and significantly improves the grooming efficiency. Since the services advance, all-optical network grooming and all-optical cross-connect equipment also faces various challenges. Specifically, backbone transmission networks are evolving toward higher-rate ports, higher-dimensions, faster grooming, and wider spectrum. Aggregation networks (also called metro networks) need more flexible deployment models, lower cost, and a simplified O&M. To address these technical challenges, a low-cost OXC solution with few ports, 64-degree or higher with many ports, and C+L-band integrated Wavelength Selective Switch (WSS) is used in F5G Advanced.

Key technologies of all-optical network using OXCs are as follows:

- New architecture: optimized optical path design for multiple line ports and compact super C+L wavelength window.
- New algorithm: Liquid Crystal On Silicon (LCOS) and crosstalk control algorithms to improve port isolation;
- New material: metasurface materials enabling less optical components and reduced cost;

NOTE: Metasurfaces are artificial two-dimensional materials composed of multiple passive scatterers with a sub-wavelength periodicity.

7.6.4 Wavelength-Shared WDM aggregation network

With the rapid growth of home and enterprise traffic, agile service provisioning, network automation, OTN/WDM connectivity to the site is needed. It has gradually extended from the aggregation core layer to aggregation layer and Central Office (CO) equipment rooms. With an optical-electrical converged network architecture, the levels of hierarchical electrical-layer grooming on aggregation networks are reduced. Driven by XR, 8K, cloud computing, and cloud storage services, OTN optical transmission is further extended to service the access sites and deployed in equipment rooms, outdoor cabinets, and telecommunication poles. The distance between optical transmission equipment and users can be as little as 300 m, achieving all-optical access premium services within the vicinity. Services are transmitted in one hop from the access network to the core network/DC at the optical layer.

Reducing network deployment cost and improving O&M efficiency is a major concern when OTN/WDM moves to the CO site. The wavelength-shared WDM solution uses all-optical switching, innovative pooled wavelength resources, and optical label technologies to implement efficient wavelength resource sharing and network-wide automation, improving network energy efficiency, reducing network deployment costs, and reducing OPEX. The wavelength-shared WDM solution helps to build a target network featuring a simplified architecture, high-quality user experience, and future-oriented evolution.

Key technologies of wavelength-shared WDM aggregation networks include:

- Integrated M*N Wavelength Selective Switch (WSS): integrate M sets of 1*N WSSs into one M*N WSS, which supports shared wavelength resources among different rings.

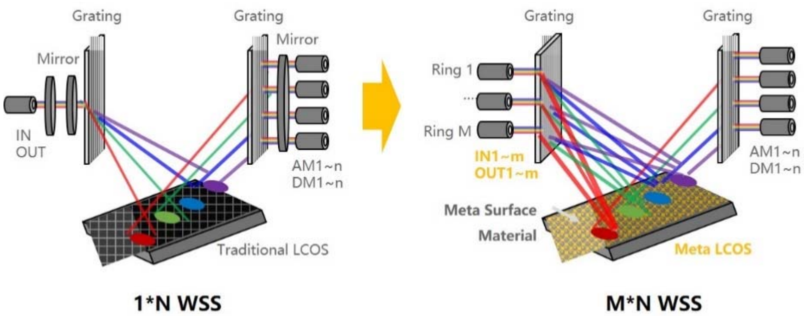

Figure 11: Schematic diagram of integrated M*N WSS

- Optical layer digital label: multi-carrier low-speed modulation of label information superimposed on a carrier of high-speed digital signals, realizing real-time monitoring of channel performances, automatic wavelength planning, automatic configuration and provisioning of services.

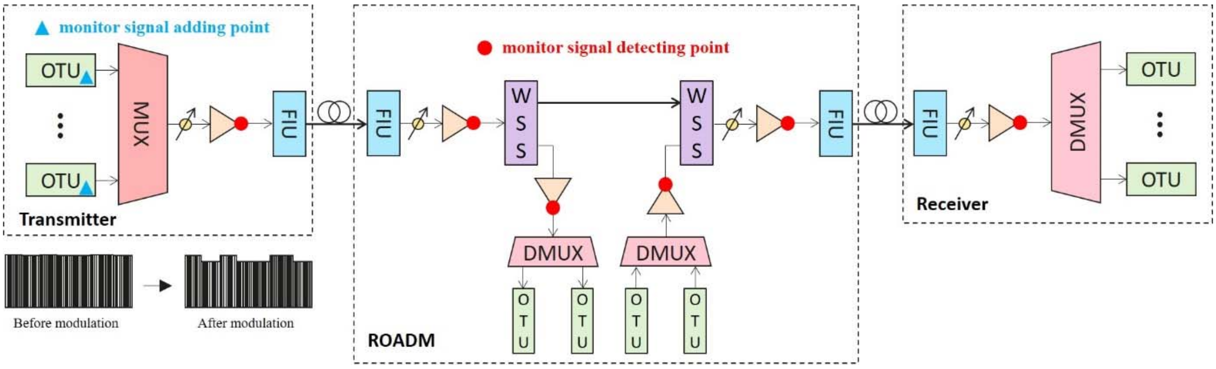

Figure 12: Illustration of optical layer digital label technology in an OTN network

7.6.5 Agile Optical Service Provisioning Protocol

The agile optical service provisioning protocol provides simplified and efficient control for all-optical services supporting cloudification of computing:

- Optical Service protocol: It controls service routes and separates control and forwarding.
- Optical Connection protocol: Control signalling is forwarded along with the data channel. The forwarding performance is decoupled from the number of pipes, and the high-performance and high number of connections can be quickly established and adapted.

In the 2B/2H cloud access service scenario, users need to access multiple clouds at one or more points. An OTN edge node needs to detect the destination addresses or VLANs of service packets and automatically map them to corresponding fgOTN/ODUk pipes. In addition, the OTN edge node detects service application types and traffic, calculates the needed bandwidth based on the application traffic model, and automatically triggers bandwidth adjustment for the corresponding fgOTN pipe. OTN edge nodes use service protocols to forward private network addresses of enterprises through controllers, greatly reducing the operation complexity of intermediate NEs in the network.

A fibre cut affects thousands or even tens of thousands of small-granularity services, and with that also the restoration performance. To mitigate this issue, the Automatically Switched Optical Network (ASON) path computation unit pre-computes a pre-set restoration path and configures the pre-set resources on each node of the path. As such, when a fibre cut occurs, the connection protocol is forwarded along with the data channel to quickly activate bandwidth and achieve fast restoration within 10 ms.

8 Outlook

8.1 Summary

F5G Advanced generation is the evolution of the F5G generation, enabling new and enhanced services, addressing a wide range of environments (residential, enterprise, industry) and taking advantage of the optical network capabilities closer to the end user (FTTR, FTTD, FTTM). From the network perspective a major driver is the further automation of network operations that reduces costs and improve service agility. The green challenge is also addressed, being critical to ensure a growing sustainable optical network.

The evolution of business requirements, both services and applications as well as network transformation are the key drivers for the F5G-A generation, as described in clause 5.

In order to address the new business requirements, the goal of F5G Advanced generation is to enhance the capabilities of the three already defined F5G dimensions - eFBB (enhanced Fibre BroadBand), FFC (Full Fibre Connection) and Guaranteed Reliable Experience (GRE) - and adds three new dimensions to F5G Advanced - Real-time Resilient Link (RRL), Optical Sensing and Visualization (OSV) and Green Agile Optical-network (GAO) as described in clause 6.

To foster this evolution, F5G Advanced considers the adoption of a wide range of key enabling technologies as described in clause 7.

Based on the vision developed, Table 1 (below) summarizes the main technology characteristics considered for F5G-A, comparing with those from previous fixed network generations. This table is an evolution of Table 1 in ETSI GR F5G 001 [i.12], where F5G-A information is added and F5G generation information updated with ISG F5G activities results. For better readability, the information on older generations is not presented, focusing on generations supported by fibre access technologies (F4G, F5G and F5G-A).

Table 1: Fixed network generations

Fixed Network Generation	F4G	F5G (revised)	F5G Advanced
Generation reference	UltraFast BB (UFBB)	Gigabit BB (GBB)	MultiGigabit BB (mGBB)
	Mbits	Gigabit	10 Gigabit
Reference Downstream Bandwidth per User	100-1000 Mbps	1-5 Gbps	5-25 Gbps
Reference Upstream Bandwidth per User	50-500 Mbps	1-5 Gbps	5-25 Gbps
Reference services	UHD 4K Video	VR Video Cloud Gaming Smart City	Extended reality Metaverse Digital twins Industrial optical network
Reference Architecture	FTTH/FTTdp	FTTH/FTTR	FTTR/FTTM/FTTT
Access Network Technology Reference	GPON/G.Fast	10GPON	50GPON
Technical Specification reference	G.984.x G.9701	G.987.x (XG-PON) G.9807.x (XGS-PON)	G.9804.x
On-Premise Network Technical Specification reference	FE/GE+Wi-Fi4/Wi-Fi5	GE/10G 2.5 Gbps FTTR (G.FIN) WiFi6 (802.11.ax)	10 Gbps FTTR (G.FIN) WiFi7 (802.11be)
Radio Frequency (RF) Video over Fibre (LAN Coaxial) reference	Yes	Yes	Yes
Aggregation and core network	IP/MPLS WDM	IP/Eth OTN/ROADM	IP/Eth OTN/fgOTN/fgMTN/OXC
Reference Bandwidth per wavelenght	100 Gbps	200/400 Gbps	400/800 Gbps
Autonomous network level	-	3	4

Brief explanatory notes of table 1:

A quick reference of the user's expectation for each generation is given in the "Generation reference" field in the table, where the access technologies plays an important role since its capabilities are a key enabler to the services that can be delivered to the end customer.

These capabilities leverage the new broadband applications referenced in the table as "Reference services" for given generation, adding to the services identified in previous generations.

The evolution to F5G-A envisages a roadmap to a full end-to-end optical network, with increasing synergies between the different network segments. The introduction of new technologies in the access network is complemented by the evolution in the aggregation network and customer premises network and F5G-A considers the most recent standardized technologies available.

Fibre solutions are extended to the end user in a trend of fibre to everywhere and everything (FTTR, FTTM and FTTT), leveraging the development of new "Reference architectures" that complement the access network in the customer premises network.

The core and aggregation network, are essential fixed network asset, and also supports the evolution of other networks such as mobile, cable and cloud interconnection. New performance enhancements are considered for these networks in the F5G-A generation. It worth mentioning the adoption of fgOTN/fgMTN at the edge and Aggregation segments, enabling wider bandwidth granularity to directly support a much greater number of services at different rates, from a few Mbits/s to over 100 Gbit/s.

The F5G-A goal is to a more autonomous network in order to improve network agility while reducing costs and complexity.

8.2 Actions and roadmap for F5G Advanced

ISG F5G has organised of its work into Releases that group the technical features, documents and aspects of a network system representing a major stage on the development of standardization on a specific fixed network generation.

The logic of an ETSI ISG F5G release is a consistent content set that includes, at a minimum, a description of use cases, a specification of requirements, and based on that an evaluation of current gaps, and an end-to-end network architecture.

ETSI ISG F5G intends to produce a new Release of its specifications everyone and a half year, accumulating the work produced during that period.

A high-level view of ISG F5G releases is presented in Figure 13. Note that the finishing times are the current best guess of ETSI ISG F5G and might change over time.

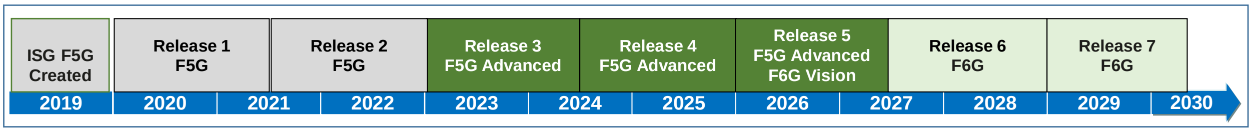

Figure 13: High level ETSI ISG F5G release plan

ISG F5G already published Release 1 and Release 2, addressing the F5G generation specifications, see [i.28] and [i.29].

F5G Advanced releases are addressed in Releases 3 and 4. The time plan for these releases is intended to be in line with the standardization of the main supporting technologies, including 50G-PON, fgOTN, fgMTN, 400/800 Gbps and Wi-Fi® 7.

The intention for Release 5 is to add some additional standardization work that may be needed for the F5G-A specifications while including a high-level vision of the next fixed network generation - F6G. It is expected that this new F6G generation will be addressed in Releases 6 and 7.

The PoC framework developed by F5G is extend to F5G-A, encouraging F5G-A Proofs of Concept that validate and provide feedback on the application of the standardization work developed in ISG F5G.

8.3 Outlook for F6G

The service innovation and the exponential growth of the traffic demands will drive the need for future fixed network generations that would be even more cost and energy efficient while enhancing performance, autonomous network operation, flexibility and security.

Optical technology-based solutions will be widely used, addressing all network segments - home, business, utilities, industry - and being pervasive, going deeper and closer to the end-user. The network can be capable of supporting multiple types of E2E slicing (strict and permissive) for differentiated and guaranteed SLA in the all-optical space, with dynamic slice creation and on-demand resource scheduling.

The use of embedded AI applications and the evolution towards the autonomous network paradigm will make the network more agile and reconfigurable.

The growing footprint of the optical infrastructure, namely the passive infrastructure in access, needs more efficient management tools exploring fibre cable digitization, optical sensing capabilities and AI applications.

Envisioning rates in the order of 200 Gbps in access, keeping deployment costs and power consumption as low as possible, needs enhancements of the current PON architectures with new technologies and multiplexing/multiple-access techniques.

Coherent detection technologies are gaining momentum, enabling higher capacities and improved reach. The evolution of network requirements and cost reduction of coherent technology will leverage a gradual shift from direct detection to coherent detection. Once this trend is justified from an end-user requirements and costs point of views, it will open the way for radical new approaches in design and operation of the access network.

The support for wireless communications is another challenge to be addressed, enabling the connectivity of a growing and diverse number of access points, using a wide variety of wireless systems (5G, 6G, Terahertz and Optical Free-Space Optics (FSO)) that may need very different network capabilities. Looking forward to the development of 6G, some further integration between optical and mobile networks may be needed to achieve an efficient and cost-effective network, namely photonic integration and optical transparency, replacing/bypassing power hungry and costly electronic processing systems. This integration includes the management level with enhanced ML-enabled SDN control and management plane approaches.

Although the work to be developed by ISG F5G in the following years focuses on the present document of the F5G-A network, the group will also follow the new trends and technology evolutions, which will contribute to the definition of future fixed network generation, the sixth generation fixed network (F6G).

History

Document history		
V1.1.1	November 2023	Publication