STANDARDIZATION OF THE 5TH GENERATION FIXED NETWORK FOR ENABLING END-TO-END NETWORK SLICING AND QUALITY-ASSURED SERVICES

Luca Pesando, Johannes K. Fischer, Behnam Shariati, Ronald Freund, Jose Cananao, Hongyu Li, Yi Lin, Olivier Ferveur, Ming Jiang, Jialiang Jin, David Hillerkuss, Marcus Brunner, Jun Zhou, Juan del Junco, Hakim Mkinsi, and Xiang Liu

ABSTRACT

Fixed networks play an increasingly important role in supporting broadband services to homes, offices, shopping centers, business buildings, factories, smart cities, and much more. Reaching closer to end-user access points in rooms, office desks, and even factory machinery, optical fiber will realize its full potential to support a fully connected, intelligent world with high bandwidth, high reliability, low latency, and low energy consumption. With the fiber-to-everywhere vision, the European Telecommunications Standards Institute (ETSI) established an industry specification group (ISG) dedicated to the definition and specification of the 5th generation fixed network (F5G) in 2020. In this article, we describe the overall architecture of F5G, which consists of three interacting planes, the management, control and analysis plane, the service plane, and the underlay plane. F5G enables the quality of service (QoS) of each of the various services carried to be satisfied via end-to-end (E2E) network slicing over the customer premises network, access network, aggregation network, and core network segments. With the comprehensive service-oriented features of F5G, 14 use cases have been conceived under three main application scenarios, enhanced fixed broadband, guaranteed reliable experience, and full fiber connection. We show that F5G is capable of supporting these use cases with the requested QoS in terms of bandwidth, latency, agile service creation and bandwidth adjustment, fine granularity of bandwidth reservation, and automated E2E network orchestration and management. To further show the capabilities of the F5G architecture, we discuss the E2E network slicing in a cloud virtual reality demonstration, as well as a time-sensitive optical network for supporting cloud-based industrial applications. Finally, future perspectives of F5G and its standardization are discussed.

INTRODUCTION

Over the last 40 years, mobile communication networks have evolved from 1G, 2G, 3G, and 4G to 5G. Widespread deployments and applications of 5G are underway in the decade of the 2020s. In the 5G era, fixed networks, which include customer premises networks (CPNs), access networks (ANs), aggregation networks (AggNs), and core networks (CNs), are playing an increasingly important role in supporting broadband services. By the first half of 2019, 570 million fiber-to-the-home (FTTH) users have been registered worldwide [1]. It is also estimated that 700 million households will use optical access networks by 2023. Optical fiber is expected to realize its full potential to support a fully connected, intelligent world by reaching deeper into the CPN toward rooms, office desks, and even factory machines. It is with the fiber-to-everywhere vision that the European Telecommunications Standards Institute (ETSI) established an Industry Specification Group (ISG) in early 2020 to define and specify the 5th generation fixed network (F5G) [2, 3]. Like mobile networks, fixed networks have entered 5G around 2020, characterized by 10 Gb/s passive optical network (10G-PON) for the AN segment and dense wavelength-division multiplexing (DWDM) with 400 Gb/s wavelength channels for AggN and CN. In this article, we describe the standardization of F5G with the focus on the enablement of E2E network slicing and quality-assured services. We show that F5G is capable of supporting a diverse set of services with hard isolation and low latency, agile second-level service creation and bandwidth adjustment, fine granularity of bandwidth reservation (10 Mb/s), and automated E2E network orchestration and management. This article is organized as follows. The next section presents the various use cases supported by F5G. We then introduce the overall network architecture of F5G. Following that, we describe E2E network slicing in F5G, as well as a proof-of-concept demonstration of cloud virtual reality (VR) supporting agile lossless bandwidth adjustment with fine granularity. We then detail a representative use case for cloud-based industrial applications.The final section provides concluding remarks and future perspectives of F5G evolution.

Luca Pesando is with Telecom Italia, Italy; Johannes Fischer, Behnam Shariati, and Ronald Freund are with Fraunhofer Heinrich Hertz Institute, Germany; Jose Cananao is with Altice, Portugal; Hongyu Li and Yi Lin are with Huawei Technologies, China; Olivier Ferveur is with POST Luxembourg; Ming Jiang and Jialiang Jin are with China Telecom Research Institute, China; David Hillerkuss, Marcus Brunner, and Jun Zhou are with Huawei European Research Center, Germany; Juan del Junco is with Sampol Digital, Ltd., Spain; Hakim Mkinsi is with ETSI France; Xiang Liu (corresponding author) is with Huawei Hong Kong Research Center, China.

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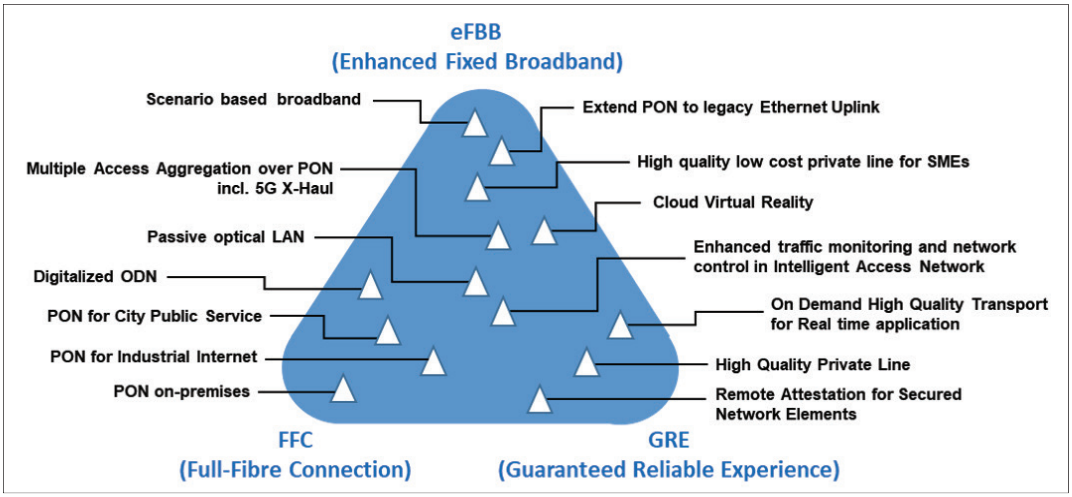

FIGURE 1. Main application scenarios and use cases supported by F5G.

VARIOUS USE CASES SUPPORTED BY F5G

5G has three well-known application scenarios: enhanced Mobile BroadBand (eMBB), supporting applications such as ultra-high definition video, 3D video, work and play in the cloud, and VR; ultra-reliable low-latency communications (uRLLC), supporting applications such as self-driving cars and drones, industry automation, remote medical procedures, and other mission critical applications; and massive machine type communications (mMTC), supporting applications such as smart home, smart building, smart city, and massive Internet of Things (IoT). Similar to 5G, F5G has three main application categories [2, 3]:

- Enhanced fixed broadband (eFBB): supporting applications that require significant bandwidth
- Guaranteed reliable experience (GRE): supporting applications that require high reliability and determinism
- Full fiber connection (FFC): supporting applications that require massive fiber connections

Figure 1 illustrates the three main application scenarios of F5G, as well as six service-oriented features. Overall, F5G aims to provide over 10 times higher bandwidth in eFBB, 10 times better reliability and latency in GRE, and 10 times denser fiber connections in FFC. For eFBB, F5G increases the bandwidth over the previous generation fixed network (F4G) by applying new technologies in WiFi, PON, and OTN. For GRE, F5G improves the network reliability and the quality of experience (QoE), and reduces latency. E2E network slicing capability is introduced to guarantee the key QoS requirements of different services with the optimized total network cost and/or power consumption. For FFC, F5G uses the fiber-to-everywhere infrastructure to support ubiquitous connections, including FTTH, fiber-to-the-room (FTTR), fiber-to-the-office (FTTO), fiber-to-the-desk (FTTD), and fiber-to-the-machine (FTTM). The coverage of fiber connections is expected to expand by 10 times. At the same time, the fiber connection density may increase by 10 times. Thus, the total number of fiber connections may increase by 100 times in the F5G era. The application scenarios of F5G can thus be dramatically expanded, for example, to include many emerging vertical industry applications. In February 2021, ETSI ISG-F5G published the first release of F5G use cases [4]. There are 14 use cases identified in the first release under the three main use case categories of F5G, eFBB, GRE, and FFC, as shown in Fig. 1. These use cases can be categorized into three application types, new/enhanced services to users, expanded fiber infrastructure and services, and management and optimization.

Evidently, F5G enables a diverse set of use cases to directly deliver values to end users, network operators, and vertical industries via fixed networks, effectively complementing the 5G use cases supported by mobile networks. To better support these use cases, F5G offers a comprehensive set of service-oriented features. Traditionally, the service flows are carried by IP/Ethernet packets mapped into optical network tunnels. The quality of experience (QoE) of the services is managed separately by different network layers and network segments, so the end-to-end QoE is complex to assure. In F5G, to ensure the QoE of the services, the aggregation network needs to be aware of the services and be able to enable flexible connections on-demand.

In effect, the aggregation network is becoming *service-oriented*. As illustrated in Fig. 2, the key service-oriented features are the following.

Service-Type Awareness: It needs the ability to be aware of the service type information (such as its QoE requirements and priority), so that the F5G network can best support each service.

Service Agility: The ability of on-demand service provisioning with fast service establishment/initiation, delivery, and termination, driven by the arrival of the service flow, is required.

Service Adaptation: It needs the ability to provide an elastic optical connection adapted to the bandwidth requirement of the service flow with fine resolution and supporting hitless bandwidth adjustment on demand.

Service Assurance: The ability to ensure the QoE of the service, to enable the "deterministic service," including, for example, deterministic bandwidth, deterministic latency, and deterministic recovery time and recovery route is required.

Service Availability: The ability to protect the service against network failures, for example, to ensure availability of higher than 99.999 percent, is required.

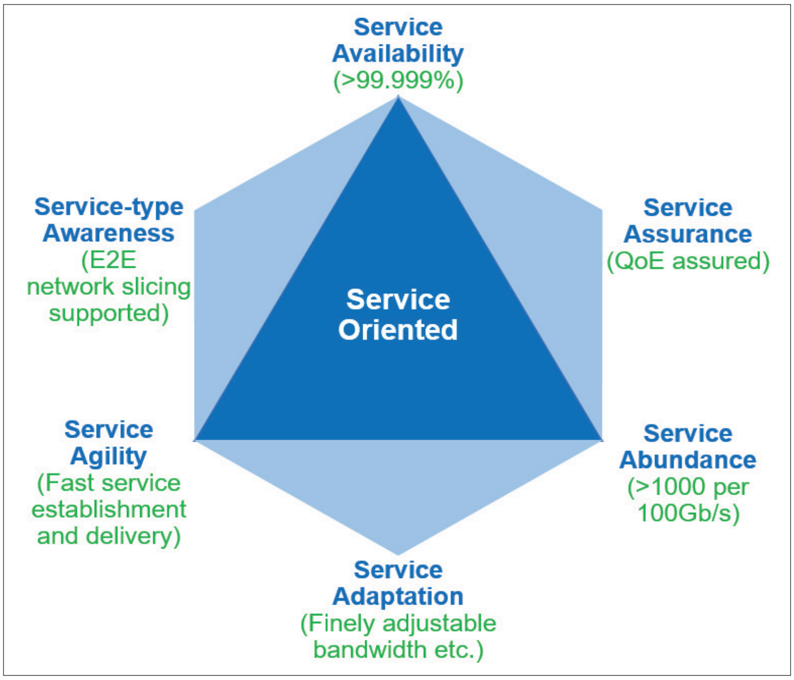

FIGURE 2. Illustration of the six service-oriented features of F5G.

Service Abundance: This is the ability to carry the increasing number of services in optical networks, for example, by supporting over 4000 services per 100 Gb/s of optical transport bandwidth via the use of a fine-granularity optical service unit (OSU).

With the above service-oriented features, a diverse set of F5G services can be effectively supported in the same network. In the following section, we briefly discuss how various F5G services are supported via dedicated slice instances.

F5G ARCHITECTURE

F5G network architecture consists of three planes:

- Management, control, and analysis (MCA) plane — Responsible for the management, control, and operation analysis of the E2E network
- Service plane — Providing service connections for customers and broadband services
- Underlay plane — Providing the physical connections to transport the network traffic via multiple network segments such as the CPN, AN, AggN, and CN

Figure 3 illustrates the overall network architecture of F5G. In the MCA plane, there are three key elements:

- Autonomous management and control, which enables autonomous network configuration, service deployment, and network operation
- Artificial intelligence (AI) analyzer, which uses AI to perform network analysis and reasoning
- Digital twin, which provides a real-time representation of the E2E network in order for the AI analyzer to perform the needed network analysis and reasoning to support autonomous management and control

AI is sometimes referred to interchangeably as machine learning (ML) or deep learning (DL). In our context, AI is considered as the overarching terminology referring to a series of algorithms that learn from the network data, with the aim to model particular patterns and behaviors of the system to achieve a predefined goal for a given communication service. AI is one of the critical pillars contributing to the automation of the F5G network, which can be employed in all three planes of the envisioned architecture.

In the service plane, new service connections can be dynamically created and configured by

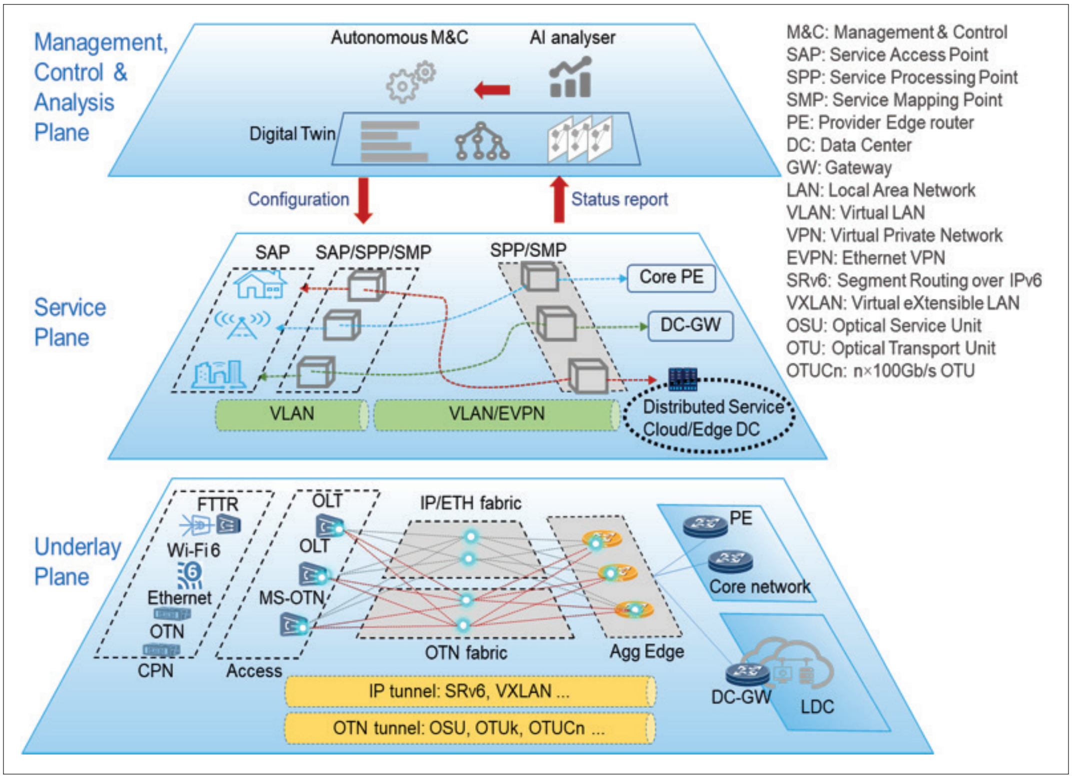

FIGURE 3. Illustration of the F5G overall network architecture consisting of three interacting planes and four network segments, CPN, AN, AggN, and CN for supporting end-to-end services.

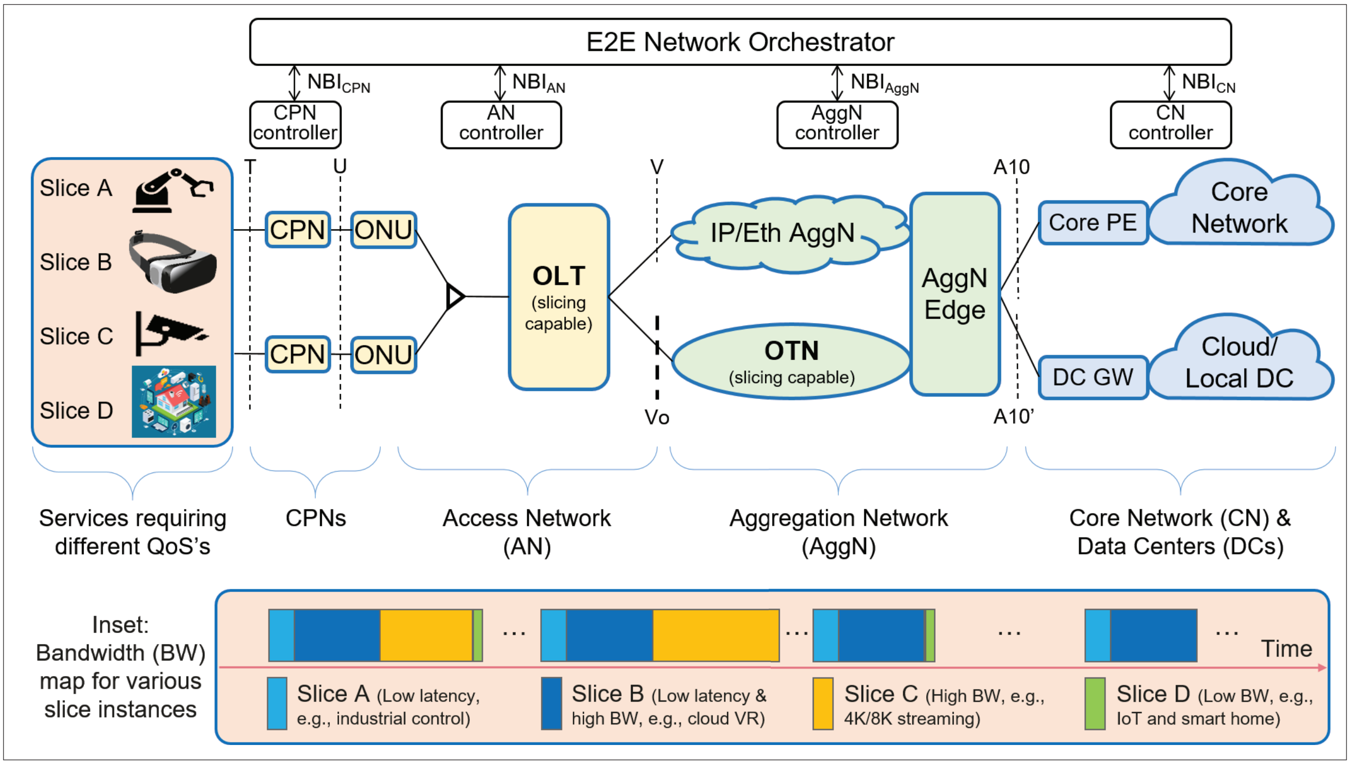

FIGURE 4. Illustration of an end-to-end network slicing architecture defined by the ETSI ISG-F5G, where various services requiring different QoS are supported via dedicated slice instances across CPN, AN, and AggN to CN and cloud/local data centers. PE: provider edge router. GW: gateway.

coordinating with the MCA plane and the underlay plane. The service plane contains the following key elements:
- Service access point (SAP) — Providing service access to the end user
- Service processing point (SPP) — Performing cross-layer network service processing
- Service mapping point (SMP) — Mapping service traffic to proper underlay channels

Services with different service level agreements (SLAs) can be supported by communicating the SLAs from the service plane to the underlay plane and querying the necessary resources with the coordination of the MCA plane.

In the underlay plane, there are physical layer equipment and devices to provide the physical connections and dynamic programmable path selection under the control of the MCA plane. The three planes collectively support four network segments:
- CPN — Mainly based on wireless technologies such as WiFi and Bluetooth and optical network unit (ONU)
- AN — Mainly based on passive optical network (PON), multi-service optical transport network (OTN), and packet transport network
- AggN — Mainly based on OTN and Internet Protocol (IP) network
- CN — Mainly based on OTN and IP network

There are technology boundaries between network segments, but all the network segments are controlled by the MCA plane to achieve E2E network operation and optimization. The E2E management and control of F5G consists of an E2E network orchestrator and multiple domain controllers on top of the F5G network topology [5], as shown in Fig. 4. In the domain controller layer, four domain controllers are introduced for the four network segments in the F5G network topology. The E2E network orchestrator cooperates with each domain controller through a northbound interface (NBI) and performs the needed resource orchestration and service provisioning functions. As interoperability is essential, standardized network interfaces are desired. Within the scope of F5G, network interfaces such as the four NBIs shown in Fig. 4, NBICPN, NBIAN, NBIAggN, and NBICN, will be standardized. In addition, reference service models will be provided to enable faster and easier integration and interoperation of all the network segments of F5G.

END-TO-END NETWORK SLICING IN F5G

Network slicing is seen as a foundational 5G capability [6], which enables the same mobile network physical infrastructure to support multiple network slices that are tailored to collectively fulfill a diverse set of QoS requirements. In F5G, E2E network slicing over the CPN, AN, AggN, and CN network segments is needed in order to meet the QoS requirements of all the services carried in the same fixed network physical infrastructure. The E2E network slicing in F5G is supported by the coordination between the E2E network orchestrator and the domain controllers for the CPN, AN, AggN, and CN segments, enabling quality of experience assurance, as shown in Fig. 4. In the CPN segment, the network slicing capability has been implemented in modern WiFi technologies through carrier- and space-based slicing. In the AN segment, PON ports support slicing based on service types. The network slicing capability in high-speed PON is being enhanced [7]. In the

As the application scenarios of the end users change, the E2E network management plane needs to reconfigure the underlay network to re-optimize for the upcoming application scenarios. Thus, the support of scenario-based use cases calls for both E2E network slicing and agile network automation.

AggN segment, the IP network supports soft network slicing, while OTN is being enhanced to support the hard network slicing (or hard isolation) capability, which provides guaranteed bandwidth and deterministic QoS independent of other concurring services in the same network [8–11]. Notably, the next-generation optical transport network (NG-OTN) uses OSUs with fine bandwidth granularity of ~2 Mb/s [9–11], capable of supporting a diverse set of services more efficiently, including high-quality private line services.

Figure 4 also illustrates how various services requiring different QoS are supported via dedicated slice instances across CPN, AN, and AggN to CN and cloud/local data centers. As an example, four types of slices are considered:

- Slice A — Requiring low latency for applications such as real-time control of industrial actuators/robots
- Slice B — Requiring both low latency and high bandwidth (BW) for applications such as cloud virtual reality (VR)
- Slice C — Requiring high BW without low latency for applications such as 4K/8K video streaming
- Slice D — Requiring low BW without low latency for applications such as IoT and smart home.

An appropriate BW map can be assigned to accommodate the QoS requirements of these slices, as illustrated in the inset of Fig. 4. This BW map needs to be supported in all the segments of an F5G network with suitable network interfaces. As illustrated in Fig. 4, there are six key interfaces denoted as T, U, V, Vo, A10, and A10′. Interface T connects the end-user devices with the CPN, while interface U connects the CPN with the AN. The interface between the slicing-capable PON and the slicing-capable OTN is denoted as the Vo interface. Interface V is traditionally the legacy IP/Ethernet-based handover points between the AN and the AggN, and will need to be enhanced to a Vo interface in order to support new capabilities such as seamless network slicing through PON and OTN, meaning that the data exchange between the two network segments requires negligible extra bandwidth and processing latency. Interface A10 is the handover point between the AggN edge and the provider edge router (PE) of the CN, while interface A10′ is the handover point between the AggN edge and the gateway (GW) to a cloud/local data center (DC). Thanks to the OTN's ability to adapt the BW of each OSU with fine granularity, the BW map matching between the PON and the OTN can be made to be virtually seamless, thus effectively supporting the E2E network slicing.

In F5G, network slicing and slice instances have the following characteristics:

- The network slice characteristics are defined by a network slice template.
- A network slice may have multiple service capabilities.
- An instance of a network slice that is actually deployed on a network can be independently operated and managed.
- Slice instances are implemented on a unified physical infrastructure, including computing, storage, and network resources.
- Resource occupation modes include shared priority-based scheduling, guaranteed resource reservation, and exclusive resource reservation.
- The network slice SLA includes QoS guarantees for each service flow.

In essence, the requirements of the application scenarios of the end users need to be considered and differentiated to optimally satisfy all the users who share the same underlay network. This scenario-based broadband approach effectively configures an F5G network to support multiple application scenarios optimally. As the application scenarios of the end users change, the E2E network management plane needs to reconfigure the underlay network to re-optimize for the upcoming application scenarios. Thus, the support of scenario-based use cases calls for both E2E network slicing and agile network automation. Recently, the first proof-of-concept (POC) demonstration under the scope of the ETSI ISG-F5G was conducted by China Mobile, Huawei, and Beijing University of Post and Telecommunications, showing real-time cloud-VR with agile (second-level) service creation/deletion and fine (~2 Mb/s) service bandwidth adjustment over an E2E F5G network consisting of CPN, AN, AggN, and CN [12]. In this demonstration, an optical service protocol is used for the automatic creation/deletion of the E2E optical path for each network slice, triggered by each VR application. In addition, the bandwidth of the E2E connection (including the OSU-based OTN segment) can be automatically adjusted in a lossless way to support a changing number of VR users from a given CPN, satisfying the 130 Mb/s per user requirement for the comfortable level of VR [13]. This POC demonstration shows the E2E network slicing in F5G as a key enabler for supporting agile lossless bandwidth adjustment with fine granularity.

An Exemplary Use Case for Cloud-Based Industrial Applications

We are currently in the so-called Industry 4.0 era, where the automation of traditional manufacturing and industrial practices by using modern information and communications technology (ICT) is ongoing. The enabling technologies for Industry 4.0 include large-scale machine-to-machine communication, industrial Internet of Things (IIoT), industrial robots, industrial cloud, and computer vision, all of which need time-sensitive and reliable communications.

Figure 5 illustrates the use of a time-sensitive optical network for industrial applications where various time requirements such as latency and latency variation are satisfied. In this use case, a PON is used with the time-sensitive optical network to simultaneously support the communication needs of an industry process field data network, an office network, and a surveillance network in production site X. This time-sensitive optical network also supports cloud-based visual inspection for automatic quality assessment in production site Y.

The main advantages of using PON for industrial manufacturing are:

- Long reach (e.g., 20 km), by using low-loss ODN

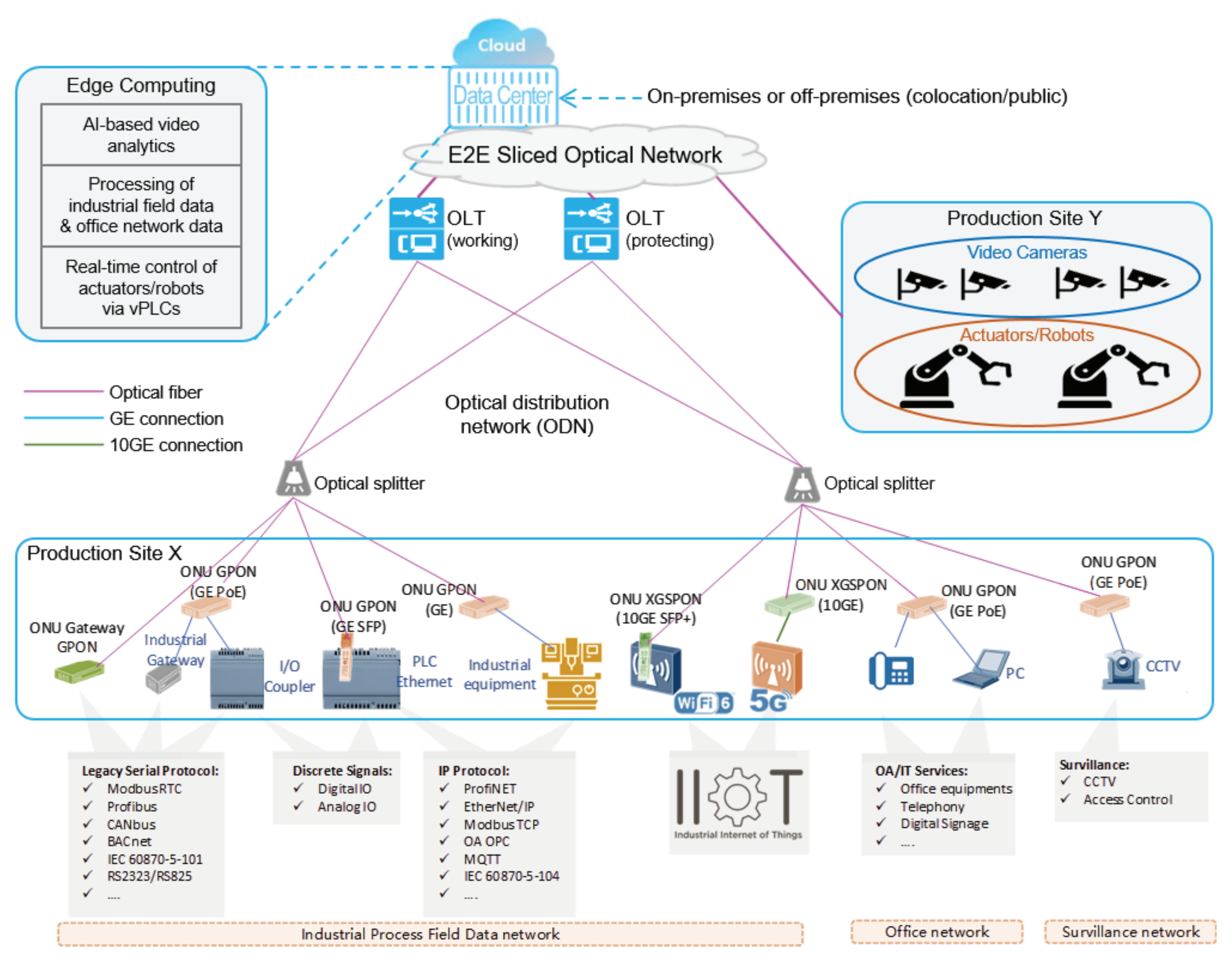

FIGURE 5. Illustration of a time-sensitive optical network for supporting cloud-based industrial applications.

- Low cost, by leveraging the well-established FTTH ecosystem
- Low latency, by eliminating intermediate electrical switches
- Low power consumption, by using passive ODN
- High availability, by using dual-OLT for failure protection
- High bandwidth, by the use of fiber optics
- High immunity to EMI, due to the use of optical fiber in the ODN

To fully unleash the potential of industrial PON, the optical modules and components used in the industrial setting needs to meet the corresponding environmental requirements [14]. The collaboration between PON and wireless technologies (e.g., WiFi, 5G, Bluetooth, LoRa) needs to be further explored to realize low-cost and low-power-consumption IIoT. E2E network slicing can be used to provide guaranteed QoS for different communication data streams with the optimal network resource utilization.

For the application of cloud-based visual inspection for automatic quality assessment in production site Y, we look at camera-based vision inspection, where the video analytics functions and the control logic are moved to the edge cloud, as shown in Fig. 5. Due to cooling, power consumption, space, and environmental effects, local programmable logic controllers (PLC) on the factory shop floor are costly and often proprietary solutions. In contrast, virtual control functions for real-time control of actuators and robots run as virtual PLCs (vPLCs) on cloud infrastructure (e.g., as micro-services) composed of standard off-the-shelf IT equipment (Fig. 5). This removes the need for dedicated hardware PLCs on the factory shop floor. Industrial video cameras located in a vision inspection station of a production line monitor the produced parts. Their video streams are transported to a nearby data center for real-time analysis, providing IT resources for running cloud services for video analytics, control, and communication with the equipment on the field level using industrial Ethernet protocols. Based on the video analytics results, vPLCs hosted in the cloud control actuators/robots at the production line take appropriate actions. A critical metric is the minimum achievable cycle time, which is determined by the time required for the vPLC to send all control signals to its assigned targets and receive all their feedback in return. Typical vision inspection applications require maximum cycle times of 5–10 ms, while some very time-critical vision inspection scenarios may even require 2 ms or less. The privacy of such data is often paramount

The production sites may be different factory buildings on the same campus or geographically distributed sites. The edge data center may be located on-premises (On-Premises Edge) or off-premises, for example, in a shared location hosted by a colocation provider (Colocation Edge) or by a cloud service provider (Public Edge).

to enterprises as it contains confidential information on production processes. Consequently, distributed/federated learning paradigms [15] are considered to keep confidential data local.

The relevant locations for the use case are multiple production sites and an edge data center site where computing and storage resources are available. The production sites may be different factory buildings on the same campus or geographically distributed sites. The edge data center may be located on premises (On-Premises Edge) or off-premises, for example, in a shared location hosted by a colocation provider (Colocation Edge) or by a cloud service provider (Public Edge). A time-sensitive optical network provides data communication between the sites. Depending on the locations of edge data centers and production sites, urban or regional network scenarios may apply with respect to the distances between the sites. Typically, due to the stringent latency requirements of the use case, the round-trip propagation delay through the transport network should remain below 1 ms, corresponding to a fiber reach of up to 100 km. As the typical distances between a production site and an edge data center in the on-premises, urban, and regional scenarios are less than 10 km, 50 km, and 80 km, respectively, these edge data centers are well suited for this time-sensitive application of cloud-based visual inspection for automatic quality assessment.

With the expansion of the cloud infrastructure and further advances in F5G, it is expected that optical networks will become the true enablers for cloud-based applications in Industry 4.0.

Concluding Remarks

Fixed networks are fundamental to high-quality broadband services that are becoming increasingly important to our society, such as remote work, remote education, and remote healthcare. With its unprecedented service-oriented features, F5G is capable of supporting a diverse set of use cases within the application scenarios of eFBB, GRE, and FFC. In many of the new F5G use cases, E2E network slicing will be essential to accomplish the QoS of any given service. More specifically, F5G provides new capabilities such as E2E network slicing to meet the QoS requirements of each service such as hard isolation (where the QoS of a given service is unaffected by other services under all cases), low latency, agile second-level service creation and bandwidth adjustment over an E2E F5G network, fine granularity of bandwidth reservation (10 Mb/s) in the OTN network segment, and automated network orchestration and management.

Due to the broad scope of fixed networks, the standardization of fixed networks has long been conducted in multiple standards development organizations (SDOs) including the International Telecommunication Union Telecommunication Standardization Sector (ITU-T), the Institute of Electrical and Electronics Engineers (IEEE), the Broadband Forum (BBF), the Internet Engineering Task Force (IETF), the China Communications Standards Association (CCSA), and so on, in addition to ETSI. Cooperation among these SDOs is essential to the effective development of F5G. While ETSI ISG-F5G has been leading the efforts in defining the F5G use case and developing the overall architecture of F5G, cooperation with other SDOs has been established to effectively standardize important topics such as FTTR, OSU-based OTN, and network management and control. For the FTTR topic, a joint workshop organized by ETSI ISG-F5G, ITU, BBF, and CCSA was first held on June 14, 2021, aiming to coordinate the standards development efforts on FTTR. The second joint workshop was held on June 28, 2022, indicating the continued cooperation among the relevant SDOs on this topic. For the OSU-based next-generation OTN topic, ITU-T Study Group 15 Question 11 (Q11/SG15) has been working on a work item named G.osu since 2020, which aims to complement the existing OTN with an additional OSU path layer network that provides bandwidth-efficient support for sub-1 Gb/s services, while ETSI ISG-F5G is developing use cases based on the availability of fine-granularity OSU-based OTN. For the network management and control topic, ETSI ISG-F5G is collaborating with BBF and IETF on YANG-based network configuration protocols for optical access and transport networks.

To meet the ever-increasing demands on fixed networks, the future evolution of F5G is also being studied by the ETSI ISG-F5G. Further enhancements to address energy-efficient (or green) and agile optical networking, real-time resilient communication, and harmonized communication and sensing are currently under consideration. With its new and unique capabilities, F5G is well positioned to complement 5G to jointly serve our global society in the decade of the 2020s by providing unprecedented communication experiences.

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BIOGRAPHIES

LUCA PESANDO has more than 25 years of experience in ICT with Telecom Italia. In the company, he has been a standards manager since 2006. At present, he is a Board member of ETSI and Chairman of ISG F5G. He is also a Council member in the Italian national standards body CEI.

JOHANNES K. FISCHER [SM] heads the Digital Signal Processing Group in the Department of Photonic Networks and Systems of Fraunhofer Heinrich Hertz Institute (HHI). He authored or coauthored more than 120 publications. He is a member of the VDE/ITG. He has served as Technical Subcommittee member and Chair for various conferences (e.g., OECC, OFC).

BEHNAM SHARIATI [M] (B.Sc., M.Sc., PhD.) leads the AI-related activities within the Department of Photonic Networks and Systems of Fraunhofer HHI. He has co-authored 55+ articles and is one of HHI's contributors to ETSI's ISG F5G. He is a member of OSA.

RONALD FREUND is with the Technical University of Berlin and is leading the Department of Photonic Networks and Systems at Fraunhofer HHI. He has authored/co-authored more than 150 scientific publications and holds an M.B.A. from RWTH Aachen.

JOS CANANO is a senior expert of fixed network architecture, solutions and strategy and currently head of network automation at Altice Portugal. He received his M.Sc. from IST Lisbon in 1991. He is active in research, development, and implementation with detailed experience in a variety of fields. He is involved in ETSI ISG-F5G.

HONGYU LI is a senior expert of fixed network architecture and solutions. He has actively participated in SDOs including ITU-T, ETSI, IETF, and BBF for over 15 years. Currently he is the Rapporteur of Technology Landscape WI and Architecture WI in ETSI ISG F5G, as well as Board member and Technical Vice Chairman in BBF.

YI LIN is a software standard and ecosystem expert at Huawei Technologies. He has been working for the research department of the optical network product line of Huawei for 14 years, and has rich experience of technical research and standard promotion in the management and control of optical networks, including ASON/GMPLS, transport SDN, and F5G end-to-end management and control.

OLIVIER FERVEUR received his Ph.D. in informatics from the University of Lorraine, France. He is a senior network architect at Post Luxembourg with more 15 years of experience in telecommunications. He has been actively involved in the R&D and standardization of F5G as the Vice Chair of ETSI ISG F5G.

MING JIANG received her Ph.D. degree in communication and engineering from Shanghai Jiaotong University. She works at China Telecom Research Institute. She leads the broadband access research team, working on technology research, network planning and application in the field of optical access. She has been involved in the R&D and standardization of F5G, as the Vice Chair of ETSI ISG F5G and Vice Chair of the Chinese AII (Alliance of Industry Internet) network group. Her recent research work focuses on industrial PON, 5G RAN, 10G PON, 50G PON, SDN in access, and so on.

JIALIANG JIN received his Ph.D. degree in optical engineering from Zhejiang University in 2012. He currently works with China Telecom Research Institute as a senior engineer in the field of optical access technology. He has been mainly involved in the R&D and standardization of optical access networks, including industrial PON, 50G TDM PON, and so on.

DAVID HILLERKUSS is a senior scientist at Huawei European Research Center and secretary of the ETSI ISG F5G. He has authored or co-authored over 200 publications and numerous patents on novel devices and systems for classical and quantum communications. He served as Program and General Chair for SPPCOM and on Program Committees for OFC, ECOC, SPPCOM, and CLEO.

MARCUS BRUNNER is chief expert of F5G standardization at Huawei European Research Center. He received his Ph.D. from ETH Zurich in 1999. He is active in research, development, and standardization with detailed experience in a variety of fields. He is involved in international organizations on future telecommunication technologies including ETSI ISG-F5G.

JUN ZHOU is head of transport and access standards at Huawei European Research Center. He has over 20 years of industry experience in the research and development of fixed access networks. He is actively involved in ETSI ISG-F5G.

JUAN DEL JUNCO is CEO and co-founder SAMPOL DIGITAL, Ltd. In 2015, he pioneered the introduction of Passive Optical LAN in the hotel market, which today is a world standard, where he has developed more than 100 POL projects. He is currently leading the POL-F5G beginnings in other enterprise markets such as banking, industry, and so on.

HAKIM MKINSI is F5G technical officer and works for ETSI. He has worked for over 10 years developing, writing, and implementing world-class standards from various international organizations (ISO, IEC, and ETSI).

XIANG LIU [F] (xiang.john.liu@huawei.com) is chief expert for optical communications standards at Huawei Technologies. He has over 20 years of working experience in optical communications. He received his Ph.D. degree in applied physics from Cornell University in 2000. His research interests include optical communication technologies, systems, networks, and standards. He is a Fellow of OPTICA (formerly OSA).