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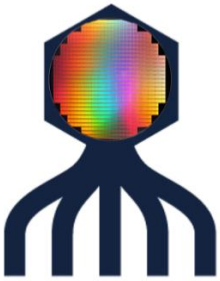

Optical circuit switched time sensitive network architecture for high-speed passive optical networks and next generation ultra-dynamic and reconfigurable central office environments

D2.1 Initial Report on Use Cases, System requirements, KPIs and Network Architecture

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Abstract: OCTAPUS aims to deliver an agile, low-cost and energy-efficient Photonic Integrated Circuit (PIC) technology framework to address the capacity-latency predicament currently faced by incumbent Central Offices (COs) and re-architect the Next Generation Central Office (NGCO) ecosystem, by transparently upgrading its capacity beyond 51.2 Tbps, through an innovative optically-switched backplane and transceiver toolkit, combined with Time Sensitive Networking (TSN) transceiver engines under the overall control of a hierarchical Software Defined Networking (SDN)-driven multi-domain coordinator. The optical and electronic components developed within OCTAPUS will be synergized with OCTAPUS's TSN nodes and SDN control plane to yield an NGCO architecture that can support three different layers of latency, targeting, in order of delay requirements (from less relaxed towards more relaxed) i) ultra-real-time traffic with highly demanding < 1ms end-to-end latency, ii) TSN-compliant traffic which must be delivered within a service-specified latency budget, thus providing deterministic latency guarantees for time-sensitive services, such as mobile fronthaul and Ultra Reliable Low Latency Communications (URLLC), and iii) Best Effort traffic, with no guarantees on achieved delivery latency. This document elaborates on the applicability and scope of OCTAPUS within the 5G and Beyond ecosystem as well as the OCTAPUS use cases, mostly targeting dense urban areas, and the end-user and system requirements considering usage/traffic scenarios (based on the concurrent use of 5G-related services and future 6G applications that are expected to emerge) in a real geographical area of the city of Paris, France. The document also identifies network architectures to support the OCTAPUS use cases, as well as the initial set of Key Performance Indicators (KPIs) against which the OCTAPUS technologies will be evaluated.

Keywords: Central Office, optical backplane, optical transceivers, PON architecture/transceivers, SDN control plane, Use Cases, mobile X-haul, URLLC, KPIs.

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Abbreviations

3GPP	3rd Generation Partnership Project
50G-PON	50 Gbps capable Passive Optical Network
5G-FMC	5G-Fixed Mobile Convergence
5GC	5G Core
(A)DSL	(Asymmetric) Digital Subscriber Line
AI	Artificial Intelligence
API	Application Programming Interface
AR/VR	Augmented Reality / Virtual Reality
BBF	BroadBand Forum
BBU	BaseBand Unit
C-RAN	Centralized Radio Access Network
CAPEX	Capital Expenditure
CNC	Centralized Network Controller
CO	Central Office
CPRI	Common Public Radio Interface
Co-DBA	Cooperative Dynamic Bandwidth Allocation
CSG	Cell Site Gateway
CTI	Cooperative Transport Interface
CU	Centralized Unit
CUC	Centralized User Configuration
D-RAN	Distributed Radio Access Network
DBA	Dynamic Bandwidth Allocation
DSL	Digital Subscriber Line
DU	Distributed Unit
E2E	End-to-End
eCPRI	Enhanced CPRI
eMBB	Enhanced Mobile Broadband
ETSI	European Telecommunications Standards Institute
F5G	Fifth Generation Fixed Network
FE	Fast Ethernet (100 Mbps)
FPGA	Field Programmable Gate Array
FTTH	Fiber to the Home
FTTR	Fiber to the Room
FTTT	Fiber to the Thing
GE	Gigabit Ethernet (1000 Mbps)
GPON	Gigabit capable Passive Optical Network
HS-PON	Higher Speed PON
IF	Interface
InP	Indium Phosphide
IoT	Internet of Things
IOWN	Innovative Optical and Wireless Network
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
KPI	Key Performance Indicator
LAN	Local Area Network
LT	Line Termination
MEC	Mobile Edge Computing
mMTC	Massive Machine Type Connectivity
MNO	Mobile Network Operator
MZI	Mach-Zehnder Interferometer
NGCO	Next Generation Central Office
NGMN	Next Generation Mobile Networks Alliance

NG-PON2	Next-Generation PON 2
NRZ	Non-Return-to-Zero
O-DU	Open Distributed Unit
O-RU	Open Radio Unit
OAM	Operations, Administration and Maintenance
OCS	Optical Circuit Switching
OBSAI	Open Base Station Architecture Initiative
OLT	Optical Line Terminal
ONT	Optical Network Terminal
ONU	Optical Network Unit
OOK	On-Off Keying
OPEX	Operational Expenditure
PCM	Phase Change Material
PIC	Photonic Integrated Circuit
PON	Passive Optical Network
PtP	Point-to-Point
PtMP	Point-to-Multipoint
QoS	Quality of Service
RAN	Radio Access Network
RU	Radio Unit
SiN	Silicon Nitride
SDN	Software-Defined Networking
SFP	Small Form Pluggable
SLA	Service Level Agreement
S-NSSAI	Single Network Slice Selection Assistance Information
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TIA	TransImpedance Amplifier
TSN	Time-Sensitive Networking
UE	User Equipment
URLLC	Ultra Reliable Low Latency Communication
US	Usage Scenario
VDSL	Very-High-bit-rate Digital Subscriber Line
WDM	Wavelength Division Multiplexing
XaaS	Anything as a service
xDSL	x Digital Subscriber Line
XG-PON	10 Gigabit Capable PON
XGS-PON	10 Gigabit Capable Symmetrical PON

1 Executive Summary

The OCTAPUS project aims at launching an agile, low-cost and energy-efficient Photonic Integrated Circuit (PIC)-based technology framework to re-architect the current Central Office (CO) ecosystem into a Next Generation Central Office (NGCO), with an upgraded capacity reaching 51.2 Tbps and beyond, through an innovative optically-switched backplane, based on novel material properties, and a 50 Gbps low-power transceiver toolkit (including optical/electronic components and low loss diplexers/ interposes), assisted by a powerful Time Sensitive Networking (TSN) transceiver engine and a Software Defined Networking (SDN)-based control plane coordinating the actions of the entire NGCO.

This Deliverable (D2.1) is the first report on the OCTAPUS Use Cases, System Requirements, Key Performance Indicators (KPIs) and Network Architecture. Being also the first technical Deliverable within the project, the document provides some introductory information on the innovations and technological advancements of the OCTAPUS solution, which will be further elaborated in subsequent Deliverables.

Specifically, after a high-level description of the overall OCTAPUS solution architecture, D2.1 provides an overview of the current status and expected enhancements of fixed access and mobile services, focusing on the applications which are expected to particularly benefit from OCTAPUS, namely X-haul mobile transport (with fronthaul having the most stringent service requirements) and Ultra Reliable Low Latency Communications (URLLC). The synergy of OCTAPUS with the planned upgrades of 50G-PON access and the evolution of Fixed and 5G services is described in detail, including a description of transceiver specifications and typical deployment densities, and a preliminary list of KPIs for the Beyond 5G and forthcoming (but not yet defined in terms of scope and requirements) 6G is provided. Along with a description of the verticals associated with the above services, the document identifies all potential involved stakeholders as well as their interests and roles in the OCTAPUS value chain.

The main added value of D2.1 is the detailed description and study of the actual Use Cases targeted, and technologically addressed, by OCTAPUS, based on a real-world scenario (i.e., considering actual geographical areas, with known characteristics in terms of topography, population demographics, offered coverage and service demands) and the development of a generic methodology for network provisioning in these scenarios. This approach aims to avoid the vague, and sometimes conflicting, definitions of “areas”, “services” and “usage scenarios” found in the literature (typically in documents from Standard Developing Organization (SDOs) such as ITU, ETSI, 3GPP, NGMN), and used for traffic estimation, while allowing the OCTAPUS stakeholders to reach a concrete set of conclusions and deployment options to support the current 5G and future 6G ecosystems and related services.

Specifically, the real-world area under study where the Use cases are examined is a typical European dense urban area in the city of Paris, consisting of districts (“arrondissements”) 14, 15, with an estimated combined population of more than 300,000 inhabitants, and exhibiting different characteristics in terms of subscriber densities, commuter vs. indoor users and service usage, while also accounting for the natural temporal cycles of human activities (i.e., day/night and busy/idle cycles, people at work/home or commuting). The above area is considered ideal for the OCTAPUS usage scenarios for another important reason: having a French mobile operator (ORAN) in the OCTAPUS Consortium, the above provisioning/network traffic calculations can be further expanded and/or updated as more information becomes available, allowing for a potential validation at later stages of the project, based on real network information.

Following the above network provisioning calculations, a high-level description of the OCTAPUS solution (and network architecture) particularly deployed for the above scenario is presented. More details, including confidential information (omitted from D2.1 due to its public dissemination level) and the complete specification of the OCTAPUS components and interfaces will be provided in D2.2. The information provided and the analysis performed in D2.1 is expected to comprise a guideline framework for the rest of the OCTAPUS Work Packages (WPs) by providing input to them and leading to the refinement/finalization of the OCTAPUS architecture and specifications to be reported in D2.3 (in M24), also including information about OCTAPUS’s lab and field trials to be conducted for the validation of the OCTAPUS solution.

2 Introduction

2.1 Purpose of this document

The present document comprises the outcome of the activities performed in Task 2.1 (titled "Use Cases, Requirements and Key Performance Indicators") of the OCTAPUS project, towards defining the project's scope and associated technical specifications that will act as input for the next Tasks of the project. It focuses on the main use cases that OCTAPUS targets, as well as on the user and system requirements derived from analyzing the use cases and elaborating on various related scenarios, leading to the design of the overall system architecture. The identification of the KPIs against which OCTAPUS will be evaluated is also included in the document as an initial step towards the experimental validation of the project's outcomes.

Additionally, this document describes a general methodology for determining the aggregated traffic requirements of the current 5G services, expected to be supported concurrently in a geographical area, along with future 6G services, expected to emerge in the future, and applies this methodology to create a "synthetic" Use Case comprising multiple different services in an actual area of Paris, France. A high-level overall OCTAPUS network architecture tailored to the above Use Case is also presented.

It is noted that the specification of the hardware components and software controller blocks, as well as the assembly process flow of the optical/electronic chips to be developed, will be described in Deliverable D2.2 (due M12), whereas the updated/final version of the OCTAPUS Network Architecture, along with the complete hardware/software specifications will be provided in Deliverable D2.3, which is planned for M24.

2.2 Document structure

The present deliverable is split into seven Chapters:

- **Chapter 2** (i.e., the current Chapter) contains an outline of the document's structure and contents.
- **Chapter 3**, titled *"Key Aspects of the OCTAPUS Project*", provides a high-level overview of OCTAPUS's scope, objectives, and major technological innovations and advancements beyond current state-of-the-art solutions, along with a high-level description of the main building blocks of the OCTAPUS-envisioned NGCO.
- **Chapter 4**, titled *"OCTAPUS (5G and Beyond) Ecosystem"*, describes the fixed (i.e., fiber-based) and mobile network services comprising the current 5G, and upcoming 6G, technology generations, along with their respective KPIs, as determined by SDOs and relevant bodies, and involved stakeholders/actors. The "placement" of OCTAPUS within this ecosystem is determined, with the OCTAPUS NGCO acting as the primary enabler of both advanced Fixed Services and 5G and Beyond mobile transport.
- **Chapter 5**, titled *"OCTAPUS Use Cases",* elaborates on the project's Use Cases and identifies the end-user and system requirements based on specific usage/traffic scenarios. A synthetic Use Case, combining fixed access, 5G fronthaul transport and a variety of URLLC services in a dense urban area of Paris is described for 3 different scenarios of communications services, along with their respective Quality of Service (QoS) requirements.
- **Chapter 6**, titled "*OCTAPUS Network Architecture"* presents the architecture of the OCTAPUS NGCO, and demonstrates its capability of supporting the diverse Use Cases described in Chapter 5.
- **Chapter 7** contains the summary and conclusions of the deliverable and completes the deliverable.

2.3 Audience

This document is intended for the public audience.

3 Key Aspects of the OCTAPUS Project

3.1 OCTAPUS Vision and Objectives

Fixed and mobile network capacity demands continue to rise exponentially, mostly due to i) the popularity of Over-The-Top (OTT) video streaming services, experiencing an estimated Compound Annual Growth Rate (CAGR) of 21% until 2028 [1], and ii) the rapid emergence of Machine-to-Machine (M2M) communications as a major contributor to network traffic (in applications such as Smart Home, Smart Grid, Industry 4.0, IoT), especially considering the fact that the number of IoT devices, which already exceeds the number of non-IoT devices, is expected to triple by 2030 [2]. In addition to the above trends, emerging 5G and Industrial Internet applications, classified under the term “Ultra-Reliable and Low Latency Communications (URLLC)”, introduce a new strict latency-oriented framework severely challenging the current 5G infrastructure and calling urgently for new radical architectural changes directly at the Central Office (CO), which is the major aggregation infrastructure in local proximity to the subscribers [3].

To support the aforementioned enormous traffic volumes and retain the capability of flexible and efficient rollout of new services at reduced Capital/Operational Expenditure (CAPEX/OPEX) towards shorter Time-to-Market deployment and increased revenues, the telecom industry envisions the exploitation of virtualization and SDN technologies to restructure the traditional CO architecture and bring it closer to that of a mini data center running on generic hardware and supporting automatic service provisioning and orchestration [4], while also hosting new flexible data services (e.g., public and private cloud-based Anything as a service (XaaS) services) as part of a distributed cloud environment. However, despite this proposed architectural shift of the CO, a careful look into the CO anatomy still reveals pressing unresolved issues that require a multi-faceted approach to truly realize the NGCOs:

- Although the switching capacity on the Optical Line Terminal (OLT) side is still the primary enabler for a plethora of access technologies ranging from DSL/GPON Internet subscriber services to Mobile Gateways for the Mobile Network Operators (MNOs), recent state-of-the-art CO-grade switches are not considered sufficiently future-proof and even the most advanced datacenter-grade switches cannot offer line-rate switching above 51.2Tbps [5], [6], [7], thus struggling to keep pace with the increasingly volatile traffic volumes. At the same time, as shown in Fig. 3.1, conventional OLTs employ an electrical backplane to interconnect the respective line cards, which cannot keep up with the development of next-generation solutions due to the huge power consumption and latency incurred in the high-power SerDes and DSP interfaces [8] required to route high-bandwidth signals between the different cards.
- The OLT’s electrical backplane typically provides static, i.e., non-configurable, and non-scalable connectivity between Uplink Switches (facing the metro network) and Interface (IF) cards (facing the access network), as the OLT chassis crucially limits the number of IF cards. Attractive features such as load balancing and bandwidth steering (which depend on the existence of many-to-many, or even all-to-all, connectivity) among multiple Uplink Switches within the electrical backplane would necessitate the use of ultra-high-speed switches beyond the current technological capabilities, as the aggregate capacities of these switches would vastly exceed the current ceiling of 51.2 Tbps, while also adding further store-and-forward delay.
- With the first version of ITU-T’s single wavelength 50G PON standard released in September 2021 (and amended in September 2022 to support symmetric 50G Upstream/Downstream rates and coexistence with previous generation PONs), along with the relevant wavelength bands allocated within 1340-1344 nm and 1260-1280 or 1290-1310 nm for Downstream/Upstream, respectively [9], there is a clear and urgent need to equip the NGCO’s access-side IF cards with energy- and cost-efficient 50G O-band transceivers capable of supporting the challenging optical link budget.
- Regarding virtualization, despite the growing maturity of the SDN technologies, progress in consolidation of the software controllers with the underlying NGCO physical layer (and particularly the optical layer interfaces) remains an open issue with vendors providing, at best, limited proprietary controllers [10].

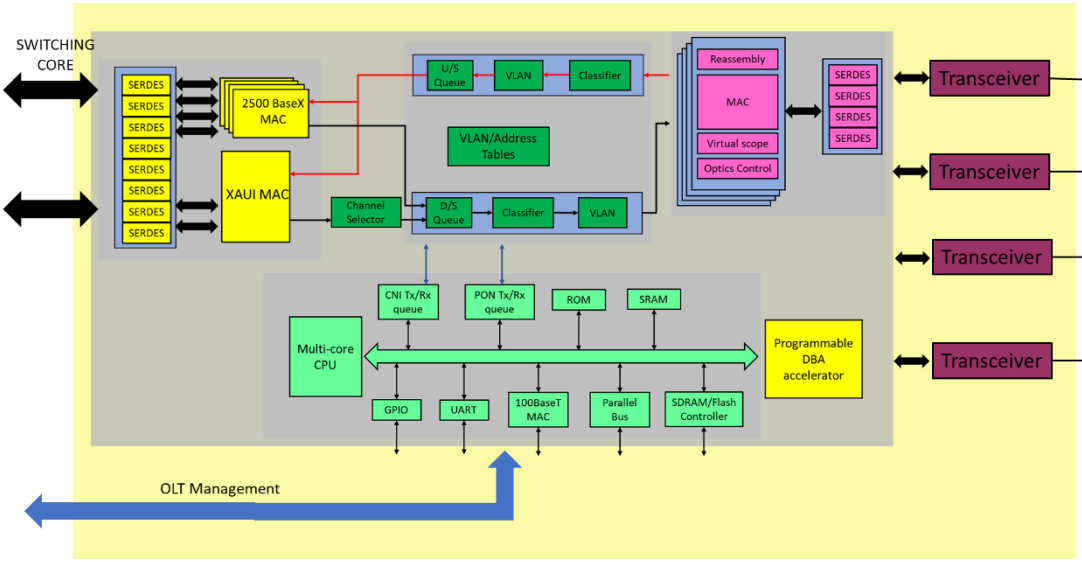


Fig. 3.1: Block diagram of traditional OLT with electrical backplane [8].

- The 5G RAN disaggregation, i.e., the splitting of the monolithic Base Station into distinct Central Unit (CU), Distributed Unit (DU) and Remote Unit (RU) entities, which has been actively pursued in the last 5 years (spearheaded by the O-RAN Alliance) to create “more intelligent, open, virtualized and fully interoperable mobile networks” [11] by allowing the mobile operators to independently design open hardware and interfaces targeting faster innovation, has introduced two major challenges: i) the need for coexistence of multiple different types of X-haul flows (i.e., fronthaul traffic between DU and RU, midhaul traffic between CU and DU, and backhaul traffic between CU and 5G Core), with disparate traffic requirements in terms of throughput, latency, and jitter, all of which may concurrently require service from the NGCO (depending on the relative position of the endpoints with respect to the NGCO), and ii) the increased distance between CU/DU and RU exacerbates the limited delay budget of time-critical applications, particularly for fronthaul services, and necessitates that the NGCO delivers deterministic latency bound guarantees in the spirit of the TSN family of standards [11]. Thus, the NGCO, serving as the tier-1 aggregation point, should incorporate the required TSN capabilities, demarcating from existing CO approaches which currently offer no such capabilities. For more latency-stringent applications, where even standard store-and-forward packet processing may introduce unacceptable delays, there is currently no mechanism within COs for creating “Express” paths that would bypass most active equipment and directly interconnect TSN service endpoints with the minimum possible latency.

The capacity/latency predicament described above underlines the need for the employment of innovative technological solutions, with photonics emerging as the key enabling technology to establish a new ultra-high capacity and energy-efficient NGCO ecosystem where component-level advancements can yield unparalleled architectural benefits. To this end, the OCTAPUS project specifically aims to fill the gaps described above by targeting the following objectives:

- Design and develop an **ultra-low-power, ultra-high-capacity, reconfigurable and modular Optical Circuit Switching (OCS)-based backplane for NGCOs** to replace the OLT’s current power-hungry electrical backplane, while offering any-to-any connectivity and allowing for on-demand bandwidth steering and transparent capacity upgrades beyond 51.2 Tbps.
- Design and develop **an energy- and cost-efficient O-band 50GHz On-Off Keying (OOK) Non-Return-to-Zero (NRZ) transceiver component and I/O portfolio** and combine it with low-power **electronic driver and Transimpedance Amplifier (TIA) ICs for board-to-board and long-reach PON communication 800 Gbps (16x50 Gbps) transceiver engines**, in anticipation of the wide deployment of emerging 50G PON solutions.
- Rearchitect the NGCO infrastructure and **equip the NGCO’s Uplink switches and IF cards with TSN functionality (never included in the COs before) to concurrently support multiple different layers of latency** with respect to traffic provisioning and secure low congestion and guaranteed service delivery for time-sensitive traffic.

- Develop and deploy an overarching **SDN-driven network orchestration framework** to coordinate the NGCO's control plane and provide the means of **flexible network and device (re)configuration, network slicing and service multiplexing targeting low latency, unified and vendor-agnostic configurability** and support for custom SDN applications (e.g., traffic monitoring and engineering, end-to-end transport services over multi-layer networks, load balancing etc.).

Encompassing all the above innovations in the hardware and software layers, Fig. 3.2 presents the general scope and vision of OCTAPUS, whereas the specific means by which these innovations will be realized are described in the following Section.

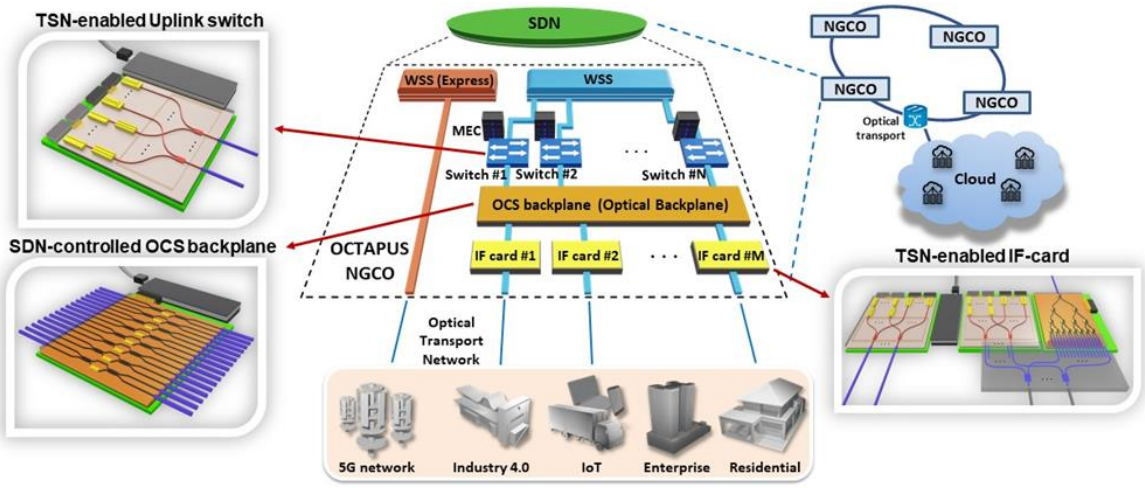


Fig. 3.2: Vision and concept of the OCTAPUS project.

3.2 OCTAPUS INNOVATIONS & TECHNOLOGICAL ADVANCEMENTS

As previously described, OCTAPUS will launch an agile, low-cost and energy-efficient Photonic Integrated Circuit (PIC)-based technology framework that will re-architect the NGCO ecosystem, transparently upgrading its capacity to 51.2 Tbps and beyond, through an innovative optically-switched backplane and transceiver toolkit. Specifically, OCTAPUS will introduce the following innovations:

- By exploiting the low-loss waveguide routing of SiN and leveraging the novel integration of antimony-based Phase Change Materials (PCM) on the low-loss, low-cost and temperature-insensitive N-rich SiN platform, OCTAPUS will develop, for the first time, **a non-volatile electro-refractive Mach-Zehnder Interferometer (MZI)-based optical switching technology with ns-reconfiguration times**, i.e., zero power is required to maintain its switching state and the light path after its establishment through the switch, towards realizing an ultra-high capacity optical backplane. The ensuing switching fabric will be highly modular based on an elementary O-band low-loss 2x2 PCM switching unit, multiple copies of which can be combined to produce a high-radix OCS architecture, serving as the OLT's photonic backplane connecting 2 Uplink switches (each of them with aggregate capacity of 25.6 Tbps) to multiple IF cards within the NGCO. Taking advantage of this scalability, multiple 2x2 PCM units will also be combined in an 8x8 Benes configuration allowing for up to 8 Uplink switches to be connected and paving the way for future NGCO capacity upgrades up to 200Tbps. A C-band version of the 2x2 PCM MZI-based switching unit will also be developed and deployed in a tree-switch layout to establish dedicated all-optical express paths between the Metro/Core network to the end-users, bypassing the latency-inducing OLT forwarding to serve the most delay-sensitive traffic.
- OCTAPUS will exploit a leading-edge InP foundry process to deliver **O-band InP lasers and low-voltage 50GHz Quantum-Confined Stark-Effect (QCSE) EAMs/PDs monolithically integrated on the same substrate** as part of a 50 Gbps OOK NRZ optical transceiver toolkit with up to 8X power savings compared to current High Speed-PON transceiver solutions. The InP lasers will be designed to support semi-cooled operation up to 45ºC, thus minimizing the need for power-hungry Temperature Controllers (TECs), while low-loss glass-based optical diplexer components, embedded in off-the-shelf glass Waveguide Array to Fiber Transposers (WAFT) interposers to achieve decreased PIC-fiber interconnect coupling, will also be developed.

The InP-based PICs will be synergized with tailor-made 50Gbps electronic driving and receiver circuits employing a scaled CMOS process to achieve low power consumption and supporting burst-mode operation as a key feature of compatibility with High Speed PON.

- OCTAPUS will develop and deploy, **for the first time in a CO environment, powerful FPGA-based implementations of TSN-enabled Uplink switch and IF card endpoints** supporting the Ethernet-based TSN family of protocols and offering low-latency through frame prioritization and scheduling (built on top of accurate time synchronization across multiple devices) among different traffic classes. OCTAPUS will **support 3 different layers of latency** with respect to traffic provisioning: i) "Express" paths bypassing all active components of the NGCO and directly connecting the metro network with the appropriate access side IF card output to serve the most time-critical traffic, whose latency budget necessitates the elimination of any unnecessary processing in intermediate nodes, ii) TSN-enabled paths passing through the NGCO offering deterministic latency guarantees for delay-sensitive fronthaul and/or URLLC services and industrial applications, and iii) Best-effort paths without explicit guarantees, targeting the least delay-sensitive services. Additional software entities in the TSN stack, such as the Centralized Network Controller (CNC) and Centralized User Configuration (CUC) agent, will also be developed to collect the TSN traffic requirements, determine proper scheduling/forwarding and interact with the OCTAPUS SDN-based service provisioning framework.
- OCTAPUS will develop and deploy an overarching, hierarchical, multi-domain **SDN-driven network orchestration framework with open, established APIs (**based on extensions to TAPI and OpenConfig standards) **and YANG models to control the NGCO's physical layer as well as interact with the relevant TSN plane's entities** (for TSN stream admission, scheduling, etc.) **and manage higher-layer functions** (i.e., load-balancing, power-aware routing etc.). To this end, specialized interfaces and APIs will be developed for the OCTAPUS SDN coordinator to enable the necessary inter-controller procedures (i.e., interaction with TSN's CUC and, potentially, CNC controller) as well as the OCS path (re)configuration.

To demonstrate its innovations, OCTAPUS will synergize its components portfolio in the following prototypes: i) an SDN-controllable 16×16 OCS-based photonic backplane, ii) a TSN-enabled Uplink Switch prototype interfaced to a PCB-packaged low-power optical engine for intra-NGCO communication, and iii) a TSN-enabled IF-card prototype interfaced to a PCB-packaged intra-NGCO optical engine and PCB-packaged long-reach optical engine for communication with 50G-PON endpoints. OCTAPUS will evaluate the delivered prototypes, TSN and SDN software plugins in time sensitive application scenarios by following a stepwise lab- and field-trial demonstration approach starting from component to module-level testing and extending up to the subsystem and network level.

3.3 OCTAPUS High-Level Architecture

Since all of OCTAPUS's hardware and software innovations focus on transforming the current Central Office into an enhanced NGCO with advanced reconfigurability and programmability features, in addition to upgraded transceiver hardware and switching fabric, the OCTAPUS solution should naturally be deployed at the locations of existing Central Offices, as shown in the upper part of Fig. 3.3 below. In fact, an OCTAPUS-derived NGCO can seamlessly interact with other non-OCTAPUS COs in the metro network (where COs are typically interconnected within a ring topology, as depicted in the central "island" of Fig. 3.3), without any alterations to the latter, as OCTAPUS's only modification (albeit, an important one) to the way a CO/NGCO connects to the metro is the introduction of the Wavelength Selective Switches (WSS) and the additional "Express" paths, the latter offering optical bypass of all NGCO-based processing towards achieving lower E2E latency. The goal of the OCTAPUS WSS is to properly guide network traffic, on a per wavelength basis, through either the NGCO itself (i.e., through the Uplink switches and IF cards comprising the OCTAPUS NGCO, as shown in the lower part of Fig. 3.3, which contains a zoom-in view of the OCTAPUS NGCO) or, by bypassing the NGCO completely via the Express paths, to the proper IF card output and its downstream connected entity (e.g., a Base Station, a fixed PON-based subscriber etc.).

At the same time, the advanced SDN-driven network provisioning features and support of TSN-enabled services offered by OCTAPUS, eventually, require similar features and interfaces to be available in the NGCO's endpoints that are using these services. Since these features/interfaces are typically implemented in software (e.g., TSN-enabled nodes require only TSN-capable Network Interface Cards,

supporting the well-documented TSN standards, while multiple NETCONF-based approaches can be employed for network monitoring, management, and reconfiguration), which can be enabled locally at the endpoints via software upgrades, OCTAPUS offers a smooth and piecemeal migration/upgrade path according to the operators' needs and subscriber base.

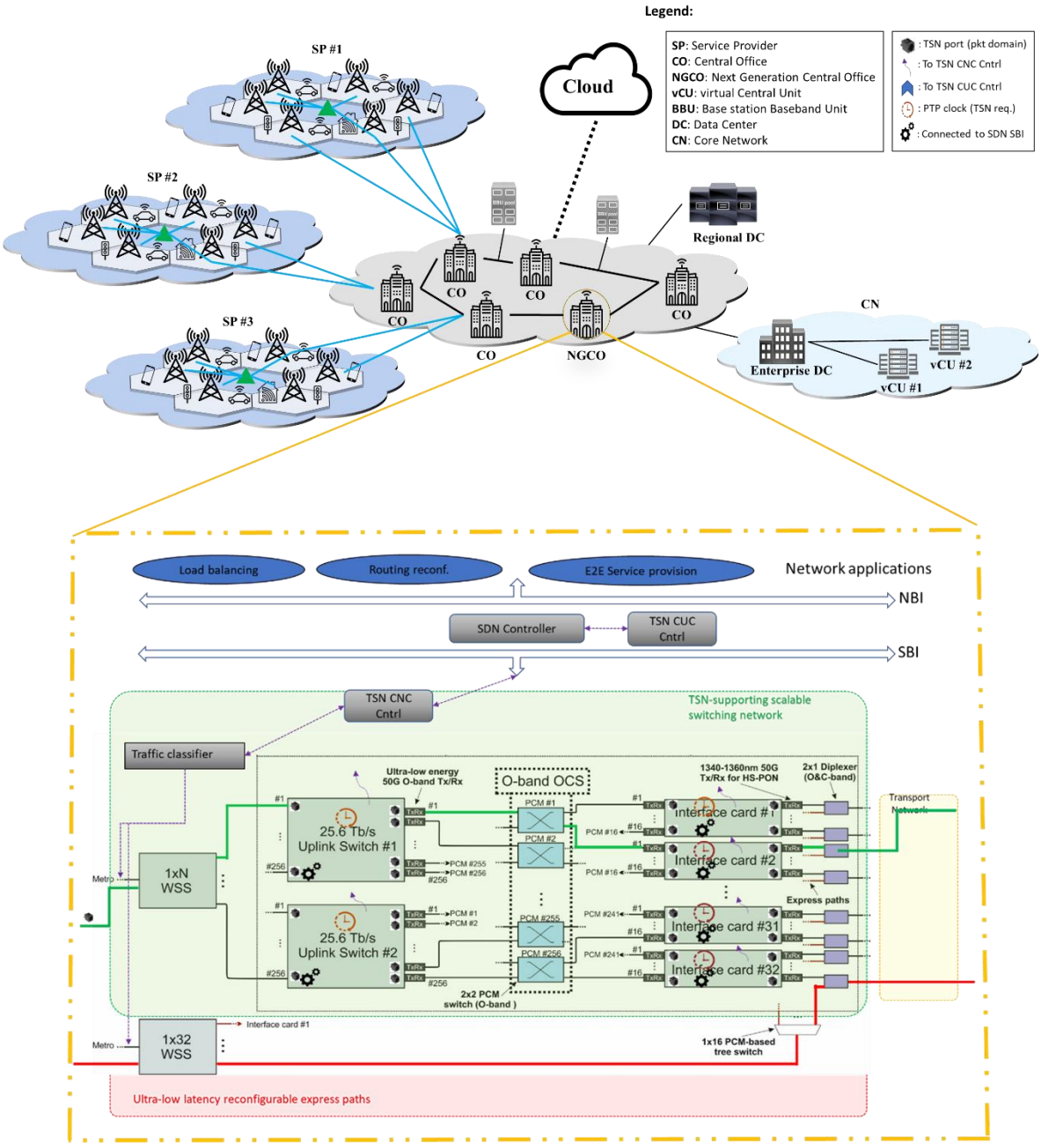


Fig. 3.3: The OCTAPUS NGCO as part of the overall end-to-end network architecture.

In addition to being capable of serving fixed residential/business subscribers via PON access, OCTAPUS is eminently suitable for transporting multiple mobile X-haul, (i.e., front/mid/back-haul) flows, depending on the type of nodes that are deployed at its "edges" (i.e., on the left and right sides of the lower part of Fig. 3.3), i.e. RU and DU for fronthaul, DU and CU for midhaul, and CU and Core for backhaul). Considering the current trends in network virtualization, both for mobile Core and RAN, which propose moving the RAN processing nodes (other than the RUs) closer towards the metro and cloud segments, the heterogeneity and diverse QoS requirements of the traffic passing through the CO/NGCO is only expected to increase in the future, which further signifies the impact of OCTAPUS in future metro networks.

We next describe the major building blocks of the OCTAPUS NGCO itself, as depicted in the lower part of Fig. 3.3. We only provide a high-level view of the OCTAPUS building blocks, with the actual implementation details and component specifications to be included in Deliverable D2.2 (titled "Initial modelling of system architecture, component/controller specifications and assembly process flow definition" and planned for M12).

- **Uplink Switches and IF cards with novel transceiver blocks**: The Uplink Switches and IF (Interface) cards shown in Fig. 3.3 serve the same purpose as in legacy COs, i.e., the Uplink Switches provide the connectivity to the metro network, while the IF cards receive traffic from the Uplink switches and serve the NGCO's downstream subscribers (e.g., PON line cards). As shown in Fig. 3.3, OCTAPUS considers Uplink switches with 256 ports towards the metro side and 256 ports towards the IF cards, respectively, whereas each IF card has 16 ports towards the Uplink switches and 16 ports for its subscribers. OCTAPUS targets ultra-high-speed OOK 50 Gbps transceivers at each port (combining O-band InP lasers with electronic driver and TIA ICs for the ports connecting the Uplink switches to the IF cards), leading to a downstream capacity of 800 Gbps for each IF card and an aggregate switching capacity of 25.6 Tbps for each Uplink switch. This is only one of the possible numerologies supported by OCTAPUS, which can be scaled up/down depending on the operator's needs and hardware complexity constraints. An additional advanced feature present in OCTAPUS Uplink switches and IF cards is the inherent support of TSN networking, as described next.
- **Multi-band O/C-band Glass-diplexers:** Low loss and compact interfaces to fibers, through advanced glass-based interposers with integrated diplexer functionalities will be assembled to OCTAPUS' novel SiN and PIC technology. Specifically, OCTAPUS will exploit low-loss glass-based 1340/1550nm optical diplexer components, embedded in off-the-shelf glass WAFT interposers, to achieve advanced on-chip wavelength-routing functionality on the glass and decreased PIC-fiber interconnect coupling losses. The diplexers will be placed at the InP TxRx of the OLT, i.e., being interleaved at the front-panel of the NGCO (facing towards the access part of the network), allowing to simultaneous multiplex/demultiplex the O-band and C-band traffic. This will effectively allow to pass the O-band PON traffic towards the line card where the line will be terminated, as foreseen for conventional HS PONs and marked with a green line in Fig. 3.3, while at the same time discern the C-band low-loss traffic and route it towards an "express path" in an all passive manner, as noted with the red line in Fig. 3.3.
- **TSN-enabled switching devices**: TSN networking, as implemented by the corresponding family of IEEE standards, enhances Ethernet networks by i) introducing network-wide time synchronization based on a Grandmaster clock via the generalized PTP (gPTP) profile defined in IEEE 802.1AS, and ii) exploiting time synchronization to offer features such as time-aware scheduled transmission (via IEEE 802.1Qbv) and delivery, flow prioritization, low queueing delay and deterministic latency guarantees, similar in concept to how train schedules guarantee departure and arrival at the specified times. TSN functionality is particularly important for periodic, Constant Bit Rate traffic, such as low-layer functional split fronthaul, or for URLLC services with very tight delay budgets. Since these TSN features must be present at all intermediate nodes along the E2E service path, OCTAPUS's innovation lies in adding, for the first time in the context of a CO, this functionality into the Uplink switches and IF cards via FPGA-based TSN implementations (scaled down with respect to the number of ports and line rates) to be evaluated in lab and field trials.
- **TSN networking stack and controllers**: For TSN flows to be properly managed by OCTAPUS, additional TSN-related entities are required, apart from the 802.1AS-achieved time synchronization between Uplink switches and IF cards (depicted in Fig. 3.3 by the clock icon). Initially, a software block termed the Centralized User Controller (CUC) must periodically collect the TSN traffic requirements, in terms of E2E throughput and latency, so that a suitable schedule satisfying the requirements is constructed and proper match+ action forwarding actions are inserted into the Uplink switches and IF cards processing the TSN flows. It is noted that TSN-compliant scheduling is performed on a per Ethernet port basis, which requires the network topology to be known (e.g., via the Link Layer Discovery Protocol, LLDP). The topology and TSN service requirements information is then fed to the Centralized Network Controller (CNC), with the critical intervention of the multi-domain SDN Coordinator (referred to as "SDN Controller" in Fig. 3.3), and the CNC constructs the proper TSN schedule (for the TSN flows only), with any remaining slots becoming available for non-TSN (i.e., Best Effort standard Ethernet) traffic. The TSN scheduling decisions, i.e., when each port gate should open/close for

transmission, are then sent to the Uplink switches and IF cards to be enforced via the proper match+action rules determined for the schedule.

- **SDN-driven multi-domain coordinator:** In addition to its close collaboration with the TSN control plane entities (i.e., CUC, CNC), the SDN Coordinator/Controller in Fig. 3.3 is responsible for coordinating higher layer functions (such as power/congestion-aware routing, load balancing etc.) as well as the OCS hardware reconfiguration (discussed below), based on consistent network state information collected through monitoring probes. To this end, the SDN Coordinator follows a hierarchical structure, (with specific internal sub-components in charge of the above tasks) and exposes two standard interfaces, a Northbound Interface (NBI) towards the network applications running on top of it (e.g., routing, load balancing, network analytics) and a Southbound Interface (SBI) towards the devices controlled by it and/or executing the SDN Controller's decisions.
- **All-optical, reconfigurable backplane**: The electrical backplane of legacy COs offering "pre-configured" connectivity to the line cards (e.g., PON cards) is replaced in OCTAPUS by an SDN-controllable, reconfigurable OCS backplane consisting of multiple 2x2 O-band low-loss PCM switching devices, which can be configured to one of 2 switching states (i.e., "straight" vs. "cross" switching) via suitable electrical waveforms driving the heating circuits of the PCM switches and suitably changing the material state from crystalline to amorphous (and vice versa). This adds tremendous flexibility to the backplane fabric, as the intra-NGCO ports of the IF cards can be dynamically connected to any of the Uplink switches in any combination desired, allowing for load balancing among the Uplink switches and/or potentially placing an Uplink switch in low-power ("sleep") mode in situations of very low traffic demands which can be met by the remaining active Uplink switches. The state of the 2x2 PCM switches is reported to the SDN Coordinator, which may request a reconfiguration of one or more PCM switches if it determines that the new switch state (and, thus, the ensuing backplane connections) would yield performance benefits in terms of power expenditure, latency etc. In such a case, the SDN Controller will issue an instruction (via suitable NETCONF-based messages) to a separate control FPGA board (distinct from the FPGA implementations of Uplink Switches and IF cards) to create the proper control waveform for the PCM's heating circuit to transition into the new switch state.

4 OCTAPUS (5G and Beyond) Ecosystem

4.1 Fixed Network Services, Requirements and KPIs

Fixed access networks rely today on either Point-to-Multipoint connectivity with different generation of PONs or Point-to-Point connectivity with a trend to generalize single fiber interfaces with bidirectional transmissions to reduce the fiber-scale footprint.

In parallel to the evolution of mobile networks from 2G, 3G, 4G to 5G today, a recent initiative in the ETSI standardization body proposes to describe the evolution of the fixed access networks from the service and network perspectives. Fig. 4.1 presents the evolution of the fixed network toward its fifth generation "F5G" (Fiber Fifth Generation) in terms of technologies and services. To this end, the Industry Specification Group (ISG) for F5G, which includes more than 32 members (among them Huawei, TIM, Orange, China Telecom, Fraunhofer, Commscope etc.) plus the EU Commission as an observer, published the F5G Release 1 (Year 2020 and 2021) in [12].

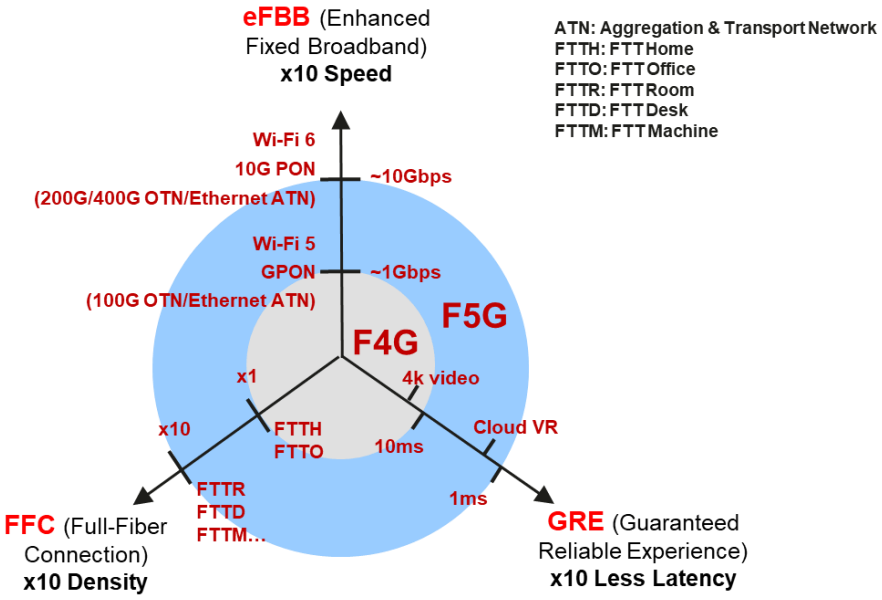


Fig. 4.1: Evolution of fixed access networks.

As shown in Fig. 4.1, the new fifth-generation fixed networks aim to upgrade previous solutions, considered as the 4th generation of fixed networks "F4G", by introducing three main features:

- A Full-Fiber Connection (FFC).
- An Enhanced Fixed Broadband (eFBB).
- A Guaranteed Reliable Experience (GRE).

F5G will utilize FFC, eFBB and GRE to provide over 10× higher bandwidth, 10× denser fiber connections and 10× better reliability and latency. F5G will create new possibilities by extensively deploying fiber technology across diverse scenarios and extending its reach to all aspects of life, with the aim of benefiting various industry sectors such as telecom, education, healthcare, finance, energy, transportation, and manufacturing. This expansion of fiber connectivity seeks to provide opportunities and advantages to all verticals within these industries.

More recently, further progress was made to expand the view of this fixed network evolution with a first publication of the F5G Release 2 in September 2022 [13] and another release for "F5G Advanced" in 2023 by ETSI [14]. The latter document describes the scope of F5G Advanced in terms of the six dimensions shown in Fig. 4.2; out of these dimensions, three of them (i.e., "faster", "quicker", "wider") are evolutionary upgrades of already existing F5G network features and capabilities, whereas the remaining ones (i.e., "smarter", "more aware", "greener") are considered as new directions.

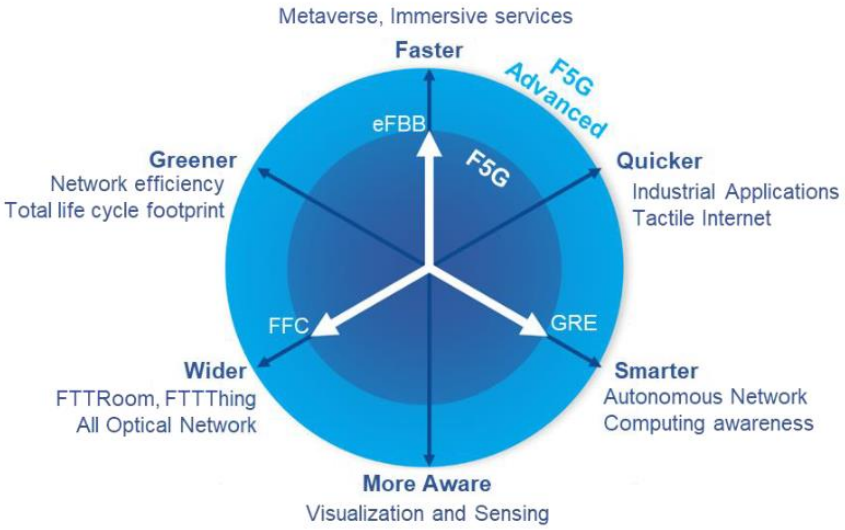


Fig. 4.2: The six envisioned dimensions targeted by F5G Advanced.

The fixed network capacity is expected to evolve across all six key aspects mentioned above. Firstly, networks will enhance their speed by increasing bandwidth, allowing for a greater number of services to be accommodated. Secondly, networks will strive to minimize latency as much as possible, enabling the development of new applications. Additionally, networks will expand in terms of their scope and number of endpoints, effectively becoming "wider". Moreover, efforts will be made to enhance energy efficiency, making networks more environmentally friendly (i.e., "greener") through various means. Information processing systems will also be exploited by adding computational capabilities at all levels of the network, resulting in smarter operations. Furthermore, networks will develop a higher level of awareness, aiding in the improvement of operations and maintenance and increasing their overall trustworthiness.

OCTAPUS is expected to mostly contribute to four of the above six factors, as briefly discussed next:

- **Faster (increasing bandwidth):** F5G Advanced foresees a growth of application bandwidth and the need for modernization in transport, access, and home networks to accommodate this growth. Application bandwidth has been increasing at a rate of around 40% per year, with factors such as the growing number of endpoints, the emergence of new applications (such as Facebook's Metaverse and immersive services), and increased usage in existing applications contributing decisively to this growth. In the optical transport network, technologies like 200G and 400G per lambda are currently prevalent in the F5G era. To accommodate further bandwidth growth in the F5G Advanced era, [14] suggests increasing the capacity to 800G per lambda and expanding the number of wavelengths or channels. **In terms of optical access systems, the default system in the F5G era is XG(S)-PON, which is constantly gaining in popularity. In the future, the deployment of the 50G-PON system is expected to begin during the F5G Advanced timeframe** with Fig. 4.3 presenting a schematic view of some specification of interest in the 50G-PON recommendation edited by ITU-T in 2021 and 2023 (Amendment 1) [15].
- **Quicker (reducing latency):** this is most relevant to reducing latency in future networks due to the emergence of UHD immersive experience services and the requirements of applications such as Tactile Internet and industry applications. **Current PON standardized technologies based on TDMA schemes do not fully guarantee the desired latency and jitter conditions or protect against a potentially rogue Optical Network Terminal (ONT), leading to a demand for new solutions that ensure real-time and reliable connections.** Also, the digital transformation of energy and transportation industries requires high-bandwidth and reliable hard-pipe connections. The Optical Service Unit (OSU) hard pipe technology offers flexible link bandwidth, low latency, high reliability, and physical isolation, supporting the digital transformation of industrial production networks.

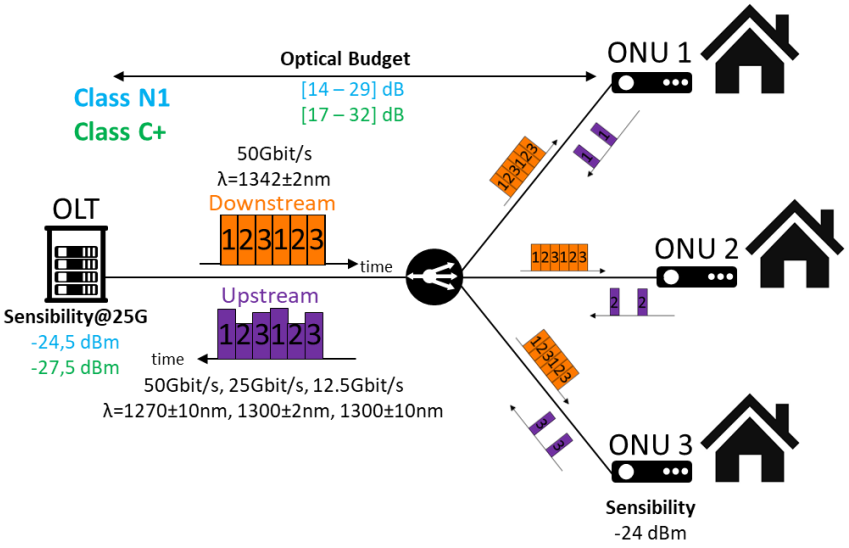


Fig. 4.3: 50G-PON recommendations for optical budget and wavelength allocation.

- **Wider (increasing the network scope and number of endpoints):** in F5G Advanced, there will be an expansion in the network scope and number of endpoints to accommodate more services and broader coverage. This expansion aligns with the dominance of cloud networking and aims to establish F5G Advanced as the foundation of the network, offering high capacity, performance, and reliability as a ubiquitous intelligent bearer for cloud and digital transformation. **The focus will be on the All-Optical Network (AON), consisting of backbone, metro, access, and data center interconnection (DCI) optical networks.** Each network layer has specific requirements and utilizes different technologies. The service plane is supported by the various layers of the all-optical networks, with enhancements in the backbone and inter-city networks. Additionally, F5G Advanced will provide robust support to Data Centers (DCs) at all levels. As depicted in Fig. 4.4, F5G Advanced encompasses applications like Fiber-To-The-Room (FTTRoom) for smart homes and Fiber-To-The-Thing (FTTThing) for fiber-based IoT applications in Machine-to-Machine communications. It also incorporates more advanced physical layer technologies, including high-speed optical transceivers, multi-band optical amplification, new ultra-low loss optical fibers, and Reconfigurable Optical Add/Drop Multiplexers (ROADMs) with increased capacity and flexibility. These advancements elevate F5G Advanced as a pivotal component in the future cloud and digital transformation, serving as the foundation for the new information and communication infrastructure. Also, the Innovative Optical and Wireless Network (IOWN) forum has introduced a new network architecture called the Open All-Photonics Network (APN) [16] to meet the demanding bandwidth and latency requirements of its use cases and published the Release 1 architecture document for APN. The APN concept involves utilizing optical components (e.g., optical switches) for networking purposes, aiming to eliminate delays caused by electrical packet processing. The APN is a connection-oriented network based on wavelength switching, designed to support different physical deployment scenarios, including the use of wavelength multiplexing/switching nodes in customer premises. The APN's open and disaggregated architecture provides deployment flexibility through three functional components: APN-T (Transceiver), APN-G (Gate), and APN-I (Interchange) to create a Group of Optically Interconnected Points (GOIP), as shown in Fig. 4.5. By utilizing multiple wavelengths and establishing optical wavelength connections dynamically between communication endpoints, the APN offers high scalability on the road to 6G and enables high-speed data transfer with minimal latency, achieving speeds in the tens or hundreds of Gbps and sub-millisecond latency. This capability makes APNs well-suited to efficiently support IOWN use cases.

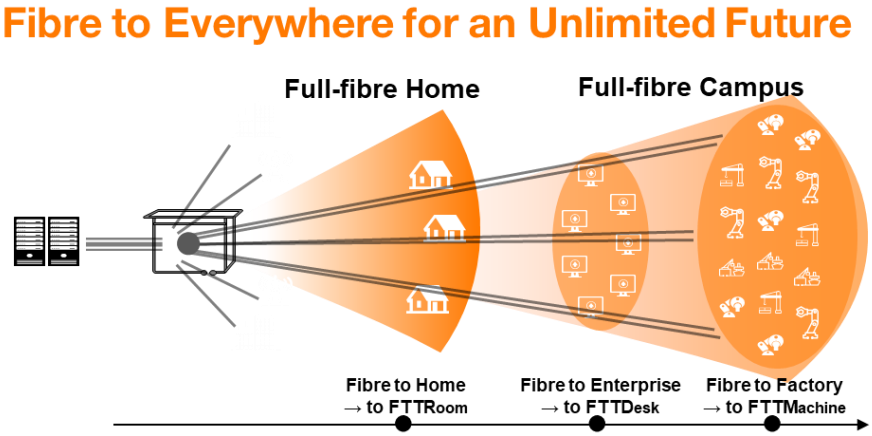


Fig. 4.4: Wide fiber connectivity penetration in F5G Advanced supporting diverse services.

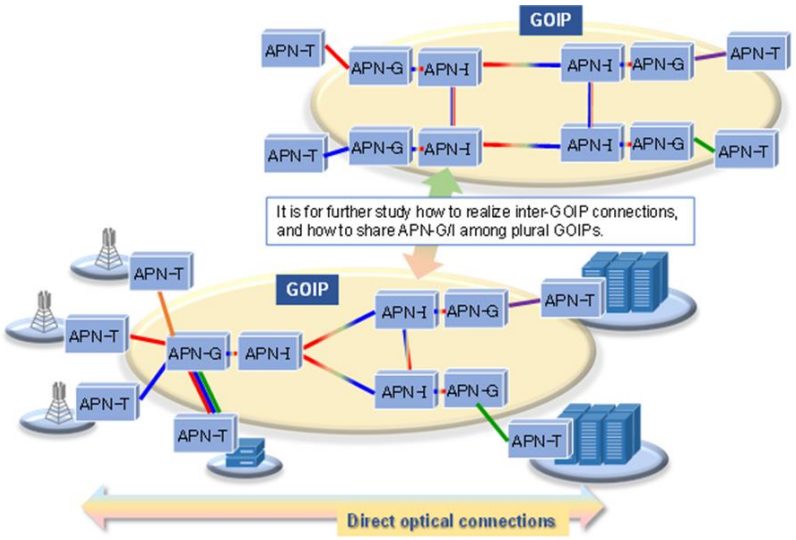


Fig. 4.5: An example of a GOIP enabled via an APN [17].

- **Greener (enhancing energy efficiency):** The transition to green energy is a global challenge, and the European Green Deal aims to make the European Union climate-neutral by 2050. To achieve this goal, decarbonizing the energy system and reducing greenhouse gas emissions are crucial components, with a focus on clean energy from renewable sources and energy efficiency. **The ICT industry can contribute by minimizing energy consumption in network infrastructure and data centers, especially through the deployment of energy-efficient optical networks. Additionally, F5G Advanced technology can address power consumption in optical access networks by implementing energy-efficient technologies and reusing existing network equipment. In an end-to-end optical network for FTTH (Fiber-to-the-Home), the optical access network consumes approximately two-thirds of the energy (60% by the ONU and 7% by the OLT) [18] while the core and aggregation network account for the remaining one-third.** To effectively manage power consumption, F5G Advanced technology needs to address all aspects of the fixed network, with a particular focus on reducing energy usage in optical access networks. This can be accomplished through **the development of energy-efficient technologies for optical network elements such as ONU and OLT**. For instance, implementing energy-aware switching and routing, as well as application-specific energy reduction for optimized distribution of high-definition video streaming, can contribute to lower power consumption. Additionally, integrating power-saving modes in optical networks with mobile and wireless access points, or allocating specific network functions (e.g., keep alive) to the optical edge, can also reduce energy consumption. Overall, F5G Advanced offers solutions to reduce the environmental footprint of networking equipment throughout its lifecycle.

Table 1 below provides an overview of indicative requirements, specifications, and timelines for various fixed access network technologies [19] with the last two columns being estimations for F5G Advanced and F6G and suggesting potential access technologies to facilitate the progression from F5G to F5G Advanced and beyond. In optical access systems, XG(S)-PON has emerged as the default system to meet the F5G era and is steadily gaining popularity. Moving forward, the deployment of the 50G-PON system is anticipated to start during the F5G Advanced phase. F5G Advanced aims to deliver rates ranging from 10 Gbps to 100 Gbps in future PONs and PtP interfaces. Furthermore, in terms of future advancements for F6G, the very-High-Speed PONs (vHSP) technology that emerges from ongoing discussions within the Full Service Access Network (FSAN) association could potentially serve as the reference technology. This progression would pave the way for the development of multi-100 Gbps systems. If these estimations hold true, access networks might have the capability to support speeds of up to 1 Tbps for access networks beyond 2030.

Table 1: Specification and timeline of fixed access network technologies [19].

Fixed Network Generation	F1G (ETSI)	F2G (ETSI)	F3G (ETSI)	F4G (ETSI)	F5G (ETSI)	F5G Advanced (estimation)	F6G (estimation)
Reference downstream rate per user	< 2 Mbps	2-30 Mbps	30-100 Mbps	100-1000 Mbps	1-10 Gbps	**10-100 Gbps**	**100-1000 Gbps**
Reference upstream rate per user	0.5 Mbps	1-2 Mbps	15-100 Mbps	50-500 Mbps	1-10 Gbps	**10-100 Gbps**	**100-1000 Gbps**
Reference services	Voice, dial Internet	High speed Internet, SD video	HD video	UHD 4K video	VR video, cloud gaming, smart city	**Industrial IoT, smart cities**	**Industry 4.0, AR, eHealth**
Reference architecture	CO LE	CO DSLAM	FTTC/ FTTB	FTTH/ FTTdp	FTTH/ FTTR	**FTTH/FTTR/ FFTeverything**	**Advanced Fiber Infra-structure, APN**
Access Network Technology Reference	PSTN/ ISDN	ADSL/ ADSL2+	VDSL2	GPON/ G.Fast	XGS-PON	**50G-PON**	**50G-PON vHS-PON**
Technical Specifications Reference	I.100-I.699	G.992.x	G.993.x	G.984.x, G.9701	G.9807.x	**G.9804.x**	**G.9804.x, G.vshp (under discussion)**
Reference user network interface	RJ11/ RJ45	FE+ WiFi1/2 (802.11b, 802.11a)	FE+WiFi3 (802.11g)	FE/GE + WiFi4/5 (802.11n/ac)	GE/10GE + WiFi6 (802.11ax)	**10 GE/100GE + WiFi7 (802.11be)**	**100GE + 1000GE + IoT + new WiFi**
Specification timeline	1998-1993	1999 (ADSL), 2003 (ADSL2+)	2006	2006 (GPON), 2014 (G.fast)	2017	**2023**	**~2030**
Production Timeline (significant volume)	1990	2000	2007	2010 (GPON), 2014 (G.fast)	2018	**2027**	**> 2030**

4.2 5G and Beyond services, Requirements and Network KPIs

The first step towards determining the use cases that are addressed by OCTAPUS advancements and innovations is to recognize the technical and business environment that has already started to revolve around 5G and beyond solutions. To this end, it is necessary to identify the target end-users/market segments/industries, their services, operations etc. along with the service requirements and KPIs to be met by a beyond 5G system. In this context, the work of standardization bodies such as 3GPP, ETSI and ITU, as well as industry alliances and regulatory bodies with regards to the definition of the applications and network services and the required QoS in 5G deployments and beyond plays a key role.

4.2.1 Introduction to 5G services and Network KPIs

When 5G was conceptualized, it was intended to be a disruptive technology, not only in terms of technical advancements but also in the range of services it would offer. 5G was initially defined based on the following three generic service classes shown in Fig. 4.6 as the triangle vertices.

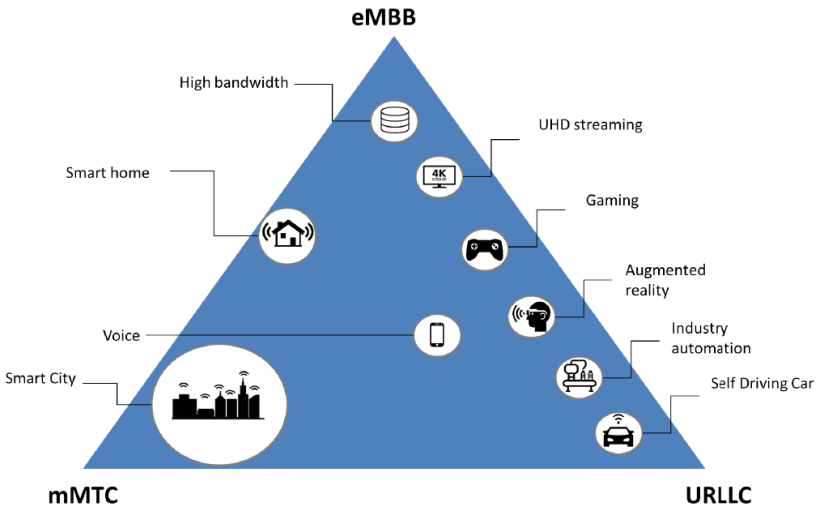


Fig. 4.6: Fundamental 5G use cases.

- Enhanced Mobile Broadband (eMBB): Introduced in 3GPP TR 22.863 [21], this service class aims to 5G applications with high bandwidth capabilities, motivated by the ever-increasing demand for bandwidth due to the growing number of users and their data/Internet usage patterns. eMBB applications primarily consist of bandwidth-intensive applications such as video streaming, video conferencing and virtual reality, requiring user data rates of up to 100 Mbps and even up to 1 Gbps for Augmented/Extended Reality (AR/XR) [22]. eMBB represents a natural evolution of 4G in terms of higher bitrate, enabling connectivity solutions like Fixed Wireless Access (FWA) [23], which offers an “FTTH-like" experience through a mobile connection.
- Ultra-Reliable Low-Latency Communication (URLLC): Introduced in 3GPP TR 22.862 [24], this service class is associated with emergency and mission critical communication services with stringent reliability, availability and delay requirements, often requiring end-to-end round trip times of less than 1 millisecond. URLLC is a special service class specifically introduced in 5G to enable services that demand extremely low latency, such as self-driving cars and industrial automation. 3GPP Release 15 introduced the concept of low latency and ultra-reliability, while Release 16 provided the full technical specifications, including processes for scheduling and managing radio resources.
- Massive Machine Type Connectivity (mMTC): Introduced in 3GPP TR 22.861 [25], this service pertains to communication among a large number of connected devices. Similar to URLLC, mMTC is a newly introduced specification in 5G that aims to enable connectivity for both small and large-scale connected entities. mMTC requires efficient coordination with low-bandwidth requirements in the range of kilobits per second. It focuses on applications that require extensive interconnectivity and is primarily defined by the density of connections. IoT (Internet of Things) applications heavily rely on mMTC, where ubiquitous connectivity is essential for seamless communication among different nodes.

The technical specifications for these services are outlined in [26], while Table 2 provides a summary of the main technical requirements for each 5G service and their corresponding target values. For instance, eMBB services can achieve peak data rates of up to 20 Gbps for downlink and 10 Gbps for uplink. URLLC requires a one-way latency of 1 ms and transmission reliability of 5 nines (i.e., probability of successful communication above 99.999%) for successfully transmitting a layer 2 Protocol Data Unit (PDU) of 32 bytes within a 1 ms window. Lastly, mMTC should support a density of connections reaching up to 1 million devices per square kilometer.

Table 2: KPIs for primary 5G services as defined in [26].

Targeted service				
	eMBB	**URLLC**	**mMTC**	**Target value**
Peak data rate	✓			Downlink: 20 Gbps – Uplink: 10 Gbps
User experienced data rate	✓			Downlink: 100 Mbps – Uplink: 50 Mbps

User plane latency	✓	✓		URLLC: 1ms – eMBB: 4ms
Control plane latency	✓	✓		20 ms (10 ms encouraged)
Connection density			✓	10^6 devices/km^2
Reliability		✓		Probability of failure 10^{-5}

The above specifications target the definition of vertical end-user service requirements from the network point of view. These aggregate KPIs have been further augmented considering 5G and beyond systems. Specifically, with 3GPP Rel. 17 being frozen in June 2022, Rel. 18 officially marks the start of 5G-Advanced standardization aiming to enable even more highly demanding services to appear on the horizon of Beyond 5G (B5G) and 6G systems.

4.2.2 Beyond 5G and 6G Network KPIs

6G officially set off with the first global 6G summit in Finland in 2019, marking a significant step in telecommunications research. The primary goal of 6G is to exceed the main 5G KPIs, namely data rate, latency, reliability, and density and introduce new use cases, such as enhanced location accuracy, mapping capabilities, environmental sensing, and body sensor data [27]. In addition, 6G envisions a new dimension known as the digital world, or as digital twinning, besides providing seamless mobile connectivity between the physical and human worlds.

Various white papers from companies worldwide [28], [29], [27] have outlined three important milestones for the implementation of 6G in the telecommunications ecosystem:

- By 2025, the focus is on defining 6G requirements, initiating the standardization of 6G technology, and commencing technical studies.
- By 2028, the goal is to have the initial specifications in place and begin the evaluation phases, including the Proof of Concept (PoC) design.
- By 2030, commercialization of 6G is anticipated to be available in select countries.

The Hexa-X European research project, which commenced on January 1, 2021, led by Nokia (as project coordinator) and Ericsson (technical manager), with participation from Orange and other contributors, is dedicated to studying beyond 5G and 6G technologies [30]. Hexa-X aims to achieve five key objectives for 6G: i) establishing foundations for an end-to-end system, ii) enhancing radio performance, iii) enabling connected intelligence, iv) facilitating network evolution and expansion, and v) creating impact. Initial research studies have already been presented at conferences and published in journals [31], [32].

At the same time, EU-funded 5GPPP ICT-52 projects commenced in January 2021 to pave the way for 6G by investigating technologies that can enable 6G developments. These projects include MARSAL [33], RISE6G [34], DEDICAT-6G [35], REINDEER [36], B5GOPEN [37], DAEMON [38], AI@EDGE [39], TeraFlow [40] and 6GBRAINS [41]. More recent and future 6G-related projects will be under the auspices of the European Smart Networks and Services Joint Undertaking (SNS JU: https://smart-networks.europa.eu/), a Public-Private Partnership whose mission is to fund projects that shape a solid research and innovation (R&I) roadmap and deployment agenda.

The 6G KPIs and their relation to the 5G counterparts, as identified by various stakeholders in the telecommunications ecosystem, are summarized in Table 3 below.

Table 3: Envisioned 6G KPIs [28], [29], [42].

KPI items/ company	Compared to 5G	Orange	NTT Docomo	Samsung	ZTE	China Mobile	Huawei
Data rate	>100x	100 Gbps to 1 Tbps	>100 Gbps (>100x capacity)	1 Tbps (user experienced data rate 1 Gbps)	1 Tbps	1 Tbps (user experienced 10-100 Gbps)	
Latency (ms)	>10x	-	<1	<1 (Air latency 0.1)	(Air latency <0.5)	<1 (ultra low jitter)	Air latency <0.1 (+- 1µs jitter)
Reliability	>100x	-	99.99999%				
Positioning	>100x	-	<1 cm	< cm scale	Out/indoor < 10/1 cm	Out/indoor < 1m/1 cm	Out/indoor < 50m/1 cm

KPI items/ company	Compared to 5G	Orange	NTT Docomo	Samsung	ZTE	China Mobile	Huawei
Mobility (km/h)	2x	-	-	>500	-	>1000	-
Battery life	2x	-	-	-	20 years	-	20 years
Density (number of devices/km^2)	>10x	10-100M	10M	10M	100M	10-100M	100M

In parallel to the industry foresights, and although not rigidly defined yet, 3GPP working groups are focusing on identifying the requirements of next generation networks, while at the same time ITU-R WP5D is working on the new recommendation under the title "IMT Vision 2030 and Beyond". NetworldEurope 2022 Strategic Research and Innovation Agenda 2021-2027 (SRIA) defined a pathway to network evolution within the 2020-2030 timeframe [43], and the EU research community (i.e., EU projects, 6G-IA) are working closely to align on a unified 6G networks vision. The KPIs and Targets for 5G and beyond are depicted in Table 4, as aligned with SRIA 2021-2027.

Table 4: KPIs and Targets for 5G and beyond in terms of Short/Middle/Long Term Evolution (SEVO/MEVO/LEVO) alligned with SRIA 2021-2027 [43].

Target KPI	Target in 5G	Target in 5G SEVO	Target in 5G MEVO	Target in 5G LEVO
Spectrum	<52.6 GHz	<150 GHz	<300 GHz	<500 GHz
Bandwidth	<0.5 GHz	<2.5 GHz	<5 GHz	<10 GHz
Peak Data Rate	DL: >20 Gbps; UL: >10 Gbps	DL: >100 Gbps; UL: >50 Gbps	DL: >200 Gbps; UL: >100 Gbps	DL: >400 Gbps; UL: >200 Gbps
User Data Rate	DL: >100 Mbps; UL: >50 Mbps	DL: >500 Mbps; UL: >250 Mbps	DL: >1 Gbps; UL: >0.5 Gbps	DL: >2 Gbps; UL: >1 Gbps
Density	>1 device/m^2	>1.5 device/m^2	>2 device/m^2	>5 device/m^2
Reliability	URLLC: >5 nines	>6 nines	>7 nines	>8 nines
U-Plane Latency	URLLC: <1 ms	<0.5 ms	<0.2 ms	<0.1 ms
C-Plane Latency	<20 ms	<10 ms	<4 ms	<2 ms
Net. Energy Efficiency	Qualitative	>30% gain vs IMT 2020	>70% gain vs IMT 2020	>100% gain vs IMT 2020
Term. Energy Efficiency	Qualitative	>30% gain	>70% gain	>100% gain
Mobility	<500 Km/h	<500 Km/h	<500 Km/h	<1000 Km/h
Positioning accuracy	<1 m	<30 cm	<10 cm	<1 cm

4.2.3 5G and Beyond KPIs Decomposition

To meet the aforementioned service requirements and KPIs, 5G and beyond network architectures promote the placement and integration of compute resources in various segments of the deployed networks in order to co-locate parts of end-user applications and services together with the required softwarized network functions. Mobile Edge Computing (MEC), Network Function Virtualization (NFV) and various RAN disaggregation approaches practically aim to materialize these principles and, at the same time, drive the joint provisioning of compute/storage resources and network services. In this context, optimization of resource allocation by exploiting the spatio-temporal character of demand for compute or network services and resources arises naturally. To this end, 5G network systems are

moving towards supporting complete service lifecycles, i.e., specific service types, at specific locations and time periods, which places strong emphasis on a unified service orchestration framework.

Considering these, in the context of early activities of 5G-PPP, the infrastructure and service KPIs defined by standardization bodies and industry alliances have been compiled and decomposed to more concrete, measurable and relevant operational 5G network and service deployment KPIs, considering the 5G equipment capabilities as well as network deployment specificities. Initially, latency and service deployment time have been refined in 5G PPP PMR [44] as follows:

- The end-to-end latency KPI has been decomposed to a number of delays (latencies) accounting for transmission along the network segments (RAN, Backhaul, Core), processing by network components (equipment) and application layer processing, as shown in Fig. 4.7.
- The service deployment time KPI has been decomposed to timing KPIs related to the following distinctive operations: i) Platform Provisioning, ii) Service/Application Onboarding, iii) Service Instantiation/Configuration and Activation, iv) Service Modification and v) Service Termination.

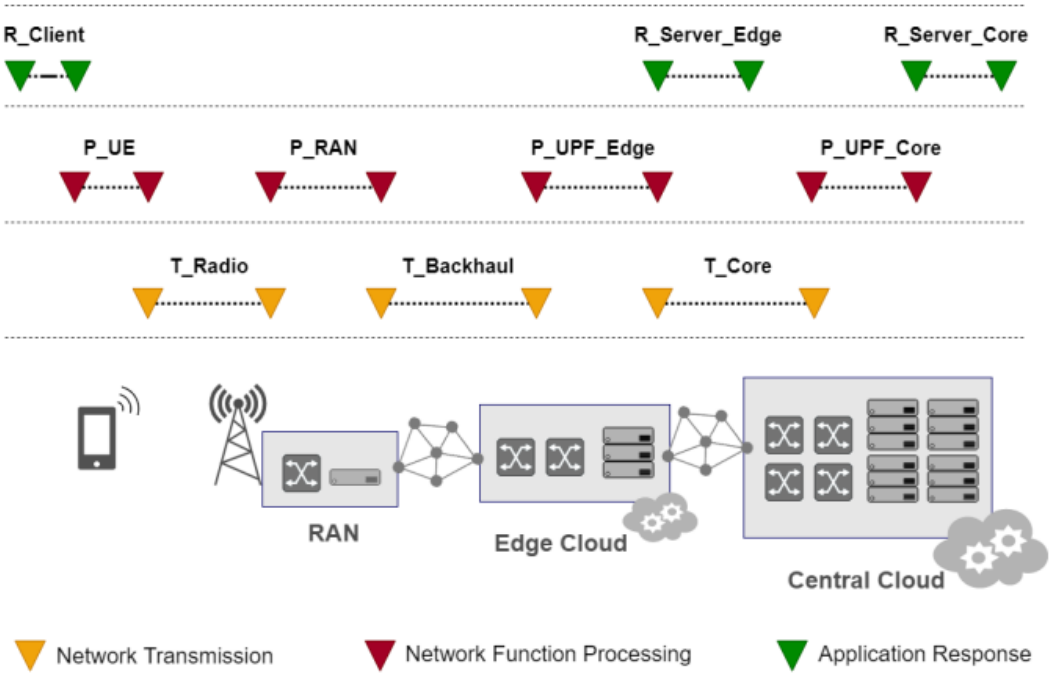


Fig. 4.7: Components of Latency KPI. Components starting with T, P, R indicate latencies induced by Transmission, Processing and Responses, respectively.

Moreover 5G-PPP has made an effort to identify the Beyond 5G and 6G KPIs at early stages in [45] and [46]. Table 5 provides a list of refined KPIs by SDOs, the 5G Infrastructure Public Private Partnership (5G-PPP), and the newly established 6G-IA (6G Infrastructure Association), that can be considered as applicable to the solution and positioning of OCTAPUS regarding 5G and beyond networks and services. It shall be noted that Peak User Data rate, Experienced User Data rate, User Density, U/C-Plane latencies, and Energy Efficiency adhere to the definitions given by ITU-R (M.2410-0, [47]), while reliability KPIs adhere to the definitions adopted by 3GPP TS 22.104. The rest of the KPIs definitions adhere to [44] and [45]. Table 5 provides a list of refined KPIs by SDOs and the 5G Infrastructure Public Private Partnership (5G-PPP), that can be considered as applicable to the solution and positioning of OCTAPUS in 5G and beyond networks.

Table 5: List of refined 5G and Beyond 5G KPIs by SDOs and 5G-PPP applicable for OCTAPUS.

Category	KPI	Source
Telecom Operator - specific	Multitenancy support	3GPP, 5G-PPP
	Energy Efficiency	ITU, 5G-PPP
	Radio Network node capacity	5G-PPP, 3GPP

Network Level - specific	Fronthaul link capacity between the CU and RU		3GPP, SDOs
	Latency	Fronthaul Latency	5G-PPP, SDOs
		Backhaul Latency	5G-PPP, SDOs
		C-Plane Latency	3GPP, ITU
		U-Plane Latency	3GPP, ITU
Service Level – specific	Peak User data rate		ITU, 3GPP
	Experienced User Data Rate		ITU, 3GPP
	Reliability		ITU, 3GPP
Service Level - specific	**Service Deployment Time**		5G-PPP
	Phase 0. Platform Provision	Platform configuration	5G-PPP
		Platform deployment	5G-PPP
	Phase 1. Onboarding	Network Slice Template (NEST)	5G-PPP
		Network Service Descriptor (NSD)	5G-PPP
		VNF package (VNFD)	5G-PPP
		MEC Application Descriptor (MEC AppD)	5G-PPP
	Phase 2. Instantiate, Configure & Activate	Instantiate Network Slice (NSI)	5G-PPP
		Instantiate & Activate Network Service (NS)	5G-PPP
		Instantiate & Configure VNFs in service chain (VNF)	5G-PPP
		Instantiate & Configure MEC Application (MEC App)	5G-PPP
		Configure SDN infrastructure	5G-PPP
		Configure Optical WAN	5G-PPP
	Phase 3. Modify	Modify Network Slice configuration	5G-PPP
		Modify Network Service configuration	5G-PPP
		Detect scale out/in decision	5G-PPP
		Implement manual scale out/in	5G-PPP
		Implement autoscale out/in	5G-PPP
		Modify configuration of other NFVI elements	5G-PPP
		Modify configuration of SDN infrastructure	5G-PPP
		Modify Optical WAN circuit	5G-PPP
	Phase 4. Terminate	Terminate Network Slice (NSI)	5G-PPP
		Terminate Network Service (NS)	5G-PPP
		Remove configuration from SDN infrastructure	5G-PPP
		Terminate Optical WAN circuit	5G-PPP

The above KPI decompositions accurately capture, besides the obviously evaluated network capabilities (e.g., user data rates and latency):

- The technical factors influencing the end-to-end service provisioning and, therefore, the perceived user experience.
- The various business operations involved in the service provisioning lifecycle.
- The various 5G and beyond provisioning layers interactions.
- Versatile connectivity QoS guarantees over multiple links.
- Compute resource requests.
- Specific time constraints and allowances between network segments.

- Any scaling capabilities in terms of resources, number of links, etc.

To sum up, stakeholders anticipate significant improvements between 10X and 100X in terms of bit-rate, reliability, and positioning. In addition to the expected metrics of data rate, latency, reliability, and density, different actors in the telecommunications field have also quantified and highlighted the importance of positioning, mobility, and battery life for 6G. In this context, optical transport networks, photonic systems and devices will play a crucial role in supporting 6G network architectures, as a prevalent technology of the transport network segments. To this end, to accommodate the expected traffic growth for the envisioned services in the 2030s, it is necessary to undergo a paradigm shift that maintains energy consumption and carbon footprints at sustainable levels. Orange, as member of the IOWN Global Forum, aims to achieve such advanced capabilities through state-of-the-art photonics-based technologies, providing low-power consumption and ultra-wide bandwidth, and has identified several technical directions for future optical networks that are specifically relevant to 6G mobile networks. By enhancing photonic integration, incorporating optical bypasses, and enabling coordinated optical switching functions, photonic devices can reduce overall latency in 6G networks while significantly lowering energy consumption. The exploitation of multi-core and hollow core fibers (which have demonstrated exceptional performance in [48]) can also be a ground-breaking technological advancement, potentially leading to significant increases in data transfer rates per fiber in the upcoming years.

4.3 Fixed access networks for 5G mobile transport

With the advancements in mobile networks, reliable connectivity of the antenna sites is becoming increasingly crucial. However, the existing PON technologies face significant limitations in terms of bandwidth, latency, jitter, and synchronization. Currently, there are ongoing discussions about future PON standards to address latency concerns through cooperative Dynamic Bandwidth Allocation (DBA) (G.sup.66 initiative) and deliver higher line rates, such as 100Gbps or higher, as discussed in the Very High-Speed PON initiative in FSAN. Nevertheless, it should be noted that these solutions will be available on the market after the deployment of 5G networks.

Fiber connectivity has become the prevalent method for connecting antenna sites, with dedicated fiber connections utilizing Point-to-Point (PtP) connectivity from the site to the aggregation point for macro-cell sectors. In the case of 4G, macro-cells were linked to a switch-router for aggregation, but the prevailing trend now is to utilize only the OLT as the aggregation equipment, as shown in Fig. 4.8. For 5G, a PtP card in current FTTH OLTs (equipped with several PON cards) is employed to share the OLT equipment for aggregation in a Central Office. Fig. 4.9 illustrates such an example of PtP links used in the current deployment of 5G backhaul and fronthaul, where backhaul links are connected through an OLT PtP card, housed in the same equipment shelf as OLT cards used for fixed business or residential users, such as Fiber to the Enterprise (FTTE) or FTTH connections. The OLT PtP cards in FTTA (Fiber to the Antenna) applications are currently being upgraded to support 10G, and in the near future, 25G Ethernet ports.

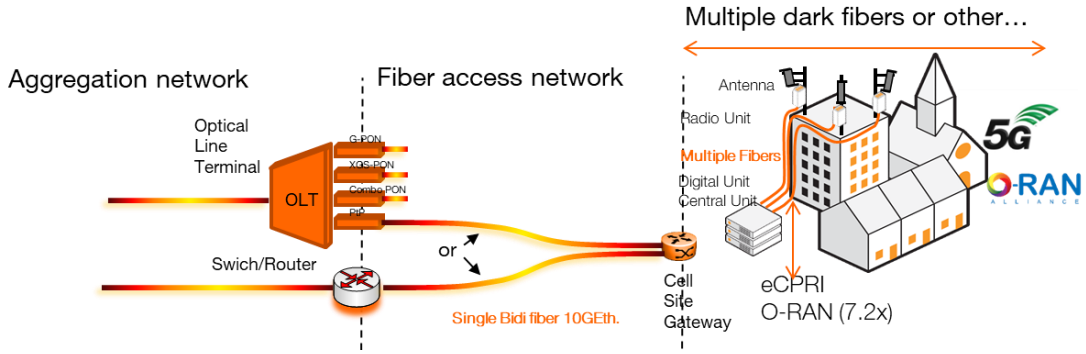


Fig. 4.8: Fiber connectivity of antenna sites.

Additionally, the OLT, with its specific Physical Layer Operation Administration and Maintenance (PLOAM) inherited from PONs, offers more advanced Operations, Administration, and Maintenance (OAM) features for FTTA links compared to a standard switch. In the case of fronthaul links between Open Distributed Units (O-DUs) and Open-Remote Units (O-RUs), most of these connections remain highly localized at the antenna site. Therefore, O-DUs and O-RUs are equipped with short reach transceivers that support distances of 2-10 kms, which are suitable for typical FTTA implementations.

These fronthaul links will soon carry CPRI10 (at 25Gbps) or eCPRI traffic, depending on the RU technologies and radio configuration deployed to meet the extensive bandwidth requirements imposed by Beyond 5G. However, it is important to note that no CPRI interface has been defined for rates beyond 25 Gbps at present time. Moreover, outdoor Industrial Temperature (I-Temp) transceivers, capable of operating within a temperature range of -40 to +85 degrees Celsius, are necessary at the antenna site, which adds some complexity in the design of optical modules for mobile X-haul.

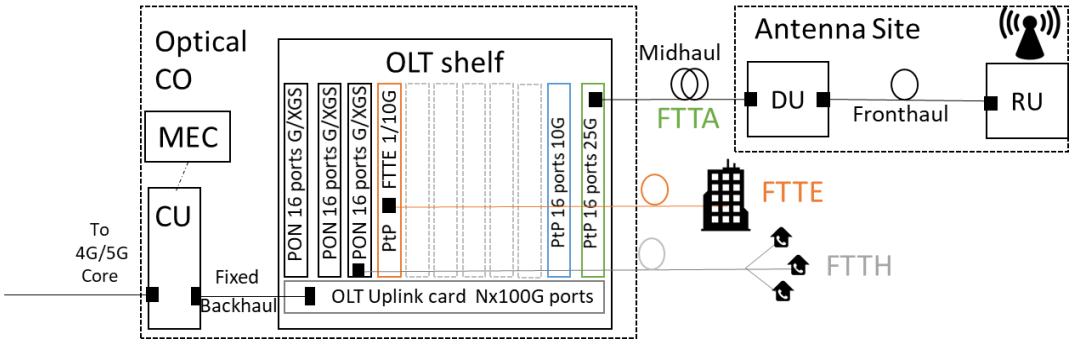


Fig. 4.9: An OLT acting as aggregator of fixed and mobile traffic via PtP links.

PtP interfaces are experiencing widespread deployment across various network segments, particularly in the growing Data communications market. According to forecasts from [49] presented in Fig. 4.10, there is a significant surge in the demand for 25G CPRI or eCPRI interfaces, which will become the dominant market for fronthaul optical interfaces in the coming years. To accommodate this trend and the overall increase in bandwidth and bit-rates, new standards are being released by IEEE and ITU-T for single-fiber transceivers operating above 10 Gbps. Specifically, IEEE 802.3.ca and ITU-T G.9806 are being developed, with ongoing efforts to align physical layer parameters across these standards. These new technologies specify a data rate of 25 Gbps and utilize the same wavelength pair for upstream and downstream transmissions (at the bands of 1270 nm and 1330 nm, respectively)

Two primary optical budget classes have been defined to cater to the requirements of 5G X-haul: BR20 or Class S (allowing for optical loss of 0-15 dB) for a reach of 20 km, and BR40+ or Class B- (allowing for optical loss of 10-23 dB) for a reach of 40 km. For transceivers operating at up to 25 Gbps, the NRZ modulation format has been chosen. However, for 50 Gbps, IEEE and ITU-T have opted for a 4-level Pulse Amplitude Modulation format (PAM4), which enables the utilization of lower-bandwidth optical components, allowing for the reuse of 25G electrical interfaces and optics.

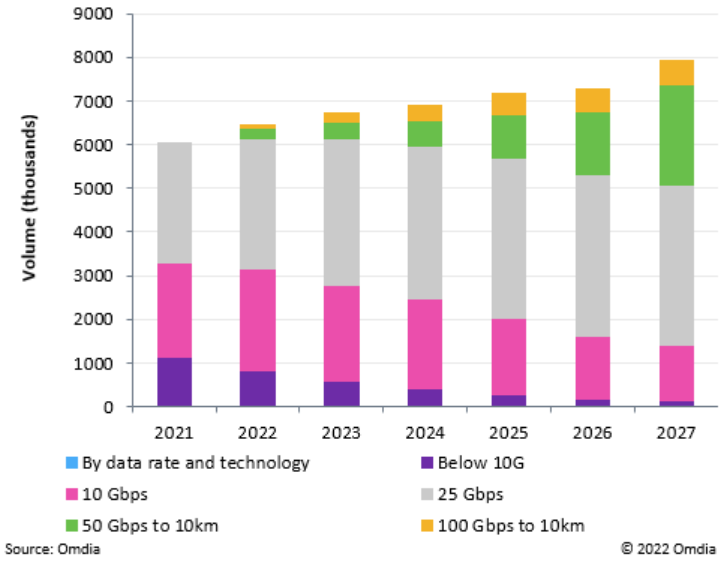


Fig. 4.10: Total available market volume for CPRI/eCPRI transceiver devices, as forecasted by OMDIA in Dec. 2022 [49].

Table 6 provides a summary of the main single-mode fiber transceivers available on the market. These transceivers are compatible with the I-Temp class (i.e., capable of operating between -40°C and +85°C),

making them suitable for outdoor installations, such as antenna sites. For indoor deployments in central offices (COs) or houses, C-Temp (0°C to +70°C) class transceivers can be used.

Table 6: Main characteristics of I-Temp Eth, CPRI and eCPRI compatible transceivers commercially available with bit-rates of 10 Gbps and 25 Gbps.

Single Mode Transceivers I-Temp compatible	From Factor	Reach (km)	Single/Dual Fiber	Wavelength (nm)	Tx (NRZ mod)	Rx
10GBase-LR	SFP+	10/20	Dual	1310	DFB	PIN
10GBase-ER	SFP+	40	Dual	1550	DFB	PIN
10GBase-ZR	SFP+	80/100	Dual	1550	EML	PIN
10GBase-Bidi	SFP+	10/60	Single	1270 - 1330	DML	PIN/APD
25GBase-eSR	SFP28	0.3	Dual	1310	DML	PIN
25GBase-LR	SFP28	10	Dual	1310	DML	PIN
25GBase-ER	SFP28	40	Dual	1310	DML	APD
25GBase-Bidi	SFP28	10	Single	1270 - 1330	DML	PIN

For data rates up to 25 Gbps, transceivers commonly employ SFP, SFP+, or SFP28 Small Form-factor Pluggable modules. Dual-fiber or single-fiber “Bidi” transceivers are also available, with Bidi transceivers utilizing a specific wavelength pair to differentiate between upstream and downstream optical carriers. The optical components used in these transceivers do not require narrow spectral discrimination, as the laser (Tx) and receiver (Rx) filters are designed to operate over a wavelength range of at least +/- 10nm. Furthermore, the adopted modulation format remains simple and is based on NRZ encoding. Low-cost optics such as Directly Modulated Lasers (DML) and PIN receivers can achieve distances of up to 10 km without the need for Digital Signal Processing (DSP) or amplification. However, for longer distances, External Modulated Lasers (EML) and/or Avalanche Photodiode (APD) receivers are required, albeit at increased costs. EML, with lower chirp compared to DML, help reduce signal degradation caused by chromatic dispersion in the fiber, whereas APD receivers can achieve higher bandwidth, typically up to 17GHz, and offer better sensitivities than PIN receivers, providing higher optical budgets for longer fiber distances.

Anticipated advancements for 5G phase 2 (as captured in Rel. 16) involve the evolution of these interfaces to support higher bit-rate than 25 Gbps, with Fig. 4.11 summarizing the main characteristic of those interfaces (in terms of bit-rate and power levels) required for 5G fixed backhauling. 100G access interfaces could be required in the future for 6G and recent efforts in ITU-T (G.9806 Amendment 1, 2 and 3) have led to a new recommendation to support bitrates up to 100 Gbps with PtP bidirectional interfaces.

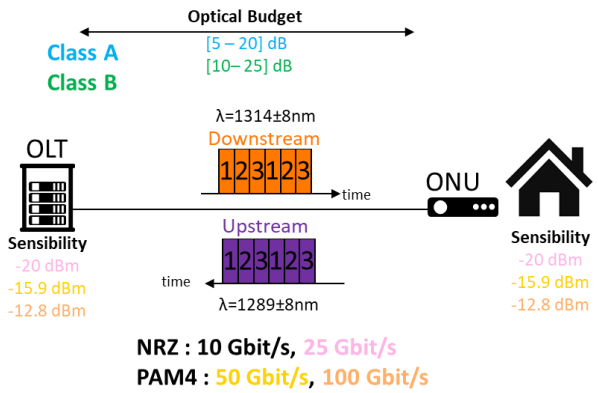


Fig. 4.11: Bit-rate and power level requirements for PtP bidirectionnal interfaces, as specified in ITU-T G.9806 amendementt 1, 2 and 3.

Table 7 provides the main characteristics of C-Temp Ethernet transceivers available on the market, operating at bit-rates of 50 Gbps and 100 Gbps. These transceivers employ QSFP28 packaging, which allows the reuse of 25G electrical interfaces and optics. However, for interfaces delivering bitrates above 25 Gbps, there is a technology gap that requires PAM4 for 50 Gbps or CWDM4 and Local Area Network (LAN)-WDM for 100 Gbps (achieved as 4x25Gbps over four different wavelengths). This introduces new challenges in terms of metrology designs and additional costs for signal monitoring when performing PAM4 and WDM differentiation in the field. The use of PAM4 modulation also leads to optical power penalties compared to NRZ, and achieving high optical budgets comes with higher costs and the need for better-performing optics such as EML and/or APD. Currently, there are no long-reach (ZR) transceivers available at 50 Gbps, and there are limited I-Temp compatible products, as temperature variations impact both the emitted wavelengths and the integrated passive filters, which affects single fiber or PtP WDM transceivers.

Table 7: Main characteristics of C-Temp Ethernet transceivers commercially available with bit-rates of 50 Gbps and 100 Gbps for 5G X-haul.

Single Mode Transceivers (Eth or CPRI/eCPRI) (C-temp)	From Factor	Reach (km)	Single/ Dual Fiber	Wavelength (nm)	Tx	Mod. type	Rx
50GBaseLR	QSFP28	10	Dual	1310	DFB	PAM4	PIN
50GBaseER	QSFP28	40	Dual	1310	EML	PAM4	APD
50GBase-Bidi	QSFP28	10	Single	1270-1330	LAN WDM DFB	PAM4	PIN
100GBase-CWDM4	QSFP28	2	Dual	1271; 1291; 1311; 1331	DML CWDM	NRZ	PIN
100GBase-LR4	QSFP28	10	Dual	1310	4x LAN WDM DFB	NRZ	4x PIN
100GBase-ER4	QSFP28	40	Dual	1310	4x LAN WDM DFB	NRZ	4x APD
100GBase-ZR4	QSFP28	80	Dual	1310	4x LAN WDM DFB	NRZ	APD

Fig. 4.12 presents a cost comparison of the transceivers listed in the previous Table, with costs normalized based on a reference 10GBase-LR SFP+ (these costs refer to products from the same vendor). Since there are no I-temp transceivers available yet for 50 Gbps and 100 Gbps, only C-Temp costs are represented for these line-rates. It is worth noting that there is currently no bidirectional 100G reference available. Considering that the technology gap associated with using PAM4 or LAN-WDM for transceivers above 25Gbit/s results in higher costs, as well as the increased cost of EML- and/or APD-based devices, leads to the conclusion that 10 Gbps and 25 Gbps with DML and PIN receivers will remain the preferred transceivers as long as they meet the bandwidth and distance requirements.

Considering the various PtP transceiver technologies and the market landscape, there are numerous optical solutions available to meet the needs of 5G RAN optical transport. This variety of solutions is useful for accommodating the diverse configurations required by different xHaul segments (in terms of bit-rate, distance, protocols, costs etc.). It is also important to note that a significant portion of 4G antenna sites are already connected using PtP links. As we transition to 5G, this trend will persist unless there is a shortage of fiber availability. In cases where the operator is required to incur high costs for renting or deploying new fibers, alternative optical transport solutions can be explored to optimize fiber sharing through WDM and/or TDM interfaces.

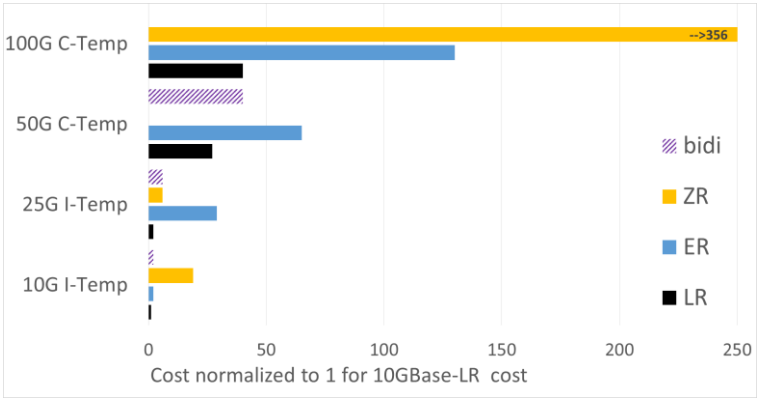


Fig. 4.12: Typical Point-to-Point links with local fronthaul at the antenna site and backhaul through a shared OLT at CO.

Meanwhile, PON technologies remain of interest for 5G transport if bit-rates and latencies can be adapted to 5G needs. Fig. 4.13 provides a visual representation of the latency and bandwidth requirements associated with different use cases that can be accommodated over PON technologies. In fixed services, such as sensor networks or device remote control, user devices are assumed to remain stationary in a specific geographic location. On the other hand, “on the go” refers to scenarios where the user's device maintains a data service session while moving at pedestrian or vehicular speeds within a limited network coverage area, as opposed to nomadic users, who require service availability only at their sojourn locations (typically via wireless connectivity within a confined area) and not while moving.

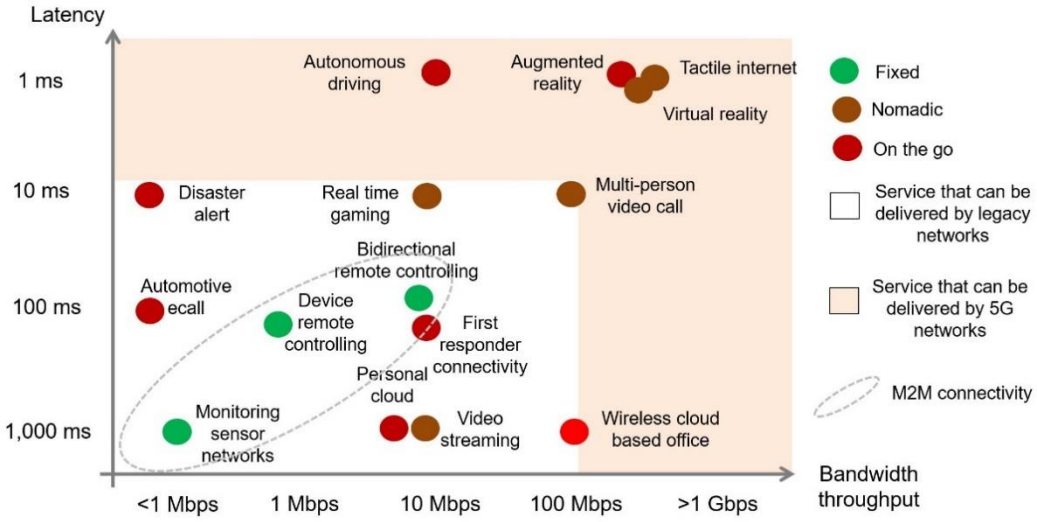


Fig. 4.13: Latency and bandwidth requirements for PON-supported services.

Many of these applications can be delivered using existing PON infrastructure. M2M connectivity and IoT devices, for instance, can function adequately with low data rates and relatively higher latency. Video conferencing requires lower latency while video streaming can tolerate some latency through buffering. On the other hand, services like VR/AR, Tactile internet, and autonomous driving demand capacities exceeding 1 Gbps and latencies of less than 1 ms, which necessitate the deployment of 5G networks and/or new PON technologies. These advanced technologies can support additional use cases, including entertainment (e.g., gaming) as well as practical applications in fields like manufacturing and medicine. Furthermore, they can extend their reach to encompass various wearable technologies. Being the initial link in the 5G transport network, the access network doesn't encounter bandwidth limitations thanks to its ample capacity and ever-evolving PON technology. However, traditional PON technologies introduce significant uplink delays due to upstream DBA. To enhance the quality of service for 5G cloud-based VR services, it becomes imperative to enhance the transmission delay performance of PON technology, thereby enabling the provision of deterministic delay services [50].

Evolution of access network to support evolution of 5G-RAN

The RAN devices themselves have incorporated innovative designs to alleviate the burden on their specifications. To achieve this, various functional divisions of the RAN segment have been established as “functional splits” [51]. Accordingly, new network segments, known as Xhaul links, have been defined to connect the Radio equipment and Core Network. These segments include Fronthaul, Midhaul and Backhaul. The 5G radio base stations (gNBs), as defined by the 3GPP 5G RAN architecture, consist of three primary functional modules: the CU, the DU and the RU. These modules can be deployed in different ways, depending on the desired network topology, service requirements, antenna site configuration and location. The Distributed RAN (D-RAN) and Centralized RAN (C-RAN) architectures are essentially the two extreme points in the 5G RAN deployment spectrum and corresponding functional splits, as illustrated in Fig. 4.14. D-RAN is the conventional and most widely adopted configuration in which the CU, DU and RU functions remain at the antenna site, connected to the 5G Core Network (5GC) through a simple backhaul link. On the other hand, C-RAN enables a reduction in the physical space required at antenna sites by centralizing and pooling the CU and, optionally, the DU at a remote location such as a Central Office or Main Office. A local C-RAN fronthaul link is typically employed when the antenna site cannot accommodate a fully updated RAN equipment due to limited real estate, energy resources, or complicated access to the facility.

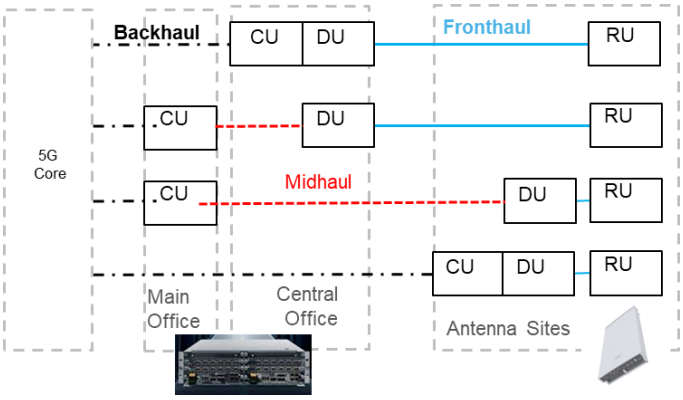


Fig. 4.14: 5G functional splits and Xhaul links.

The choice of functional split [51] determines the different interfaces used in transport networks, including CPRI, OBSAI, ORI, Ethernet-based eCPRI etc., each of them with specific transport requirements. The expected throughput ranges from 10 Gbps to 100 Gbps (and even higher) due to the quantization of mobile signal samples in the time/frequency domain, aggregation rates applied in different RAN equipment and the implementation of high or low layer splits. For instance, at the RU level, the CPRI/eCPRI throughput depends on radio settings such as frequency range, bandwidth, number of frequency carriers and MIMO configuration. CPRI traffic includes synchronization features necessary for RAN fronthaul, and the latest option, CPRI-10, has a line-rate of 24.3 Gbps. In contrast to CPRI interfaces, eCPRI encapsulates the data fronthaul in an Ethernet protocol with 10G/25G/40G/100G interfaces. This Ethernet encapsulation allows for a flexible functional decomposition, while reducing the fronthaul data rate requirements and simplifying the complexity of the RU. With a high layer split, most functionalities are concentrated in the DU, resulting in a simplified and smaller footprint on towers or in building antenna sites. The latest specifications of eCPRI, released in 2019, also decrease latency and jitter for high-priority traffic and support time-sensitive traffic when carried over an Ethernet network. Regardless of the functional split, new synchronization methods (in frequency, phase, and time) will need to be adopted to support both frequency and time division duplexing transmissions in the radio layer for DU and RU. Furthermore, congestion in optical aggregation equipment must be effectively managed to ensure proper QoS for URLLC flows, which can be implemented using various TSN strategies [52].

Since 2018, the Open RAN Alliance (O-RAN) has aimed to merge and advance the efforts of both the C-RAN Alliance and xRAN Forum. The O-RAN groups are actively working towards providing specifications for new RAN systems that are open, intelligent, virtualized and fully interoperable [53]. The specifications for Xhaul transport interfaces are currently being discussed in O-RAN Working Groups 9 and 4; initial specifications can be found in [54]. Operators are not only driven by the diverse

constraints on Xhaul interfaces but also by the desire to transform their optical networks from simple pipelines to high-capacity infrastructure capable of supporting different service classes in the optical domain.

Existing legacy equipment can already accommodate varying bit rates, latency/jitter requirements and service availabilities for the numerous 5G verticals. However, the introduction of network abstraction through SDN has the potential to revolutionize the industry by enabling network slicing and Fixed Access Network sharing. Initially, SDN simplifies automation of equipment configuration through vendor-agnostic solutions. Eventually, software-based network abstraction and orchestration would facilitate practical implementations of multi-tenancy and multi-operator use cases. It would also align optical solutions with the evolving virtualization trends in the mobile domain, enabling intelligent and cooperative fixed-mobile convergence. An intelligent optical node based on generic hardware could address the stringent latency requirements of various 5G services by hosting virtualized RAN functionalities, content platforms or Multi-access Edge Computing (MEC) capabilities [55], [56].

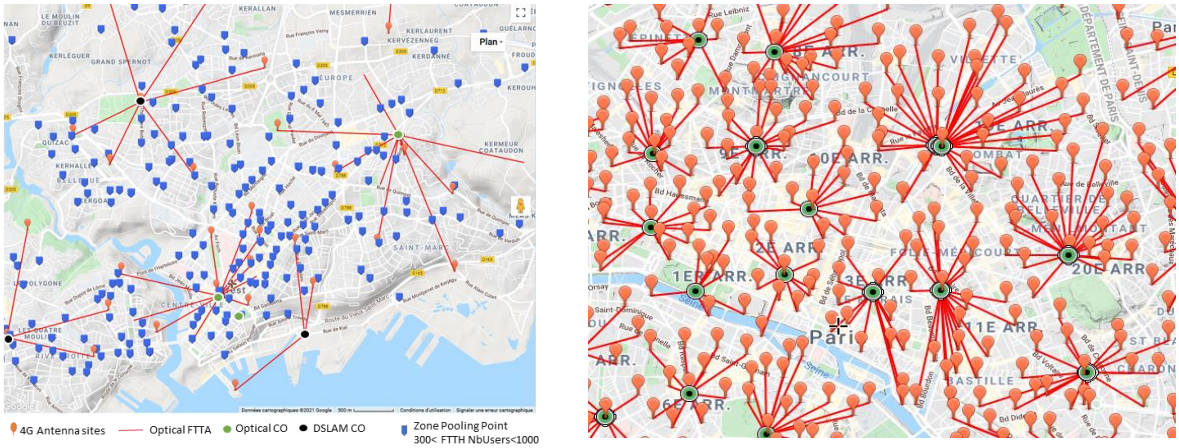


Fig. 4.15: Map of dense urban areas in France (on the left : city center of medium-size city, Brest; on the right: city center of a big city, Paris) with the position of antenna sites, Optical and DSLAM COs and FTTH passive pooling points.

In France, as of 2020, over 88% of Orange's antenna sites were connected using PtP optical fiber for Fiber to the Antenna (FTTA) deployments, connecting Central Offices to the antenna sites. The remaining sites utilize microwave wireless links. However, with the deployment of 5G's new mobile technology, the availability of fiber resources can become strained, leading to discussions about utilizing fibers deployed for FTTH purposes. Fig. 4.15 illustrates a map of a densely populated urban area in Brest, France, depicting the positions of 4G macro sites, FTTH and DSL COs, and FTTH passive pooling points (street cabinets hosting PON passive optical splitters for multiple operators). Each street cabinet enables coverage for at least 300 FTTH users, connected to GPONs ONUs in their homes. The plotted antenna sites are equipped with 2G/3G/4G macro antennas and are connected to a remote CO site

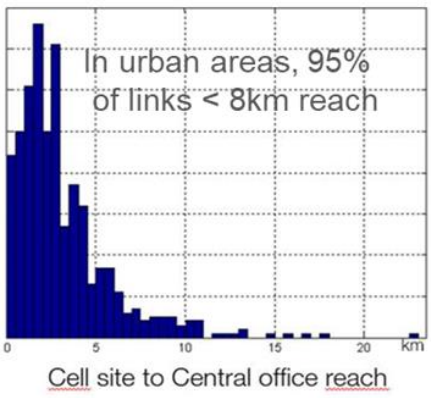


Figure 4.16: Distribution of fiber distance from Central Office to antenna site in dense area.

using fiber backhaul, employing an optical PtP card located in an OLT or a Digital Subscriber Line Access Multiplexer (DSLAM). However, 5G antenna sites are not yet represented on the map, and it is

estimated that 5G macro and small cell sites will be deployed approximately every 300 meters, resulting in a density comparable to that of 4G macro sites.

Considering the demographic view of FTTH and FTTA, the density of mobile X-Haul terminations will remain significantly lower compared to the residential market, and PtP fiber connectivity already exists for FTTA and between COs and FTTH passive pooling points. Therefore, FTTH fibers will not serve as a universal solution for mobile network connectivity, as mobile networks will primarily rely on their own dedicated fiber infrastructure. Figure 4.16 represents the distribution of fiber distance between the antenna site and the central office in a dense area, where it can be noted that 95% of the fiber links are shorter than 8 km.

4.4 Stakeholders/actors and their roles

The 5G principles and vision shift the telecom industry from a hardware-based to a software-based foundation; from single to multi-domain infrastructure deployments; from silo to distributed, disaggregated infrastructures. This shift offers a more dynamic way of provisioning services at various layers and opens up opportunities for multiple stakeholders. To this end, 5G networks can be considered as platforms where various stakeholders can operate in a layered service provisioning approach. Through various technical and business interfaces, these stakeholders eventually contribute to offer services to a **Service Customer (SC)**, i.e., a 5G service customer such as an individual end-user, a vertical industry customer, etc. Automotive/transportation, manufacturing/Industry 4.0, Media and Entertainment, Energy and Facilities, e-Health, Public safety and Smart cities are some of the most commonly identified vertical industries which would benefit from digital services enabled and/or enhanced through the 5G network capabilities and principles. Based on the 3GPP standard [57], which defines various service provisioning layers, the 5G PPP Architecture WG [58] has provided a representation of the processes and activities related to the 5G service provisioning. These have been grouped in coherent roles along with the relationships and interfacing options between them, as shown in Fig. 4.17.

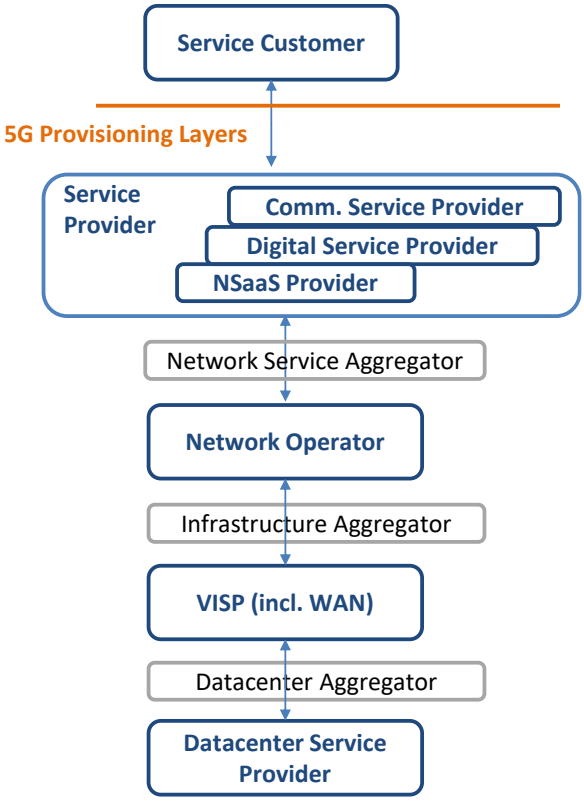


Fig. 4.17: Roles and interfacing in 5G provisioning systems (based on 5GPPP [57]).

The **Service Provider (SP)** is a principal actor in the 5G system, which directly interfaces the SCs and obtains and orchestrates resources from **Network Operators (NOPs)**, **Virtualization Infrastructure Service Providers (VISPs)** and **Datacenter Service Providers (DCSPs)** (collectively mentioned in

parts of this document as **Infrastructure Providers**). The role of the SP can be further distinguished into: i) a **Communication Service Provider (CSP)**, entailing the activities for offering traditional telecom services, ii) a **Digital Service Provider (DSP)**, entailing the activities for offering digital services such as eMBB and IoT to various Vertical industries, and iii) **Network Slice as a Service (NSaaS) Provider**, entailing the activities for offering a network slice along with the services that it may support and configure. These roles include, among others, the business service provisioning activities towards their interfacing roles, and are technically related to Business Support System (BSS)/Operations Support System (OSS) interfacing the virtual or actual infrastructure resources operated and maintained by the NOP.

The **NOP** operates a programmable 5G network infrastructure, spanning from the radio and/or fixed access to the edge, transport and core network (CN), including the operation of virtual resources leased by other Infrastructure Providers through appropriate Application Programming Interfaces (APIs).

The **VISP** role entails activities related to offering virtualized network or cloud/edge computing resources available through APIs and it practically corresponds to the cloud/edge infrastructure provider.

The **DCSP** performs activities related to offering raw computing resources in the context of the Information Technology (IT) world.

Additional roles can be identified such as the **Service Aggregators (SA)** at various layers, i.e., the **Network Service Aggregator**, the **Infrastructure Aggregator** and the **Datacenter Aggregator**. The role of SAs involves activities of service provisioning across multiple domains of a specific layer, namely: across multiple NOPs required, e.g. in cross borders (country/territory borders) or in multiple private and public network environments, across multiple cloud/edge providers for the deployment of a distributed service/Vertical application, across multiple datacenter providers for similar purposes.

For illustration purposes, we also provide a concrete description of the relationship among the above actors with respect to the OLT unit, which constitutes the primary NGCO technology, as well as a key device in future optical access networks, to be upgraded within OCTAPUS. Specifically, OLT equipment manufacturers (e.g., Nokia, ZTE, Huawei, Cisco, etc.) design and produce OLTs, often in close collaboration with Service Providers and Infrastructure Owners to supply them with equipment that meets their requirements for scalability, performance, and compatibility with existing infrastructure. Network operators are responsible for managing, maintaining and ensuring the smooth operation of the OLTs in the fixed access networks and also collaborate with Service Providers (e.g., Datacenter Providers or Internet Service Providers) to deploy OLTs in central offices or data centers and offer uninterrupted service delivery. To this end, Network Operators may employ the services of System and Network Service Integrators, who specialize in integrating various components of a fixed access network (including OLTs) with existing infrastructure and provide expertise in network design, installation, and configuration, ensuring smooth integration and interoperability. System Integrators often collaborate with Service Providers and equipment manufacturers to deliver customized solutions that meet specific requirements. Service Providers, such as telecommunications companies and Internet Service Providers (ISPs), then operate the deployed OLTs to expand their network coverage, increase subscriber capacity, and deliver reliable broadband connectivity, such as high-speed Internet, voice, and video services, to residential and business customers. The latter constitute the end-users or Service Subscribers/Customers, who ultimately rely on the performance and reliability of the OLTs to have a seamless Internet experience. Finally, the level and quality of service offered to the end-users may be affected by regulating and policy making bodies (typically at the regional/national level), who establish guidelines, regulations/policies, licensing requirements, and/or quality of service benchmarks to ensure fair competition, consumer protection, and the efficient rollout of broadband services.

4.5 Positioning of OCTAPUS in the ecosystem

Since the 5G market has not yet reached globally the maturity level of large scale, fully-fledged 5G system deployments (as evidenced by a global market size of only 19.3 billion USD in 2023, compared to the estimated 994.8 billion USD market in 2030 [59]), there is a scarcity of concrete 5G provisioning ecosystem paradigms, although specific aspects and visions concerning the complete 5G ecosystem are targeted by Research & Development (R&D) actions and by the Industry, as they are moving towards the layered service provisioning approach. It is clear, however, that the OCTAPUS NGCO is uniquely suited to serve as a facilitator for various enterprise use cases, including indoor RAN deployments (in settings like campuses, buildings, subways etc.) and Industry 4.0 environments while also enabling fiber connectivity to small and medium-sized enterprises (SMEs), as well as factories for industrial

automation. This suitability of the OCTAPUS NGCO stems from its combination of advanced technologies, which are crucial for the future evolution of OLTs and access networks, as driven by the

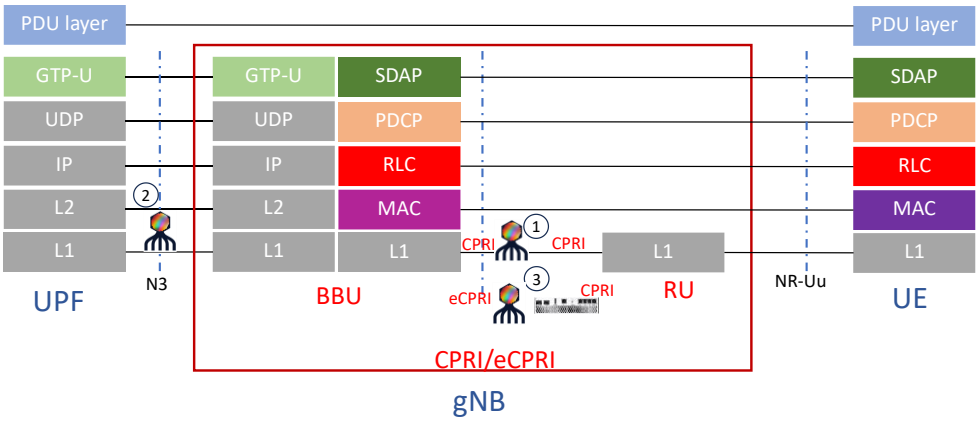


Figure 4.18: 5G protocol stack for the data plane.

increasing demand for ultra-high-speed interfaces (e.g., 50G-PON and 100G PtP access interfaces), with ground-breaking architectural features such as: i) the integration of "Express" paths, enabling URLLC services with an optical front-end based on Wavelength Selective Switching technology, ii) multi-layered energy efficiency through the utilization of ultra-low-energy switching and transceiver photonic technologies and iii) the implementation of SDN-driven power-aware routing and the support of sleep mode scenarios. Since, in addition to novel vertical services, OCTAPUS also targets the provisioning of enhanced network operation services, with specific E2E QoS guarantees that are enabled by standardized mechanisms and interfaces, it is important to ensure that these mechanisms, especially those belonging to the complex 5G protocol stack, can operate transparently within the OCTAPUS NGCO. This consideration can affect the "logical" (or "functional") placement of the OCTAPUS NGCO, in terms of the service endpoints that are attached to its sides. To provide a concrete example, which is also described in Section 5.3.11 regarding the URLLC services, the 5G protocol stack provisions for QoS Flow Identifier (QFI) tags, employed between the User Plane Function (UPF) in the mobile core and the gNB (i.e., on the N3 interface shown in Fig. 4.18, to be used to distinguish between different types of services with disparate service requirements. Based on the QFI values, the gNB (or the BBU in the case of disaggregated gNBs) then maps, via the SDAP protocol, the corresponding flows on suitable Data Radio Bearers (DRBs) which are in turn mapped onto Physical Resource Blocks (PRBs) on the air interface (NR-Uu in Fig. 4.18).

Hence, if the OCTAPUS NGCO is placed between the BBU and the RU (i.e., option 1 of the OCTAPUS logo's position in Fig. 4.18, and a pure legacy CPRI-based implementation (i.e., a low-PHY functional split between BBU and RU) is employed at the fronthaul segment, the QFI tags of different flows (whose processing terminates at the BBU before entering the NGCO) cannot be distinguished within the OCTAPUS NGCO, as CPRI is a point-to-point interface, historically designed for the transport of radio signals and not for carrying higher-layer network protocol information. Therefore, any QFI information necessary for service differentiation essentially "disappears" within the CPRI stream and becomes invisible to the OCTAPUS NGCO. In this case, three options are still available:

- The OCTAPUS NGCO is placed instead between the UPF and the gNB, spanning across the N3 interface of Fig. 4.18 (i.e., the Core UPF connects to the Uplink switches and the IF cards to the gNB, corresponding to option 2 of OCTAPUS placement in Fig. 4.18, so that QFI information is properly available, and Ethernet transport is employed at L1/L2, essentially amounting to a backhaul connection. Note that this case is conceptually similar to the architecture shown in Fig. 3.3, since it is only the specific endpoints at opposite sides of the NGCO which change in each case. A graphical illustration of this fact is also provided in Fig. 6.1 of Chapter 6.
- The OCTAPUS NGCO remains between the BBU and RU (placement option 1 in Fig. 4.18) in a CPRI-based setting where QFI information is not directly available. In this case, different QoS flows can still be identified and managed through the alternative techniques described in Section 5.3.11 (i.e., manually preconfigured mapping of flows to CPRI channels, packet inspection and classification etc.). However, the implementation of these techniques by the network operator would probably necessitate the addition of non-standardized extensions to the 5G stack.

- The most preferred and robust solution, which is expected to become commonplace as more commercial products begin to appear, is the employment of dedicated eCPRI gateways, placed between the BBU and RU, to convert CPRI streams to packetized eCPRI flows [60] and vice versa, corresponding to placement option 3 in Fig. 4.18. Being natively Ethernet-compatible and also carrying higher layer information, the eCPRI flows can be handled by the OCTAPUS NGCO + gateway via standardized Ethernet-based flow/priority mechanisms e.g., VLAN-based Priority Code Point (PCP), thus providing a more streamlined mechanism for service differentiation. This solution offers support for legacy CPRI-only RUs and also future-proofs OCTAPUS for the time when pure eCPRI RUs become widely available. At the same time, the critical mapping/conversion functions between CPRI and eCPRI are localized at a single point (i.e., the gateway) allowing for dynamic and programmatically-driven configuration of the CPRI streams, instead of the manual approach in option 2 of Fig. 4.18.

Thus, the above discussion indicates that the OCTAPUS NGCO architecture is flexible enough to allow for its placement in multiple “logical” positions, provided that any necessary protocol translations, performed at the NGCO’s boundaries, eventually generate suitable traffic streams that can be transported over Ethernet.

5 OCTAPUS Use Cases

In this chapter, we elaborate on the set of use cases which are addressed by OCTAPUS and describe the validation and evaluation of the OCTAPUS solution against the requirements and KPIs imposed by these use cases.

5.1 Potential use cases for the OCTAPUS NGCO

The innovative technologies offered by OCTAPUS play a crucial role in enabling Fiber to Everywhere/Everything, facilitating the widespread deployment of fiber optics and bringing the fiber closer to end-users. Next, we present the reasons behind adopting these cutting-edge technologies for the different use cases of Fiber to Everywhere graphically depicted in Fig. 5.1.

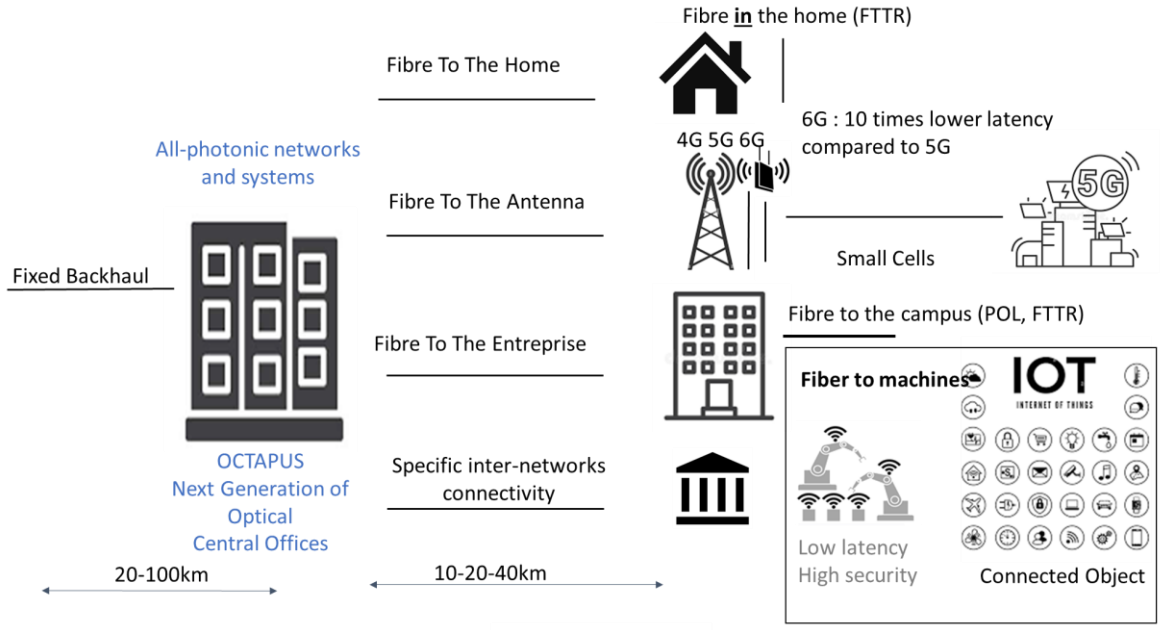


Fig. 5.1: Fiber to Everywhere envisioned use cases and scenarios.

5.1.1 OCTAPUS for Fiber to the Antenna (macro-cells) (short term)

As described in Section 4.3, most of the macro cell sites are connected to the core network through the OLT and higher bit-rate requirements are expected due to increased mobile traffic demands. Consequently, the OLT architecture should be upgraded to support such evolution with higher bit-rate interfaces and higher switching/aggregation capacity to avoid traffic congestion at the central office. This perfectly aligns with the planned advances brought forth by the OCTAPUS NGCO, as presented in Section 4.5. Specifically, for fiber to the antenna use cases, OCTAPUS will exploit its optical "Express" paths bypassing the NGCO to offer the following benefits:

- **Enhanced resiliency:** the optical bypass could provide a protection path for redundancy of mobile Xhaul links. In case of OLT port failure, traffic could be redirected to other interfaces in another OLT located in a remote CO via the optical bypass.
- **Support of URLLC and fronthaul services**: In case of C-RAN, the O-CU/O-DU is placed behind the OLT and may be collocated with a MEC server to accelerate content delivery. In such scenarios, meeting strict latency and jitter requirements necessitates a highly efficient network transport solution. OCTAPUS introduces optical bypass and optical backplane capabilities, enabling fronthaul transport through the OLT, thereby facilitating the most efficient network transport for achieving the desired latency and jitter targets. Since this scenario captures the most stringent use cases in terms of latency/jitter, these two service classes (i.e, fronthaul, URLLC) will be studied in more detail in later Sections, where the relevant service requirements and KPIs will be presented.

- **Sleep modes**: as an additional enhancement enabled by the OCTAPUS NGCO, the dynamic optical bypass also allows OLT reconfiguration for opportunities of implementing sleep modes of OLT ports (if supported by the underlying hardware), depending on traffic demand. During idle hours, the OLT could be bypassed to reach another OLT to group users and activate sleep mode function of unused ports.

5.1.2 OCTAPUS for Small cell backhauling (short term)

By leveraging 50G-PON technology developed in OCTAPUS, small cell backhauling can benefit from the high bandwidth and reliability of fiber-optic connections. PON utilizes a passive optical splitter that enables multiple ONUs, including small cell base stations, to share the same optical fiber for upstream and downstream data transmission. The advantages of small cell backhauling by PON include:

- **High bandwidth:** PON can support high-capacity data transmission, allowing for the efficient transport of data between small cell base stations and the core network.
- **Scalability:** PON networks can easily accommodate the addition of more small cell base stations as network capacity demands grow.
- **Cost-effectiveness:** PON infrastructure can be cost-effective compared to other backhaul technologies, especially when deployed in dense urban areas.
- **Flexibility:** the high bit-rate offered by 50G-PON can support various small cell deployment scenarios, including outdoor and indoor environments, making it suitable for diverse network architectures.

Overall, small cell backhauling by PON offers a reliable and efficient solution for connecting small cell base stations to the core network, enabling the delivery of high-quality mobile services and meeting the increasing demand for data connectivity in densely populated areas. This use case is foreseen as the first use case of 50G-PON to be deployed widely in 2027 in Asia [61] and later around the world.

5.1.3 OCTAPUS for Fiber to the Campus/Enterprise (short term)

50G-PON can also serve as the access network technology that enables the delivery of high-bandwidth services to multiple endpoints, such as offices, classrooms, research facilities, or residential areas within the campus or enterprise. In this setting, local PON architectures are employed with OLTs located at the central point of the enterprise/campus and Optical Network Units (ONUs) installed at each endpoint. 50G-PON is seen as the rightful successor of XGS-PON that is currently being deployed for Passive Optical Local Access Networks (POL) to bring fiber connectivity in offices. The deployment of POL has been steadily increasing in volume as organizations recognize the benefits it offers over traditional copper-based Local Area Network (LAN) infrastructures. While the exact figures may vary, the trend indicates a growing adoption of POL in various sectors and its market size is projected to reach Multimillion USD by 2029.

The advantages of implementing Fiber to the Campus/Enterprise by 50G-PON include:

- **High-speed connectivity**: PON technology can provide Gbps or higher data transmission speeds, ensuring fast and reliable connectivity for various applications and services within the campus or enterprise.
- **Scalability:** PON networks can easily scale to accommodate additional endpoints and increasing bandwidth requirements. New ONUs can be added as needed without significant disruption to the existing infrastructure.
- **Cost-effectiveness:** By utilizing a shared fiber-optic infrastructure, Fiber to the Campus or Enterprise by PON can be a cost-effective solution compared to deploying individual dedicated connections to each endpoint.
- **Network efficiency**: PON allows for efficient bandwidth allocation and utilization, optimizing network resources and minimizing latency or congestion issues.
- **Flexibility:** PON can support various services and applications, including data, voice, and video, enabling a wide range of use cases within the campus or enterprise environment.

By deploying Fiber to the Campus/Enterprise by PON, organizations acquire a future-proof infrastructure that can adapt to the growing demands of the campus/enterprise network that offers high-speed and reliable connectivity, enhanced productivity, improved communication, and the ability to support advanced digital applications and services.

5.1.4 OCTAPUS for Fiber to the Home/building and Fiber to everything (long term)

According to the recent report of [62], the number of terminations for FTTH/B (Fiber to the Home/Building) connectivity is projected to reach nearly 1 billion in 2023. Currently, the majority of these terminations are connected using GPON technology. However, there is also a growing trend worldwide towards adopting XGS-PON technology. In the long run, there is an expectation for further evolution towards higher bit-rates to meet the increasing bandwidth demands of residential customers, with 50G-PON being the technology that can provide such capabilities. The widespread adoption of 50G-PON terminations in FTTH is anticipated to occur after 2030, resulting in much higher volumes of deployments. As described in Chapter 4, Fiber to Everywhere holds great potential for empowering individuals, businesses, and communities with faster Internet speeds, improved communication capabilities, and access to advanced digital services. It forms the foundation for supporting emerging technologies such as Internet of Things (IoT), cloud computing, high-definition streaming, telemedicine, smart cities, and more.

From the above discussion, it becomes evident that the OCTAPUS-envisioned NGCO will be a key element of future networks in their quest to support the next generation of mobile X-haul transport, in addition to the evolved 50G-PON services for fixed access subscribers. To facilitate the subsequent description of the OCTAPUS Use Cases, we distinguish between:

- **architecture-driven use cases,** which exploit the inherent scalability of the OCTAPUS NGCO and its proper placement within the overall network architecture to enhance the “architectural” properties of the deployed network (e.g., being able to transport different types of X-haul flows, supporting different RAN architectures, offering more fine-grained slice support etc.), and
- **service-driven use cases**, which exploit OCTAPUS’s novel TSN-enabled transceiver portfolio and “Express” paths to enhance currently offered 5G services and/or enable new services with stringent KPIs (in terms of throughput, latency, jitter, reliability etc.). As URLLC services are expected to play a major role in the context of current and future smart cities, OCTAPUS targets a diverse group of URLLC-driven use cases, as will be described in subsequent sections.

5.2 OCTAPUS for mobile X-Haul

5.2.1 Architecture-driven use cases for mobile X-Haul

Within the infrastructure of the Radio Access Network (RAN), the fronthaul links play a vital role in connecting DUs with physically dispersed RUs, whether in a traditional or O-RAN setup. As the global rollout of 5G technology continues and research progresses towards technologies beyond 5G, the significance of fronthaul and its diverse requirements for throughput, delay, reliability, and security have escalated significantly. According to a recent technology analysis report based on insights from a consortium of Tier 1 operators involved in 5G deployment, the market for 5G fronthaul transport is anticipated to generate revenue exceeding USD 2 billion by 2024, which reflects a 3X increase compared to the current level of deployment.

The OCTAPUS consortium has identified four distinct use cases for the OCTAPUS NGCO that hold significant importance for 5G X-Hauling and serve as strong motivators for the advancement and implementation of the OCTAPUS NGCO as follows:

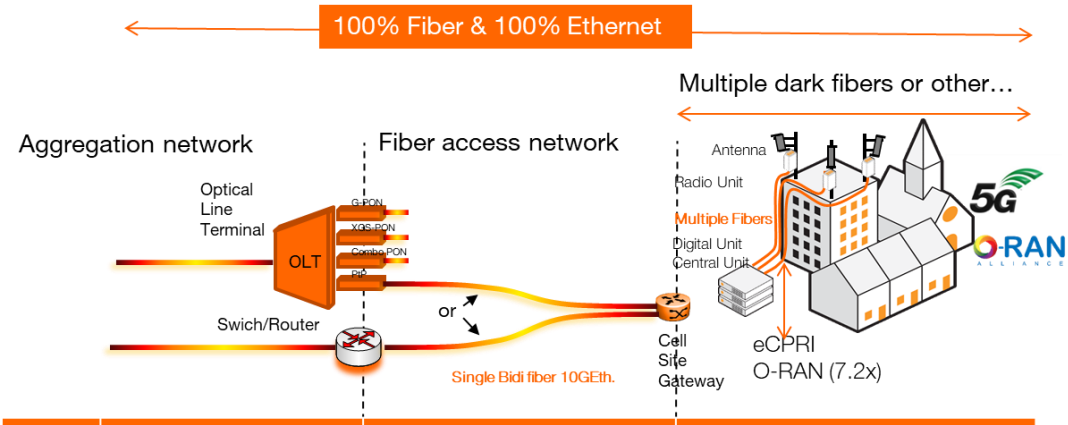
- **Fixed backhaul and Distributed RAN (D-RAN) with local fronthaul:** This use case involves the utilization of the OCTAPUS NGCO for fixed backhaul connections in D-RAN architectures, along with the integration of local fronthaul links to ensure efficient connectivity within the network.
- **Extended fronthaul in Centralized RAN (C-RAN):** In this use case, the OCTAPUS NGCO is employed to support extended fronthaul connections within a centralized RAN environment. This enables the seamless transmission of data between centralized baseband units and Remote Radio Heads, facilitating optimized network performance.
- **Fronthaul in specific areas (Distributed Antenna Systems (DAS)):** The OCTAPUS NGCO is designed to cater to the requirements of fronthaul connectivity in the context of Distributed Antenna Systems (DAS), emphasizing the efficient provision of fronthaul links to support DAS deployments and enhance overall network coverage and capacity.

- **5G end-to-end slicing:** The OCTAPUS NGCO is particularly well-suited for enabling end-to-end slicing in 5G networks. This use case involves the implementation of network slicing technologies to create customized, isolated network segments tailored to specific requirements, such as differentiated service levels, varying bandwidth needs, and distinct security measures.

The above four architecture-driven use cases, which have been pivotal in driving the development and advancement of the OCTAPUS NGCO, showcasing its versatility and capability to address diverse networking scenarios and requirements, are described in more detail next.

5.2.1.1 Fixed backhaul and D-RAN with local fronthaul (<1Km reach)

The primary use case for 5G microcell backhauling in OCTAPUS involves the architecture illustrated in Fig. 5.2, which captures the most prevalent scenario (as described in Section 4.3, over 90% of antenna sites are interconnected through dedicated PtP fibers) of fixed access backhauling with bidirectional 10 Gbps interfaces. As a result, the fronthaul links remain local, typically spanning between the bottom and top of buildings or towers, or even within the same room depending on the location of O-CU/O-DU and O-RU. Such links employ PtP short reach transceivers that can transmit eCPRI up to 25 Gbps, with 10 Gbps being the prevailing capacity today. Considering the advancement of 5G radio configuration and spectral bandwidths, we anticipate a potential evolution in the O-RU and O-CU/DU interfaces, potentially reaching up to 100 Gbps. This evolution would necessitate the development of new protocol standards to transport an eCPRI-equivalent protocol for future fronthaul links. Furthermore, to accommodate the progression of this new 5G radio technology and increased fronthaul capacity, the fixed access backhaul will need to be upgraded to 25 Gbps or even 100 Gbps.



	Backhaul aggregation (mesh)	Backhaul access (typ. 10 km) (PtP, option: dual adduction)	Fronthaul (local < 2km) (N x PtP links]
Now	100Gbit/s [bidirectional recently available]	Bidirectional 10Gbit/s	N = number of RU interfaces N x 10 or 25 Gbit/s ≈ 100 Gbit/s
Future	200, 400, 800Gbit/s [bidi. not available]	25Gbit/s and 100Gbit/s	RU interface = 100 Gbit/s

Fig. 5.2: 5G use cases enabled by OCTAPUS in the case of local fronthaul.

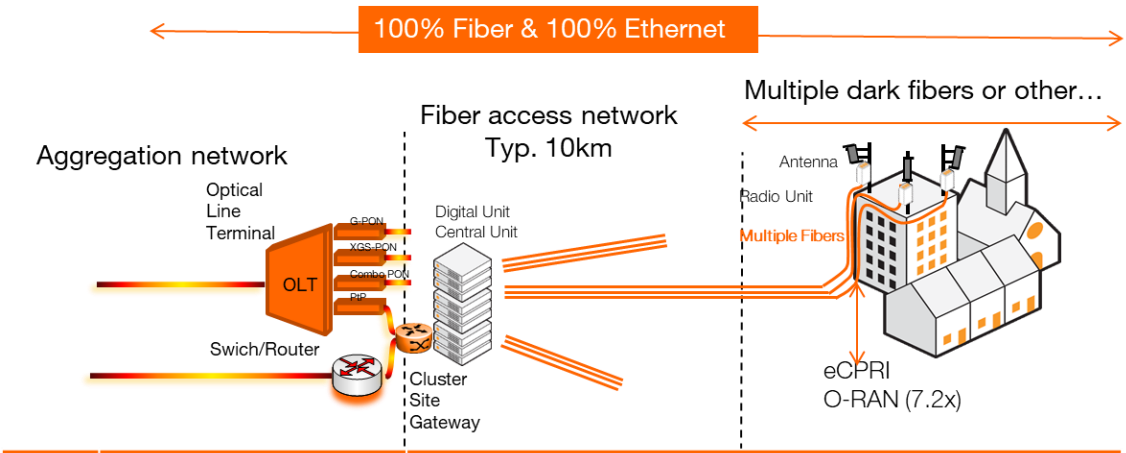
5.2.1.2 Extended fronthaul in case of C-RAN (<15km reach)

C-RAN has garnered significant interest among network operators due to its potential benefits with regards to site engineering, particularly in densely populated urban areas. By moving the CU/DUs to a CO and leaving only the compact power supply and battery-equipped RUs at the antenna site, the installation process is simplified, and the overall footprint is reduced. These factors, coupled with shorter installation and repair times, are expected to bring cost benefits. Additionally, C-RAN enables the possibility of introducing new RAN generations on existing sites with limited space availability.

Another driver for C-RAN adoption is its potential to reduce energy consumption. Through a detailed analysis based on existing infrastructure and available RAN equipment, it has been demonstrated that C-RAN can achieve energy savings of 40-50% compared to traditional macro-cell installations with backhaul. The primary gains come from placing RUs close to the antenna, eliminating power dissipation on coaxial feeders and the need for cooling or air conditioning at the antenna site. Furthermore, C-RAN is expected to bring even higher power savings by enabling CU/DU pools to dynamically allocate processing resources based on traffic load.

C-RAN, while offering numerous advantages, also presents challenges specifically related to the fronthaul segment. Some of these challenges include:

- **Bandwidth Requirements**: Fronthaul in C-RAN requires high-capacity and low-latency links to support the transport of a large amount of data between the CU and RUs.
- **Synchronization**: Precise synchronization between RUs is crucial in C-RAN to ensure coherent transmission and reception across multiple cells. Achieving accurate synchronization over the fronthaul network is complex and requires synchronization protocols and mechanisms to compensate for delays and jitter introduced in the transport.
- **Latency**: The fronthaul segment of C-RAN must meet stringent latency requirements to support real-time applications such as voice and video.
- **Fronthaul Capacity and Scalability**: As the number of RUs increases, the fronthaul network must scale accordingly to accommodate the growing capacity requirements. Ensuring sufficient capacity and scalability while maintaining low latency and high reliability can be a significant challenge, particularly in dense urban areas with a high concentration of RUs.
- **Fronthaul Transport Cost**: The deployment and maintenance costs associated with building a high-capacity fronthaul network can be substantial. Implementing dedicated fiber connections or high-capacity microwave links to support the fronthaul traffic can be costly, especially when extending the network to remote or hard-to-reach locations.
- **Network Slicing**: Enabling network slicing in CRAN introduces additional challenges in the fronthaul segment. Each network slice requires dedicated resources and isolation, necessitating efficient partitioning of fronthaul capacity and dynamic allocation of resources to different slices based on their specific requirements.



	Backhaul aggregation (mesh)	Fronthaul access and local (typ. 10 km) (PtP, WDM)
Now	Multiple 100Gbit/s	N = number of RU interfaces; P = number of Antenna site N x P x 10 or 25 Gbit/s ≈ 1 Tbit/s
Future	200, 400, 800Gbit/s [bidi. not available]	RU interface = 100 Gbit/s

Fig. 5.3: 5G use cases enabled by OCTAPUS in the Centralized RAN with extended fronthaul.

Fig. 5.3 illustrates a C-RAN architecture use case. Today, operators typically connect ~10 RUs to a single CO at 10 or 25Gbps (or even up to 100 Gbps in the near future) via PtP or WDM fiber topologies. This results in an overall fronthaul throughput approaching 1 Tbps. Future predictions of the throughput requirement per RU are expected to reach 100 Gbps, leading to 4X-10X higher fronthaul capacity compared to today. Addressing these fronthaul challenges is crucial for the successful deployment and operation of C-RAN, as they directly impact the performance, reliability, and cost-effectiveness of the network.

5.2.1.3 Fronthaul in specific areas ("indoor mobile") with DAS systems: subways, stadiums

To connect 5G mobile antennas in challenging indoors environment (e.g, subways, subterranean parking spots, shopping malls or large buildings etc.) or dense urban areas, a distinct mode of infrastructure deployment is used, i.e., Distributed Antenna Systems (DAS) with RAN sharing. DAS is a system used to enhance wireless coverage and capacity in those specific areas by distributing the antennas throughout the area to provide better signal coverage and capacity and connecting these antennas to a central hub, which in turn connects to the mobile network operator's infrastructure. DAS helps overcome the challenges of signal attenuation and interference in complex indoor or dense urban environments by distributing the signal from a centralized source. When DAS and RAN sharing are combined, multiple mobile network operators can share the distributed antenna system infrastructure to reduce costs, simplify deployment, and provide improved connectivity to their subscribers in challenging environments. DAS systems typically rely on Analog Radio over Fiber (A-RoF) links between the DAS RUs and the DAS master node, which hosts the active aggregation equipment connected to the O-RU, as depicted in Fig. 5.4. Digital-RoF is also considered in the case where the O-RU unit is at the antenna location and the O-DU and O-CU remain at a central site. In that case, the fronthaul link requires a Fronthaul Master (FHM) equipment to ensure RAN sharing and a Transport Network Equipment (TNE) at the central site to aggregate traffic to each operator's equipment.

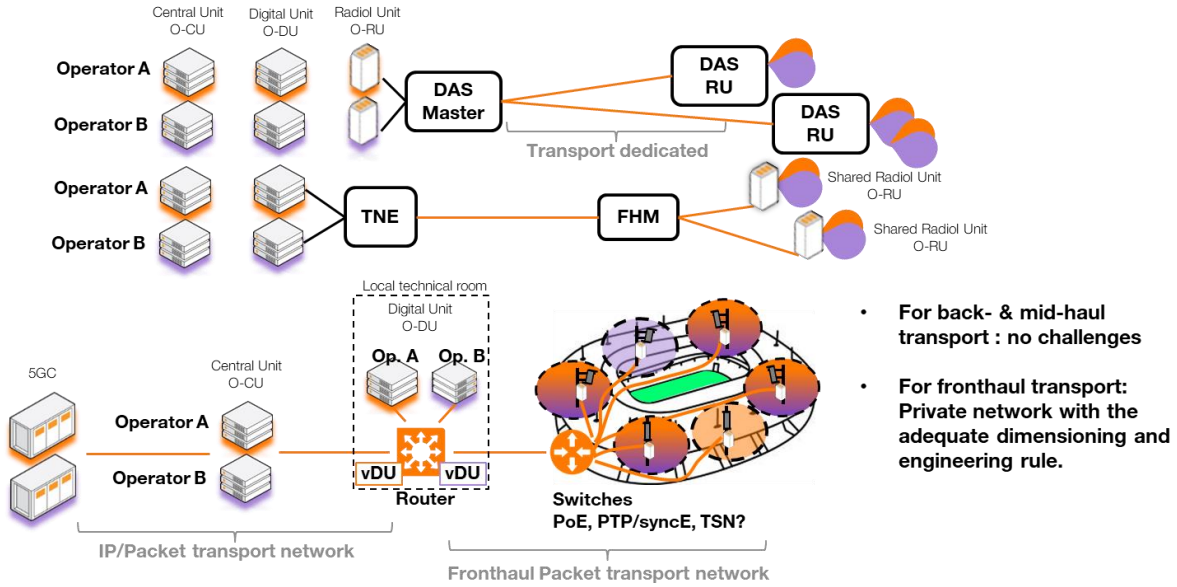


Fig. 5.4: Deployment options for DAS-enabled fronthaul systems.

5.2.1.4 OCTAPUS slicing for mobile X-Haul use cases

Slicing, in the context of 5G, refers to the partitioning or segmentation of a physical network into multiple, logically isolated, virtual networks (known as slices), with diverse service requirements. 5G slicing borrows principles and techniques from network virtualization in IT, where physical infrastructure is logically partitioned into multiple virtual instances so that each slice can have its own network functions, radio access technologies, connectivity options, and management policies, providing flexibility and adaptability to the evolving needs of different applications. Hence, each slice is, essentially, a self-contained network instance with its own set of resources, configurations, and characteristics, tailored to meet the unique needs of different services/applications. By creating independent slices, 5G networks can provide dedicated and isolated environments, ensuring that the performance and requirements (or even performance degradations, due to unforeseen circumstances) of one slice do not impact others, as depicted in Figure 5.5 with two end-to-end network slice instances. This allows for optimized network performance, efficient resource utilization, and improved end-user experiences.

In addition to superior efficiency and network management, slicing offers fine-grained control over the achieved bandwidth, latency, security, and quality of service (QoS), and plays a crucial role in delivering the promised capabilities of 5G, such as ultra-low latency, high reliability, massive connectivity, and

enhanced network capacity, while accommodating the specific requirements of different verticals and applications. In this way, slicing allows operators to unlock the full potential of the technology to support the digital transformation across various industries and offer customized and differentiated services to sectors such as healthcare, transportation, manufacturing, and entertainment, each with their specific demands.

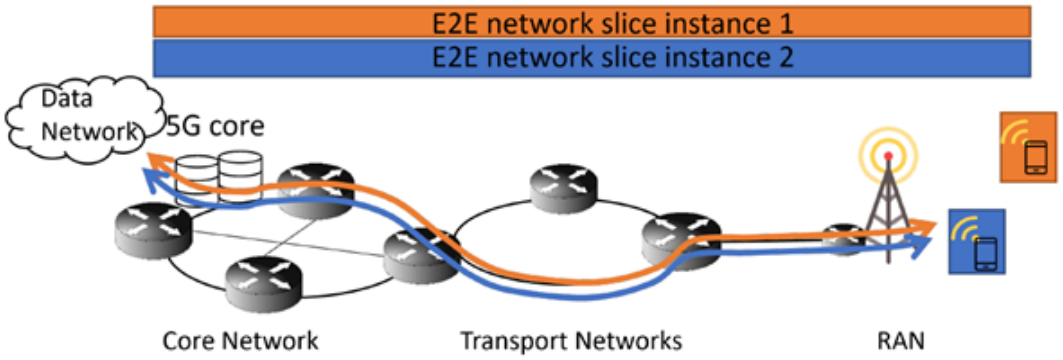


Figure 5.5: An example of E2E slicing with two network slice instances.

The architecture of the OCTAPUS NGCO is well-suited to enable end-to-end 5G slicing via its designed features of i) inherent scalability, ii) high-aggregate switching capacity, iii) multiple levels of supported latency via Express paths, allowing for dynamic optical bypass, and iv) TSN support and tight multi-domain coordination within an SDN-based control plane. In particular, as part of enabling end-to-end 5G slicing, the role of a multi-technology SDN control plane is fundamental for the seamless management and monitoring of the resources in the transport network, and especially within the NGCO. The aforementioned enhancements are crucial in unlocking the network's potential to meet the specific demands of individual slices. Furthermore, the evolution towards Open-RAN interfaces and systems facilitates the sharing of O-RAN Remote Units (O-RUs) among multiple operators. This incentivizes the inclusion of multiple fronthaul interfaces at the O-RU level, which may result in shared maximum radio bandwidth that will limit the required optical transport line-rates. While this evolution increases the complexity of links to the O-RUs, it also enables a greater degree of flexibility and multiplicity in catering to the needs of different slices. Consequently, in the context of O-RAN, the OLT assumes a pivotal role in the overall architecture, and the OCTAPUS NGCO is actively pushing the boundaries of its current capabilities to support these evolving requirements.

5.3 Service-driven Use Cases: URLLC

URLLC and TSN are core components of the 5G architecture aiming at addressing time critical networking needs, strict synchronization across the network and enabling important use cases and critical applications that necessitate extremely low latency (in the order of 1 ms) and a high degree of guaranteed reliability (>3 nines) which cannot be supported by 4G networks.

Such applications and services span across various domains, including automotive, transportation, industrial automation, (remote) healthcare, public safety, critical infrastructure monitoring and control, emergency response, education, media production, entertainment and gaming (AR/VR/MR/XR), banking, financial trading, smart agriculture, UAVs, logistics and supply chain, manufacturing, smart energy and grid [63].

The metropolitan areas comprise an ideal playground for the realization of the 5G and beyond 5G potential in many ways, innovation and scaling being among them. In such areas, telco operators may offer (on top of fixed and eMBB and mMTC), a wide range of comprehensive low-latency, high-reliability services/applications (such as the ones mentioned before) to various verticals, thus transforming the metropolitan area into a connected and intelligent smart city. Towards this end, telco operators shall deploy a robust mobile and fixed network infrastructure (including, base stations, edge computing nodes, network slicing capabilities and advanced network optimization mechanisms) to efficiently support efficiently all kinds of current and potential future applications' QoS requirements.

A non-exhaustive list of URLLC use case categories [64], [65], [66], [67], [68], [69] is depicted in fig. 5.6 and described in the following paragraphs. Specific QoS requirements (latency, reliability, etc.) are given in Table 8 in Section 3.5.10.

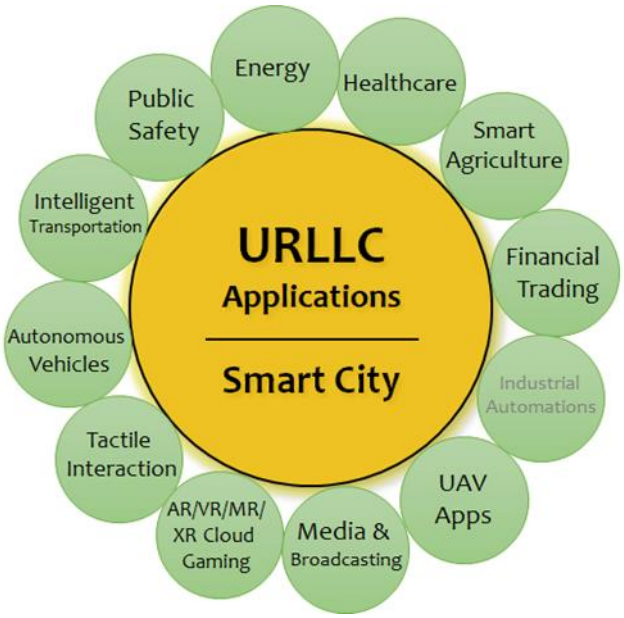


Figure 5.6: Indicative URLLC UC categories for Smart Cities.

It shall be noted that applications that are related to specific industries/verticals (e.g. airports, cruise ships, hotels, hospitals, malls, underground, Universities, parking lots, factories, warehouses) to cover own needs within the area they operate, will not be considered in the following, since the deployment of a dedicated private campus 5G network is considered as more appropriate/recommended (compared to a public 5G network). Indicative such applications include: predictive maintenance (to prevent faults), supply chain optimization (to speed up production), food/parcel delivery using AGVs/robots (to guarantee reliable and fast services), training/education (to offer employees/students advanced experience using AR/VR glasses), entertainment (multi-player gaming and 3D movies using AR/VR glasses), smart manufacturing (for quality assurance purposes), healthcare (cases of robotic surgery, local examination without physical/close contact, etc.), advanced physical security (utilizing cameras, UAVs for airports).

5.3.1 Energy

By leveraging URLLC fixed and mobile services, edge computing, network slicing and advanced analytics, a smart city may achieve advanced real-time monitoring and control of the electrical grid to improve energy efficiency and grid reliability. Specifically, URLLC connections provide the required ultra-low-latency communications between the smart meters, distribution networks and energy management/control systems to enable a highly intelligent energy grid (termed as “smart grid”) supporting dynamic load balancing, quick identification and resolution of power outages and faults, efficient integration of renewable energy sources into the grid, energy distribution optimization and enhanced grid stability. Indicative energy-related scenarios enabled by URLLC services include:

- **Automation of distributed power distribution:** Optimized energy distribution and fully automatic load/voltage level management can be achieved by collecting and analyzing real-time data (supported by the URLLC service) from sensors, smart meters and distributed energy sources.
- **Fault management for distributed electricity generation:** URLLC smart grid communications allow for the real time detection (via machine learning algorithms) of faults or anomalies, the prompt isolation of the affected areas, the reroute of power via alternate circuits and the restoration of power, with minimal downtime and improved grid resilience.
- **Low-latency monitoring/control and decision making:** URLLC enables real-time monitoring of energy parameters, such as voltage, current and power quality, and facilitates immediate control actions for optimal grid performance by supporting local decision-making edge computing nodes (within the energy infrastructure) for the processing of critical data near the source.

5.3.2 AR/VR/MR/XR

This UC category focuses on the delivery of immersive Augmented/Virtual Reality (AR/VR) and interactive (MR/XR) experiences over 5G and/or a combination of fixed and mobile networks. By leveraging low-latency communication, edge computing, network slicing, and content delivery optimization, users can enjoy realistic augmented and virtual experiences in various sectors/domains. Indicative URLLC-supported scenarios in this domain include:

- **Augmented worker assistance:** AR is used to provide real-time guidance and information to workers in various industries. For example, maintenance technicians can wear AR glasses that display step-by-step instructions and virtual overlays on equipment, assisting them in performing complex tasks efficiently and accurately. By exploiting the URLLC services, multiple users can share the same virtual space, interact with virtual objects and collaborate on tasks.
- **360-degree panoramic VR view video broadcasting**: Using 5G networks, live or recorded 360-degree panoramic VR videos can be streamed to AR/VR devices. Users can experience immersive virtual environments, such as virtual tours, live events or remote training sessions, in real time. Real-time rendering and interaction in such AR/VR environments require ultra-low latency to maintain responsiveness and avoid motion sickness, enhancing the overall quality and usability of these applications.
- **Real-time AR/MR/VR/XR cloud gaming:** By leveraging 5G connectivity to stream ultra-high quality gaming content to AR/VR/XR devices, users can enjoy interactive gaming experiences but also navigate in virtual tours, live events and educational simulations that merge the virtual and real-world environments, thus enhancing the immersion and gameplay experience.
- **Low latency rendering and streaming services:** 5G's low latency support enables real-time rendering and streaming of AR/VR content. This ensures that the virtual content is synchronized with the user's movements, providing a seamless and immersive experience.
- **Content delivery optimization services:** CDNs integrated with 5G networks may optimize the distribution of AR/VR content, reduce latency and ensure efficient content caching and streaming, enabling seamless and uninterrupted experience for users, even in high-demand scenarios.
- **Virtual orchestra:** A virtual orchestra performance where musicians located in different geographical locations can "virtually" come together and create a synchronized and immersive musical experience for the spectators. URLLC services are crucial to ensure that the musicians can perform together in real-time without perceptible delays.

5.3.3 Healthcare

URLLC enables real-time remote robotic surgery, AR-based surgical training, remote telemedicine and medical data transmission, stroke diagnosis, etc. facilitating prompt and accurate healthcare services even in remote locations. All of these critical healthcare services that rely on real-time interactions, precise control and immediate decision-making, ultimately improving patient health condition, critically depend on URLLC. Indicative URLLC-supported healthcare scenarios include:

- **Remote (AR) Robotic Surgery:** It utilizes a surgical system comprised of robotic arms equipped with surgical instruments, high-definition cameras, AR/VR glasses and haptic/tactile feedback capabilities enabling a sense of touch during the operation. The surgeon, located at a remote site, controls the robotic arms that mimic the surgeon's movements, with high precision and accuracy, using a console that provides a 3D visualization of the surgical site. The low latency and high reliability of URLLC ensure minimal delay and minimal risk of data loss, allowing surgeons to successfully perform intricate surgical procedures from a distance.
- **Emergency Telemedicine (e.g., stroke diagnosis and treatment):** HD/4K video streaming, enabled by URLLC service, enables doctors to remotely assess stroke patients, review imaging scans, vital signs, blood glucose levels and other health metrics, to proceed with prompt decision-making and provide time-critical recommendations (e.g., interventions for thrombolysis).
- **5G-enabled ambulance:** First responders in the case of accidents often need to share large amounts of data from multiple sensors as well as 4K videos from the ambulance on its way to the hospital and receive feedback/guidance in case of remote surgeries or help with diagnosis. Since 5G URLLC may deliver latencies below 10 ms (even on the move), real-time and reliable communication and interaction with hospital personnel can be achieved to potentially save human lives.

5.3.4 Financial Trading

Real-time financial trading refers to the process of buying and selling financial instruments, such as stocks, bonds, commodities, and currencies with a focus on achieving instant trade execution and leveraging real-time market data. This application requires URLLC to ensure that traders receive timely and accurate information, execute trades swiftly and respond to market conditions in real-time. Especially in highly volatile markets, financial actors offering such URLLC-enabled real-time trading services are expected to obtain unique competitive advantages. Indicative URLLC-supported financial scenarios include:

- **Low-latency global market data feeds:** Real-time financial trading relies on low-latency data feeds that deliver market information, including prices, trade volumes and other relevant data, to traders. These data feeds must be delivered with ultra-low latency to provide up-to-date information and support quick decision-making.
- **Instant trade execution:** Financial trading systems require URLLC to ensure rapid communication between the trading platform and market data providers, to achieve high-speed order routing/submission/execution, thus minimizing the impact of trade execution delays and price changes.
- **Risk management and compliance:** Real-time financial trading platforms often include risk management and compliance mechanisms to ensure adherence to regulatory requirements and mitigate financial risks. URLLC helps in transmitting real-time risk assessment and compliance checks to prevent erroneous trades and manage exposure in volatile markets.

5.3.5 Public Safety and Emergency Response

In a smart city environment, the provisioning of public safety and emergency response services during critical incidents (e.g., accidents, fires, criminal activities, natural disasters, etc.) is of vital importance. These services can improve situational awareness and assist in taking proper security measures to efficiently manage the incident and reduce response times by the public safety personnel/first responders (including police, fire departments, medical services, disaster management teams), thus, creating a safer and more resilient environment for the citizens. The support of such services necessitates the deployment of a robust 5G URLLC-capable network as well as surveillance and situational awareness systems, enabling critical infrastructure monitoring, real-time video, facial and object recognition and tracking, real-time information exchange among emergency responders, command centers, and field personnel, instant visual feedback to security personnel, real-time identification of persons of interest etc. Indicative URLLC-supported scenarios include:

- **Immediate identification of potential security threats:** HD/4K video streaming fed by real-time video surveillance cameras operating in public spaces, can be combined with appropriate AI algorithms to enable facial/object recognition and provide real-time identification or tracking of suspects or suspicious incidents.
- **Real-time situation awareness:** Real-time 4K video feed and alerts on incidents or emergencies, emergency calls and location data can be exchanged with extremely low latency for immediate response and effective coordination of efforts among the involved stakeholders.

5.3.6 Autonomous Vehicles & Intelligent Traffic Management

To enhance the overall quality of life for its residents, a smart city needs an intelligent traffic management system to monitor/control/optimize vehicular traffic and improve safety in real-time. The system will collect and process in real-time data from various sources such as CCTV cameras, vehicle sensors and mobile apps to improve road safety, minimize accidents, optimize vehicular traffic flow, and enhance overall transportation efficiency and responsiveness. This use case utilizes various URLLC applications to ensure immediate response times and highly reliable communication among the stakeholders/systems. Indicative URLLC-supported scenarios include:

- **Autonomous connected vehicles:** The city incorporates autonomous vehicles equipped with advanced sensors (based on lidar, radar and cameras), communication modules (i.e., 5G modems) and decision-making capabilities based on object detection, hazard identification, etc. These Level 3 and/or Level 4 [70] vehicles operate in a cooperative manner, exchanging real-time information (e.g., position, speed and intention, traffic conditions, road condition information, etc.) with each other (V2V), with road-side infrastructure (V2I), such as traffic lights, road signs, surveillance cameras, and with the pedestrians (V2P) while making rapid decisions,

based on AI, to ensure safe transportation (collision avoidance, movement coordination, congestion and travel time reduction).

- **Cooperative driving:** URLLC enables cooperative driving scenarios (adaptive cruise control, platooning, etc.), where autonomous vehicles can collaborate to improve traffic efficiency, by synchronizing their movements to improve energy efficiency and reduce congestion.
- **Remote vehicle control & monitoring:** URLLC enables real-time remote control and monitoring of autonomous vehicles, facilitating fleet management, diagnostics, maintenance activities without physical presence and Over-the-Air (OTA) software updates/bug-fixes/security-patches without interrupting their operation.
- **Precise positioning services:** URLLC can enable precise positioning services, including cellular and 5G NR-based positioning. This is valuable for applications such as navigation, logistics and asset tracking, where highly accurate and real-time positioning information is required.
- **Intelligent traffic management and dynamic route planning:** By leveraging intelligent algorithms and real-time data, the intelligent traffic management system enables dynamic route planning to optimize the traffic flow and enhance the overall transportation infrastructure. The system utilizes various data sources, including traffic sensors, GPS information, weather station data, events, and emergency situations, historical traffic patterns and real-time data feeds, to monitor traffic conditions and provide recommendations (e.g., to suggest fleet re-routing), alerts and traffic guidance to the individual vehicles or to the on-board Advanced Driver Assistance Systems (ADAS). In addition, the system can implement proactive measures such as signal timing adjustments, lane management or adaptive traffic control systems to dynamically optimize real-time traffic flow and reduce travel time, fuel consumption and gas emissions.

5.3.7 Tactile Interaction

Tactile interaction services/applications have the potential to greatly improve citizens' lives and foster innovation in various ways, as the promised ability "*to sense and manipulate objects or receive feedback through touch in a virtual or remote environment*", opens-up new possibilities for training, design, remote collaboration, entertainment and rehabilitation. Tactile interaction can:

- Provide a more immersive and realistic virtual experience.
- Make digital content and interfaces more accessible to people with disabilities.
- Enhance remote collaboration and communication.
- Assist individuals in regaining motor skills or recovering from injuries.
- Enhance the interaction between humans and machines (e.g., in robotics, automotive interfaces or industrial control systems).
- Empower designers, artists and creators, etc.

Indicative URLLC-supported scenarios include:

- **Gaming and entertainment:** On top of the AR/VR/MR experience, players can feel the impact of in-game actions, such as physical contact or environmental effects, enhancing realism and immersion.
- **Rehabilitation and physical therapy:** Haptic devices can provide sensory feedback to patients during virtual exercises or rehabilitation sessions, facilitating motor skill development and improving the overall therapeutic experience.
- **Remote maintenance and repair:** Technicians can remotely assess and diagnose equipment issues, and with haptic feedback, they can feel the physical resistance, vibrations or other tactile cues that help guide their troubleshooting and repair process.
- **Virtual training and simulations:** Haptic feedback devices can simulate the sensation of touching and manipulating tissues, providing a realistic training experience. For example, firefighters can experience the sensation of heat or pressure in virtual fire simulations or pilots can feel the control inputs and vibrations in virtual flight training. Medical students or surgeons can practice surgical procedures in a virtual environment.
- Other tactile-related applications include VR-based Art and Creativity, Virtual Design and Prototyping etc.

5.3.8 UAVs

This use case category considers a UAV traffic management system that is deployed to regulate, co-ordinate, optimize and safeguard the operations of multiple UAVs in a given geographical area. The system is composed of: i) a fleet of UAVs, ranging from small drones to larger unmanned aircraft, equipped with 5G communication modules (e.g., for command/control and telemetry data exchange purposes), positioning systems and onboard sensors for navigation, situational awareness, and payload operations and ii) a coordinated flight management control system. By leveraging low-latency communication, real-time data exchange and advanced traffic management capabilities, the system optimizes UAV operations, enhances airspace safety and enables a wide range of applications such as aerial surveillance, delivery services and infrastructure inspection. Indicative URLLC-supported scenarios include:

- **Collision avoidance and flight coordination:** The traffic management system uses the real-time telemetry data from UAVs, ground-based sensors and air-traffic management systems to monitor the airspace, calculate safe flight paths, detect potential conflicts, manage traffic flow and coordinate UAV operations. The system leverages 5G connectivity to rapidly communicate collision avoidance instructions to UAVs, ensuring safe and efficient airspace utilization.
- **Command and Control (C2):** The UAV controller communicates with individual UAVs utilizing reliable, low-latency 5G links to enable remote piloting, navigation and mission control functionalities. The 5G network supports the seamless and efficient data transmission between UAVs, the UAV controller and the UAV traffic management system.
- **Airspace monitoring:** Ground-based sensors, such as radars and cameras, are integrated into the UAV traffic management system to monitor the airspace. These sensors provide additional situational awareness, detect intrusions or unauthorized UAVs and enhance overall airspace security.
- **Remote diagnostics and maintenance:** UAVs may transmit real-time data and receive software updates over 5G, ensuring optimal performance, identifying issues in real-time and minimizing UAV downtime.
- **Real-Time object detection/classification:** UAVs equipped with 4K/thermal cameras send the video feed in real-time over 5G to a ground station (e.g., edge computing equipment) where it will be processed in real time, using AI/ML techniques, to detect and/or track the motion of specific object(s).
- **Package delivery services:** By leveraging the capabilities of the 5G network (i.e., low-latency and reliable communications, precise positioning, seamless connectivity, etc.), efficient, secure and timely delivery of packages and goods can be offered to the citizens via drones. The service necessitates, among others, the existence of a (drone) delivery management platform for drone delivery route monitoring, optimization and control in real-time, by taking into account various factors such as traffic conditions, airspace regulations, weather conditions, package priority, etc.
- **Remote infrastructure inspection:** Efficient, risk-free, cost effective and remote precise inspection (via 4K live video feeds) in real-time of critical infrastructure, such as bridges, power lines, base stations, buildings, etc. can be enabled using drones and 5G's URLLC services. Utilizing this service, potential issues and/or anomalies that require further investigation can be identified and timely actions can be taken.

5.3.9 Smart Agriculture

Smart agriculture utilizes advanced technologies and data-driven approaches to optimize agricultural practices and improve productivity, sustainability and efficiency in the farming industry. It leverages a combination of technologies, including IoT, AI, big data analytics and remote sensing, to enable real-time monitoring, analysis and decision-making in agricultural operations. Various components including IoT sensors, drones, satellite imagery and weather stations gather information related to soil moisture, temperature, humidity, crop growth, pest infestation and other environmental factors which are then processed using AI algorithms to generate insights and recommendations to farmers about irrigation scheduling, fertilizer application, pest control, crop harvesting, etc. Indicative URLLC-supported scenarios include:

- **Precision farming and livestock monitoring:** IoT sensors deployed in the field collect and upload measurements to a central control system. The collected data are analyzed and insights for precise irrigation, fertilization and pest control are provided. Livestock monitoring (via smart tags or collars) could provide continuous info on the animals' vital signs and health, location and behavior, enabling prompt interventions and ensuring their optimal health conditions.

- **Crop disease detection and prevention:** Advanced imaging technologies, such as drones or remote sensing, are employed to capture high-resolution images of crops. These images are processed by advanced image processing algorithms to identify signs of disease, pest infestation or nutrient deficiencies. Early detection of these events allows farmers to take immediate corrective action, implementing targeted interventions and preventing the spread of diseases, ultimately improving crop yield and quality.
- **Smart irrigation and water management:** By continuously monitoring soil moisture levels, weather conditions, and evapotranspiration rates, quick adjustment of irrigation schedules can be achieved, thus minimizing water wastage.
- **Automated machinery and harvesting**: Operational efficiency and reduction of labor-intensive tasks can be achieved by utilizing autonomous drones or robots equipped with sensors and cameras performing crop monitoring, scouting, and even selective spraying of pesticides or fertilizers. Harvesting processes can also be automated with real-time data transmission, allowing machines to identify crop maturity and optimize harvesting operations based on precise timing, resulting in increased productivity and reduced labor costs.

5.3.10 URLLC Use Case Scenarios Latency/Reliability KPIs

Table 8 presents indicative KPI values latency and reliability for the use case scenarios described above are depicted based on the literature (i.e., 3GPP, NGMN, publications). As it can be seen, there is a wide range of use cases and scenarios with different and highly demanding KPIs even for the scenarios of the same use case. The criticality of such scenarios necessitates special handling of the URLLC traffic by the 5G network and the OCTAPUS switch deployed therein to preserve the QoS related parameters.

Table 8: Latency and Reliability KPIs for URLLC use case scenarios.

Use Case group	Use Case example	E2E latency	E2E reliability	User experienced throughput	Devices / km^2	Ref
Energy	Automation of electrical power distribution	< 50 ms	6 nines			[68]
	Fault management for distributed electricity generation	< 30 ms	5 nines	1 Mbps	< 2000	[64]
	Low-latency monitoring/control and decision making	< 5ms	6 nines			[68]
AR/VR/MR/XR	Augmented worker assistance	< 10 ms	6 nines			[64]
	360-degree panoramic VR view video broadcasting	< 20 ms	5 nines	40-700 Mbps	< 3000	[68]
	Real-time AR/MR/VR/XR cloud gaming	< 20 ms				[68]
	Low-latency rendering and streaming services	10-50 ms				[65]
	Content delivery optimization services	< 4 ms				[68]
	Virtual orchestra	20 ms	6 nines			[65]
Healthcare and safety	Remote (AR) robotic surgery	10-100 ms	6 nines			[68]
	Emergency telemedicine (e.g., stroke diagnosis and treatment)	10-100 ms				[68]
	5G-enabled ambulance	10-100 ms				[68]
Financial trading	Low-latency global market data feeds	1-10 ms	6 nines			
	Instant trade execution	< 1 ms				[68]
	Risk management and compliance	1-10 ms				
Public Safety & Emergence Response	Immediate identification of potential security threats	< 100 ms	6 nines			
	Real-time situation awareness	< 10 ms				[65]
Autonomous Vehicles & Intelligent Traffic Management	Autonomous connected vehicles	1-20 ms	6 nines			
	Cooperative drivingf	3-100 ms				[68]
	Remote vehicle control & monitoring	10-30 ms				[68]
	Precise positioning services	< 10 ms				[68]

	Intelligent traffic management and dynamic route planning	3-100 ms				
Tactile interaction	Gaming and entertainment	< 7 ms (uplink)	5 nines	1 Gbps	< 3000	[64]
	Rehabilitation and physical therapy					
	Remote maintenance and repair	10-100 ms				
	Virtual training and simulations	< 1 ms				[71]
	Other: VR-based art and creativity, virtual design and prototyping	10-100 ms				
UAVs	Collision avoidance and flight coordination	< 10 ms	5 nines			
	Command and Control (C2)	< 100 ms				[64]
	Airspace monitoring	< 15 ms				
	Remote diagnostics and maintenance	10-100 ms				
	Real-time object detection/ classification	10-100 ms				
	Package delivery services	10-100 ms				
	Remote infrastructure inspection	10-100 ms				
Smart agriculture	Precision farming and livestock monitoring	< 20 ms	5 nines			
	Crop disease detection and prevention	10-100 ms				
	Smart irrigation and water management	10-100 ms				
	Automated machinery and harvesting	< 20 ms				

5.3.11 User/System Requirements

The provisioning of URLLC services in a 5G mobile network requires careful consideration and implementation of various technical aspects at both the network architecture level (i.e., support of network slicing, incorporation of edge computing, overarching orchestration framework) and the RAN level (i.e., support of advanced features such as beamforming, massive MIMO, dynamic spectrum sharing) towards offering i) End-to-End QoS guarantees (i.e., proper network resource provisioning, priorities etc.), ii) proper synchronization (via high-precision time synchronization mechanisms, such as IEEE 1588 PTP), iii) security (advanced authentication, encryption and integrity mechanisms to protect sensitive data) and, iv) SLA management (requiring proactive network monitoring, real-time performance analytics and fault management).

The QoS of the offered 5G URLLC services, and the traffic differentiation between different types of services (e.g., eMBB, mMTC, URLLC) in particular, is based on the QoS Flow Identifier (QFI), wherein a unique QFI value is associated to each QoS flow within a network slice. By leveraging the QFI parameter, the 5G network can effectively identify and handle the URLLC traffic, and allow for traffic differentiation, prioritization and enforcement of QoS mechanisms specific to URLLC flows. More specifically, the QFI may offer the following “capabilities”:

- **QoS differentiation:** For the URLLC traffic, specific QFIs can be assigned to prioritize and handle URLLC traffic differently compared to other types of traffic within the same network slice.
- **Traffic mapping and prioritization:** The QFI value provides a mapping between the specific flow and its QoS requirements and as such it can be used for URLLC traffic prioritization or preferential treatment against the other flows (via traffic shaping, admission control, scheduling algorithms and other QoS management techniques) to ensure that the URLLC flows meet the latency and reliability targets.
- **End-to-End QoS mapping:** Since the QFI is propagated within the network, it is used throughout the 5G network to maintain end-to-end QoS guarantees, allowing all network elements to apply the appropriate QoS treatments.
- **Interoperability and compliance:** Since the QFI value follows the 3GPP standards and guidelines, it ensures interoperability between different network elements and vendors. This

compliance ensures consistent handling and prioritization of URLLC traffic across the entire network.

It is noted that the relative position of the OCTAPUS NGCO with respect to CU/DU/RU nodes crucially affects the implementation of the above QoS mechanisms. For example, if the OCTAPUS NGCO is located between the RU and the BBU and a pure-CPRI-based implementation is employed for the fronthaul, the QFI information will "terminate" at the BBU and not be visible or accessible within OCTAPUS. This is because the CPRI is a point-to-point interface between the RU and BBU, primarily designed for the transport of radio signals and not for carrying higher-layer network protocol information. Nevertheless, even in such a CPRI-based fronthaul scenario, the QoS requirements for URLLC traffic can still be addressed through other means, including:

- Traffic Differentiation based on CPRI Channels: Different CPRI channels can be dedicated or prioritized for URLLC traffic, allowing the switch to handle them separately and allocate the appropriate resources.
- Quality of Service (QoS) Policies: QoS policies based on traffic characteristics, such as packet size, packet inter-arrival time or specific protocol headers can be applied within the CPRI traffic. These policies can be defined to prioritize URLLC traffic or allocate specific resources to ensure low latency and high reliability.
- Traffic Analysis and Classification: Traffic analysis and classification techniques, such as deep packet inspection, flow-based analysis or protocol analysis could be applied on the CPRI traffic. By analyzing the traffic patterns, the OCTAPUS NGCO can identify URLLC traffic based on its unique patterns and handle it accordingly.

Additionally, since time synchronization between the RU and BBU is crucial for URLLC applications, the supported TSN features of OCTAPUS, including IEEE 802.1AS (itself an adaption of IEEE Precision Time Protocol (PTP)), will ensure precise time coordination between the RU and BBU, facilitating low-latency and time-critical operations even in the presence of a stringent CPRI-based fronthaul segment.

By addressing the system-related requirements listed in Table 9, the OCTAPUS NGCO can effectively support the diverse URLLC applications, ensuring high-speed connectivity, low latency, QoS differentiation, scalability, reliability, security and interoperability in a smart city environment. For easier classification, the notation **<U/S>-<F/P/NF>-<RQXX>** is used below to denote a requirement enforced on the NGCO, where

- U/S indicates whether this is a User or System requirement.
- F/P/NF indicates whether this is a Functional, non-functional Performance or non-Functional qualitative requirement. The latter is related to security/privacy, modularity, extensibility, maintainability, interoperability requirement.
- RQXX is an incremental number uniquely identifying the requirement.

Table 9: Classification of high-level OCTAPUS NGCO Requirements.

Req.ID	Description [Descriptive text]	Priority [H/M/L]	KPIs and Parameters [to be measured]
S-F-RQ1	**High-Capacity switching:** Each Uplink switch in the NGCO shall support an aggregate throughput of 25.6 Tbps, by offering multiple 50 Gbps line-rate ports to accommodate efficient data transmission for all supported services. Each IF card shall support 800 Gbps.	High	User-plane data rate per IF card, aggregate capacity/ throughput
S-F-RQ2	**Fast-switching operation:** Optical path reconfiguration within the NGCO shall occur within 100 ns via changing the state of the PCMs comprising the OCS backplane	High	Duration of PCM state transition during NGCO path reconfiguration under medium and heavy load conditions

U-F-RQ3	**Low Latency:** The NGCO shall offer mechanisms to minimize E2E latency. At least 32 optical Express paths, bypassing NGCO and offering minimum possible latency, shall be present. TSN protocol support for time-sensitive streams, with application-specified requirements, shall be available.	High	min/max/average E2E latency (and jitter) of URLLC applications, measured between user terminal and network termination, under medium and heavy load conditions shall meet the respective requirements
S-F-RQ4	**High energy-efficiency:** The NGCO's OCS backplane shall consist of non-volatile PCM switches with reduced energy consumption. Optical transceivers for intra-NGCO and access links shall target improvements of 4x and 8x, respectively.	High	Targeted energy efficiency values for optical transceivers are 4.5 pJ/bit and 8 pJ/bit, respectively, for intra-NGCO and access links
S-F-RQ5	**QoS differentiation:** The NGCO shall support QoS mechanisms to prioritize URLLC traffic over non-critical traffic and ensure that latency-critical applications receive the required network resources and bandwidth to maintain optimal performance.	High	min/max/average latency, jitter and throughput under heavy loading conditions simultaneously supporting different service classes
S-F-RQ6	**Network Slicing Support:** The NGCO shall be capable of supporting different services with different end-to-end QoS requirements while also providing isolation, resource allocation and QoS management tailored to specific requirements. Slice management and orchestration shall be applied at different levels across slices and at different times.	High	Number of supported slices, actual user-plane data rates per slice, QoS characteristics of links (capacity/latency/etc.).
S-NF-RQ7	**Scalability:** The NGCO shall accommodate the increasing number of IF cards and traffic volumes, support high port densities and be able to handle the growing demands of URLLC, eMBB and mMTC applications without performance degradation. Adding new Uplink switches and IF cards shall not disturb the operation of existing ones.	High	At least 256 ports at the Uplink switches, at least 16 access ports per IF card, at least 2 Uplink switches per NGCO
S-NF-RQ8	**Interoperability and Standards Compliance:** The NGCO hardware and software shall adhere to industry standards and protocols to ensure interoperability with other network devices and legacy optical distribution networks. Compliance with standards like IEEE, IETF and ITU-T (e.g., G.983.1 and G989.2) specifications enables seamless integration into the overall network infrastructure.	High	Hardware: power budget, optical transmitter output level, optical receiver sensitivity Software: adherence to IEEE TSN family of standards, standardized YANG models for data representation
S-NF-RQ9	**Flexibility and Programmability:** The NGCO shall support programmability and SDN capabilities. This allows for easier management, customization, and adaptability to evolving application requirements, protocols and network configurations.	High	Development of hierarchical SDN multi-domain coordinator (for more details, see Table 10)

S-F-RQ10	**Management and Monitoring Capabilities:** The NGCO shall provide comprehensive management and monitoring capabilities to facilitate network administration, troubleshooting and performance optimization. Traffic monitoring on a per port/Uplink switch/IUF card level is needed. Remote management interfaces, traffic monitoring tools, and performance analytics are also essential.	Medium	Capability of obtaining information regarding: current network topology, user plane data rates, service consumption, link congestion status, throughput per IF card and/or per port.
S-NF-RQ11	**Reliability and Redundancy:** The NGCO shall be designed with high reliability and redundancy features to ensure uninterrupted operation. Local Uplink switch/IF card port failures should be identified quickly and alternative paths through functioning ports should be set up. Redundant power supplies, hot-swappable modules, and redundant links can also minimize downtime and enhance service availability.	Medium	Effective operation of fault detection mechanism, fault recovery implementation and notification.
S-NF-RQ12	**Security:** The NGCO hardware and software shall incorporate robust security measures to protect against unauthorized access, data breaches, and cyber threats. Features like access control, code signing, authentication protocols, encryption, and intrusion detection systems help safeguard the switch and the connected URLLC applications.	Low	Implementation of various rigidly defined authorization levels for different users/roles.

In the context of OCTAPUS, a tightly-coordinated NGCO control plane is required to ensure high-speed connectivity, low latency, QoS differentiation and scalability of URLLC applications. For this reason,

Table 10 lists the high-level requirements of the SDN Coordinator in charge of the OCTAPUS control plane.

Table 10: Definition of SDN Coordinator requirements.

Description	Priority
• **Data plane information management** The SDN coordinator must be capable of managing the information concerning the data plane of the transport network from the RU to the DU/CU, where the TSN talker and listener(s) are logically placed.	**High**
• **NGCO topology and flows abstraction** The SDN coordinator must be capable of processing and then abstracting the information available from the non-TSN and TSN domains. This information can include the TSN flows, the physical and logical topologies of the network etc.	**High**
• **NGCO TSN flows management** The SDN coordinator must be capable of dynamically managing the TSN flows in a network that also serves non-TSN flows, by processing the high-level requirements and translating them into proper configuration towards the NGCO devices.	**High**

• **Multi-technology interoperability** The SDN coordinator must be able to operate with the different domains available in the NGCO, i.e. the non-TSN domains (OCS devices) and the TSN domains (the CNC Controller). In the latter case, the proper specification must be used.	**High**
• **NGCO performance monitoring** The SDN Coordinator must be capable of collecting (where available) the metrics related to the NGCO, towards checking the status of the TSN flows.	**High**
• **SDN Coordinator usability** The SDN Coordinator should provide an easy way for a user (typically a network administrator) to manage the control plane management of the NGCO. This could include OpenAPI and other interface specifications, user interface etc.	**Low**

In general, the role played by the SDN Coordinator is fundamental for what concerns satisfying high-level QoS service requirements. In the case of OCTAPUS, the flexibility provided by the SDN Coordinator must guarantee the seamless update of the control plane within the NGCO.

In the next Section, we identify the services/applications to be supported by OCTAPUS in a representative urban area, the corresponding geographical area of study and the expected traffic density associated with these services. To this end, the NGCO control plane must be continuously monitored and supervised by the SDN Coordinator so that up-to-date information on active service status is always available and their traffic demands to ensure that all QoS requirements are met.

5.4 Usage Scenario

In this section, we quantitatively elaborate on the previous Use Cases (UC), and present a provisioning example of OCTAPUS aiming to provide a suitable and SDN-controllable NGCO-based infrastructure capable of efficiently supporting the telecom demands of all potential stakeholders (subscribers/individuals, tenants/verticals, infrastructure owners, etc.) under ultra-high traffic demands in a specific geographical area, while adhering to the strict performance QoS requirements (e.g., bit-rates, latency, reliability, etc.) of the 5G/6G services that are concurrently utilized or expected to be deployed in the near future. These strict QoS requirements are first translated and then processed by the SDN Coordinator, resulting in a seamless mapping into control and management plane actions within the OCTAPUS NGCO towards satisfying the different traffic demands. Moreover, all traffic flows within the NGCO are continuously monitored and analyzed: the main aim is to keep the same level of required QoS during the service's lifespan, preventing, when possible, traffic congestion and, thus, service degradation.

Specifically, a synthetic group of multiple services expected to be offered within a dense urban area, along with 3 different usage scenarios representing the typical spatio-temporal fluctuations of traffic demands, will be investigated. To avoid the inconsistencies or ambiguities found in the literature (regarding definitions of areas/services, subscriber/traffic densities etc.), we have selected an actual geographical area, consisting of Paris districts ("arrondissements") 14, 15, with known population/subscriber density, coverage area etc., allowing for a concrete study on the basis of specific and realistic usage scenarios. The overall applied methodology is summarized below:

1. Identification of the services/applications (or broader categories, for future applications which have not established themselves yet), along with their QoS requirements, to be supported in the area under study. To this end, the service categories that have been described in Sections 5.1, 5.2. of the current Deliverable will be taken into account.
2. Selection of a dense urban geographical area which not only exhibits high population/subscriber (comparable to the population currently served by a small group of COs) and/or (IoT) devices densities, but also includes touristic locations, hotspots (e.g., malls, stadiums), open areas/parks etc.

3. Calculation of the traffic density for a range of scenarios/events, distinguishing between low/high daily traffic profiles, busy/rush/idle hours etc., while accounting for the number of potential subscribers/devices and the usage of concurrent 5G services.
4. Design and provisioning of the OCTAPUS-based NGCO solution to address the needs of this specific area, taking into account the QoS requirements for the specific scenario/events as well as area characteristics, such as mobility degree (e.g., number of highways, etc.), average distance between small cells, number of incumbent MNOs etc.

5.4.1 Area and traffic definitions and assumptions

A typical European urban area in the city of Paris has been selected, consisting of Paris districts ("arrondissements") 14, 15 as shown in the map of Fig. 5.7, exhibiting different subscriber densities and service usage, both under normal conditions and on specific events basis. The area under study includes both residential and business/industrial premises and is a highly touristic area (the Eiffel tower being on the outskirts of district 15), while also including large open spaces (e.g., multiple parks) and being interconnected through a dense transportation network utilized by millions of cars daily (a main road axis in district 15, where commuters move to and from the area, is clearly evident in Fig. 5.7 in a diagonal direction from SW to NE). The area is also amenable to hosting extended smart city services, including smart lighting, smart (electrical) grid, environmental monitoring (e.g., pollution, fire), surveillance security cameras etc.

The selected area covers 14.123 km^2 and contains a population of 366,112 [72], [73] as summarized in Table 11. Since OCTAPUS targets an ultra-high capacity, low-latency, energy–efficient NGCO solution, particularly for dense urban areas, the selected region is considered ideal for the OCTAPUS usage scenarios to be investigated below. We also assume the presence of 4 incumbent MNOs in this area.

Table 11: Demographics of area under study.

Arrondissement	Population	Area (km2)	Population density (people/km^2)	Number of mobile telephony antennas [74]
14	134,926	5.621	24,003.91	730
15	231,186	8.502	27,191.95	1125

We consider the following concrete usage scenarios, each of them generating different amounts of traffic densities:

- Everyday traffic during rush hour (US1): Normal usage of 5G/6G services at high mobility conditions (rush hour) e.g., 8-9 am, when people typically commute to their work locations.
- Everyday traffic during busy hour (US2): High usage of 5G/6G services during or after working hours (e.g., 12 am -1 pm, and 7-8 pm, respectively).
- Everyday traffic during night hours (US3): Low usage of 5G/6G services during night hours (e.g., 2-5 am), when most people are asleep at home.

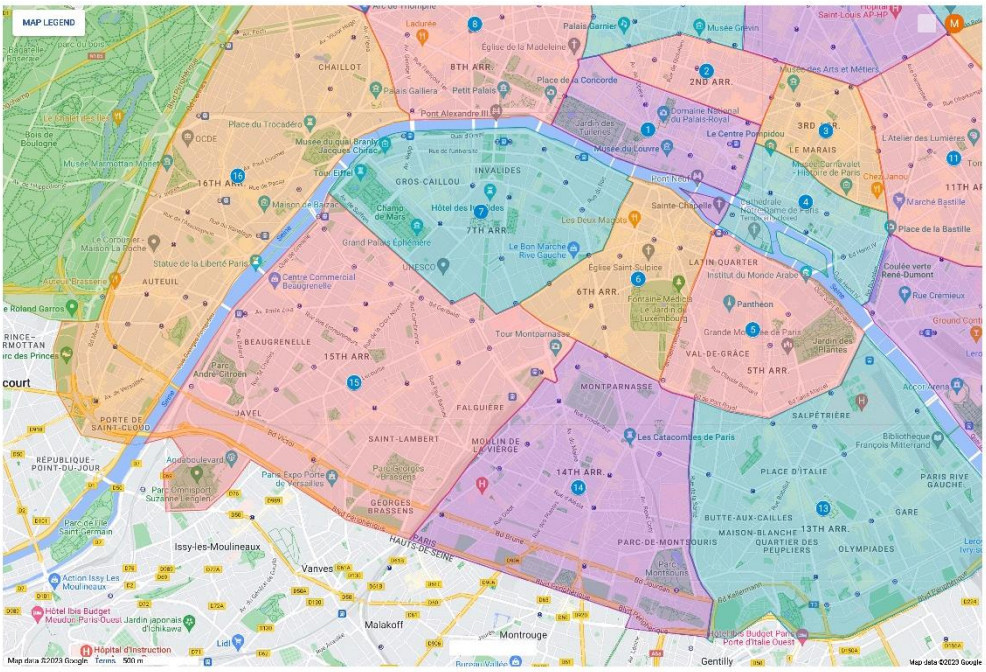


Fig. 5.7: The Paris area under study: arrondissements 14, 15.

Obviously, the above Usage Scenarios (USs) are characterized by a different mix of people commuting, working or staying at home due to typical spatio-temporal variations of human activities. We have made the following assumptions in the calculation of the area traffic demands:

- As this is also a business area with a dense road network, there are commuters to and from the area resulting to a 10% increase of the population during the rush and busy hours (but not at night times).
- The percentage of fixed or wireless service subscribers in the population is assumed to be 75% and 4 operators are assumed to operate within this area.
- During rush hour (US1), we assume 20% of the population is at home, 30% at offices/work buildings and the remaining 50% is commuting, some of them in vehicles. The respective values for busy hour (US2) are 20%/70%/10%, while at night hours the population decomposition, respectively, becomes 92%/3%/5%.
- Smart city and massive IoT services cover only 25% of the area, where IoT/sensor density is 1 device per m^2 of covered area (i.e., 20% of the overall area). For the area under study, this corresponds to 2,824,600 fixed location IoT devices. We additionally assume 0.75 devices carried per subscriber (e.g., various wearables such as smart/sports watches, activity trackers, health monitoring devices etc.).
- The "Indoor hotspot" scenario (to appear below) refers to service subscribers at businesses/offices, while the various 3G/4G services and broadcast-like services refer to all subscribers.
- It is assumed that 75% percent of the mobile subscribers are served by eNodeB/gNodeB/Small Cells with a backhaul connection to the core, while the remaining 25% are served by RUs with fronthaul connections to BBUs. Considering the existing densification trends in urban areas, the RU radio range is assumed to be 100 m. The assumption that 25% of the area is covered by RUs implies that 0.25*14.123= 3.53 km^2 are served by RUs which, for an RU coverage of 100 m, leads to a total of 113 fronthaul RU flows within the area of study.

The above assumptions are summarized in Table 12. Although some of these values have been derived from general estimates, either in the literature (e.g., [75] for the percentage of commuting population, assumed to be in the age interval 6-64 years old) or from specific 5G KPIs (e.g., the 5G IoT device density KPI of 10^6 devices/km^2 corresponds to 1 device/m^2), the proposed methodology is general enough that the assumed values can be tailored to each specific area considered, if supporting data is available.

Table 12: Population, location characterization and mobility assumptions for the different Usage Scenarios.

	US1 *Rush hour*	*US2* *Busy hour*	*US3* *Night hour*
% added population (e.g., in transit through area)	*10%*	*10%*	*0%*
Actual present population in rush/busy/night hours	402,722	402,722	366,111
% population commuting (mobility)	*50%*	*10%*	*5%*
Actual population commuting (mobility)	201,361	40,272	18,306
% population at home	*20%*	*20%*	*92%*
Actual population at home	80,544	80,544	336,822
% population at offices/ businesses	*30%*	*70%*	*3%*
Actual population at offices/ businesses	120,817	281,905	10,983

5.4.2 Targeted services to be offered

From the previous description of the Usage Scenarios, it is evident that the demands can range from very high (busy hours) to low (night hours). Furthermore, the need for specific services as well as mobility aspects can be quite diverse at different hours of the same day. Indicatively, some targeted services are mentioned below:

Legacy services:

- This includes standard voice calls and non-demanding data services (e.g., push notifications) whose service requirements can be met by legacy 4G networks.
- Broadband non-time-sensitive data services (e.g., email, web browsing, non-VR/AR gaming, videoconferencing etc.) for everyday business requirements.
- Location-based services, e.g., offering retail shop/restaurant recommendations based on location and user profile along with relevant directions, notifying on the number of people waiting in queues and estimated waiting time.

High capacity eMBB services:

- Uploading/streaming of UHD videos (e.g. YouTube), uploading photos by residents/ commuters in their private clouds and/or social media, video-conferencing etc.
- Smart services from verticals that require UHD streaming, VR/AR applications based on accurate user location estimation. For example, a mall owner could offer smart retail recommendations based on potential customer's location and personal profile so that an AR application could then display the personalized offers, e.g. displaying the shop itself, discount, distance to shop etc.
- Broadcast-like services, offering a number of TV channels.

mMTC services:

- Massive IoT services may include monitoring & control sensors (such as heating/cooling/presence sensors, fire detectors, control of security devices, etc.) in buildings.
- Other smart city services (e.g. smart lighting).

URLLC services:

- Smart (electrical) grid services, related to power generation/distribution, fault identification and management, dynamic (electrical) load balancing.

- Advanced healthcare services, including remote medical appointments, smart ambulances (e.g., with networked medical scanning equipment which can directly send the results to the hospital in case of emergency, or connect to proper databases to retrieve the patient's medical record) and remote surgery.
- Intelligent transportation, related to all V2X services, in addition to real time accident/road congestion updates.
- Autonomous vehicle navigation (i.e., self-driving cars) and UAVs (e.g., used by retailers or for monitoring urban construction or waste management).
- High Definition (HD) monitoring services, e.g., security cameras.
- Dedicated emergency communications (typically at the city level), ensuring access for security staff and first responders in case of an incident (e.g. fire/ terrorist attack).

X-haul services:

- Fronthaul transport for the BBU-RU connections (typically, via CPRI/eCPRI) is the most challenging X-haul case with the most stringent throughput and latency KPIs. Of course, all of the services previously mentioned in the list (i.e., legacy, eMBB, mMTC, URRLC) can be transported over fronthaul and according to the RU coverage assumptions described in Section 5.4.1, 25% of the traffic generated by the above services **is assumed to be transported** over fronthaul, with the remaining 75% being transported over traditional backhaul connections. The reason we mention fronthaul service separately from the previous services is that fronthaul traffic, particularly for CPRI- and low-functional-split eCPRI-based fronthaul, **is load-independent and characterized as Constant Bit Rate (CBR)**, with much higher throughput requirements than the actual end-user service (e.g., eMBB, URLLC etc.) transported over fronthaul. Hence, this type of fronthaul service constitutes an "inelastic" component of the total throughput requirements placed on the OCTAPUS NGCO and, for this reason, will appear as a separate term in the traffic estimation of the subsequent Use Cases (and, similarly, as a separate entry in Tables 16-18) to describe the amount of CBR traffic served in total by the RUs.

Enhanced Fiber Broadband:

- Ultra-high capacity (i.e., 25 Gbps) PON-based access allowing for telework, tele-education.

We next provide the aggregate traffic estimations for each of the three Usage Scenarios.

5.4.3 US #1: Everyday Rush hour

Based on the assumptions in Section 5.4.1, the population in the area under investigation (districts 14, 15) is estimated at 366,111. Assuming a normal day, the population may vary taking into account the commuters moving to and from the area, people passing through the main roads especially in the case of rush hour traffic jams and maybe remaining for long periods of time within the area. Fig. 5.8 shows the main roads of the area (~10.5 Km), focusing on district 15 (which has a larger road network compared to district 14) where a large number of commuters can be found during rush hour.

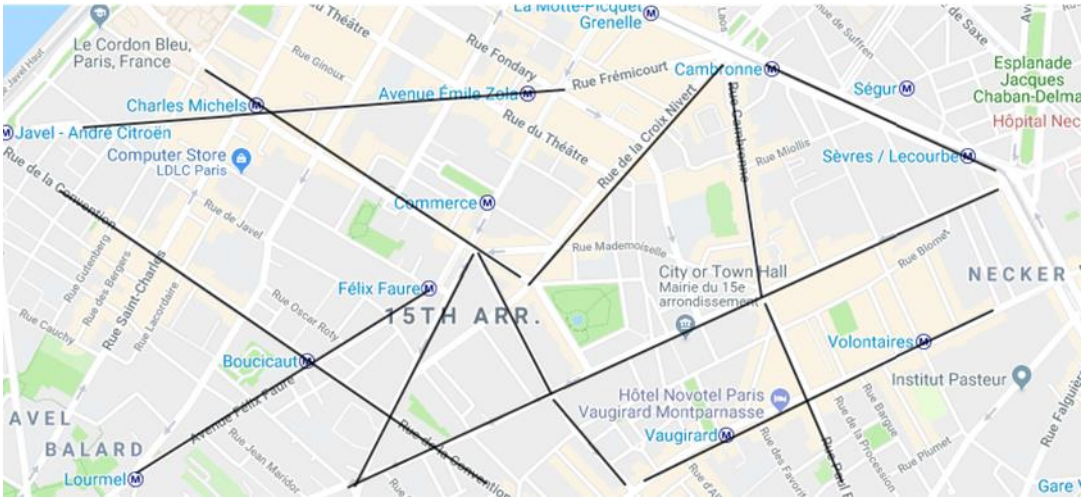


Fig. 5.8: Main roads of Paris arrondissement 15.

The assumptions made in Section 5.4.1 regarding subscriber base (as percentage of population), percentage of additional people in transit through the area and the percentages of people at home/work and/or commuting produce the results shown in Table 13.

Table 13: US1 General Assumptions: Everyday Rush Hour Scenario.

US1 - General Assumptions	
Area Characteristics	Total area: ~14.123Km^2 % of area for Smart City: 25% Subscriber percentage in population: 75%
Subscriber's/ population/ device statistics	Population (including persons in transit): 402,722 % people at home: 20% #subscribers at home: 60,408 % people at offices: 30% #subscribers at offices/businesses: 90,613 % people commuting: 50% #subscribers commuting: 151,021 # IoT devices (fixed and also carried by subscribers): 3,757,282

5.4.4 US #2: Everyday Busy hour

For the area under investigation, during busy hours we expect a low number of commuters and vehicle traffic, with the vast majority of the population being at work and mainly at indoor locations. As the percentages of people at home/work and/or commuting are different than during the morning Rush hour, the number of subscribers within each group are listed in Table 14.

Table 14: US1 General Assumptions: Everyday Busy Hour Scenario.

US2 - General Assumptions	
Area Characteristics	Total area: ~14.123km^2 % of area for Smart City: 25% Subscriber percentage in population: 75%
Subscriber's/ population/ device statistics	Population (including persons in transit): 402,722 % people at home: 20%

	#subscribers at home: 60,408 % people at offices: 70% #subscribers at offices/businesses: 211,429 % people commuting: 10% #subscribers commuting: 30,204 # IoT devices (fixed and also carried by subscribers): 3,757,282

5.4.5 US #3: Everyday Night Hour

During night hours, very low usage and vehicle traffic is expected, since most businesses are closed at that time (and the ones operating typically have modest traffic demands), and most people are at home (and, most likely, asleep). Similarly, as there are very few non-residents in transit though the area under study, we make the simplifying assumption that only the resident population of the area under study should be considered for estimating the traffic demands. Table 15 contains the percentages and amounts of people at home/work and/or commuting in this Usage Scenario.

Table 15: US1 General Assumptions: Everyday Night Hour Scenario.

US3 - General Assumptions	
Area Characteristics	Total area: ~14.123Km^2 % of area for Smart City: 25% Subscriber percentage in population: 75%
Subscriber's/ population/ device statistics	Population (assuming no transit): 366,111 % people at home: 92% #subscribers at home: 252,616 % people at offices: 3% #subscribers at offices/businesses: 8,237 % people commuting: 5% #subscribers commuting: 13,730 # IoT devices (fixed and also carried by subscribers): 3,791,604

5.4.6 Traffic estimations for the Usage Scenarios

Based on the assumptions described in Section 5.4.1 and the subscriber profiles in Sections 5.4.3-5.4.5, the traffic demands of each targeted service are listed in Tables 16, 17, 18, for the Rush, Busy and Night hours, respectively. The user data rates and latency requirements have been collected from the literature, whereas the usage factors (highlighted in yellow), which denote the percentage of subscribers actively using each service, are based on estimates. The proposed methodology is sufficiently general that the fixed/mobile operators can employ it as a general provisioning tool and modify the usage factor values, depending on area and demographics, to determine the expected aggregate traffic in a given area.

A careful examination of Tables 16, 17, 18 provides many interesting observations, as described next:

- The service traffic demands, being largely an outcome of human activities, follows a natural cycle of fluctuation from morning (Rush hour) to Noon (Busy hour) to Night, with corresponding aggregate traffic capacities of 66.178 Tbps, 192.437 Tbps and 8.134 Tbps, respectively.
- Considering a minimum aggregate switching capacity of 51.2 Tbps for a "base" OCTAPUS NGCO, with only 2 Uplink switches, implies that 4 OCTAPUS NGCOs are needed to cover the peak area traffic. This is not an extreme number for such a dense urban area (with a peak subscriber base of 302,041), considering that this area is served by 4 operators, which would split the CAPEX/OPEX costs of the NGCOs. Furthermore, exploiting the inherent scalability of the OCTAPUS NGCO and placing more Uplink switches within it (e.g., 4 Uplink Switches per NGCO instead of 2) decreases the number of required NGCOs accordingly.

- Since the Night hour traffic demand is only ~8 Tbps (assuming, for simplicity, a uniform demand of ~2Tbps for each of the 4 OCTAPUS NGCOs mentioned above), it is possible to route all traffic of each NGCO through a single Uplink switch, which has an aggregate capacity of 25.6 Tbps, and put the other Uplink switch into sleep (or low-power) mode during night-time, thus leading to significant energy savings. Furthermore, exploiting the potential spatial variation of traffic demands at Night time and considering that COs/NGCOs are typically deployed in a ring topology for redundancy reasons, it may even be possible to use the "Express" paths of each OCTAPUS NGCO to completely bypass the energy-consuming Uplink switch and IF card devices (i.e., directly connect the access equipment to the core, CU, DU nodes, depending on the actual connection type), offering even higher energy savings. For example, considering again the base OCTAPUS NGCO with 32 Express paths each offering 50 Gbps of capacity, implies that each OCTAPUS NGCO can still serve 32*50= 1.6 Tbps of traffic in sleep mode. Hence, any NGCO serving up to 1.6 Tbps of traffic during Night time can put all of its Uplink switches and IF cards into sleep mode. This advantage is intensified for scaled-up NGCOs with more Express paths.
- As expected, based on the throughput requirements per service, a minority containing the most throughput-demanding services constitute the bulk of the requested traffic (in this case, the autonomous navigation, enhanced fiber broadband, and the indoor hotspot mobile access service), in a typical illustration of the Pareto principle of economics [76].
- CPRI-based fronthaul, even when employing CPRI's compression features, forms an inelastic Constant-Bit-Rate traffic component, which contributes significantly to the Night hour capacity demands. Migration to the more efficient eCPRI protocol and the employment of higher layer functional splits would significantly reduce this "traffic demand floor" and offer additional options for placing NGCOs into low power state. Although MNOs have already made the first steps in this migration, the prominent status of CPRI in Xhaul transport makes this a long and arduous process.
- Despite the stringent latency requirements of most URLLC applications, which are addressed in OCTAPUS by the TSN-enabled Uplink switches and IF cards (along with the "Express" paths), the aggregate traffic demand of URLLC services is well within the capabilities of the NGCO infrastructure (even when their activity factor is increased beyond the values selected in Tables 16-18), provided that the latency budget is met.
- Finally, although not all of the 6G services and applications have been specified yet (as the first 3GPP study items for 6G are planned for Rel. 20 after 2026), the scalability of the OCTAPUS NGCO suggests that the OCTAPUS solution will be well-prepared to address the upcoming 6G challenges.

Table 16: UC1 Traffic Estimation - Everyday Rush Hour Scenario.

	Provided Services	User Data Rates		Activity factor	Aggregate Traffic Volume			User Latency	Criticality	Indicative services
		DL (Mbps)	UL (Mbps)	% Usage	DL (Gbps)	UL (Gbps)	Total (Gbps)			
3G/4G services	Voice Calls	0.03	0.03	10%	0.91	0.91	1.82	10 ms	Medium	
	Non-critical/Non-demand-ing data services	0.1	0.1	2%	0.60	0.60	1.20	> 50 ms	Low	On-line bidding, contests, IP-messaging, push notifications. etc.
	High Speed Broadband Services	75	25	4%	906.13	302.04	1208.17	2-4ms:50 ms	Medium	Video, email, web surfing (latency of 50ms<), interactive video (2-4ms latency), etc.
mMTC	Massive low-cost/long-range/low-power MTC	0	0.05	60% (of IoT devices)	0.00	112.72	112.72	10 ms – few sec	Medium – High	Personal devices/ non-critical massive IoT, e.g. user device tracking for location based services, massive notifications, promotional messages etc.
eMBB	Dense urban	300	50	2%	1268.57	211.43	1480.00	<50ms	Low	(UHD) video sharing/ streaming, photo sharing, tour videos etc.
	Indoor hotspot	1000	500	10%	9061.28	4530.64	13591.91	2-4ms:50 ms	Medium	Everyday business requirements, cloud storage, video conferencing etc.
	Broadcast like services	200		2	0.4		0.4	< 100 ms	Low	4K/8K video watching
			0.5	2%		3.02	3.02	< 100 ms	Low	
URLLC	Smart grid	2	10	3%	5.44	27.18	32.62	15-140 ms	High	Distributed power generation, fault identification
	Advanced healthcare services	200	20	3%	543.68	54.37	598.04	10 ms	High	Telesurgery, smart ambulances
	Intelligent transportation	100	50	40% (of commuting subscribers)	3624.51	1812.26	5437.77	1-10 ms	Medium-High	Infotainment, real time accident/ congestion updates, V2X
	Autonomous navigation	10	4000	15% (of commuting subscribers)	135.92	54367.65	54503.57	1-20 ms	High	Self-driving cars, UAVs
	Provided Services	**User/Service Data Rates**		**Activity factor**	**Aggregate Traffic Volume**			**Latency**	**Criticality**	**Indicative services**
		DL (Mbps)	**UL (Mbps)**	**% Usage**	**DL (Gbps)**	**UL (Gbps)**	**Total (Gbps)**			

F5G-Advanced	Enhanced Fiber Broadband	500	100	5%	2265.32	453.06	2718.38	< 1 ms	High	Cloud AR/VR (e.g., museum tours), telework, tele-education
	Provided Services	**Service Data Rates**		**Number of flows**	**Aggregate Traffic Volume**			**Latency**	**Criticality**	**Indicative services**
		DL (Mbps)	**UL (Mbps)**		**DL (Gbps)**	**UL (Gbps)**	**Total (Gbps)**			
Xhaul	Frontaul	25000	25000	113	2825.00	2825.00	5650.00	0.1-10 ms	Ultra-high	CPRI rate-10, 25G eCPRI fronthaul
	Slicing Services for Tenants	**Min (Gbps)**	**Max (Gbps)**	**#Tenants**	**Min (Gbps)**	**Max (Gbps)**	**Mean (Gbps)**	**Latency**	**Criticality**	**Indicative services**
eMBB	Slice for Broadcast like services	5	10	4	20	40	30.0	< 100 ms	Medium	TV subscription services
mMTC	Slice for emergency smart city services (e.g. control & management sensors, i.e. minimum of 100000 sensors, 10% activity factor)	1	1	2	2	2	2.0	1 ms – few sec	High	Massive IoT services for smart lighting, management (e.g., fire detectors etc.), and control services (incl. control of security devices, presence sensors), etc.
URLLC	Reserved Slice for Emergency	6	10	4	24	40	32.0	1 ms – few sec	High	Emergency services / first responders communications, 50 surveillance/ security cameras

	DL	**UL**	**Total Average**	**Total Max**
Totals (Gbps)	**16,782.9**	**49,377.2**	**66,128.1**	**66,178.1**
Latency	**0.1 – 100 ms**			

Table 17: UC1 Traffic Estimation - Everyday Busy Hour Scenario.

	Provided Services	User Data Rates		Activity factor	Aggregate Traffic Volume			User Latency	Criticality	Indicative services
		DL (Mbps)	UL (Mbps)	% Usage	DL (Gbps)	UL (Gbps)	Total (Gbps)			
3G/4G services	Voice Calls	0.03	0.03	15%	1.36	1.36	2.72	10 ms	Medium	
	Non-critical/Non-demand-ing data services	0.1	0.1	5%	1.51	1.51	3.02	> 50 ms	Low	On-line bidding, contests, IP-messaging, push notifications etc.
	High Speed Broadband Services	75	25	10%	2265.31	755.10	3020.41	2-4ms:50 ms	Medium	Video, email, web surfing (latency of 50ms<), interactive video (2-4ms latency), etc.
mMTC	Massive low-cost/long-range/low-power MTC	0	0.05	60% (of IoT devices)	0.00	112.72	112.72	10 ms – few sec	Medium – High	Personal devices/ non-critical massive IoT, e.g. user device tracking for location based services, massive notifications, promotional messages etc.
eMBB	Dense urban	300	50	5%	1359.18	226.53	1585.71	<50ms	Low	(UHD) video sharing/ streaming, photo sharing, tour videos etc.
	Indoor hotspot	1000	500	25%	52857.19	26428.59	79285.78	2-4ms:50 ms	Medium	Everyday business requirements, cloud storage, video conferencing etc.
	Broadcast like services	200		3	0.6		0.6	< 100 ms	Low	4K/8K video watching
			0.5	2%		3.02	3.02	< 100 ms	Low	
URLLC	Smart grid	2	10	3%	12.69	63.43	76.11	15-140 ms	High	Distributed power generation, fault identification
	Advanced healthcare services	200	20	5%	2114.29	211.43	2325.72	10 ms	High	Telesurgery, smart ambulances
	Intelligent transportation	100	50	25% (of commuting subscribers)	5285.72	2642.86	7928.58	1-10 ms	Medium-High	Infotainment, real time accident/ congestion updates, V2X
	Autonomous navigation	10	4000	10% (of commuting subscribers)	211.43	84571.50	84782,93	1-20 ms	High	Self-driving cars, UAVs
	Provided Services	**User/Service Data Rates**		**Activity factor**	**Aggregate Traffic Volume**			**Latency**	**Criticality**	**Indicative services**
		DL (Mbps)	**UL (Mbps)**	**% Usage**	**DL (Gbps)**	**UL (Gbps)**	**Total (Gbps)**			

F5G-Advanced	Enhanced Fiber Broadband	500	100	10%	10571.44	2114.29	12685.73	< 1 ms	High	AR/VR, tele-medicine
	Provided Services	**Service Data Rates**		**Number of flows**	**Aggregate Traffic Volume**			**Latency**	**Criticality**	**Indicative services**
		DL (Mbps)	**UL (Mbps)**		**DL (Gbps)**	**UL (Gbps)**	**Total (Gbps)**			
Xhaul	Frontaul	25000	25000	113	2825.00	2825.00	5650.00	0.1-10 ms	Ultra-high	CPRI rate-10, 25G eCPRI fronthaul
	Slicing Services for Tenants	**Min (Gbps)**	**Max (Gbps)**	**#Tenants**	**Min (Gbps)**	**Max (Gbps)**	**Mean (Gbps)**	**Latency**	**Criticality**	**Indicative services**
eMBB	Slice for Broadcast like services	5	10	4	20	40	30.0	< 100 ms	Medium	TV subscription services
mMTC	Slice for emergency smart city services (e.g. control & management sensors, i.e. minimum of 100000 sensors, 10% activity factor)	1	1	2	2	2	2.0	1 ms – few sec	High	Massive IoT services for smart lighting, management (e.g., fire detectors etc.), and control services (incl. control of security devices, presence sensors), etc.
URLLC	Reserved Slice for Emergency	6	10	4	24	40	32.0	1 ms – few sec	High	Emergency services / first responders communications, 50 surveillance/ security cameras

	DL	**UL**	**Total Average**	**Total Max**
Totals (Gbps)	**75,709.6**	**116,709.6**	**192,387.2**	**192,437.2**
Latency	**0.1 – 100 ms**			

Table 18: UC1 Traffic Estimation - Everyday Night Hour Scenario.

	Provided Services	User Data Rates		Activity factor	Aggregate Traffic Volume			User Latency	Criticality	Indicative services
		DL (Mbps)	UL (Mbps)	% Usage	DL (Gbps)	UL (Gbps)	Total (Gbps)			
3G/4G services	Voice Calls	0.03	0.03	1%	0.08	0.08	0.16	10 ms	Medium	
	Non-critical/Non-demand-ing data services	0.1	0.1	2%	0.55	0.55	1.10	> 50 ms	Low	On-line bidding, contests, IP-messaging, push notifications. Etc.
	High Speed Broadband Services	75	25	2%	411.87	137.29	549.17	2-4ms:50 ms	Medium	Video, email, web surfing (latency of 50ms<), interactive video (2-4ms latency), etc.
mMTC	Massive low-cost/long-range/low-power MTC	0	0.05	60% (of IoT devices)	0.00	112.10	112.10	10 ms – few sec	Medium – High	Personal devices/ non-critical massive IoT, e.g. user device tracking for location based services, massive notifications, promotional messages etc.
eMBB	Dense urban	300	50	1%	799.04	133.17	932.21	<50ms	Low	(UHD) video sharing/ streaming, photo sharing, tour videos etc.
	Indoor hotspot	1000	500	0.5%	41.19	20.59	61.78	2-4ms:50 ms	Medium	Everyday business requirements, cloud storage, video conferencing etc.
	Broadcast like services	200		1	0.2		0.2	< 100 ms	Low	4K/8K video watching
			0.5	1%		1.37	1.37	< 100 ms	Low	
URLLC	Smart grid	2	10	3%	0.49	2.47	2.97	15-140 ms	High	Distributed power generation, fault identification
	Advanced healthcare services	200	20	1%	16.47	1.65	18.12	10 ms	High	Telesurgery, smart ambulances
	Intelligent transportation	100	50	2% (of commuting subscribers)	16.47	8.24	24.71	1-10 ms	Medium-High	Infotainment, real time accident/congestion updates, V2X
	Autonomous navigation	10	4000	2% (of commuting subscribers)	1.65	658.98	660.63	1-20 ms	High	Self-driving cars, UAVs
	Provided Services	User/Service Data Rates		Activity factor	Aggregate Traffic Volume			Latency	Criticality	Indicative services
		DL (Mbps)	UL (Mbps)	% Usage	DL (Gbps)	UL (Gbps)	Total (Gbps)			

F5G-Advanced	Enhanced Fiber Broadband	500	100	2%	82.37	16.47	98.85	< 1 ms	High	AR/VR, tele-medicine
	Provided Services	**Service Data Rates**		**Number of flows**	**Aggregate Traffic Volume**			**Latency**	**Criticality**	**Indicative services**
		DL (Mbps)	**UL (Mbps)**		**DL (Gbps)**	**UL (Gbps)**	**Total (Gbps)**			
Xhaul	Frontaul	25000	25000	113	2825.00	2825.00	5650.00	0.1-10 ms	Ultra-high	CPRI rate-10, 25G eCPRI fronthaul
	Slicing Services for Tenants	**Min (Gbps)**	**Max (Gbps)**	**#Tenants**	**Min (Gbps)**	**Max (Gbps)**	**Mean (Gbps)**	**Latency**	**Criticality**	**Indicative services**
eMBB	Slice for Broadcast like services	5	10	4	20	40	30.0	< 100 ms	Medium	TV subscription services
mMTC	Slice for emergency smart city services (e.g. control & management sensors, i.e. minimum of 100000 sensors, 10% activity factor)	1	1	2	2	2	2.0	1 ms – few sec	High	Massive IoT services for smart lighting, management (e.g., fire detectors etc.), and control services (incl. control of security devices, presence sensors), etc.
URLLC	Reserved Slice for Emergency	6	10	4	24	40	32.0	1 ms – few sec	High	Emergency services / first responders communications, 50 surveillance/ security cameras

	DL	**UL**	**Total Average**	**Total Max**
Totals (Gbps)	**4,194.0**	**3,922.1**	**8,084.1**	**8,134.1**
Latency	**0.1 – 100 ms**			

6 OCTAPUS Network Architecture

The general OCTAPUS network architecture addressing the dense area Use Case and relative usage scenarios and associated services/applications, as described in Chapter 5, entails the deployment of an optical network infrastructure compatible with existing 10G/25G PON infrastructure (and the upcoming 50G PON standard) and capable of transporting multiple types of X-haul traffic and TSN flows, with diverse QoS requirements, under an SDN-based multi-domain coordinator. Fig. 6.1, which shows the basic OCTAPUS NGCO with two Uplink switches, illustrates the flexible connectivity options offered by OCTAPUS for both fixed and mobile service subscribers, aiming to maximize the exploitation of already deployed infrastructure in urban areas. Solid lines in Fig. 6.1 denote actual fiber links, whereas dotted lines are used to represent the actual E2E paths of the user plane traffic from the cloud and/or the MNO mobile core network all the way to the Base Station antenna and/or the fixed subscribers; the different colors in Fig. 6.1 are only used to visually distinguish among the different paths.

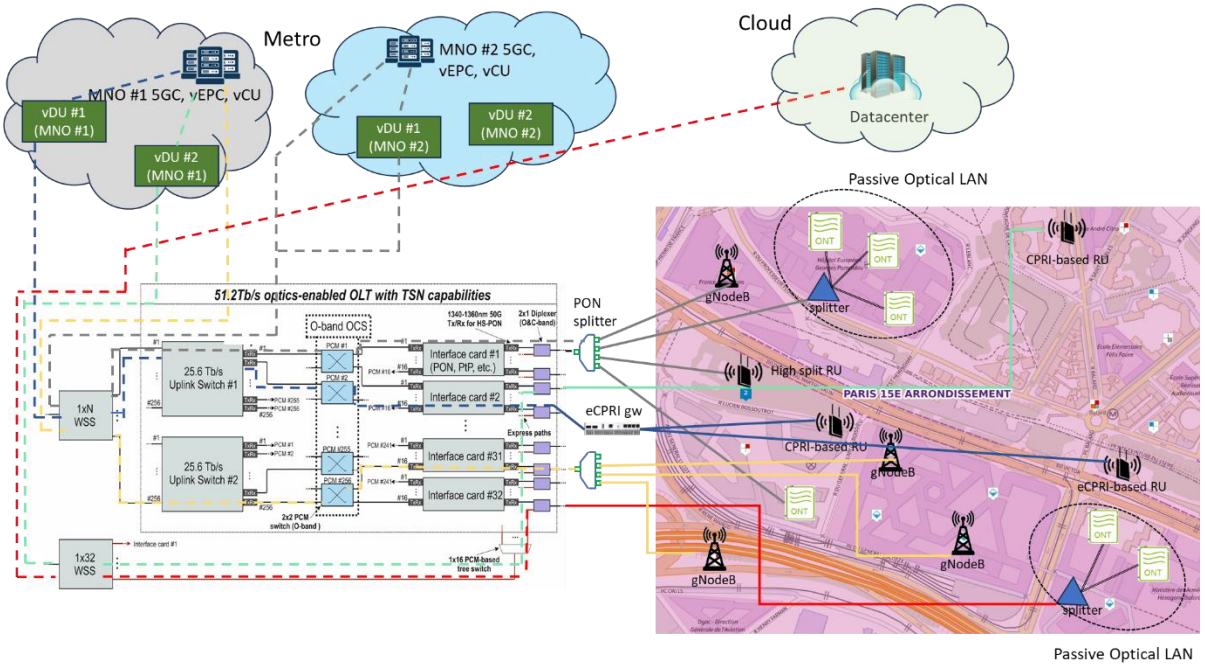


Fig. 6.1: Representative urban area OCTAPUS network architecture.

The positions of Base Stations (e.g., eNodeBs, gNodeBs, RUs) in Fig. 6.1 reflect the actual antenna sites in Paris arrondissement 15 (this information being publicly available [76]) studied in Chapter 5 and two major installations with very high traffic demands are also identified, namely a large hospital and a governmental building hosting a ministry's offices and personnel (enclosed in the upper left and lower right ovals, respectively, in Fig. 6.1). Especially for these two large installations, the deployment of Passive Optical LANs (POL), as described in Section 5.1.3, is a very attractive option, which is already under consideration [76] and steadily gaining ground due to its increased network management efficiency. In this case, OCTAPUS will provide ultra-high-speed (up to 50G) PON access all the way up to the optical splitter installed at the local premises (i.e., hospital, ministry), or, in cases of URLLC services with very tight latency requirements (e.g., close to 1ms), OCTAPUS may even statically allocate/reserve an Express path (shown in red in Fig. 6.1) for the installation.

Regarding X-haul mobile transport, depending on the actual traffic requirements, which are in turn determined by the actual physical split (low vs high) and Base Station operational parameters (e.g., supported bandwidth, MIMO capabilities, etc.), OCTAPUS may be provisioned by the operators to offer the following types of X-haul connections:

- X-haul access to gNodeBs and high-functional-split RUs via PON (yellow and gray lines, respectively, in Fig. 6.1).
- X-haul access to CPRI-based RUs either via PtP links through the NGCO's Express paths or via eCPRI gateways, as described in Section 4.5 (blue lines in Fig. 6.1).

- X-haul access to native eCPRI-based RUs (via eCPRI gateways) when they become commonplace (blue line in Fig. 6.1).
- a dedicated IF card connecting to a single RU for throughput-demanding 25G CPRI-based fronthaul (light green line in Fig. 6.1).
- direct connectivity between RUs and DUs/CUs by bypassing the OCTAPUS switch (light green line in Fig. 6.1).

Since X-haul flows traverse the CU-DU-RU segments, depending on the latency requirements of the X-haul flows, the CU, DU units may be placed closer or further away from the NGCO i.e., either collocated with the NGCO (not shown in Fig. 6.1 but available as a deployment option) or in the metro network in the form of vDUs (to exploit economies of scale) or even further away in the cloud (mostly for core and/or vCU) to exploit the cloud's massive processing capabilities.

In principle, the ultra-high capacity and scalability of the OCTAPUS NGCO infrastructure open the possibility of sharing the NGCO among multiple MNOs (shown in Fig. 6.1 for 2 MNOs), provided it is to their mutual advantage. The latter would be determined through careful network provisioning and CAPEX/OPEX analysis on the part of each MNO. At the same time, many non-technical aspects would also affect this decision, such as business considerations (e.g., amount of dark fiber in case new fiber connections are necessary, how OPEX should be split among the MNOs, how charging should be performed based on proper monitoring etc.), policy regulations (especially regarding data privacy and protection) and the MNO's market shares. For this reason, and considering that consolidating existing NGCOs is a time-consuming process with a high CAPEX, we envision that the possibility of NGCO sharing among MNOs will typically be considered in green-field deployments or in highly-populated areas which promise increased revenues due to the new services enabled by the OCTAPUS NGCO.

Regarding the control plane (not shown in Fig. 6.1; please refer to Section 3.3 and accompanying Fig. therein for a high level description of the main SDN and TSN control plane blocks), the SDN Coordinator's main aim is to automate the NGCO's programmability, monitoring, and management features. The set of control plane actions and the data collected from the monitoring probes allow the SDN Coordinator to construct a congestion-aware control plane for provisioning (e.g., slicing) and balancing the different (TSN) traffic flows within the NGCO itself.

In Deliverable D2.2 "Initial modelling of system architecture, component/controller specifications and assembly process flow definition", an initial elaboration of the system architecture including the SDN Coordinator functional architecture will be provided, also underlining the details related to the interaction between the SDN Coordinator and the different NGCO components.

7 Summary and Conclusions

With the continuing rise in fixed and mobile traffic demands and the rapid emergence of Machine-to-Machine communications and new latency-oriented mobile X-haul and URLLC services, the next generation (i.e., beyond 5G and 6G) of fixed and mobile networks is hard pressed to deliver advanced services with very strict capacity and latency requirements, thus calling for radical architectural changes at the CO infrastructure. To address these challenges towards building the future NGCO, OCTAPUS proposes an SDN-controlled, low-power and ultra-high-capacity all-optical backplane within the NGCO, offering unprecedented flexibility and ultra-fast reconfigurability for dynamic bandwidth steering, as well as a novel optical/electronic transceiver portfolio (enhanced by low-loss diplexers/interposers) and an advanced TSN engine offering deterministic delay guarantees and flow prioritization.

Initially, this document presents the OCTAPUS scope, objectives, and innovations, as well as the technological advancements that the project builds on. The current status of the fixed and mobile access ecosystem is also described, and an overview of the 5G and Beyond services and their respective requirements is provided. The document then elaborates on the use cases for which OCTAPUS provides suitable network solutions, capable of efficiently supporting the telecom demands of all potential stakeholders (subscribers/individuals, tenants/verticals, service providers, infrastructure owners, etc.) under ultra-high traffic scenarios with multiple concurrent service types in typical dense urban areas. It also presents a high-level view of the OCTAPUS architecture necessary to support the above services and provides a list of KPIs against which the OCTAPUS solution will be evaluated.

A “synthetic” use case has been identified and described based on an actual geographical area (i.e., Paris arrondissements 14, 15), where representative service scenarios must be supported. The presented assumptions and methodology are general enough to capture the stakeholders and any intrinsic traffic demand fluctuations due to human activities, while providing the system/technical requirements (related to the overall network performance and capabilities) to be satisfied by the OCTAPUS solution.

The information contained in this deliverable will be utilized by all other work packages and especially from those dealing with the development and the evaluation of the OCTAPUS solution(s). D2.3, which is a continuation of this deliverable (due M24), will provide updated information, if needed, on the topics having been dealt with in D2.1, while focusing on the final component/subsystem specifications and KPIs (list, definition, parameters, target values).

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