SEASON

Self-Managed Sustainable High-Capacity Optical Networks

This project is supported by the SNS Joint Undertaken through the European Union's Horizon RIA research and innovation programme under grant agreement No. 101096120

Deliverable D2.1

Definition of Use Cases, Requirements and Reference Network Architecture

Editor TID & TIM

Contributors CNIT, CTTC, ADVA, TID, UC3M, HHI, TIM, UPC, INF-P, INF-G, WEST, ACC, WIN, ERI

Version 2.1

Date March 1st, 2024

Distribution Public

DISCLAIMER

Revision	***Date***	***Responsible***	***Comment***
1.0	*February, 19, 2023*	*Emilio Riccardi*	*Final draft*
2.0	*February, 28, 2024*	*João Pedro, Filippo Cugini*	*Revision*
2.1	*March, 01, 2024*	*Marco Quagliotti, Cátia Pinho, Emilio Riccardi*	*Final quality checked version*

LIST OF AUTHORS

Partner	*Name Surname*
CNIT	*Filippo Cugini*
TIM	*Emilio Riccardi*
TIM	*Marco Quagliotti*
TIM	*Laura Serra*
TIM	*Anna Chiadò Piat*
TIM	*Mauro Agus*
TIM	*Alberto Rossaro*
INF-P	*João Pedro*
INF-P	*Nelson Costa*
INF-P	*Cátia Pinho*
INF-P	*Andre Nunes De Souza*
TID	*José Manuel Rivas Moscoso*
TID	*Francisco Javier Lopez Santoalla*
TID	*Antonio Melgar Gonzales*
TID	*Óscar González de Dios*
UC3M	*José Alberto Hernández*
UC3M	*David Larrabeiti*
UC3M	*Alfonso Sánchez-Macián*
CTTC	*Ramon Casellas*
CTTC	*Laia Nadal*
CTTC	*Ricardo Martínez*

WEST	*Cristian Antonelli*
WEST	*Stefano Tennina*
WEST	*Andrea Marotta*
WEST	*Carlo Centofanti*
WINGS	*Sokratis Barmpounakis*
WINGS	*Vasilis Tsekenis*
WINGS	*Marios Lagos*
ADVA	*Vignesh Karunakaran*
ADVA	*Achim Autenrieth*
ERI	*Roberto Magri*
ERI	*Gianluca Gambari*
UPC	*Luis Velasco*
UPC	*Marc Ruiz*
UPC	*Jaume Comellas*
UPC	*Sima Barzegar*
UPC	*Josep Prat*
UPC	*Sadegh Ghasrizadeh*
INF-G	*Antonio Napoli*
INF-G	*Carlos Castro*
ACC	*Geert Dooms*
ACC	*Revaz Berozashvili*
HHI	*Caio Santos*

EXECUTIVE SUMMARY

This document constitutes the first deliverable of WP2 of the SEASON project dedicated to use cases, requirements and network architecture.

The document provides as a premise a description of the state of the art of the networks and the technologies used in them, in general and with examples from the two operators participating on the project, TIM and Telefónica. Any evolution towards new network solutions must necessarily start from state of art (e.g., available fiber or other aspects of infrastructural legacy such as the ownership of cabinets, towers and local exchanges). Specific focuses are made on network architectures and topologies, on the cloud and virtualization infrastructure, on discussion about available, deployed and planned 5G Releases and on the current frequency assignment for the radio access for both mobile and fixed wireless access (FWA) services.

An important part of the document is dedicated to the use cases and other drivers to be considered for the solutions proposed by the SEASON project. The document reports an in-depth analysis on emerging use cases starting from various sources such as international institutions and fora (e.g., ITU.-T, GGSM) or European projects (Hexa-X) and envisions the scenario of metaverse as a complete and immersive environment, in which communication, transactions, and experiences take place pervasively and simultaneously. Detailed analyzes of three use cases of the metaverse are presented, tactile internet for telesurgery (Industrial Metaverse), professional e-learning (Enterprise Metaverse), and virtual tourism (Consumer Metaverse). Thinking about the path from today to an intermediate phase, to finally reach the mature phase when Metaverse will express its full potential, the requirements in terms of latency and data rate for these three services were extracted from an extensive selection of sources. The values of these parameters are not aligned in the available sources. For instance, latency required for telesurgery is today of the order of 20 ms (but with successful examples with more or even much more than this value), in the medium term the value is expected to drop at 5 ms while in the long term sub-millisecond latency (0.5 ms, for make possible highly dynamic haptic) will probably considered the standard for this use case. Data rate for telesurgery are today of the order of 200 Mbit/s; in medium term this value is expected to grow up to 1.5 Gb/s (more streams at higher resolution) while in the long term 6 Gb/s will be required (to support extended reality). The other drivers for the SEASON solutions considered are the expected traffic growth, the reuse of the existing fiber as an available and low-cost asset that influences the solutions to be introduced and the aspects linked to the RAN, which involve both technology (split options adopted, open architecture such as O-RAN) and radio frequencies assigned and used for the radio access (reuse/refarming of available bands and addition of new ones).

The main result with the greatest impact on the project contained in this document is the reference architecture. The high-level framework defined provides a segmentation of the network into just two domains, Access-Metro (considered and optimized as a whole) and Backbone. Telco and service functions can be placed at three levels of decentralization (Cloud in the backbone, Edge, and Far Edge in the Access-Metro) which also correspond to three classes of Central Office (CO). The most peripheral type of CO is conceived to accommodate the Far Edge functions and is expected to be of low cost and low power consumption (mini containers or reinforced cabinets are possible practical implementations). They could replace all or part of the current aggregation or access legacy COs allowing considerable savings.

Two reference periods are defined for the architecture and the solutions to be implemented in the project, the medium term, thought of 4 years from now (the late twenties) and the long term, 8 years from now, therefore beyond 2030. There are good reasons for this choice that are reported in the document. General characteristics and requirements are listed and argued for the reference architecture in the two periods. Not all of them are listed for brevity's sake, but for example the expected traffic growth in comparison to current one is x5 for the medium term and of x10, and even up to x30, for the long term. Regarding mobile technology, however, is assumed that in the medium term the system deployed will be 5G-Advanced (3GPP Rel. 18 or 19) while in the long term it will be 6G (Rel. 20 or later). Furthermore, as regards the use of fiber and related multiplexing and transmission techniques, in the medium term a limited use of new fibers, few bands (C+L with at most one additional band) and multi-fiber as basic SDM technique is expected. In the long term, technologies will have to consider the use of new type of fiber (multi-core, hollow-core) with the exploitation of all bands and SDM extended to fiber or core switching. Taking into account everything that has been listed, the diagrams of the two medium and long term architectures are provided with the main characteristic data, i.e., typical distances in the domains, data rates at the interfaces at the various network levels, probable positioning of the telco functions for the data plane (e.g., UPF, BNG) and more. The architectural solutions of the project will be developed and mapped on these architectures and the technical-economic studies will have these drawings as a starting point.

The part of the document dedicated to the SEASON architecture also includes an exhaustive list of the technologies and solutions that the SEASON project is developing in the other WPs, in particular the systems for the data plane (switching and transmission) being defined and developed in WP3, and the control, monitoring and orchestration systems, subject of WP4. One example of this part of the document is the definition of a preliminary architecture of a multi-fiber and multi-band node, suitable for the backbone given the capacity beyond Pb/s that it can provide, currently being defined in the joint working group of WP2 and WP3. More details on the architecture and the design criteria for this node are reported in D3.1.

In general, it should be noted that this deliverable is quite agnostic in relation to the actual technological solutions that could be adopted. Detailed SEASON system and design solutions both at data and control plane are developed in WP3 and WP4.

To make network studies possible on realistic cases, the consortium operators have made available some representative topologies (appropriately modified and anonymized for confidential reasons). These topologies cover the metro and backbone segments and are inspired to their networks in field. Essentially, the physical layout (fiber connectivity between nodes) is provided but indications are also given on how the packet network is organised. In addition, for the modelling of access areas, for which real data are not available, a model based on four representative geotypes is provided (a geotype is an area characterized by high or medium or low urbanization/population density, or a typical rural zone). The geotype model is based on statistical parameters and includes a medium and long-term predictions of the development of radio cells (including the expected radio carriers for each type of cell). The network architectures and topologies made available will be used for architectural designs and techno-economic evaluations after adaptation to the SEASON reference architecture.

The document presents also in the appendix a first set of requirements derived from the project objectives and KPIs, such as those relating to the data and control plane architectures and to the monitoring system. The project objectives considered at this stage are those relevant for WP2 "Use Cases, Architecture and Techno-economic", namely Obj. 2, Obj. 5 and Obj. 6, to which Obj.

4 was added because of its general relevance and high importance for the project, as it concerns the access architecture and in particular the RAN.

Other requirements, regarding specific aspects of systems and subsystems considered in the project solutions, will be detailed in other WPs, i.e., WP3 (data plane), WP4 (control plane) and WP5 (demonstrators), within which such requirements are relevant.

TABLE OF CONTENTS

1 Introduction and Purpose of the Document 1
2 State of the art and short-term trends in operator networks 3
2.1 TIM State of the Art of access and transport network 5
2.2 TID State of the Art of access and transport network 7
2.3 5G releases in the field and releases towards 5G advanced and 6G 9
2.4 Radio frequency assignment in Mobile networks 11
2.5 Edge computing resources for network and service functions in current and short-term architecture 13
3 Use cases and drivers for SEASON 15
3.1 Introduction to SEASON use cases 15
3.2 Metaverse driven use cases 18
3.2.1 Industrial Metaverse: Tactile Internet for Remote Surgery 22
3.2.2 Enterprise Metaverse: Academic/Professional e-Learning 26
3.2.3 Consumer Metaverse: Virtual Tourism in Smart City 31
3.3 Further drivers 35
3.3.1 Traffic growth predictions 35
3.3.2 Reuse of existing fibers and need for new deployments 36
3.3.3 RAN interfaces data rate and latency 37
3.3.4 Evaluation of scenarios for the evolution of the radio-station bandwidths 38
3.3.5 Perspective about new frequencies assignment for 6G 42
3.3.6 Drivers from Open RAN architecture 43
4 SEASON Architecture 45
4.1 Terminology and high-level architecture framework 45
4.2 Reference Time Periods for SEASON architecture 49
4.3 SEASON high-level architecture 52
4.4 SEASON node architecture 56
4.5 Enabling Technologies 57
4.5.1 White Boxes and Coherent Pluggable Transceivers 58
4.5.2 Multi Band Transceivers 59
4.5.3 MBoSDM Switching Technology and Network Capability for Backbone 60
4.5.4 SDM PON 64
4.5.5 Front/Mid-haul solutions 64
4.5.6 SDN-based infrastructure configuration and control 65
4.5.7 NetDevOps and Continuous Integration / Continuous development 69

4.5.8 AI/ML Empowered Network Operation 71
4.5.9 Pervasive Telemetry 73
4.6 Technology Mapping for Data Plane 73
4.6.1 Medium-term 74
4.6.2 Long-term 74
4.7 Technology Mapping for Control Plane 75
4.7.1 Medium-Term 76
4.7.2 Long-term 76
5 Reference Topologies for network studies 78
5.1 Topology for Access-Metro domain 78
5.1.1 Metro-Regional network of TIM 79
5.1.2 Metro-Regional networks of Telefónica 81
5.1.3 Geotype model for access areas 83
5.2 Topology for Backbone domain 93
5.2.1 Backbone network model of TIM 93
5.2.2 Backbone network model of Telefónica 94
6 Conclusion 96
Appendix: Requirements towards SEASON KPIs 98
Glossary 130
References 134

1 Introduction and Purpose of the Document

This document constitutes the first deliverable of WP2 and collects the work done in the various topics addressed in the first 14 months of the project.

As stated in the title the document covers three topics, use cases, requirements and network architecture and the organization of the content into chapters is as follows.

Chapter 2 is preparatory to the following chapters and introduces the state of the art on the networks with reference to the networks of the two operators involved in the project. The current network architectures, the technologies in the field (deployed fiber, optical and IP equipment, virtualization, and cloud), the state of development of 5G (in field release and next versions) and the assignment of radio frequencies to mobile services are addressed. The latter is an essential aspect for transport requirements in the RAN.

The use cases and drivers for the solutions proposed by SEASON are presented in Chapter 3. The use cases are analyzed from the point of view of the services and applications that are expected to grow significantly together with the development of 5G (5G Advanced in the medium term) and with the introduction of 6G (in the long term). Particular attention is given to the prospect of a development of the world of applications towards the Metaverse of which three applications and their requirements are analyzed in depth. Other drivers are then considered such as the expected growth of traffic (in general and not linked to specific applications), and aspects related to the RAN (requirements dictated by split options and Open RAN, as well as the frequency bands available in radio access which will be added to the current ones).

Chapter 4 defines the reference architecture for the SEASON project. Terminological definitions are provided (for example which types of Central Office are envisaged) and the two reference periods in which the solutions are aimed at (medium and long term). We then move on to define the network architecture which includes two segments, metro-access and backbone, and the preliminary node architectures. The main enabling technologies are then listed, and finally also their preliminary mapping on the data plane and control plane within the SEASON architecture framework is provided.

Chapter 5 reports on the reference networks made available by the operators. Some example topologies of the access-metro and the backbone are illustrated in the chapter. The relevant data on Excel sheets are made available to the partners for studies to be carried out in the project. This data covers the topologies of the current metro and backbone segments. For the part of the network access-metro segment, that extends from the current central offices to the terminations (end users or antennas) and given the confidentiality of data corresponding to real networks, an abstract model is proposed based on areas categorized as geotypes characterized by statistical data (i.e., size, population, household, antenna sites).

Finally, chapter 7, dedicated to the conclusions, reports the main messages that can be extracted from the work done in the first year of the WP2 project and which are contained in the present deliverable.

The document include also an appendix dedicated to a prelminary work on requirements. The approach followed was to express the requirements with a view to achieving the project KPIs, focusing in this deliverable on the general level requirements, i.e., the requirements on the architecture of the network (include a focus on the RAN) and on the systems that implement and control it. Starting from the project objectives and the related KPIs, it has been highlighted which system architectures, which measures, which technological solutions, and which studies must be carried out to be able to evaluate, achieve and satisfy the general level KPIs. Other system-specific requirements, such as those on optical systems or details of the control or monitoring system, will be covered in the relevant WPs.

2 STATE OF THE ART AND SHORT-TERM TRENDS IN OPERATOR NETWORKS

In this section, typical architectural scenarios of national Operators extended to the entire network (from Access to Metro to National Backbone) and valid for the existing networks or for the short-term are presented. Three State of the Art (SoA) scenarios with a different degree of introduction of virtualized functions in the various segments of the network are proposed.

The first, shown in Figure 2-1, presents a highly centralized scenario where all Telecom and Service functions are placed in the Cloud, which is limited to National Central Offices (COs) connected through the National Backbone. The role of the Metro segments, in this case, is limited to the transport of traffic from Access through Regional to the National COs where both Telco and Service functions reside (i.e., the so-called National Points of Presence - POP). While Broadband Network Gateway (BNG) and Provider Edge (PE) functions are present in all National COs, Mobile Core functions can reside in a subset of them. Mobile Core can rely on the Evolved Packet Gateway (EPG) functionality for 4G and 5G in Non-Stand-Alone (NSA) mode, pending the development of 5G core to enable the Stand-Alone (SA) mode.

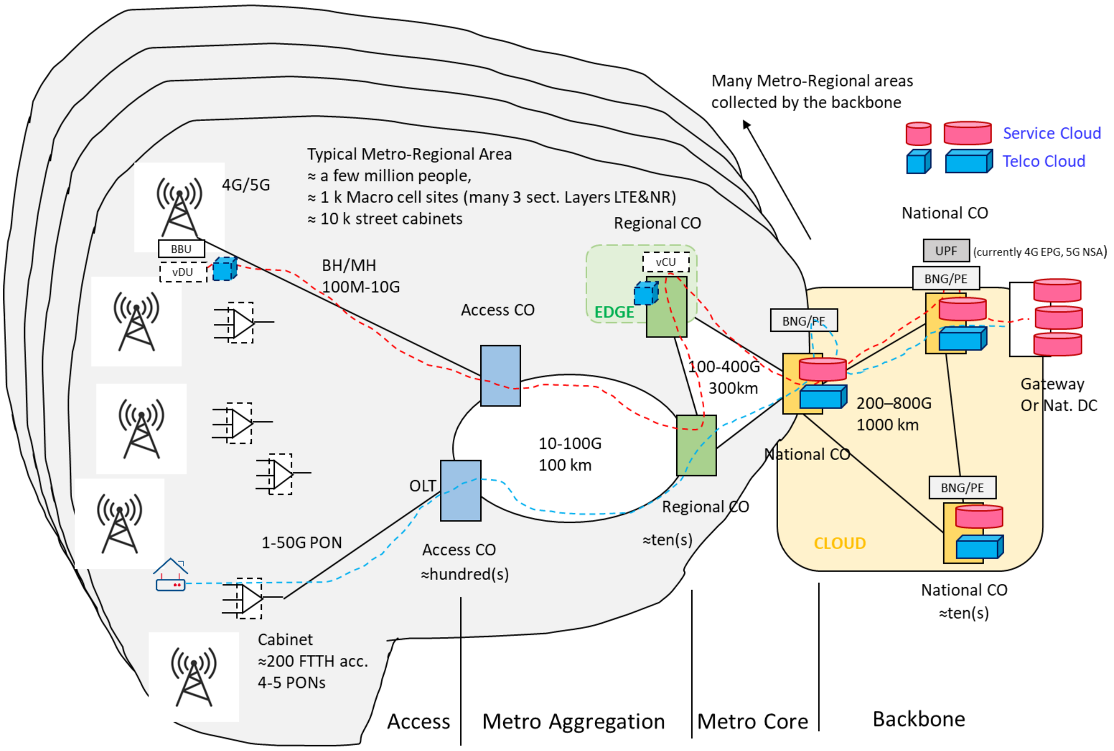


Figure 2-1 – Short-term centralized high-level network architecture.

In this scenario, a first development can be the introduction of virtualized functions at Edge level (i.e., at Regional COs), limited to the creation of a cloudified Radio Access Network (RAN) architecture with virtual Distributed Unit (vDU) at the mobile site and virtual Centralized Unit (vCU) located at Regional (or National) COs. Dotted lines from Figure 3-1 to 3-3 show the traffic flows generated by fixed (blue) and mobile (red) access, being directed to a Data Center (DC) in the cloud or to an external destination. In the case of mobile, the flow is supposed to go from vDU to vCU to Mobile Core User Plane Function (UPF) to DC/external destination.

The second scenario is depicted in Figure 2-2, where all nodes at National level have Mobile Core instances (but they are not taken out of the cloud) while a subset of functionalities, i.e., BNG/PE functions, is extended to the Edge. In this scenario, some Telco Access virtualized functions, i.e., vCU and virtual Optical Line Termination (vOLT), are placed at the Far Edge (Access COs). The virtualization of the OLT, where present, concerns only the management SW component. The data plane part of OLT continues to be implemented in dedicated devices (in Figure 2-2, the data plane part of OLT is identified as physical OLT, i.e., (p)OLT).

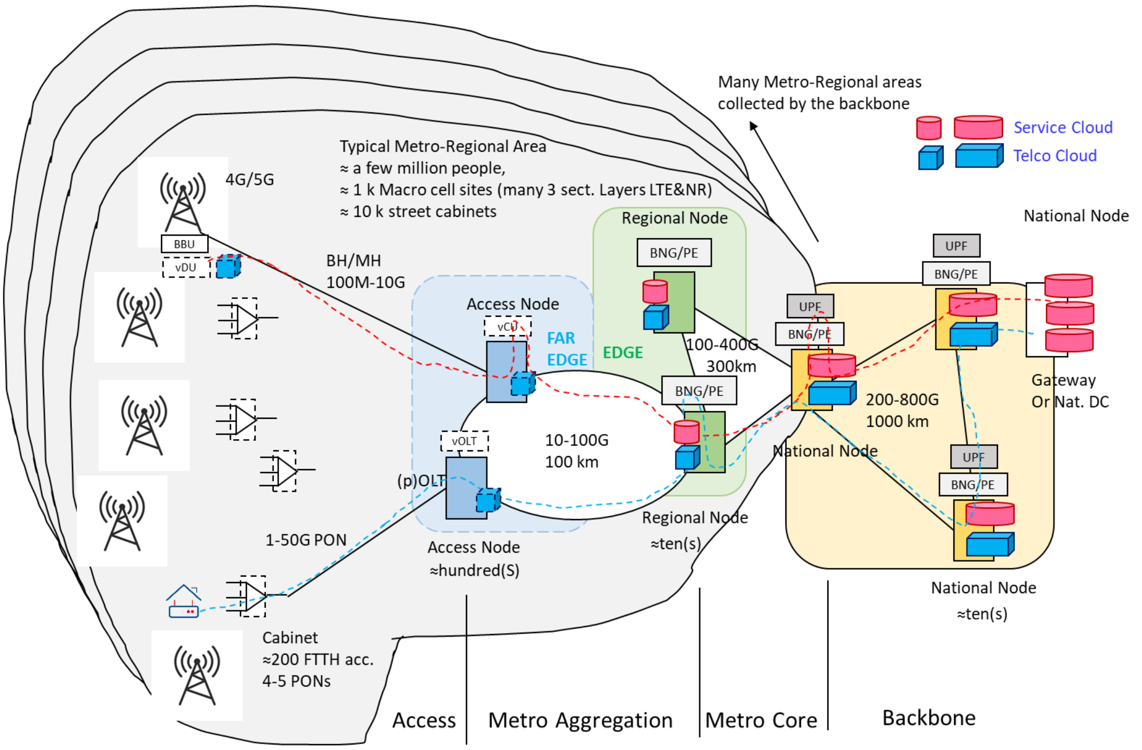


Figure 2-2 – Short-term high-level architecture with a subset of functionalities extended in the Edge and possible access virtualized functions (vCU and vOLT) placed at the Far Edge.

Finally, Figure 2-3 shows a third scenario where mobile Core functions (UPF) are extended to the Edge (Regional COs, not necessarily in all of them). In this case, the BNG function is extended to the Far Edge (Access COs), that hosts also virtualized fixed access functions (vOLT).

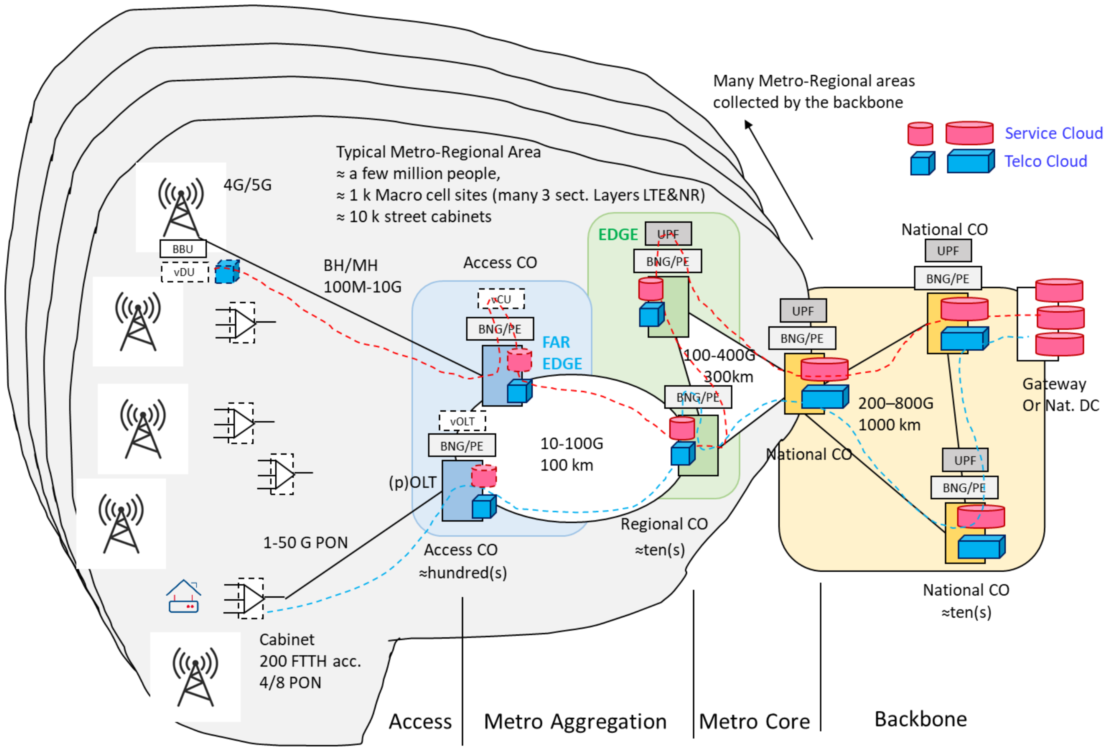


Figure 2-3 – Short-term high-level architecture with a rich set of functionalities (including mobile core) extended to the Edge, and BNG/PE as well as (potentially) service cloud, extended to the Far EDGE in addition to access virtualized functions (vCU and vOLT).

2.1 TIM STATE OF THE ART OF ACCESS AND TRANSPORT NETWORK

The scenario of Figure 2-1 generically represents current TIM's networks deployment, based on Fiber To The Cabinet (FTTCab), Fiber To The Curb (FTTCurb) and Fiber To The Home (FTTH) solutions on the Access network side, and packet over optical solutions both at Metro-Regional and National Backbone networks.

The primary Access network is physically composed by cables hosting a multifiber infrastructure (G.652 D conventional fiber) connecting the Access COs (about 3500 Access COs all over Italy) either to cabinets, curbs or homes, while the secondary access network is limited to copper pairs connecting cabinets to the access termination point, i.e., to the customer site. The most evolved access services are mainly based on FTTH (with maximum length of about 20 km and average length of about 3 km), including P2P fiber connectivity for business customers (Gigabit Ethernet - GE services) and mobile antenna sites with connections at 10/40/100GE, as well as Point to Multi Point (P2MP) connectivity for residential customers based on GPON and XG(S)-PON technologies (with optical line terminals – OLTs, installed at Access COs). By using passive splitters with a 1:64 splitting factor, GPON and XG(S)-PON provide a total bandwidth of 1 Gb/s and 10 Gb/s, respectively, allocating over each single fiber the upstream traffic flows in the O band and the downstream traffic flows in S and short-L bands, respectively.

The Metropolitan Packet Network (MAN) over Photonic Metro-Regional and the Packet Core (OPC) over Photonic National Backbone both consist of IP/MPLS networks supported by Dense Wavelength Division Multiplexing (DWDM) networks on a fiber infrastructure mainly composed of G.652 fibers in Metro-Regional and G.655 in National Backbone.

The network at packet level with its Telco and Service functions is shown in Figure 2-4. The key role of National POPs, as hinges between Metro and Backbone, and places where most of the functions (Telco and Service) are hosted, is highlighted in the central part of the figure.

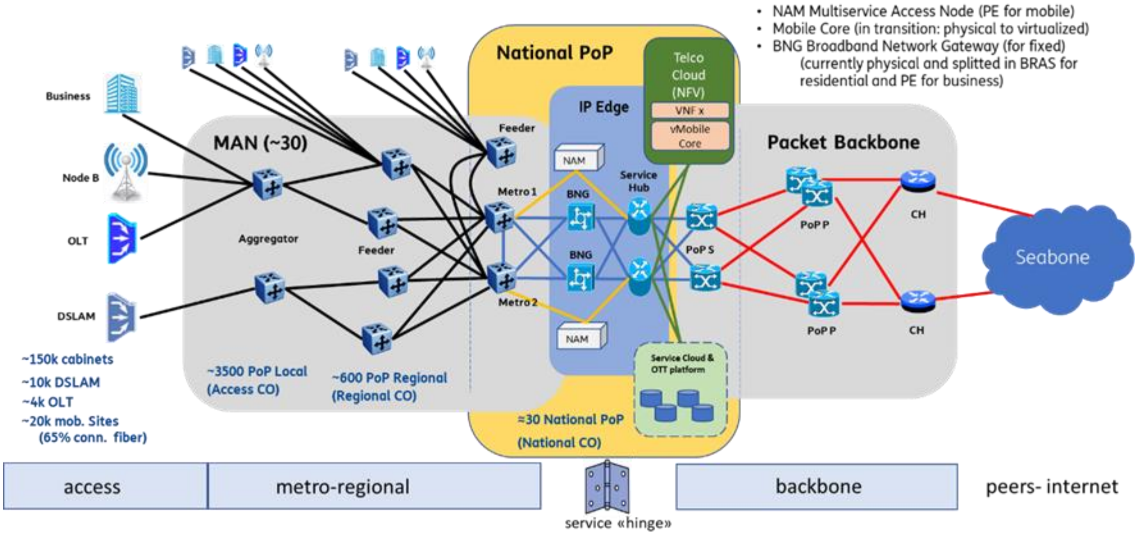


Figure 2-4 – TIM packet and network and service functions level architecture.

Each MAN (30 all over Italy) is composed by routers installed at Access, Regional and National COs (routers numbers range from 50 to more than 200 in each MAN). The router at Access CO (Aggregator) is dual homed to two routers (Feeder) in two different Regional COs (maximum distance is about 200 km). While the router located at Regional CO (whose number amounts to about 600 all over the country) is dual homed to two routers installed in the same National CO (Metro 1 and Metro 2 in Figure 2-4), with a maximum physical distance between routers in Regional CO and National CO of about 300 km. MAN exploits the photonic connections of the underlaying DWDM Metro-Regional network (each Metro-Regional DWDM network provide circuits for one, two or more IP MANs, depending on the geographical extension of the WDM Metro-Regional network).

The Packet National Backbone (right part of Figure 2-4) is based on high-performance routers interconnecting 33 National COs with circuits at 100G and 400G. Of the total of 33 National POPs, 25 are Secondary COs (25 POP S) double-hubbed to 8 Primary COs (8 POP P). Primary COs are interconnected together with a mesh. A subset done by 4 Primary COs represents the Core Hubs (CH) which is interconnected to peers and Internet through the Seabone, an infrastructure devoted to interconnect networks from different countries and operators.

Figure 2-5 shows the architecture of the Wavelength Division Multiplexing (WDM) transport network used to transport flows between routers; the WDM network is segmented in Metro-Regional Aggregation, Metro-Regional Core and Backbone, with different topologies and classes of WDM equipment (for both switching and transmission) in each segment. The first network level (the Aggregation level, between Access COs and Regional COs) is composed of direct detection transponders (operating at 10 Gb/s line rate) and Reconfigurable Optical Add-Drop Multiplexer (ROADMs) connected in horseshoe topologies (2 to 7 Access COs, acting as "leaves", ended by two Regional COs with the role of "hubs"). The second network level (the Metro-Core level, between Regional COs and National COs) is realized by 100 Gb/s coherent transponders and ROADMs connected using a mesh topology. The photonic backbone, shown in the right part of Figure 2-5, is a mesh network with around 50 nodes and 80 links. The 50 nodes include all the National CO, some Regional CO and additional transit/regeneration only sites. The optical layer consists of Colorless Directionless Contentionless (CDC) ROADMs made with Flexgrid 1x20 wavelength-selective switches (WSS) and 8x16 MultiCast Switch (MCS) add/drop modules. Concerning transponders and muxponders, the client rate is mainly 100G (lower rates, e.g.,1G and 10G are groomed by the OTN layer or through muxponders). Nevertheless, line rates ranging from 100G to 400G (used for N x 100G clients) and trials with even higher line rates were already successfully demonstrated (e.g., the successful transmission of 600 Gb/s signals in a 100 GHz channel grid along 1000 km was demonstrated in 2022).

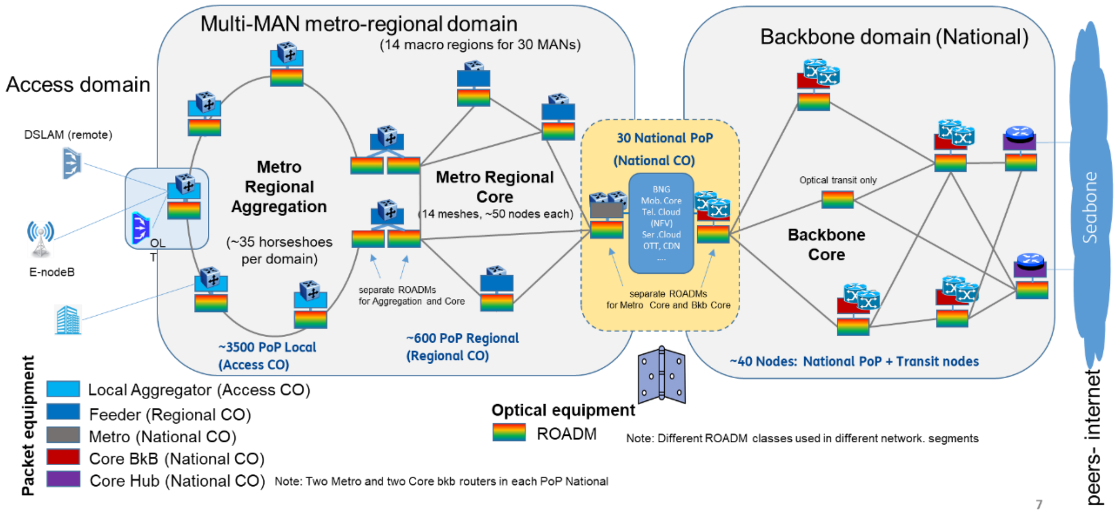


Figure 2-5 – TIM optical network level architecture.

2.2 TID State of the Art of Access and Transport Network

The third generic scenario (Figure 2-3) is the one that better matches Telefónica's current network architecture, with the caveats that will be detailed next, particularly the placement of the Mobile Core functions, which are centralized. Telefónica's data plane architecture is divided into three layers: the IP layer, the Optical Transport Network (OTN) or electrical switching layer, and the optical layer, which mainly consists of rings, horseshoes, and photonic meshes. According to the IP layer structure, the network is arranged following a typical hierarchical structure comprising five levels (HL1-HL5). The lower the number, the higher the router capacity.

The HL5 level comprises the access nodes that aggregate the data from radio access points and mobile base stations, as well as OLT, which collect the traffic from/to FTTH households. The HL4 level is composed of IP routers at metro-aggregation sites that handle traffic classification, subscriber credentials authentication, validation of users' access policies, routing data to their destination, and aggregation of traffic from different locations of the metro network, as well as from OLTs and radio access points (in densely populated areas). The HL3 level collects traffic from the HL4 and HL5 nodes within a certain region and performs IP grooming towards the next level (national photonic mesh). The HL2 level hosts critical services, such as TV and Content Delivery Network (CDN) caching. Finally, the HL1 level is the top level of the national backbone network and interfaces the IP network to the Internet as well as to other Internet service providers (ISP). The network consists of around 10,000 HL5 nodes (horseshoe structures dual hubbed to two HL4 nodes), 1,000 HL4 nodes (horseshoe structures dual hubbed to two HL3 nodes), 100 HL3 nodes, 20 HL2 nodes, and <10 HL1 nodes forming a photonic mesh.

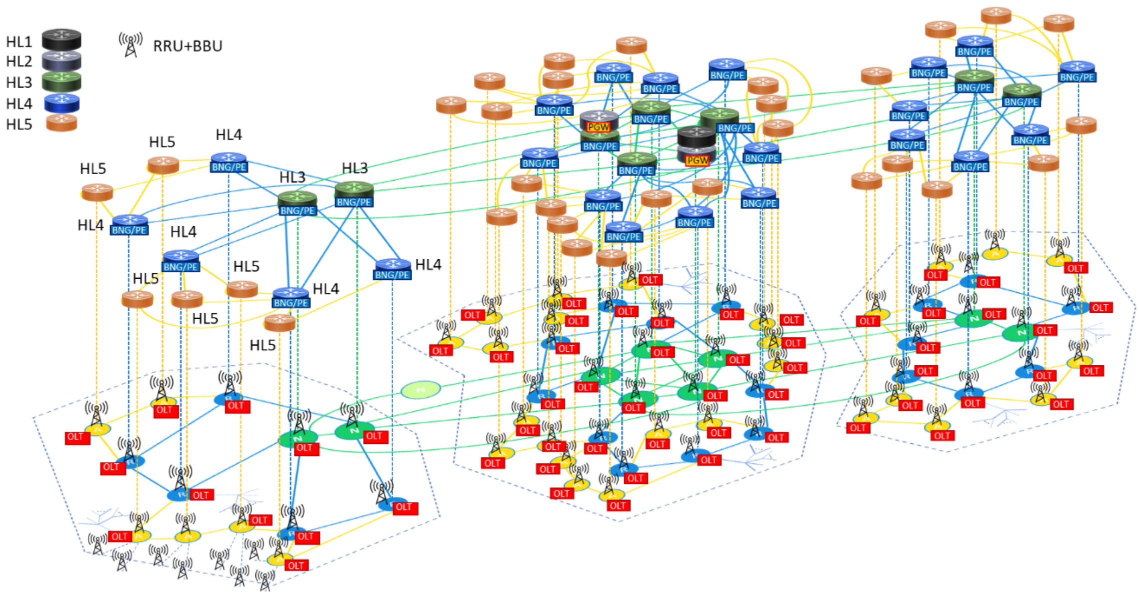


Figure 2-6 – Telefónica's simplified packet-optical network topology.

Figure 2-6 shows the current Telefónica's simplified IP and optical layer architecture, as well as the different segments in which the optical layer is structured and the associated IP hierarchical levels (HLx) at which the data from each of the network segments is aggregated and statistically multiplexed. Shown are three encircled geographical areas (left -L-, middle -M- and right -R-), which represent two medium-sized regions (L and R), consisting of HL5-HL4-HL3 nodes, and a large metropolitan area (M), where the HL2 and HL1 nodes are located. Logical connectivity between HL3-HL2-HL1 nodes is shown for all three geographical areas. The physical topology comprises the access, metro-regional, and national networks represented by orange, blue, and green structures, respectively. The light-green node between the L and M regions denotes a national-network pass-through node without traffic add/drop and, consequently, without an associated router in the IP layer. PON networks are depicted branching out from a few selected sites just for reference, but all sites with the red OLT tag are the termination point of a PON network. Radio station placement is indicated with the antenna icon. As depicted in the L region, for a few HL5 sites, the antennas not co-located with an HL5 site are linked to the nearest HL5 site through microwave (MW) or dark-fiber connections. The placement of telco functions, such as BNG, PE and PGW, are indicated in the IP layer.

The national network is divided into 50 regions (with Figure 2-6 only showing three of them) which are connected through a meshed topology based on Colorless Directionless (CD) and Colorless Directionless Contentionless (CDC) ROADMs and coherent transmission using at least 100G channels (no dispersion compensation modules deployed). Two HL3 nodes in each region serve as termination points for HL4 horseshoe structures, which are based on colourless ROADM nodes and 100G coherent transmission (no dispersion compensation modules deployed). Finally, the HL5 nodes, implemented with fixed OADMs (FOADMs) in the optical layer, form horseshoe structures dual hubbed to two HL4 nodes, based on mixed 10G/100G transmission.

The HL5/HL4 sites serve as terminating points for fixed and mobile access network deployments. FTTH is deployed through PON networks (with OLTs installed at the HL5 or HL4 nodes –hosting up to 3 racks with 2 chassis/rack, and the ONTs deployed at the customer premises) using passive splitters daisy-chained to provide a 1:64 splitting factor implementing GPON and XG(S)-PON technologies, with maximum transmission distance in the range of 10-20 km. Regarding the mobile access, there are generally less than 12 base stations per HL4 site and only up to 4 base stations per HL5 site.

Finally, regarding the placement of telco functions in Telefónica's network architecture, BNG/PE are distributed to the far edge nodes (HL4 sites), but the PGW are centralized in about 5 locations nationwide (usually at the HL2 level).

2.3 5G RELEASES IN THE FIELD AND RELEASES TOWARDS 5G ADVANCED AND 6G

The state of the art of 5G Releases (Rel.s) sees many operators still with Rel. 15 in the field in Non Stand Alone (NSA) mode. A group of operators has already equipped or is in the process of equipping itself with the Stand Alone (SA) core network. From a standardization point of view, Rel. 16 and 17 are already available but the implementations and products are still non-existent or very limited. What happens is that in some cases only a selection of the more advanced features is implemented and deployed, not the entire post-release 15 feature set.

As regards the next scheduled release, Rel. 18 is expected to be finalized in June 2024 [3GP24] and this release version should provide the features which are identified as 5G advanced. After release 18 we should arrive at Rel. 19 which is the last of 5G era. Rel. 20 and later will usher in the new era of 6G.

A brief summary of the evolution of features for the mobile technologies preceding 6G is given in [TIM21].

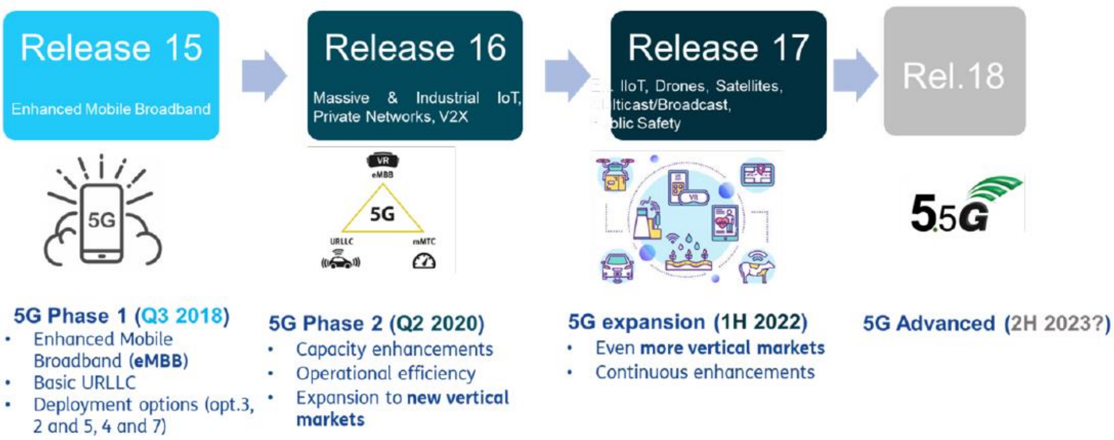


Figure 2-7 – 5G 3GPP phases [TIM21].

As reported in Figure 2-7, from *5G Phase 1 - Rel. 15*, supporting enhanced Mobile BroadBand (eMBB), Ultra Reliable Low Latency Communication (URRLC), and massive Internet of Things (mIoT) services, we should presently move to *5G Phase 2 - Rel. 16* with its capacity enhancements, while in the next few years the *5G Phase 3 - Rel. 17* should be available on the market. This “*5G expansion*” should offer KPIs improvements, for example for Industrial IoT in terms of latency, reliability and precision, and the support of new services like M2M for wearable devices or drones' control, and professional audio/visual applications.

5G Advanced in Rel. 18 is considered the real evolution phase towards 6G even if a further release, Rel. 19, is expected as the last of 5G (only), as Rel. 20 is a bridge release between 5G and 6G. As shown in the following Figure 2-8, it is foreseen as an AI/ML permeated mobile technology, whose main characteristics include even more extreme KPIs to assure, for example, multimodality (audio, video and tactile) Immersive/Extended Reality (XR) communications. Among requirements, bandwidth would amount to 100 Gbit/s, assured latency to 1 msec and end-to-end reliability six 9s.

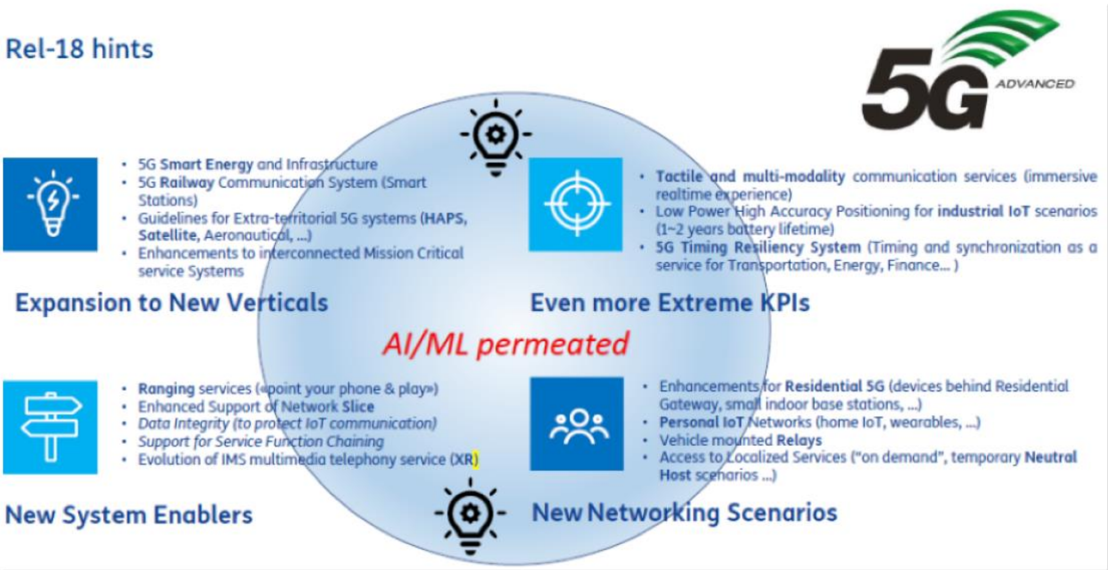


Figure 2-8 – 5G Advanced main hints.

In Figure 2-9 taken from [Qua24] the expected roadmap of releases that include 6G is shown. Rel. 20, expected for the end of 2027, will close the 5G era (from the point of view of standards, not of the networks on field) and open the 6G era. Finalization of next releases, Rel. 21 and subsequent ones (full 6G) is expected after 2030.

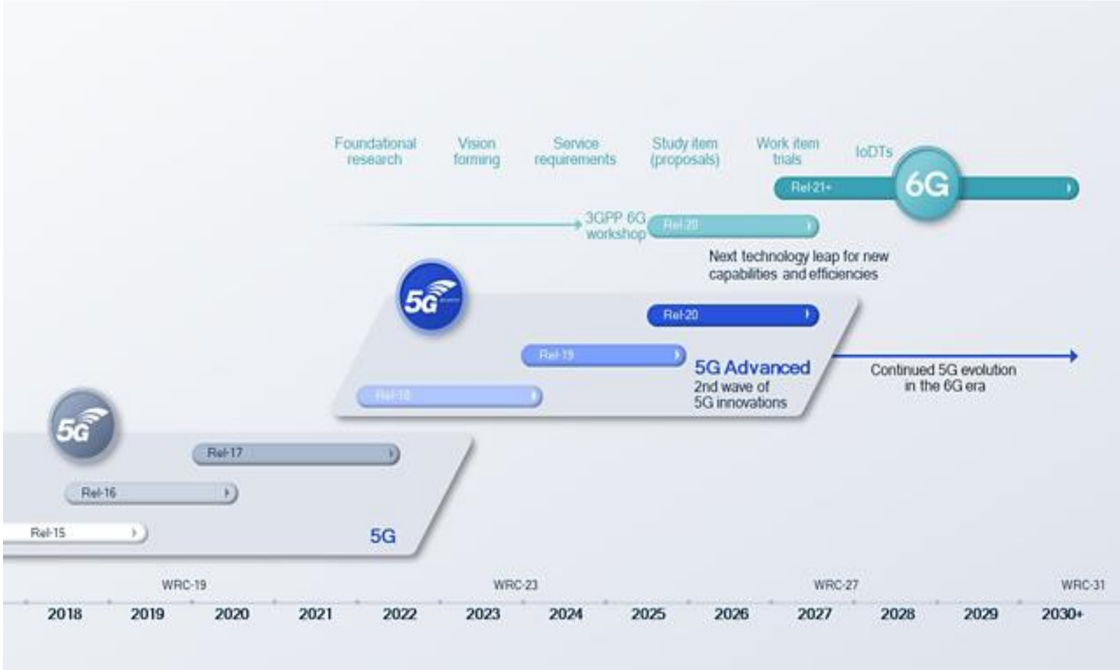


Figure 2-9 – Release roadmap towards 6G [Qua24].

2.4 Radio frequency assignment in Mobile networks

This subsection presents the current situation of frequency assignment for the mobile service of any generation of technology in the field (i.e. from 2G to 5G), taking the spectrum assignment in Italy and Spain as examples. The situation in other European countries, and more generally in the entire world, may present some differences for example in terms of the number of licensed operators and the number and width of the assigned sub-bands (carriers), but the examples can be considered representative for our purposes.

First of all, the bands currently available to mobile operators is listed below. Within each band the various countries have put out to tender sub-bands (carriers) to allow on the one hand enough operators to participate in the tenders to guarantee competition, and on the other to guarantee spectrum widths for the carriers adequate for the supply of the service. Carrier bandwidth width ranges from 10 to 30 MHz for sub-GHz bands, 20 to 110 MHz for the 3.6 GHz band, and 200 to 1000 MHz for the 26 GHz band.

- Sub GHz bands, three bands (700, 800 and 900 MHz) with typical carriers' width of 10-20 MHz and 3 to 4 carriers per band assigned;
- 1-3 GHz bands, four bands (1500, 1800, 2100 and 2600 MHz) with typical carriers' width of 5-30 MHz and 2 to 4 carriers per band assigned;
- 3-7 GHz (C-Band) bands, one band (3.6 GHz) with typical carrier width of 20-110 MHz and with 4 carriers assigned;
- Above 24 GHz, one band (26 GHz) with typical carrier width of 200-1000 MHz and usually 3 to 5 carriers assigned;

As regards the use of bands in systems, the sub-GHz bands and those in the 1-3 GHz range are used exclusively (with possible rare exceptions) for macro cells, the 3.6 GHz band is currently used for macro cells but in the future it could also be used for small cells, while the 26 GHz band, already licensed in some countries but little or not used yet, given its propagation characteristics is used exclusively for small cells.

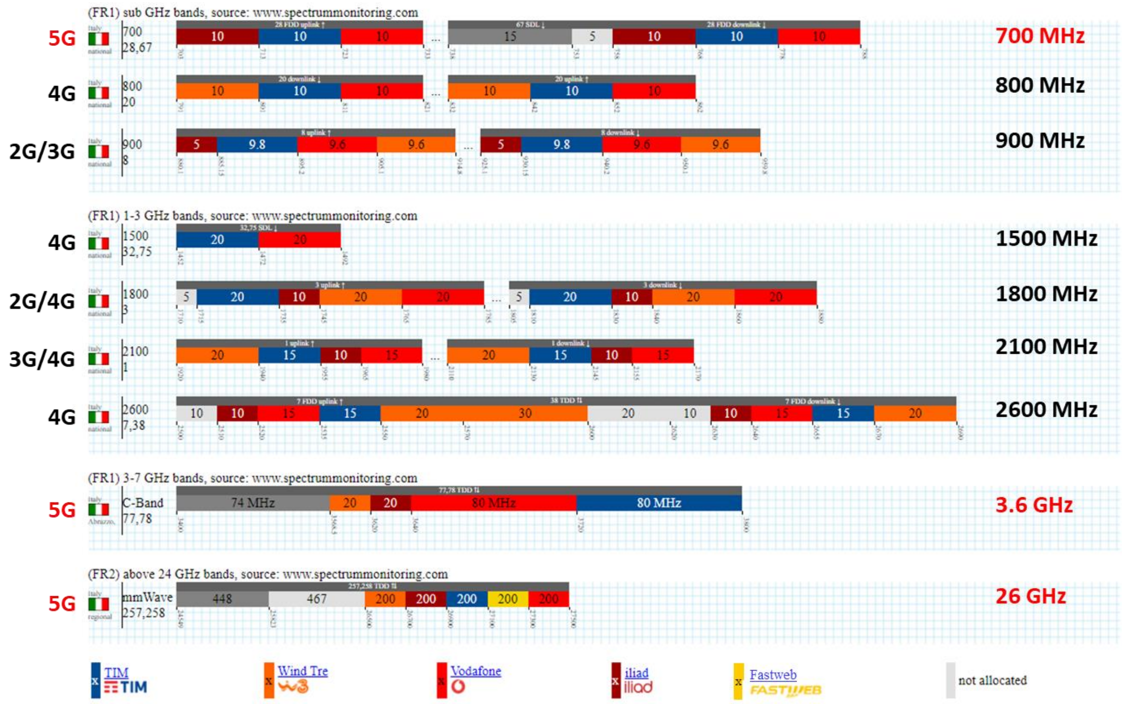


Figure 2-10 – Frequency assignment for mobile services in Italy [SMT24, SPE24].

Figure 2-10 shows the current status of frequency band and carrier assignment in Italy [SMT24, SPE24]. Five operators (TIM, Wind-3, Vodafone, Iliad and Fastweb (company owned by Swisscom)) got the pieces of spectrum for mobile services from 2G to 5G in different tenders over the years. As can be seen, in Italy, the carriers for 5G have already been assigned to the 26 GHz frequency, however, not all the operators, despite having this frequency available, are using it in their networks. The last tender for the assignment took place in 2018 and concerned the spectrum for 5G. The upward race has earned the Italian State the sum of 6.6 billion euros.

Figure 2-11 – Frequency assignment for mobile services in Spain [SMT24, SPE24].

Figure 2-11 shows the current status of frequency band and carrier assignment in Spain [SMT24, SPE24]. Four operators (Movistar, Orange, Vodafone and Yoigo) are licensers for spectrum for mobile services. The assignment is similar to the one of Italy with some differences. For example the bandwidths 1500 MHz (used in Italy for the 4G) has not been assigned in Spain while in the 26 GHz band, suitable for 5G small cells, three carriers were assigned instead of four, and with different carrier sizes, compared to Italy. The assignment of carriers in 26 GHz band was made in a recent auction (beginning 2023) with two operators (Orange and Vodafone) that got one carrier at 200 MHz each and a third (Movistar) that got one carrier at 1 GHz.

The above examples of frequency assignment to operators in Italy and Spain are to be considered indicative, the use of frequencies by operators, including their assignment or rental, and the recent events of sale and merger of the assets of some of the operators are leading to changes that will bring new maps compared to those represented in Figure 2-10 and Figure 2-11.

2.5 Edge computing resources for network and service functions in current and short-term architecture

Currently, for the two operators involved in the project, network functions as well as main service functions provided directly by the operator or from third parties such as caches of Over The Top (OTT) and content providers (e.g., Netflix), are located on a subset of nodes at National level (National POP for TIM, HL1 and HL2 for Telefónica, with the exception of BNG function that is located at HL4 level). Some functionalities that were previously implemented in physical systems (HW and SW aggregated in specialized equipment), are being shifted into virtualized functions.

As shown in Figure 2-12, network functions can be virtualized as Virtualized Network Functions (VNFs) running on the network functions virtualization (NFV) infrastructure or can be virtualized as cloud-native network functions (CNFs) running on cloud native (CN) infrastructure that uses containers instead of virtual appliances.

This happened, for example, in the case of the Evolved Packet Gateway (EPG) for the 4G/5G-NSA mobile core, for which both versions of virtualized and physical functions are still present, but newer instances have been implemented as virtual appliances on NFV infrastructure. In TIM network, the newer mobile core instances allowing the Dual Mode Core (DMC), which merges 4G EPC and 5G-SA Core network functions into a common cloud platform, are being implemented on the CN infrastructure. Some Telco functionalities, such as the BNG for the IP edge, are planned to remain in physical mode (using specialized aggregated HW-SW routers), at least for the moment and according to the short-term plan of the two operators involved in the project.

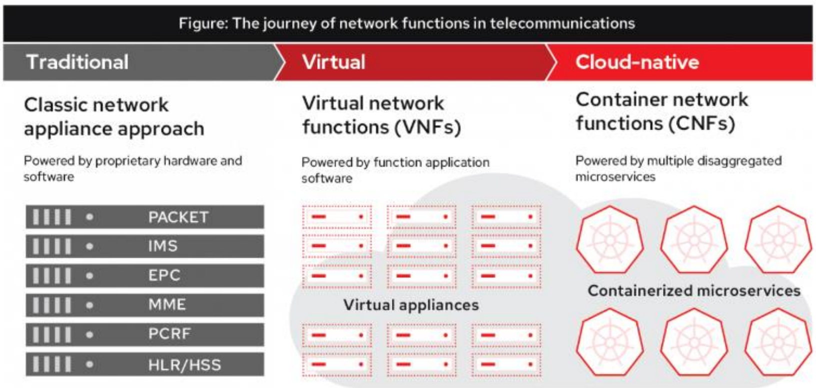


Figure 2-12 – Evolutionary view of Physical functions, Virtual network functions and Containerized network functions. Source Red Hat [RHI24].

There is a plan to move virtualized Telco functions from the National level (Backbone for TIM, HL1 and HL2 for Telefónica,) to the Regional level (Metro-regional for TIM, HL3 and HL4 for Telefónica,) but, since it requires substantial economic investment and has a huge impact on the network, it keeps to be postponed. There are no dates scheduled in operators' plans for the accomplishment of this decentralization of network functions to the Edge. Whether and when the deployment will take place depends also on the market pressure for services that require delivery from the Edge.

3 USE CASES AND DRIVERS FOR SEASON

3.1 INTRODUCTION TO SEASON USE CASES

The use cases taken into consideration as reference for the SEASON project will see a constant evolution from today's 5G developments to new functionalities and capabilities available with the introduction of B5G/5G Advanced, in turn followed by the 6G technology that will ultimately lead to what we can call as "Metaverse-driven" use cases. In previous section we illustrated the development of the mobile network releases, from those of today's 5G (up to Rel. 17) to those of the 5G Advanced phase (Rel.18 to Rel. 20) up to 6G (from Rel. 20 upwards, being Rel. 20 a bridge between 5G Advanced and 6G). Linked to the releases are the service use cases and also the requirements for the RAN, important aspect in terms of cost (given the widespread diffusion and the increase in complexity and power consumption of the systems) and transport solutions, the latter of central interest in the SEASON project.

Regarding predictions for services in 6G era, in these years many focus groups and research activities are preceding the standardization phase. One of the first visions on 6G, elaborated in 2019 [Saa19], identifies this future mobile technology as an integrator of services and functions, presently independently classified. For example, eMBB and URLLC services could be merged in the so called Mobile Broadband Reliable Low Latency Communication (MBRLLC), and a convergence of functions could occur for Communications, Computing, Control, Localization and Sensing (3CLS), useful for high performance applications like Multisensory XR applications, Connected Robotics and Autonomous Systems (CRAS), and so on.

For what it concerns RAN evolutions with 6G, future 6G deployments are expected to leverage on new RF spectral bands and massive MIMO processing to provide higher bandwidths and high spectral efficiency (x5 expected). Depending on the selected functional split option, RAN optical segments will need to support 6x higher bit rates in a future 6G scenario with an available RF bandwidth of up to 400 MHz (x4 increase of spectrum w.r.t. 100 MHz in 5G), 64 antenna ports (16x DL/UL MIMO layers as compared to 5G specs - from ~150 Gb/s to ~1 Tb/s per radio carrier, using functional split option 8 [Fio15] - and more than 120 times if compared with current 4G deployments). Higher splits will reduce the bit rate requirements to 94.5 Gb/s per radio carrier (for split 7.2), assuming 28 symbols per subframe (1 ms) on top of the above-mentioned requirements, resulting in a bandwidth increase of 12x with respect to today's deployments [ORA21]. In both cases, the aggregated user data rates for transmission bands around 3.5 GHz will be in the region of 20 Gb/s per radio carrier, with peak bit rates per user < 5 Gb/s, even though the bit rates to be transported in the xhaul, as we have seen, will be significantly higher due to functional-split-dependent overheads. In addition, AI/ML assisted Radio Resource Management (RRM) will be introduced to adapt signalling schemes and protocols according to data source, application and use case, and this will allow to achieve further increase in spectral efficiency [Nok24].

These developments will facilitate the emergence of the applications described by the ITU-T Focus Group NET-2030, generally requiring high bandwidth, low latency, and the possibility of connecting a larger number of devices, which exceed today's network capabilities. The identified representative use cases include [ITU20-1, ITU20-2]:

- Holographic type communications (HTC).

- Tactile Internet for Remote Operations (TIRO).
- Intelligent Operation Network (ION).
- Network and Computing Convergence (NCC) .
- Digital Twins (DTs).
- Space-Terrestrial Integrated Network (STIN).
- Industrial IoT (IIoT) with cloudification.
- Huge Scientific Data applications (HSD) including astronomical telescopes, the Large Hadron Collider, ITER (nuclear fusion), etc.
- Application-aware data Burst Forwarding (ABF), e.g., face recognition system and video surveillance with real time image processing.
- Emergency and Disaster Rescue (EDR), e.g., smart sensing IoT capable of sending control messages to the population and gathering data that can help predict catastrophes.
- Socialized Internet of Things (SIoT), e.g., delivery of parcels.
- Connectivity and Sharing of pervasively distributed AI data, models and knowledge (CSAI), i.e., IoT provided with AI from a centralized processor.

Generally speaking, these future services will lead to a massive increase in global mobile generated data traffic and associated requirements, e.g., extremely low latency (even below 1 msec), high reliability (from seven to nine 9s), data rates of up to 1 Tb/s, etc. In much the same way that three types of services were defined in 5G networks, namely eMBB, uRLLC, and mMTC (massive Machine Type Communication), several categorization efforts have been made to classify these future services/applications according to different criteria, such as their network requirements or the application theme. An example of the former was presented in a proposal for ITU-T FG NET-2030 made in 2019 [Eck19], where three categories of new service capabilities were defined, i.e., Qualitative Communications, High-precision Communications and Holographic Teleport, and three target research areas were presented as an evolution of the above-mentioned use cases of interest for 5G networks:

- Very Large Volume & Tiny Instant Communications (VLV & TIC), including holographic type communications, very high throughput (> Tb/s), holographic teleport (< 5ms), digital senses, qualitative communications, coordinated streams, etc.
- Beyond Best Effort and High-Precision Communications (BBE & HPC), including high precision communications (lossless networking, throughput guarantee, latency guarantee), user-network interface, etc.
- ManyNets, including satellite networks, internet-scale private networks, MEC, special-purpose networks, dense networks, network-network interface, operator-operator interface, etc.

Another example of categorization based on network requirements was proposed in [Bha21], where a non-exhaustive list of new service types based on bit rate, latency, energy efficiency, reliability or security, to name but a few, was compiled, a visual representation of which is presented in Figure 3-1:

- further enhanced Ultra-Mobile Broadband (feUMBB).
- ultra-High Sensing Low Latency Communications (uHSLLC).
- ultra-High Density Data (uHDD).
- ultra-High Energy Efficiency (uHEE).
- ultra-High Reliability and Sensing (uHRS).
- ultra-High Reliability and User experience (uHRUx).

- ultra-Low Latency Reliability and Secure (uLLRS).
- ultra-High Security (uHS).
- ultra-High Sensing and Localization (uHSLo).

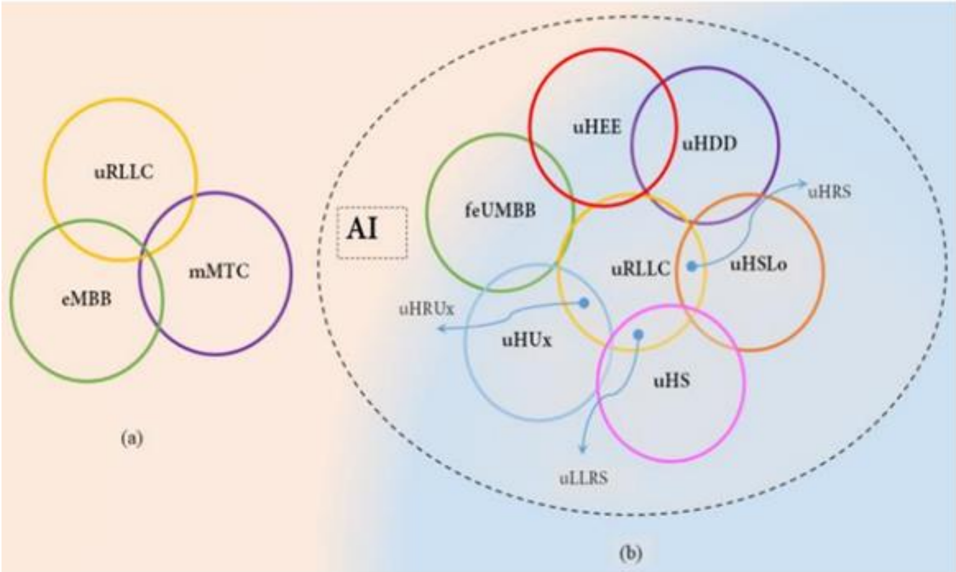


Figure 3-1 - Extension of 5G use cases to future 6G needs, according to [Bha21].

On the other hand, an example of an application-theme-based categorization is the classification made in the Hexa-X project [Hex22], where the following categories were proposed, as it is also shown in a visual way in Figure 3-2: Robots to cobots, Hyperconnected resilient network infrastructures, Trusted embedded networks, Enabling sustainability, Massive twinning, Telepresence, Additional evolving use cases.

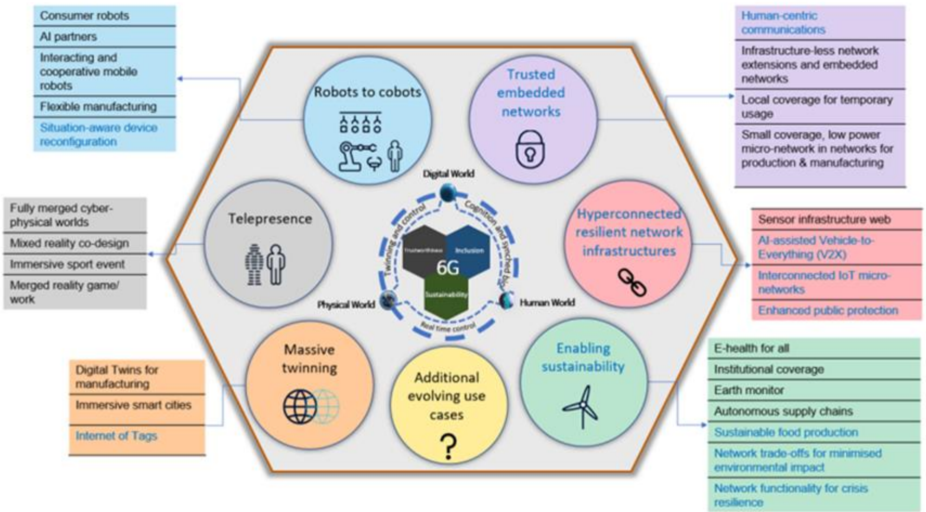


Figure 3-2 - Hexa-X 6G use case categorization [Hex22].

In order to meet the capacity requirements of the new services expected to emerge beyond 2030, affecting the RAN (especially if split option 7.1 or 8 are used), but also the other network segments up to the core, more bandwidth needs to be made available. To achieve these needs, it is possible to act in several directions: exploit more bands on existing fibers, deploy new traditional single core fibers (creating parallel multi-fiber systems) or deploy new innovative fibers such as multi core fibers (SDM which exploits the cores of the same fiber or Hollow Core Fibers, fibers which, potentially, have lower attenuation and low detrimental non-linear effects on signals). However, choosing a specific feasible solution depends on the state of the art of technologies for that solution. For example, the laying of traditional fibers is mandatory if multiband systems or new types of fiber (for example multicore) do not yet have commercial technology and equipment at the time of deployment. In the next sections, we will look at fibers and technologies in detail.

3.2 METAVERSE DRIVEN USE CASES

The Metaverse can be defined as a 3D persistent environment where physical and virtual realities merge to enable new forms of people's activities and interactions. It should leverage on the evolution from the increasingly centralized Internet of the last three decades (developed for "data search"- Web 1.0, "content production and diffusion" - Web 2.0 and "AI-assisted services" like Siri, Alexa - Web 2.5) to a sort of autonomous and decentralized Internet, that could be either the "semantic web" - Web 3.0 (proposed by Tim Berners–Lee and based on cognitive intelligence of applications to provide, in an autonomous manner, the semantic connections between contents) or the lately introduced Web3 concept, based on a trust-less and permissionless environment where applications are designed according to a "user-centric" paradigm. [TIM22]

More specifically, Web3 decentralization should be based on the Blockchain technology, that is a digitally distributed information database, i.e., a security platform for digital information representing an identity, a physical asset, an economical right/property, a cryptocurrency, etc., generically called "Tokens". Among them a distinction is made between Non-Fungible Token (NFT), that is a non-interchangeable token univocally representing an entity (e.g., a digital identity in the Metaverse) and Fungible Token, that can be exchanged (like the cryptocurrency). This could also lead to a decentralized real/virtual economy, where digital payments, real or digital property and rights exchange are seamlessly performed between the physical and the cyber worlds.

Web3 could thus give a good opportunity to create a Metaverse with the following characteristics:

- Continuous experience between physical and digital worlds.
- Persistent existence, i.e., no pause or reset for a created environment.
- Synchronous and alive experience, i.e., a coherent real time experience for everybody.
- Unlimited number of simultaneous users/attendees of events, places or activities.
- Probably decentralized, according to the Web3 paradigm.
- A functioning economical community, where people can create, own, sell and be rewarded for every work or resource capable to produce a recognized value for the community.
- Interoperability between environments, which means that data, entities, etc. should be transferable and available in every contest.

This last point is one of the main issues to be defined and standardized, because it is likely that there will be several Metaverses where users, together with their assets, should seamlessly transit through to perform different activities in different contexts. The Metaverse Standard Forum [Met24], together with the W3C Metaverse Interoperability Community Group [W3C24], coordinates different standardization bodies and companies to facilitate standards development for an open and inclusive Metaverse. Furthermore, the Open Metaverse Alliance for Web3 (OMA3) [OMA22] has the intent to guide the Metaverse evolution in line with Web3, assuring the interoperability between virtual spaces, digital resources, and services on different Web3 platforms.

In addition to Web3 applications, technological drivers for Metaverse are Immersive technologies based on XR in its different forms, i.e., Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR), and Holographic Type Communication (HTC). At software level, a reference technology is the Spatial Computing, capable of 3D digital simulation of persons (avatars), objects and environments (digital twins), with all the animations, gestures recognition and spatial mappings that give a realistic rendering of elements, situations, and people, that can interact in real time via multiplayer platforms. At hardware level, different user devices are already available. For AR/VR video, AI-supported head-mounted visors (capable of tracing and synchronize eyes and body movements, giving an immersive experience via a 3D video camera) are in commerce while smart glasses should be available on the market at the beginning of 2024; for tactile experience, haptic gloves and smart wearable devices are produced to support respectively touch sense and kinaesthetic information. HTC today involves Computer-Generated Holograms seen on a 3D holographic display, while True Holograms (that today can be reconstructed only in special rooms) could be the technology of the future. In both cases, an extremely large amount of data should be managed to record and reconstruct in a realistic way the 3D image.

The Metaverse introduction will require huge efforts for Telco Operators to provide Metaverse-ready networks. Many concurrent aspects and requirements should be available to assure shared, synchronized, persistent and seamless XR/HTC experiences to many thousands, or even millions, simultaneous users in different Metaverse environments. A complete ecosystem, done by different Telco Providers' network infrastructures (mobile, Wi-Fi, fixed access and transport as well as non-terrestrial networks and telco Edge Clouds, to create the so-called network of networks), as well as by different Service Providers' infrastructures (with datacenters requiring an enormous amount of data processing, storage and transfer) and Web Developers, will be fundamental if Metaverse will be completely and efficiently rolled-out in the long-term.

Main network requirements for Metaverse could be the following ones:

- **Very high symmetrical transmission bandwidth**: AR/VR and HTC experiences (with all the complexities described above) will require ever increasing both downstream and upstream data rates, to assure a high multisensorial Quality of Experence (QoE) to users, ranging from today tens or hundreds of Mbit/s (for 4k video and its evolutions) to 100 Gbs-1 Tbs (for HTC). Transmission bandwidth should be symmetric to assure many-to-many shared and synchronized activities in the Metaverse.
- **Extreme low latency**: real time social interactions, with all the details that will make them appear as real, or precise control of remote systems in an industrial environment (just to give a pair of examples) will require a network latency in the range from 1 msec to 0.1 msec or less (for the RAN).

- **Extremely high availability**: a high Quality of Service (QoS) for these immersive experiences in persistent environments will require maximum network redundancy, re-routing and intelligent global, end-to-end fail-over orchestration systems, to prevent service interruption with consequent bad QoE for users. In this sense, QoE metrics should be defined, standardized and correlated to network QoS metrics. The network availability target should be in the order of 10^{-9}.
- **Telco Cloud and Edge Computing solutions**: the rendering of the immersive experience should be supported by the Edge Cloud, that could receive, store and transfer the streaming contents to the end user devices (having in this way low computational complexity and cost). The peripheral location of the Service Provider datacenters, and consequently of the Telco cloud functions, would assure extreme low latency and high transmission bandwith avoiding high risks of network congestion.
- **Network Dinamicity**: the network must be able to quickly reconfigure itself to respond to significant service traffic variations over both time and space scales.

Figure 3-3 represents a pictorial view of the Metaverse value chain briefly described in this section [Rad21].

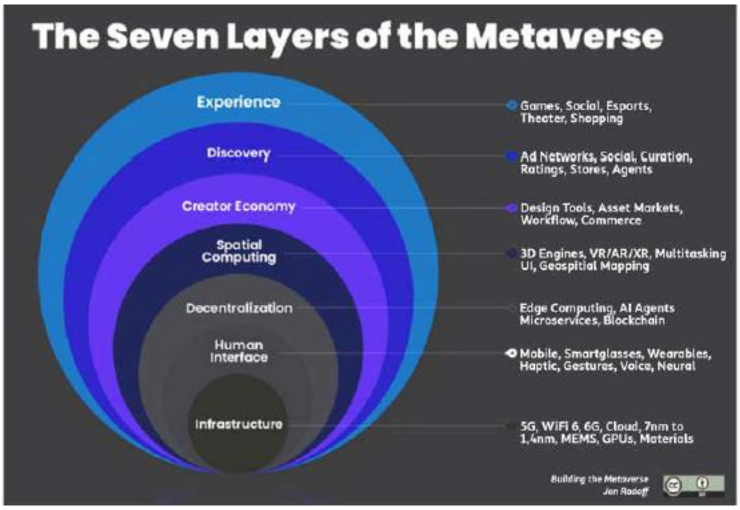


Figure 3-3 – Metaverse value chain [Rad21].

From the socio-economical and business points of view, Metaverse could be classified into three main categories (a pictorial view is given in Figure 3-4, [Vet23]):

- **Industrial Metaverse**: for applications like factory remote operation on machinery and robots, process monitoring and predictive maintenance by digital twins, security control by cameras, robots and drones, virtual R&D, prototyping and testing (e.g., simulation of expensive tests like car crash), healthcare companies performing telemedicine applications, and so on.
- **Enterprise Metaverse**: for virtual co-working spaces/offices and showrooms, virtual meetings and collaboration, virtual recruiting, hiring and on-boarding, professional soft-skills or hands-on training as well as enhanced forms of academic learning.
- **Consumer Metaverse**: for consumers performing, through digital-only or digitally-augmented means, the following activities: immersive social interactions, virtually interactive live music or sport events participation, immersive collaborative cloud

gaming, purchasing a digital asset in virtual stores, and so on; also for citizens exploiting Smart City services provided by Municipalities and Public Institutions, like smart mobility, virtual tourism, security/disaster notifications, etc.

Some relevant references on Metaverse and related use cases are the following ones: [Nok23-1], [IOW23], [IOW21-1], [IOW21-2].

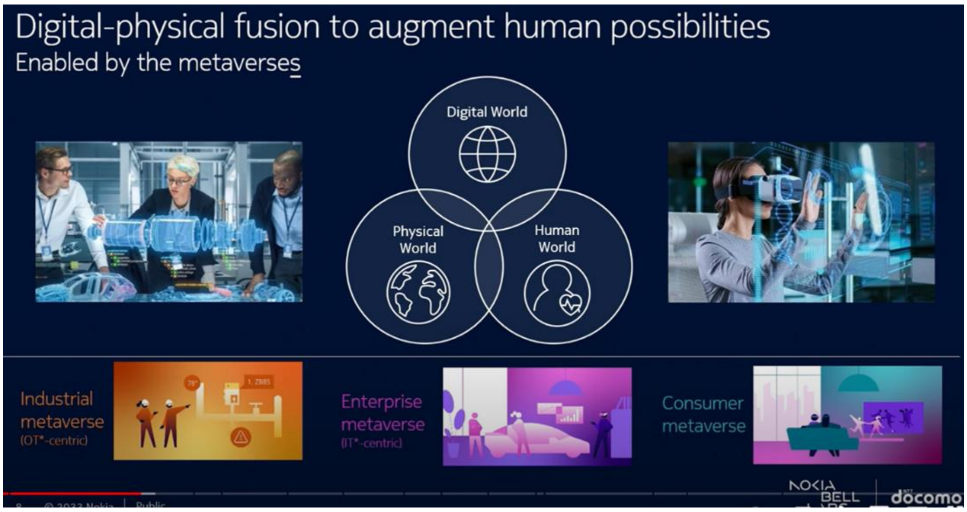


Figure 3-4 – Metaverse categories [Vet23].

One relevant example of Industrial Metaverse is represented by the Nvidia Omniverse, that is the integration of Digital Twins in the overall design, production, and maintenance process for factory plants, in other words, a sort of DevOps applied to a material production process with the aid of integrated DT [NVI24].

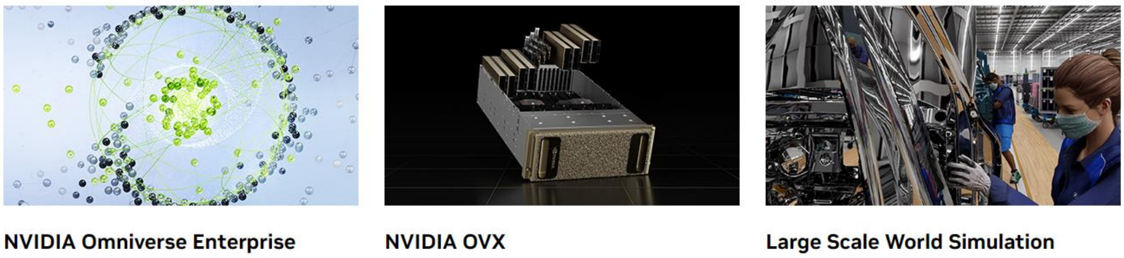


Figure 3-5 – Nvidia Omniverse concept [NVI24].

A relevant example of market evolution towards Metaverse is the introduction of VR headsets, whose market is still in its early stages of growth, but it is growing rapidly. According to Counterpoint Technology Market Research [Cou23], sales of VR headsets keep growing at a steady pace year after year with a compound annual growth of approximately 30% per year. In 2021, the unit sales of virtual reality (VR) headsets worldwide were forecasted to be about 6.1 million units. The following year, in 2022, the number of augmented reality (AR) and virtual reality (VR) devices shipped worldwide reached 9.11 million units. Concerning brands, in 2022 Meta was the leading VR headset company (Meta Quest 2), with over 40% of the market share. Sony is in second place (Sony Playstation VR), with over 15% of the market share. Other companies, such as HP, Pico and HTC, make up the rest of the market. At the end of 2022, it is estimated that about 36 million households have acquired any of these type of VR headsets worldwide, mainly in North America, EU and China, showing a penetration of about 1-2% of households, but massively growing. In 2023 there was a setback and a decline in sales of XR devices due to the absence of new innovative devices and attractive use cases for users but a recovery and significant growth is expected for 2024 (+50% YoY), given the availability of new devices such as those from Meta (Quest 3), Sony (Playstation VR2) and Apple (Vision Pro, available on the US market starting from February 2024) [JPR24].

The selected use cases, representative of the three Metaverse categories, described in their service evolution from today support by 5G, medium-term evolution with B5G and final development with 6G, are as follows:

- For Industrial Metaverse: Tactile Internet for Remote Operation in the context of Telemedicine, specifically Telesurgery.
- For Enterprise Metaverse: Academic/Professional Learning
- For Consumer Metaverse: Smart Tourism in the smart city.

3.2.1 Industrial Metaverse: Tactile Internet for Remote Surgery

Telemedicine introduces new healthcare management paradigms, where hospital hubs can be easily and dynamically connected by flexible 5G/B5G and 6G communications on a wide area covered by ambulances, remote clinics, medical offices, remotely available surgeons, and patients under constant clinical surveillance at home or wherever they are [NGM22].

Portable and intelligent medical equipment can be dislocated over this wide area allowing:

- tele-diagnosis by high-quality video and continuous vital signals monitoring for patients transported on ambulances to the hospitals, where a pre-triage evaluation can be performed, and personnel can be quickly prepared for faster intervention in case of life risk;
- tele-diagnosis for on-site medical aid in case of emergency situations;
- high quality medical analysis exchange between remote healthcare facilities and main hospitals, for easy remote medical consultation by specialized physicians;
- 24h remote health surveillance of fragile or elderly patients by means of wearable sensor devices, supporting medical staff to make timely treatment decisions and administer medication remotely;
- telerehabilitation, in which a therapist remotely controls a robotic avatar to perform patient's rehabilitation;
- remotely controlled robotic surgery, in all cases where a specialized surgeon is needed, wherever he is w.r.t. the surgical room.

In the 3GPP Release 17 summary of work items for 5G-Expansion [ETS23] it is found that performance requirements for these medical applications look out of reach for current 5G technology, especially for high quality video (even non-compressed and from different, contemporary sources) and low latency needs. Furthermore, these requirements are like those generated by VIAPA (Video, Imaging and Audio for Professional Applications) to which we refer for the Table 3-1 [ETS22].

As can be seen, UHD video or ultrasound images for medical examination can require bit rates even in the order of some Gbit/s and latencies are in most cases below 20 msec, both affordable only with B5G or 6G technologies.

Table 3-1: Requirements of medical application use cases [ETS22].

Profile	Characteristic parameter					Influence quantity				
	Communication service availability: target value in %	Communication service reliability: Mean Time Between Failure	End-to-end latency: maximum	Bit rate	Direction	Message Size [byte]	Survival time	UE speed (km/h)	# of active UEs connection	Service Area
UHD medical video over NPNs	>99.99999	>1 year	<1 ms	< 50 Gbit/s	UL; DL	~1500 - ~9000 (note 1)	~8ms	stationary	1	100 m2
Ultrasound images over NPNs	>99.9999	>1 year	<10ms	500 Mbit/s - 4 Gbit/s (note 2)	UL; DL	~1500	20-100 ms (note 2)	stationary	1	100 m2
UHD video for telesurgery over PLMNs	>99.9999	>1 year	< 20 ms	< 6 Gbit/s	UL; DL	~1500 - ~9000 (note 1)	~16 ms	stationary	<2 per 1000 km^2	<400 km (note 3)
UHD video for medical examination over PLMNs	>99.99	>1 month	<20 ms	<4 Gbit/s	UL; DL	~1500 - 9000	~16 ms	stationary	<20 per 100 km2	<50 km (note 3)
Ultrasound images over PLMNs	>99.999	>>1 month (<1 year)	<20 ms	<200 Mbit/s	UL; DL	~1500	~16 ms	stationary	<20 per 100 km2	<50 km (note 3)
CT/MR real time scan over PLMNs	>99.999	>>1 month (<1 year)	< 100ms	<670 Mbit/s	UL, DL	~1500	<100 ms	<150	<20 per 100 km^2	<50 km (note 3)

NOTE 1: MTU size of 1500 bytes is not generally suitable to gigabits connections as it induces many interruptions and loads on CPUs. On the other hand, Ethernet jumbo frames of up to 9000 bytes require all equipment on the forwarding path to support that size in order to avoid fragmentation.
NOTE 2: lower values considered for 2D ultrasounds images and higher values for 3D ultrasound images
NOTE 3: Maximum straight-line distance between UEs.

In the following, a deep analysis of the specific medical use case Tactile Internet for Remote Surgery is done.

Robot Assisted Surgery is a reality since the very end of the last century, when Da Vinci Robot was firstly used for coronary artery bypass graft surgery, and nowadays it finds application for a lot of minimally invasive surgeries (laparoscopic techniques). The main elements of a Surgery Robot are a patient cart with robotic arms having 360-degree movement for wristed instruments, visible and audible cues for guided navigation inside the patient's body (for example 3D endoscopic vision with highly magnified imaging on Full HD video), and a surgery console, externally placed w.r.t. the surgical room, based on joystick and pedal board for surgeon's remote manipulations [Int24]. The main advantage w.r.t. common surgery is precise medical operation with broader anatomical access through minimal tissue incisions, implying a fast patient recovery, even from important surgery like breast cancer removal.

Some trials have been recently performed on 5G ultra-remote telesurgery on animal model, performing controlled laparoscopic at about 3000 km distance, with an average network delay of 264 ms (including 114 ms of mean round-trip transport delay) [Zhe20].

In the 20ths, some human remote surgery with 5G support is also reported. In China, twelve robot-assisted spinal surgeries in different cities, all controlled by a master room in Bejing, allowing also one-to-many simultaneous operations, were performed with a mean network latency of 28 ms (as reported by China Telecom), [Tie20].

On September 2023, in the context of the BARIUM 5G Project, a remote corneal surgery was performed at Bari Polyclinic in Italy with the support of TIM 5G small cells, connecting the remote-control room and the operating room, and core network connection via 10 Gbit/s fiber backhaul link. Latency was below 50 msec, and Blockchain technology was adopted to ensure Data Security and Integrity, [Dux22].

Robotic technology advances move towards Intelligent Surgery Systems, supported by Augmented Reality (AR) and Artificial Intelligence (AI). In fact, in addition to super-imposed images related to guided navigation into the patient's body with computer tomography or magnetic resonance scans and 2D or 3D ultrasound, other AR tools are under development, like robotic cameras capable of emitting and quantifying tissue autofluorescence reflectance spectra (to highlight any microscopical pathology which require surgical resection). AI is another important field of progress for audio-visual and haptic feedback useful for surgeon's operation, for example with eye-tracking console system (the camera follows the eye and head movements of the surgeon) and with robotic arms feedback (e.g., on detected forces, feeling tissues consistency and consequently guiding surgeon activities), [HTe21].

Figure 3-6 –Telesurgery [RHC22] (image source: Corindus, Siemens Healthineers Company).

A recent systematic review (published on PubMed by surgeons and engineers) considers 5G transmission for remote surgery and presents all main issues about latency requirements for safe operation, textually highlighting that: "[..] there is no consensus as to what the safe or acceptable amount of latency is for remote telerobotic surgeries. There are more errors, and tasks take longer when surgeons are working under time delayed conditions. Latencies below 200 ms may be ideal, but impairment has been reported at 135 ms and even with time delays as small as 50 ms. Though successful robotic telesurgery has been reported with 450–900 ms of latency, surgery under latency greater than about 700 ms may not be feasible. Beyond work in basic surgical task models, there is a need to analyse performance with more clinically relevant robotic surgery tasks under time delay. Unfortunately, latency is not well characterized in the pre-clinical and clinical telesurgery literature. Future studies should recognize that signal latency is not static and changes over the course of a procedure. Most telesurgery publications only measure mean/average signal latency. The variance, or degree of time delay fluctuations, is never mentioned nor is its impact on a surgery ever mentioned" [Bar22].

In the second part of the 10th years, IEEE formed the 1918.1 Working Group to define and standardize the so-called "Tactile Internet", distinguishing between haptic information, i.e., the touch sense provided by the mechanoreceptor of the human skin, and kinaesthetic information such as force, torque, position, and velocity, perceived by skeleton, muscles and tendons of the human body, [Hol19].

The use cases identified for telesurgery are Teleoperation (for present and near future) and Immersive Virtual Reality - IVR (for long term).

Surgery Teleoperation has the already described characteristics, and it is considered a medium-dynamic environment in which latency requirements for haptic data exchange are between 10 msec and 100 msec.

If the Immersive Virtual Reality will take up space in future telesurgery, at least high-quality video is needed, with a communication latency below the motion-to-photon delay (the time difference between user's motion and the corresponding video image change), that amounts to less than 20 msec. Regarding the tactile sense, the kinesthetic signals feedback should be within 25 msec, implying a communication latency of less than 10 msec.

Another form of IVR for telesurgery has been considered by the ITU-T Focus group document for TIRO [ITU20-1], i.e., the Holographic Type Communication (HTC)- based video streaming method, by which the surgeon gets a real-time audio-visual feed of the patient and operating room, wearing a head-mounted device or interacting with a hologram.

Summarizing KPIs from IEEE, ITU, ETSI/3GPP for VIAPA with 5G-Advanced (Rel.17), and from Hexa-X project [Hex22], we can state the following requirements. Please consider that discrepancies between sources remain, so the values for a given parameter reported below are attributed by averaging the sources or providing a range of values, and excluding extreme values when they are very different from the others.

<u>Service Latency</u>:

- 0.5 ms ÷2 ms for highly dynamic haptic (HDH), 10 ms max for dynamic haptics (DH), 100 ms max for medium-dynamic haptics (MDH) (IEEE, [Hol19]).
- 5 msec for video and audio support (maximum to be unnoticed by human senses) (ITU-T, [ITU20-1]).
- 20 msec for UHD video over PLMN (Public Land Mobile Network) for 400km distance (ETSI/3GPP [ETS23], IEEE, [Hol19]).

<u>Synchronization</u>:

- lower than acceptable delay: 1 microsecond (ETSI/3GPP [ETS23]).

<u>Data Rate</u>:

- from 25 Mbit/s for 4K Ultra-HD 360º video to 1 Gbit/s for 32K video (mix of different inputs).
- 50M (4k), 200M (8k) (Huawei reports, [Hua17], [Hua18]).
- <50 Gbit/s for UHD over NPN (ETSI/3GPP, [ETS23]).
- from 160÷500 Mbit/s to >1 Gbit/s respectively for 2D or 3D ultrasound images (ETSI/3GPP, [ETS23]).
- 1.5 ÷ 6 Gbit/s for AR (mix of different inputs).
- 1 Tbit/s for Holographic Type Communication (HTC) (ITU-T, [ITU20-1]).

<u>Reliability</u>:

- High or very high, i.e., between 99,999% and 99,9999999% (Hexa-X1, [Hex22], and ETSI/3GPP, [ETS23]).

<u>Location Accuracy:</u>

- < sub-mm (Hexa-X1, [Hex22]).

Inferencing Accuracy (for real-time decision making):

99,999% (Hexa-X1, [Hex22]).

High Safety, Integrity, Maintainability and Interpretability level (Hexa-X1, [Hex22]).

Remote telesurgery with 5G-Advanced and 6G will have to face and solve these challenges, achieving ultra-High Sensing Low Latency Communications (uHSLLC), together with Security (uHS), Reliability and Sensing (uHRS), management of huge amount of data (uHDD) and very high bandwidth.

Regarding video transmission, despite the theoretical 5G bandwidth limit of 1 Gbit/s, present maximum capacity amounts to 800 Mbit/s, not sufficient to support future image resolutions. Furthermore, considering the multi-imaging guided surgery and the AR tools, where some Gbit/s for simultaneous video transmission are assumed, these could be supported only by 5G-Advanced or 6G. If we also consider a natural evolution towards Hologram Types Communication (HTC) for Tactile Internet, as described in the ITU-T Focus group where the bandwidth transmission demand could potentially reach the Tbit/s level, this could be achievable only with the 6G technology.

Regarding latency, the minimum 5G theoretical value amounts to 10 msec, but real applications have always registered a round-trip delay higher than 10 msec, with good performances in between 15÷20 msec. Better latency values, also below the millisecond, require different access radio technologies, together with packet prioritization schemes, achievable only with the introduction of 5G-Advanced and 6G.

A summary of present (5G), medium term (5G Advanced) and long term (6G) requirements on latency and data rate for the Telesurgery use case are reported in Table 3-2.

Table 3-2 - Telesurgery requirements from different references.

Mobile Generation / Time period	Latency [ms]	Data Rate [Gb/s]
5G / Present	20 (MDH, UHD) 100 (MDH, HD)	0.2 (UHD) 0.025 (HD)
5G Advanced / Medium term	5 (DH, AR) 20 (MDH, UHD)	1.5 (AR) 0.2 (UHD)
6G / Long Term	0.5 (HDH, XR) 5 (DH, UHD/AR)	6 (XR) 0.2-1.5 (UHD)

3.2.2 Enterprise Metaverse: Academic/Professional e-Learning

Mobile technologies are strategic to complement broadband fiber communications for Education purposes. One of the most significant examples is given by the joint UNICEF-ITU “GIGA” initiative, that has the ambition to connect every school worldwide to Internet by 2030 (see Figure 3-7, [Gig30]).

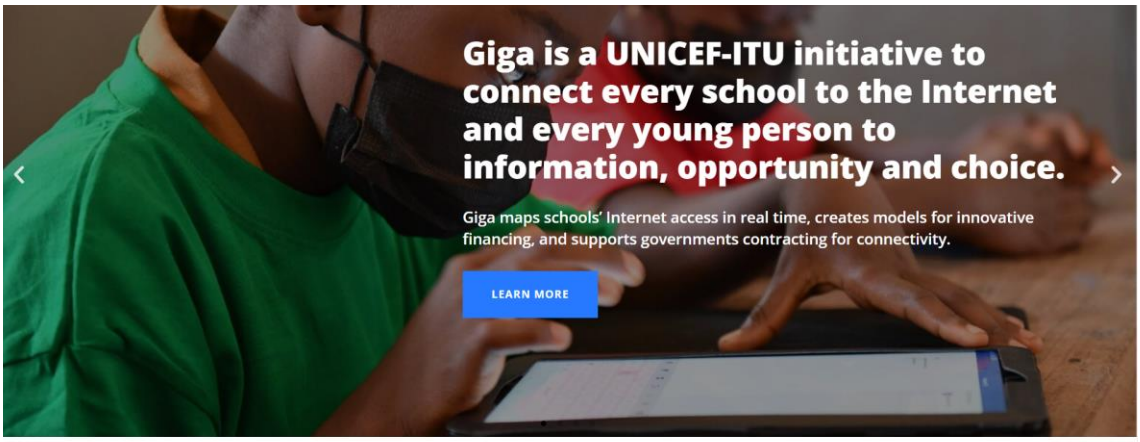


Figure 3-7 –UNICEF-ITU initiative to promote school for everyone [Gig30].

In this context, Ericsson has become a UNICEF global partner "to help to identify connectivity gaps in 35 countries", by analysing "mobile network coverage data" and extracting "valuable insights to build intelligent, automated systems that amplify the potential for connectivity in schools".

For this purpose, the company has also commissioned to "The Economist Intelligence Unit" a report in which all the barriers, needed priorities and economic advantages of e-learning for young people and for an entire community are analysed. It highlights the role of Internet in enhancing the quality of education both for students, that have access to unlimited learning materials (books in every language, live or pre-recorded lessons, tutoring/personalized education and so on) and for teachers, that can professionally grow and teach more effectively. While the Internet access is "increasingly becoming a human right", it reports that in 2021 "the global Internet penetration [...] remains only just over 50%" with [...] "large disparities between, and within, countries across rural and urban populations. In developed countries, 87% of the urban population has access to the internet. In the least-developed countries, the figure stands at only 25%—and for the rural population, access is even lower at 10%. [...] Globally, it is estimated that 2.2 billion children and young people under the age of 25—or two-thirds of this age group—do not have access to the internet." [Eco21].

At present, Ericsson reports that "5G can play the most important role in bringing reliable broadband access to schools" and that FWA seems the most adequate and cheapest solution to overcome the digital divide in underserved communities, like rural/remote areas in countries with inadequate fixed broadband access like India, or Senegal, where several schools have been connected with FWA "together with laptops, learning content, and teacher training to develop the ecosystem" [Eri24-1].

Some trials have been carried out in other countries to evaluate more advanced e-learning possibilities, like AR/VR experiences and remote robot control, as textually reported in the following: "[...] Ericsson partnered with NOS, a leading communications and entertainment group in Portugal, to develop technological projects in a school in Matosinhos. The 12th-grade Science and Technology students used a virtual reality solution over 5G to visit a science museum located over 300km away in Lisbon. The students remotely controlled a robot equipped with a 360º camera and interacted with the museum exhibits in an immersive and realistic way". [...] In addition, Ericsson and DNB conducted a landmark 5G technology showcase in Sarawak, Malaysia. The technology allowed for a seamless interaction between a lecturer at University of

Technology Malaysia (UTM), Kuala Lumpur, and a group of students located 1,400km away at Curtin University, Miri, using AR/VR headsets. The lecturer and students interacted with each other as if in the same physical environment, with no noticeable delay". [Eri24-2]

The University of Milan is offering an online bachelor's degree on Security of Computer Systems and Networks (SSRI) for 20 years, encountering difficulty in organizing synchronous interactive educational sessions (with a student population mainly constituted by already employed people) or sharing high-quality materials. In 2019 it analysed the application of 5G technology to e-learning, to evaluate the fulfilment of the following desired requirements [Bar19]:

- High-quality video broadcasting from teacher to about 100 simultaneously connected students.
- Immersive experience like Virtual Access to a huge computer centre managed by the teacher for education-in-laboratory purposes.
- Sharing of high-quality video between students for discussion and comparison of lab works during lessons.

For what it concerns video broadcasting, the consideration that online students form extemporary classrooms, dynamically requesting access to a content stored in a remote server, immediately implies that only the unicast distribution is a viable solution for the e-learning scenario, thus imposing data replication for each destination user, with consequent mobile network load. In their publication, the researchers evaluated many European 5G trials occurring in 2018/19, realizing that the most realistic measures (conducted in a Finnish urban area, with a reasonable user density) achieved download/upload data rates respectively of 700 Mbit/s ÷ 1 Gbit/s and 100 Mbit/s, and latencies in the order of a few milliseconds. They commented that this is in line with ITU-R M.2012-5 Recommendation [ITU12], which though makes a distinction in download bitrate between 1 Gbps for (almost) stationary users and 100 Mbps for high mobility users.

They also reviewed bandwidth, latency, and reliability for the different multimedia applications, as summarized in Table 3-3.

Comparing these bandwidth needs with the 5G demonstrated goals, and considering that online students can also need to take courses in mobility (for example during travels between home and workplace and vice versa), they realized that this technology can support a very good number of (almost) static learners per mobile cell, i.e., up to 100 contemporary students per cell watching a 2D/3D HD video and about 50-60 students in case of 4K video, but these numbers drastically reduce of one order of magnitude in case of course fruition under high mobility. Limitations are also present in case of AR/VR content distribution, since the high required bandwidths imply that either a poor-quality service is distributed to a maximum of 10 simultaneous students per cell or a quite good quality AR/VR application is available only for a single apprentice per cell, thus hindering experience sharing. Indeed, the concept of extemporary classroom, formed by parallel learners diffused on a large territory served by many different mobile cells, mitigates these worse impacts on allowed students' number. From a theoretical point of view, they also evidenced that simultaneous coexistence of both eMBB service for high quality video and URLLC service for AR/VR application is still an issue to overcome, since they will compete for network resources and might delay network access for eMBB traffic, thus affecting performance.

Table 3-3 - Bandwidth, latency and reliability requirements for multimedia applications [Bar19].

	Bandwidth	Latency	Reliability
Standard A/V streaming	≤ 3 Mbps	4 – 5 s	≥ 95%
HD video streaming	4-8 Mbps	4 – 5 s	≥ 95%
3D HD video streaming	9 Mbps	4 – 5 s	≥ 95%
4K video streaming	25 Mbps	4 – 5 s	≥ 95%
Interactive real-time conferencing	≥ 2 Mbps	~ 100 ms	99% – 99.5%
AR	100 Mbps – 5 Gbps	1 ms	99% – 99.5%
VR (interactive)	100 Mbps – 2.35 Gbps	10-30 ms	99% – 99.5%

All these considerations and given examples highlight the good outlook that the introduction of 5G-Advanced and 6G could take in the e-learning field, both in the Academic and Professional context, to move towards totally immersive tools, as those defined by IEEE 1918.1 Standard on Tactile Internet or by the IOWN Global Forum document on AI-Integrated Communications Use Case [Tac14], [Hol19].

The work done by the IEEE Standard highlights two suitable use cases, namely Immersive Virtual Reality (IVR) and (Haptic) Interpersonal Communication (HIC/IC).

In IVR, users are supposed to perceive all five senses (vision, sound, touch, smell, and gustation) while interacting with virtual entities in a high-field virtual environment, as if it was the real physical world. Transmission latency for high quality-video should be below the motion-photon delay, amounting to less than 20 msec. The kinesthetic signals feedback should be within 1÷50 msec, depending on the dynamicity level. The IVR environment can therefore be exploited for Digital Academic laboratories or Professional e-Learning Platforms, in which students or workers can be trained by instructors (even remotely located) on digital twins representing virtual entities/devices/machines they should become expert on.

In IC, the interpersonal communication in a virtual classroom or in a virtual work meeting is enriched by creating human models (avatars) of each participant at local and remote sites, with a continuous exchange of nonhaptic data (gestures, head movements and posture, eye contact, facial expressions). In HIC, a further social interaction enhancement is achieved by introducing tactile or kinesthetic information to reproduce the various types of human touch, such as the handshake, to realistically feel the presence of a remote user. Also in this case, service delays vary according to their criticality, with a maximum being between 50 msec and 200 msec, respectively for highly dynamic and static/quasi-static interactions.

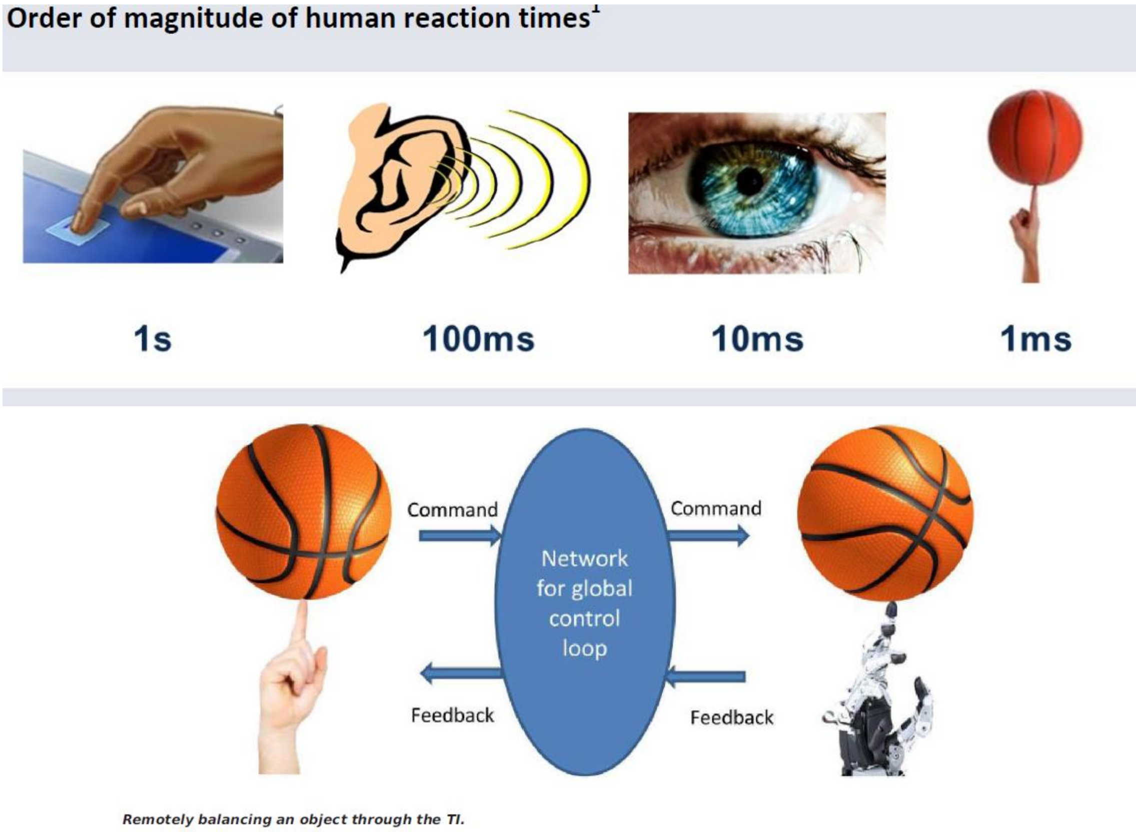


Figure 3-8 – Human reaction to sensory stimulus and its application to Teleoperation [Tac14].

In the IOWN Global Forum document [IOW21-2], the Professional Learning subject is tackled considering the requirements for XR (eXtended Reality - encompassing VR, AR and Mixed Reality) achieved by stereoscopic binoculus or glasses and, in the long future, Holographic Type Communications (HTC) achieved by glasses-free, truly holographic 3D displays(a pictorial view is in Figure 3-9). Stringent requirements are considered, to assure high QoS and reliability for synchronized rendering of audio, video and haptic response.

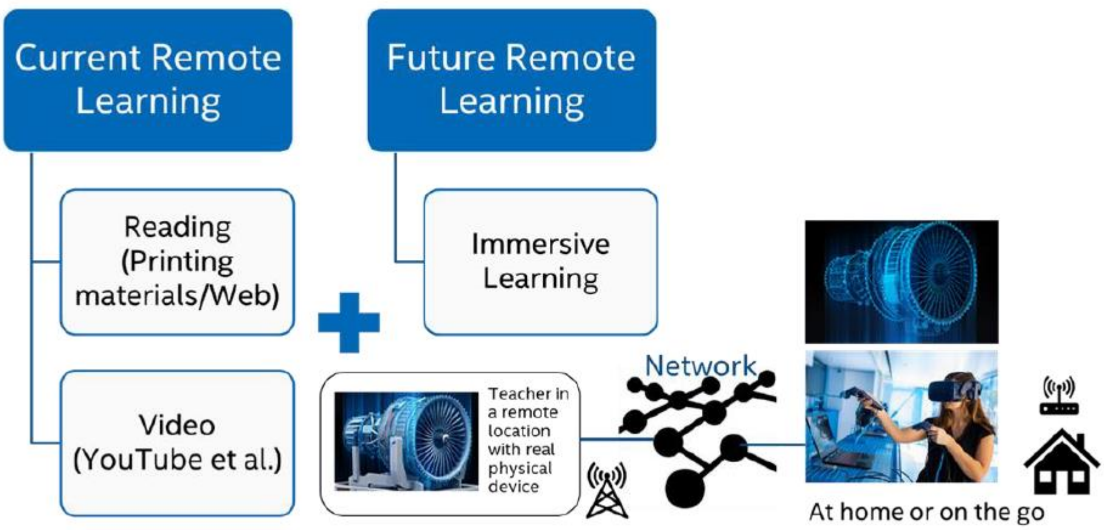


Figure 3-9 – Professional learning. [IOW21-2].

Requirements on data volume per each student or instructor are the following:

- for 8Kx8K 3D visual field: 2.35 Gbit/s.
- for Holograms: from 100 Gbit/s to 4.32 Tbit/s.

It is evidenced that the Tbit/s order of magnitude is for uncompressed volumetric capturing, while deep compression is avoided in order to guarantee a minimal delay. In the operating conditions in which compression is acceptable, in any case it would be at least in the order of hundreds of Gbit/s.

Requirements on data velocity for presentation (Time To Present-TTP) or control (Time to Control, TTC) are the following:

- TTC without haptic function: 10 ÷20 msec.
- TTC with haptic function: sub-ms÷2 msec.
- TTC + TTP for haptic feedback: 5.5 msec.

Requirements on scalability are:

- 1÷10 students within a cell.

Requirement on network jitter is 1 ms.

Requirement on network reliability is 99,9999%.

A summary of present (5G), medium term (5G Advanced) and long term (6G) requirements on latency and data rate for the AcademicProfessional Learning use case are reported in the following table:

Table 3-4 - Academic/Professional learning requirements from different references.

Mobile Generation / Time period	Latency [ms]	Data Rate [Gb/s]
5G / Present	20 (VR, MDH) 1000 (HD)	0.1 (VR) 0.025 (HD)
5G Advanced / Medium term	5 (DH, XR) 20 (VR, MDH)	2.35 (XR) 0.2 (VR+)
6G / Long Term	0.5 (HDH, HTC) 5 (DH, XR)	100 (HTC) 2.35 (XR)

3.2.3 Consumer Metaverse: Virtual Tourism in Smart City

Virtual Tourism is part of a broader theme known as Smart City, in which different stakeholders like Municipality, Solution and Content Providers, Telco Providers, etc. are involved in supporting evolved city services like efficient mobility, security solutions, and enhanced city tours to the final users, i.e., Citizen and Visitors, by means of 5G and B5G/6G solutions. In this context, one of the ultimate, futuristic goal will be the Smart City Metaverse [IOW23], that will foresee a replica of the real city (a digital twin) for different purposes, like governance on city infrastructures (e.g., simulation of effects of interventions on city assets like buildings and roads, to prevent errors on planning or accidents).

First experimentations of city replica just concern Touristic attractions like Museums and Parks, as described in the European Projects named 5G TOURS [5GT20] and TRIALSNET [Tri24].

5G TOURS activity on virtual tourism, between 2019 and 2022, focused on AR, to complement and improve the real touristic/cultural experience, and VR, to extend these experiences to a larger population, done by people settled elsewhere, in different locations, cities or countries, giving the possibility to enhance their cultural knowledge, with consequent social benefits, for example for disabled or economically disadvantaged persons. Some use cases have been performed by TIM in Turin historical sites, either indoor (such as museums) or outodoor (such as monuments, streets and squares). As an example, an Augmented Tourism Experience Mobile App was available for immersive and interactive experiences inside museums, like multimodal media contents (superimposed to real visualizations) as audio and video guides on rooms and artworks, even in 3D format (see Figure 3-10). Furthermore, a VR experience for remote visitors was available, done with a Head Mounted Device and a WebXR-enabled browser Mozilla API. These VR trials also included an interactive game for remote students, who could create their own compositions starting from the exposed paintings. Also, a Telepresence use case was performed by means of robot-assisted museum tours; a robot was also used for museum operators' remote surveillance. Finally, a mobile application also allowed users to interact with Smart City services for tourists, obtaining information on logistic (transport, opening times, crowding, etc.) and environment (weather conditions, pollution, solar radiation), provided either by the Municipality or by sensors devices deployed in the area covered by the trial.

Figure 3-10 – Example of AR experience in Palazzo Madama (Turin).

All these use cases required 5G mobile services supplied by means of a 3GPP Release 15 Non-Stand-Alone (NSA) network infrastructure, developed in the context of the 5G-EVE project [5geve], exploiting either the TIM 5G in-field Core network in Milan or a Turin in-lab EPC solution with an Orchestrator based on ETSI MANO NFV, able to manage Network Slicing, since some use cases required a mix of eMBB, URLLC and mMTC services, and also various network requirements had to be satisfied, depending on the specific use case.

The average requirements measured during the trials have been the following ones:

- Round Trip Latency:
  - 20 ms for URLLC in AR/VR, 50 msec in Telepresence.
  - 50 msec for mMTC in AR/VR, 100 msec in Telepresence.
  - 100 msec for eMBB in AR/VR.
- Data rate: 40÷600 Mbit/s for AR/VR, 30 Mbit/s for Telepresence.
- Reliability 99,9999% for AR/VR, 99,999% for Telepresence.
- Mobility: 10 km/h for AR/VR, 0,5 km/h for Telepresence.

Some impairments in the AR use case were observed.

The QoS results have been correlated also to the Quality of Experience of the trials users.

A fair QoE was notified by visitors whose latency was in between 30÷40 msec for the URLLC service slice, or in between 75÷100 msec for the eMBB slice, or in between 150÷200 msec for the mMTC slice.

A good QoE was notified by visitors whose latency was in between 20÷30 msec for the URLLC service slice, or in between 50÷75 msec for eMBB slice, or in between 100÷150 msec for the mMTC slice.

An excellent QoE was evidenced by visitors whose latency was below 20 msec for the URLLC service slice, below 50 msec for eMBB slice and below 100 msec for mMTC slice.

The Trialsnet project, that is a sort of prosecution of 5G-TOURS, envisages two use cases in Turin, devoted to XR Museum Experience and City Parks in Metaverse (for locations not physically available by visitors). The supporting mobile technologies are Baseline 5G (Rel.15 and following Rel.16 upgrade) and Advanced 5G (Rel.17 and Rel.18), this last one with technology improvements in terms of Artificial Intelligence (AI) based services (AIaaS) and Orchestration, Digital Twinning and Time Sensitive Networking (TSN), empowering the synchronization and deterministic communication of time-critical data.

Figure 3-11 – VR in Borgo Medievale (Turin).

The commercial TIM XR Platform and the experimental TIM XR Streaming Platform allow AR/VR or Mixed Reality (MR) services, with a difference related to the rendering functionality of the 2D/3D digital content, that is respectively performed either by the end user device or moved to the Cloud (server with render APP) regardless of the user equipment. In this last case, high bandwidth and low latency requirements are due to the network.

The extreme VR experience envisaged by the Park Metaverse is the visitors' transportation into an ancient time period, specifically into a Medieval Village ("Borgo Medievale", reproduced inside the most important Turin green park - Valentino Park), that will be closed for major restoration and renovation works between 2024 and 2026. A 3D Digital Twin of the Borgo (see Figure 3-11) will be produced as an immersive environment for the visitors' avatars, allowing users to feel like they are walking through its alleys, interacting with buildings, objects and other users. The user device will be the META Quest 2 or 3 Headset, that could be replaced by the end of 2023 by Apple Glasses; the video flow is a Full HD flow per each eye.

Present average requirements for the Park Metaverse use case, related to the present 5G NSA mobile network available solution, are similar to the requirements related to the VR services in the previous project, i.e.:

- Round Trip Latency:
  - 20-30 ms per user (including 10 ms latency on app).
- Data Rate:
  - 40 Mbit/s per user (for Full HD on two eyes).

The users' number in the trial is presently limited to 4-5 users, implying a total data rate of about 200 Mbit/s.

In the future, with the advent of new video formats on visors, like 8K video flows per eye, and the increasing number of simultaneous users that should be supported by commercial, widespread virtual tourism solutions, at least the B5G technology should be necessary, that will in turn be replaced by the 6G implementation when holograms will become a usual way to interact in an immersive environment.

A summary of present (5G), medium term (5G Advanced) and long term (6G) requirements on latency and data rate for the Virtual Tourism use case are reported in Table 3-5.

Table 3-5: Virtual Tourism requirements from different references.

Mobile Generation / Time period	Latency [ms]	Data Rate [Gb/s]
5G / Present	20-30 for URLLC in VR 100 for eMBB in AR	0.04, per user for 2 Full HD flows in VR 0.6, maximum experimented rate
5G Advanced / Medium term	1-20 (XR)	2,35 per user for 8k x 8k in XR
6G / Long Term	<1 (HTC)	100 per user in HTC

3.3 FURTHER DRIVERS

3.3.1 Traffic growth predictions

Predicting the evolution of traffic in networks is really difficult because, as well known, it depends on many factors, and among them the emergence of new services or use cases that can determine a significant change both in the volume and in the distribution of traffic in the network. Initially, within the SEASON project and as a preliminary selection, three representative use cases to be considered in SEASON project are chosen, i.e., Professional Learning, Citizen Security and Tactile Internet for remote operations. Data rate and latency requirements have been expressed for each of them; these characteristics will have to be considered in the formulation of case studies in the project.

However, to define the overall network requirements, it is necessary to consider not only the new use cases, those that could potentially give rise to disruptive traffic requirements (possibly also very stringent latency or reliability requirements that impose constraints to network architecture and dimensioning), but also the background traffic which continues to be present and to grow with percentages ranging from +20% to +40% year over year, depending on the geographical context and on the segment of the network (i.e., metro vs. backbone).

In a work done within the B5G-OPEN project [Rui23] a traffic model was built. The traffic model is based on a realistic characterization of the network and assuming a background traffic to which is added a traffic coming from two use cases deemed particularly significant (Digital Twin for industrial applications and delivery of contents in Volumetric Video format). In the study reported in [Rui23] the traffic flows exchanged at the various levels of the network were calculated. Expected traffic exchanged at the level of access nodes, regional nodes and nodes of the national backbone are provided for three time horizons, i.e., short- (≈2026), medium- (≈2029) and long-term (≈2032).

Results of such traffic analysis are summarized in Table 3-6. The values of traffic reported on the table can be used as rough guidelines to estimate what type of transmission and switching technology is needed in different network segments. For example, for the access nodes which take part of the aggregation metro segment, the flows directed to other nodes (mainly to regional nodes) are expected to be up to 2 Tb/s in the medium-term and up to 8 Tb/s in the long-term. Regional and National nodes, according to the traffic estimation, should handle overall traffic of the order of a few Tb/s in short-term, ten Tb/s in medium-term and up to hundred Tb/s in long-term.

Table 3-6 – Traffic exchanged by Central Offices at different level of Network architecture and different segment of the network as reported in [Rui23]. Values of traffic prediction are given for three reference periods in the future (Short-, Med- and Long-Term). Values in table are for downstream direction (upstream is lower).

From Central Office (CO)	Network Segment Involved	Short-Term (Tb/s)	Medium-Term (Tb/s)	Long-Term (Tb/s)
Access CO	Metro Aggregation	0.25	2.0	8.0
Regional CO	Metro Aggregation and Metro Core	1.2	9.8	38.3
National CO	Metro Core side	2.5	21.1	111.1
National CO	Backbone side	1.3	11	44.1
International Gateway	Backbone	3.2	41.4	171.7

3.3.2 Reuse of existing fibers and need for new deployments

The point of view of the two operators involved in the SEASON project regarding the current availability of fiber and the potential need for new deployments in their networks has already been reported in an internal project working document (Milestone MS2.1). Hereafter a summary of the development prospects of the networks linked to the exploitation of the existing fiber or the laying of new fiber taken from the above mentioned document (MS2.1) is provided.

The major investment in the short and medium-term will be concentrated in the access part of the networks, where the provisioning of broadband access is still to be completed (or even to be started, particularly in low profitability areas such as the rural ones). Due to its optimal characteristics, the optical fiber being deployed is, and will continue to be for some time, the G.652 D. The optical fiber deployment should be completed in a few years, and, at that point, it is expected that for a fairly long period (something like twenty years) the physical infrastructure will not be modified. Nonetheless, it will be possible to act on selecting the appropriate access technologies (new PONs like the coherent one, etc.). In a still undefined time frame (presumably within four to five years), the deployment of 5G RAN will also be completed and, at that point, all the use cases with stringent bandwidth and latency requirements will be enabled, even for those users who access the network resources via radio links.

In the short and medium-term, a large-scale fiber installation for metro-regional and backbone segments is not foreseen. Instead, it will be limited to precise needs where fiber shortage or aging require targeted interventions. This is true at least for incumbent operators who have substantial assets in terms of deployed fiber. The unknown is posed by the on-field durability of fibers that have an age of 20 or more years, which may soon need to be replaced. As for access, the main candidate fiber for these network segments is G.652D.

Therefore, for metro-regional and backbone networks, the main challenge for the next years is to support the increasing network capacity by almost exclusively leveraging the already existing optical fiber infrastructure. The appropriate technologies to achieve this goal are multiband (mainly C+L-band transmission but also possibly exploring a third transmission band to be evaluated on a case-by-case basis) and space division multiplexing (SDM), in the multi-fiber version.

Instead, in the long-term period (starting from seven to ten years from now, depending on technologies and markets evolution), we can imagine a massive deployment of new generation of optical fibers, possibly even multicore, and a further upgrade of multiband over SDM techniques (with multiband extended to all exploitable bands and SDM done on multicore fibers). However, this scenario is rather uncertain in terms of time and ways in which it will take place, and it should be investigated as a possibility offered, for example, by long-term technologies under analysis in the SEASON project.

3.3.3 RAN interfaces data rate and latency

The 3GPP New Radio (NR) specification allows radio channels of up to 400 MHz (even 800 MHz) and Massive Multi Input Multi Output (MIMO) (up to 64 TX/RX and above) in the RAN [Par17]. The use of Massive MIMO is well known to introduce important spectral efficiency gains. For instance, 8x2 MIMO provides 95% extra gain with respect to 2x2 MIMO, while 16x2 and 64x2 MIMO increases the efficiency to 192% and 199% respectively, as shown in [Gho17].

State-of-the-Art RAN implementation is moving from monolithic Base Transceiver Station (BTS) to distributed architecture, where the network functions are distributed across different modules, usually Radio Unit (RU), Distributed Unit (DU), or Centralized Unit (CU). Between those elements, Fronthaul (FH) and Midhaul (MH) interfaces are defined.

Different standardization bodies and alliances defined own specific functional split options, that subordinates the compliancy, for low-level split (nearest to the radio interface) that defines the fronthaul interface, and a wide used naming comes from 3GPP TR 38.801 (used in this document see [Kra17]), where the physical split is 8, other options are 7.1 and 7.2, while O-RAN suggested an intermediate approach called 7.2x. Other split namings come from eCPRI (v2), NGNM, Small Cell Forum, most popular splits are suggested by all bodies, with different names.

Depending on the functional split used in the FH and MH sections, different radio processing functions are more centralized or distributed, leading to FH bandwidth requirements of hundreds of Gb/s (even Tb/s) of bandwidth and ultra-low latency [Her21-1], thus needing for a transport optical network based on Multi Band over Spatial Division Multiplexing (MBoSDM).

New Radio (NR) is based on OFDM, very much like LTE, but it allows for flexible numerology with subcarrier spacings ranging from 15 kHz up to 240 kHz. The exact calculations on FH, MH and Backhaul (BH) capacity required to the transport network depends on multiple parameters, namely the functional split, the radio bandwidth (from 10 MHz up to 400 MHz), the MIMO configuration (both ports and layers), etc. A good theoretical overview of the functional splits and estimates of throughput needed is provided in [Wub14], and further refined in [Ote19, Her21-1, ORA21].

The bitrate necessary for 3GPP Split 8 (same as split E in eCPRI notation) can be computed using the classical sampling and quantization equations of analog radio signals. In general, Split 8 (CPRI-like) represents the case with the highest bitrate and low-latency requirements and is the one that most stresses the FH networks. Other options, like Split 7.2, require slightly less bandwidth but have the same latency requirement, i.e., 250 µs.

Table 3-8 presents some examples of 5G NR configurations requirements in terms of latency and data rate (FH segment) and their required bitrates for splits 8 and 7.2 [Tou17], with 30 bits for representing I and Q symbols. The bitrate values are indicative since the exact values depend on multiple parameters that may vary from one implementation to another, namely subcarrier spacing, timeslot duration, number of bits for I and Q symbols (mantissa and exp), number of MIMO antennas and layers, etc. While these numbers are purely theoretical, the next section shows examples of FH requirements for realistic (in-field) deployments of the network operators participating in SEASON.

Table 3-7 – Examples of 5G NR single-cell requirements.

Radio bandwidth	20 MHz	50 MHz	100 MHz	200 MHz	400 MHz
Subcarrier Spacing (Df)	15 kHz	15 kHz	30 kHz	60 kHz	120 kHz
N_{sc}	1200	3000	3000	3000	3000
T_{slot} (ms)	1 ms	1 ms	0.5 ms	0.25 ms	0.125 ms
T_{OFDM}	66.67 µs	66.67 µs	33.33 µs	16.67 µs	8.33 µs
Bitrate split 7.2 (no MIMO)	0.54 Gb/s	2.7 Gb/s	2.7 Gb/s	5.4 Gb/s	10.8 Gb/s
Bitrate split 7.2 (16 MIMO layers)	8.64 Gb/s	43.2 Gb/s	43.2 Gb/s	86.4 Gb/s	172.8 Gb/s
Bitrate split 8 (no MIMO)	0.92 Gb/s	4.6 Gb/s	4.6 Gb/s	9.2 Gb/s	18.4 Gb/s
Bitrate split 8 (16 MIMO layers)	14.72 Gb/s	73.6 Gb/s	73.6 Gb/s	147.2 Gb/s	294.4 Gb/s
Max FH Latency	250 µs				

3.3.4 Evaluation of scenarios for the evolution of the radio-station bandwidths

A key driver for the end-to-end architectural design we are developing in SEASON is the forecast traffic growth and consequent capacity and bandwidth expansion at the radio stations, motivated by the increasingly widespread use of, e.g. high resolution video on mobile devices, and the emergence of new applications, many of which will only be made available by the upcoming sixth generation mobile system standards, currently under development. This topic was first discussed in an internal project WP2 document (MS2.1) where we reviewed previous studies on forthcoming 6G applications, such as [ITU20-1, ITU20-2], and selected three use cases that have the potential to put significant stress on future transport networks in general and the metro-access segment. We exemplified the impact that application bandwidth requirements would have on the mobile access network depending on the functional split options [3GPP17] by applying the equations provided in [Fio15] for split 8 and [ORA21] for split 7.2x to a simple scenario.

This is an extension of the work initiated in MS2.1 that present three scenarios for the evolution of the radio site bandwidth in the medium- and long-term that will help in dimensioning and provisioning the transport network for MH and BH assuming a statistic multiplexing gain. As indicated in [ORA21], there are three steps in carrying out this work: (1) the calculation of the peak rate per sector within a site, (2) the addition of MH and BH overheads, and (3) the calculation of peak and average site usage, as well as applying statistical multiplexing factors for the various parts of the transport network. Figure 3-12 depicts a schematic for these three evolutionary scenarios along with a benchmarking scenario relying on the most powerful radio configuration available today (64T64R and 16-layer mMIMO).

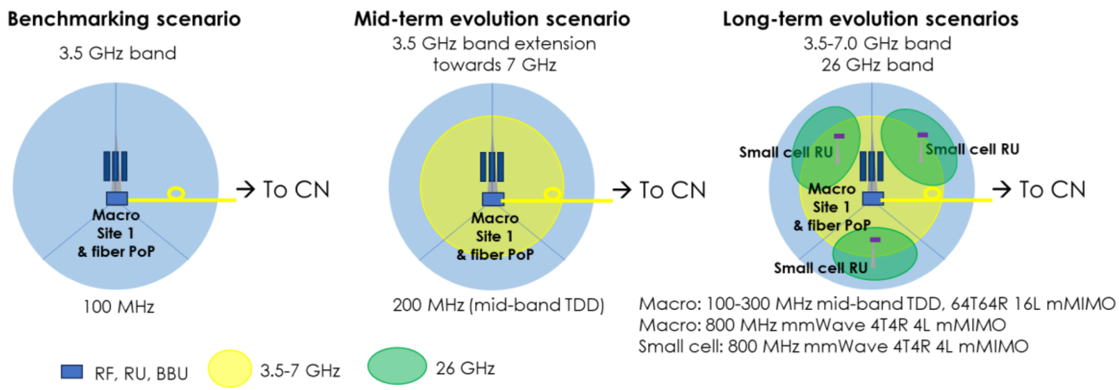


Figure 3-12 – Benchmarking and mid-term and long-term realistic scenarios for the evolution of the radio-station bandwidths. The blue box represents RF, RU or BBU depending on the functional split option.

In all cases, the study is conducted for densely populated areas with inter-site distances of 300 m. As benchmark, we considered a radio site consisting of a macro cell with a radius of 150 m and three sectors with available spectrum spanning 100 MHz in the 3.5 GHz TDD band (see Figure 3-12, left), assuming shifted 8:2 frame format (for compatibility with legacy LTE3:1 DSUDD) as used in several European countries (also DDDSU is used with some impact, see [GSM20]).

The 700 MHz FDD band, with allocations available in many regions, was disregarded as its contribution to the radio site capacity is typically small because of spectral portions of only around 10 MHz are generally available and MIMO configurations are much simpler (e.g., 4T4R). Over time, it is expected that portions of the spectrum currently used for previous mobile standards (2G to 4G) will also be re-farmed and available for 5G, adding capacity per site. In any case, to study the impact of the access network evolution and radio architecture on the transport network, it suffices to consider TDD bands with larger spectrum allocations and mMIMO configurations.

Table 3-8 – Bandwidth required for the benchmarking and the three evolutionary scenarios presented in Figure 3-12, in the fronthaul (split 7.2 O-RAN), for eCPRI connections in split 8, and in the backhaul (no split). Equations in [Fio15] and [ORA21] were used for split 8 and 7.2/no-split, respectively, with the parameters shown below the table, assuming decorrelated traffic from users and antennas (in the scenarios with a macro cell and multiple SC). In the last two columns the transmission requirements generated by one radio site and three sites (aggregated at a fourth site) are shown.

	Available spectrum (MHz)	Nº sectors	Radio site peak (Gbps)	Radio user peak (Gbps)	Radio site capacity (fully loaded) (Gbps)	Macro site capacity density (Gbps/km²)	RAN functional split option	Transmission requirement (1-site) (Gbps)	Transmission requirement (3-sites) (Gbps)
Benchmark	100	3	6.7	1.7	1.7	22	backhaul	8.5-10	8.5-15
							split 7.2x	102	408
							split 8	1100	4400
Mid-term	200	3	13.4	3.4	3.3	43	backhaul	17-20	17-30
							split 7.2x	204	816
							split 8	2200	8800
Long-term (Conservative)	100 +800	3 @ macro 1 @ SC	31	26	10	128	backhaul	41-50	44-82
							split 7.2x	500	2000
							split 8	2250	9000
Long-term (Aggressive)	300 +800	3 @ macro 1 @ SC	45	30	13.5	173	backhaul	59-70	59-112
							split 7.2x	700	2800
							split 8	4500	18000

Therefore, the evolutionary scenarios contemplated in our evaluation can deliver progressively larger access capacity per macro site area, having selected, for a mid-term slightly conservative scenario (Figure 3-12-center), 100 MHz additional bandwidth in the 3.5 GHz - 7 GHz band. For the long-term, on the other hand, we considered two additional evolutionary scenarios adding a larger spectrum allocation in mid-band TDD as well as high-band expansions including macro and small cells to deliver a much higher capacity density per macro site area. The radio site is composed of a macro cell and three small cells, as depicted in Figure 3-12 right. For the small cells (SC), we assumed 4T4R, 4-layer mMIMO, one sector, and 800 MHz bandwidth in the 26 GHz band, with an operating radius of 50m. For the macro cell, we assumed 100 MHz (more conservative long-term scenario) or 300 MHz (more aggressive long-term scenario) in the 3.5 GHz band, and 800 MHz in the 26 GHz band (radius of 50m).

The calculated required bandwidths for different FH (split 7.2x O-RAN and eCPRI split 8) compared to backhaul (legacy no-split approach), for each scenario presented in Figure 3-12 are shown in Table 3-8. Equations in [Fio15] and [ORA21] were used for split 8 and 7.2x, respectively, with the parameters shown below the table, assuming decorrelated traffic from users and antennas (in the scenarios with a macro cell and multiple SC). In the last two columns the transmission requirements generated by one radio site and three sites (aggregated at a fourth site) are shown. The radio values do not include the air interface protocol overhead.

The parameters used for the calculations, besides the spectral widths used in each scenario (which were indicated above), are:

- For the mid-band macro:
  - 16 layers, 64 antenna ports, 30kHz carrier spacing.
  - Average spectrum efficiency (loaded network) ~ 7.5b/s/Hz in downlink.
- For the mmWave macro and SCs:
  - 4 layers, 4 antenna ports, 120kHz carrier spacing.
  - Average spectrum efficiency (loaded network) ~ 2.5b/s/Hz in downlink.

Spectrum efficiency figures were set according to internal references, with values being highly dependent on deployment environment and hardware.

It must be noted that, aside access bandwidth increase, evolution in the RAN access hardware affecting available MIMO layers and antenna ports will have a direct impact on transport figures, as MIMO layers and antenna ports are direct multiplicative factors of the former in the formulas used for 7.2x and 8 split options, respectively.

Common parameters applicable to both mid-band macro and high-band macro and small cells are listed below:

- TDD with approximately 75% downlink, (8:2, see [GSM20]),
- 10% transmission overhead,
- 256QAM maximum handset modulation in downlink,
- FH compression for ORAN 7.2x split, considering 8-bit mantissa and 4 bits exponent for both I and Q (compression to around ~61%),
- eCPRI split 8 with no compression, assumed worst case. Compression in this case might deliver lower figures, depending on compression ratio,
- 7.2x and 8 with no statistical multiplexing, constant bit rate always in transmission with no dependency on access traffic level. Split 7.2x throughput dependency on actual cell traffic still not documented [ORA21]. Potentially lower values might then be viable, depending on final dependency on access traffic level, enabling multiplexing.

The results presented in Table 3-8 show that split 8 has a bandwidth requirement exceeding 1 Tbps across all proposed scenarios. In the most aggressive scenario, this requirement reaches 18 Tbps for the aggregation of three sites (at a fourth site). On the other hand, split 7.2 requires bandwidths that are one order of magnitude larger than those observed in the BH (for one site). Notably, the FH exhibits significantly higher bandwidth requirements compared to BH, particularly in the context of three-site aggregation. The ranges indicated for the BH are the result of assuming two different approaches: a more optimistic one, where the transmission requirement is given by the maximum of the radio site peak and the summation of the average values per cell (plus the transmission overhead indicated above), and a more conservative approach, where the transmission requirement is calculated as the summation of the highest peak and the averages of the remaining cells. For the FH, on the other hand, we assumed a worst-case approach, in which the transmission requirement is based on the radio peak values plus overhead.

3.3.5 Perspective about new frequencies assignment for 6G

The bands used by mobile operators in Europe (but on other continents the situation is similar) for technologies from 2G to 5G are the following:

- Sub GHz bands, three bands (700, 800 and 900 MHz) with typical carriers' width of 10 GHz and 3 carriers per band assigned;
- 1-3 GHz bands, four bands (1500, 1800, 2100 and 2600 MHz) with typical carriers' width of 10-20 GHz and 1 to 4 carriers per band assigned;
- 3-7 GHz (C-Band) bands, one band (3.6 GHz) with typical carrier width of 20-110 GHz and with 4 carriers assigned;
- Above 24 GHz, one band (26 Ghz) with typical carrier width of 200 MHz and usually 3 or 4 carriers assigned.

These bands have been the subject of tender assignment in past years, they have been very costly for operators, and it is expected that they may continue to be used in the coming years up to a medium-term horizon. In fact, on the one hand, obtaining new bands would be expensive, and, on the other, the allocated bands are not yet exploited to their maximum potential. Furthermore, the bands currently used by 2G to 4G technologies can be reused by 5G once the older technologies are removed (and this is expected in the next few years) benefiting from a greater spectral efficiency of the 5G and 6G (with a gain in the data rate estimated at a factor of at least x2). This reuse (migrating the use of a band from 2-3-4G to 5G/6G) is called refarming. The state of the art of frequency assignment in Italy and Spain are given in subsection 2.4.

Some hypotheses the future perspective in use of spectrum can be found in official documents made available by companies such as Nokia [Nok23-2] and Ericsson [Eri23-2], just to name two. In these documents a view of the spectrum used (up to 5G) and spectrum candidate to be used in future (for 5G Advanced and 6G) is explained.

About the medium term future perspective it is recently decided in World Radiocommunication Conference 2023 (WRC-23, Dubai, December 2023) [WRC23] to add additional two bandwidths (470-694 MHz and 6.425-7.125 MHz) for 5G- Advanced and 6G. Motivation for the introduction of the 470-694 MHz band was that the low bands can help expand capacity for the internet connectivity of rural communities as their signals reach over wide area, and this can constitutes an important way to reduce the digital inequality and lower the urban/rural connectivity divide. Reasons for the introduction of 6 GHz band (6.425-7.125 GHz) was that a group of Countries, which together account for the majority of the world's population, asked to include this band for the expansion of mobile capacity for 5G-Advanced and beyond. For frequencies lower then 7 GHz spectrum is as the one of today with refarming to 6G and the introduction of two new bands (470-694 MHz and 6.425-7.125 MHz) [Nok23-2].

A new mid-band pieces of spectrum from within the 7-15 GHz frequency range are introduced with the motivation that they are considered essential to balance capacity and coverage in the 6G era. This will be discussed and potentially approved in the next World Radiocommunication Conference schedule for 2027. The bands specified are within 7.125-8.5 GHz, 10.7-13.25 GHz, and 14-15.35 GHz. Focus on these ranges in the next ITU-R study cycle would enable spectrum availability in time for the introduction of 6G in the long term (Nokia expects before 2030 but it is probably an optimistic forecast).

Additional 6G research is ongoing on sub-THz spectrum. This high frequency Band can be useful for applications like sensing and positioning with high accuracy. Due to the propagation characteristics of sub-THz frequencies, such spectrum will help to complement the mid-bands, but not replace them. There are no plans to discuss this allocation in international bodies, it will likely be postponed to the World Radiocommunication Conference of 2030 and is therefore to be considered in the very long term.

3.3.6 Drivers from Open RAN architecture

A key driver for 5G Open RAN was to bring intelligence into the RAN, through the O-RAN RIC (RAN intelligent Controller), with both the Near-Real Time (Near-RT) and Non-RT RIC network functions, extensible through xApps/rApps.

As SEASON uses Open RAN architecture, a "Key Exploitable Result" of SEASON will be an enhancement of the current Open RAN telemetry framework, advanced to support the SEASON's cross-domain telemetry between RAN and transport network, but also to become exploitable for further evolution into an Open 6G architecture, in follow-on SNS and complementary 6G R&I projects, and later towards higher TRL, as a commercial market success.

While for SEASON, the implementation of the telemetry framework will be limited to the cross-domain use-case and KPI fulfillment, the architecture and design will be mindful of a 6G telemetry sub-system, supporting the following technologies:

- **Advanced Non-3GPP:** heterogenous multi-RAT (Radio Access Technologies) like Wifi 7 or 8, but also UWB and Lidar technologies. While in 3GPP 5G, the focus was on user-plane integration of N3IWF/TNGF towards the UPF, it is expected that the Positioning and capabilities will increasingly be injected into the RIC to provide enhanced cross-domain functionality, beyond SotA 3GPP ATSSS.
- **Native AI/ML in DU/RU**: while the Near-RT RIC can ingest telemetry and control some aspects of the DU/RU, through the O-RAN E2 service modules, when the intelligence becomes deeply embedded into the 6G Native AI/ML. This is the scope of the identified but unspecified Realtime RT RIC. This is outside of SEASON scope but will be needed for future 6G capabilities.
- **ICAS/JCAS**: the addition of radar-like sensing, integrated into the communication radio units will require processing and usage of this sensing information, to merge with other higher-level telemetry for advanced functionality.
- **Full duplex & IAB**: it will extend the 6G RAN coverage, but it will add additional control aspects of interference management and bandwidth scheduling, that will result in increased telemetry to be ingested and utilized.
- **Dynamic Spectrum Re-farming**: will require full sensing of the CSI (Channel Sate Information) and neighbor interference, to ingest and process the interference, extracting valuable telemetry for optimization and co-existence, instead of discarding as pure noise.
- **Cell-free mMIMO**: requires close co-ordination of DU and RU, with dynamic reconfiguration of the use-centric AP (Access Point) associations, for coherent multi-

point Tx/Rx and synchronization. Early research results show the need for RIC-like intelligence.

- **Cross-domain interaction:** within the O-RAN Alliance, the O-RAN nGRG (next Generation Research Group) focuses on research of open and intelligent RAN principles in 6G and future network standards. Within that group, OpenRAN Research Stream "RS06: Cross Domain", has a focus on research topics relevant to SEASON related to the evolution of cross-domain interaction like network exposure, cross-domain integration and network integration in 6G.
- **Dynamic user/data plane programmability and HW acceleration:** using hardware acceleration in the user plane pipeline for xURLLC in 6G, is expected to eliminate the need for unnecessary protocols like NRUPP, GTP etc and use a collapsed user plane architecture that directly uses PHY->MAC->RLC->PDCP->SDAP->IP->Application layer pipeline to speed up the processing to reach 6G xURLLC requirements.

4 SEASON ARCHITECTURE

This section presents a preliminary view of the high-level network architecture for the SEASON project. The described reference architecture constitutes the target of the SEASON project and is intended to integrate the different technologies and solutions proposed by the project. This architecture can be implemented as a gradual transformation of the current and short-term architecture (presented in section 2) but having as main reference the two different time periods identified as medium- and long-term.

The SEASON architecture taken into consideration at this stage of the project, concerns the high-level and general aspects of the architecture, including how the data plane is hierarchically organized and where Telco and Service functions could be placed. Some indications on how orchestration, control and monitoring (under definition in WP4) relate to high-level data plane architecture are also given. A preliminary introduction on terminology and network segmentation is made in section 4.1, while the reference SEASON high-level architectures for the two periods defined in section 4.2 are presented in section 4.3. A focus on a preliminary node architecture discussed in a WP2 WP3 working group is presented in section 4.4.

Indications on how the technologies proposed by the SEASON project (shortly described in section 4.5) can be mapped into the architectures defined for the two reference time periods are afterwards described in section 4.6. This mapping was built taking into account the likely degree of maturity of SEASON technologies at a given time in the future.

However, this document is quite agnostic in relation to the actual technological solutions that could be adopted. Detailed system and design solutions both at data and control plane able to comply with the general network architecture shown here are developed in WP3 and WP4. The reader is invited to consult the relevant WP3 and WP4 deliverables for further details.

4.1 TERMINOLOGY AND HIGH-LEVEL ARCHITECTURE FRAMEWORK

Figure 4-1 gives a high-level framework for the SEASON architecture definition. The key points on which this view is based on are the segmentation of the network into two domains, a “flat” Access-Metro segment and a Backbone segment, and the definition of three categories of Central Offices (COs), where equipment of any type (optical, packet, compute and their hybrids) can be placed. Furthermore, the definition of Access Point is given to allow a complete and consistent terminology.

The **Access Point (AP)** is a physical entity acting as access termination point of a full optical network architecture, exploiting Fiber To The Home (FTTH) or Fiber To The Antenna (FTTA) architectures in the last mile segment. In most scenarios, the AP is closely connected to, or integrated with, more specific devices. These devices enable fixed, nomadic and mobile users and Internet of Things (IoT) objects to be connected to any kind of digital services, such as:

- a Residential Gateway located at the home premises, connected to the Optical Network Termination (ONT) of x-PON technology or any new access optical technology and providing 3Play services to the final customer;
- a Customer Edge router providing Software Defined-WAN service to business premises;
- a 5G/6G site equipment collecting FH, MH or BH traffic from mobile users over a macro/small cell site, and connected to the mobile network via an optical link;

- a WiFi-x Hotspot covering a limited public area or indoor space to provide HSI services to nomadic users, which is connected to the Network via an optical link.

The above devices, when co-located with the Access Point, should be considered as connected to it via an Ethernet based UNI physical interface.

Concerning Central Offices, the three categories are:

Far Edge CO, in Access-Metro domain, is a small size structure that can host Telco applications and, more rarely and not necessarily, IT applications, and is the closest Central Office to the customer. It could be a controlled and conditioned building/room or an outdoor shelter, container or cabinet. It is the demarcation point from Access and Metro for all the optical flows from Access Points in case of packet aggregation or a break-out. This means that not all optical flows collected from the access in a Far Edge CO are locally terminated: a subset could bypass this CO and be terminated in a different CO of the Metro segment.

Edge CO, in Access-Metro domain, is a medium-sized structure that hosts Telco applications and possibly IT applications. It includes Telco equipment (packet and optical) and often hundreds of servers for Telco virtualized Network Functions and IT applications acting as an “Edge node”. In some cases, the Edge CO in an Access-Metro domain is the gateway to the Backbone.

Cloud CO, in Backbone domain, is a big structure that hosts Telco and possibly IT applications. It includes packet and optical equipment of the Backbone transport network and hundreds to thousands of servers for Telco virtualized Network Functions and IT applications. Some Cloud COs include dedicated packet and optical equipment to ensure the interconnection of the Backbone with Access-Metro domains. The Cloud CO hosts pieces of equipment for long distance interconnections and it’s also a possible gateway to external networks, including the Internet.

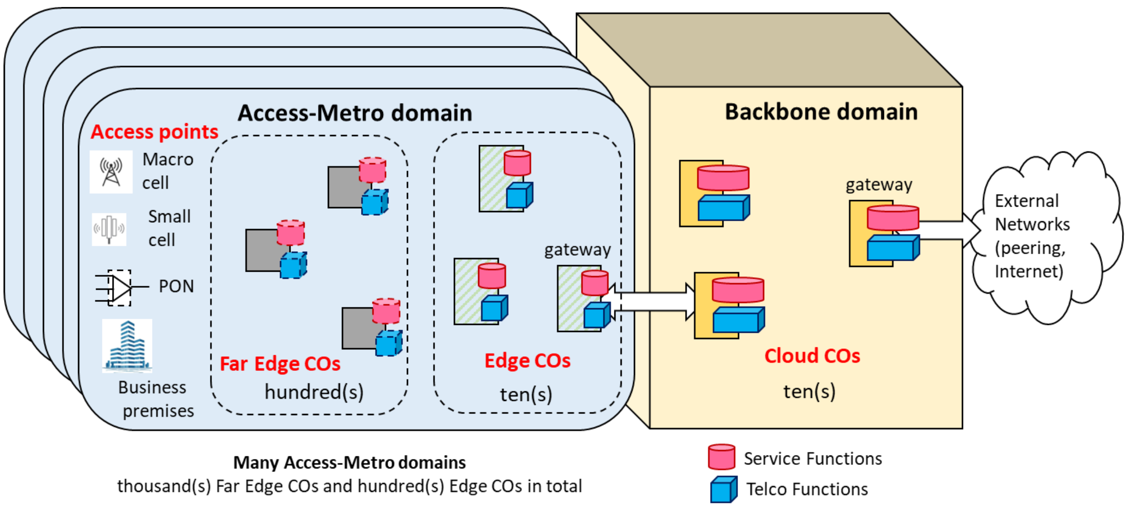


Figure 4-1 – High-level framework (segmentation in Access-Metro and Backbone domains and terminology) for SEASON architecture.

Within the Access-Metro domain, the Far Edge CO is the simplest and smallest one, which can be housed in containers or even in suitably strengthened cabinets, while the Edge CO is a more traditional CO, hosted in buildings that allow high level of physical protection and security. In that sense, Edge COs locations may coincide with legacy COs, but not necessarily all existing COs will become Edge COs given that a process of consolidation of COs at metro end regional level is underway for many operators and SEASON is expected to follow this trend.

Far Edge COs should cover all situations where there is a need for a distributed equipment hosting, but when low cost and low power consumption are a must (even mini containers, reinforced cabinets or radio base stations could be classified as Far Edge COs when they host relevant network functionalities).

A “flat” **Access-Metro Domain** or “Segment” includes the part of the network starting from a set of the Access Points (residential and business users on fixed access and radio base stations, including small cell outdoor and indoor points) and up to the Edge CO level nodes. Additionally, it includes also all the needed interconnections in a specific administrative geographical area. The Edge COs that also have the role of gateway to the backbone in their specific administrative domains, define the border of the specified area Access-Metro domain.

Therefore, from the physical infrastructure perspective, a domain is: 1) a geographic administrative area; 2) a set of Access Points; 3) a set of Far Edge COs; 4) a set of Edge COs; 5) a subset of Edge COs physically interconnected to backbone (gateways); and 6) a fiber infrastructure interconnecting the various COs and the COs with the Access Points.

An Access-Metro segment is envisioned, from the optical transport perspective, as a “flat” area, i.e., an area (as much as possible) without hierarchical internal borders. Thus, the definition and distinction of access, metro aggregation and metro core segments (or equivalent hierarchical levels), typical of legacy networks, becomes significantly blurred.

The extension (optical diameter) of each Access-Metro domain could range from about 100 km to a maximum of 300-400 km, depending on the geography and the architectural choices of network operators. Also, the number of COs (Far Edge and Edge) is highly variable and dependent on the orographic and demographic characteristics of each specific covered area. To give a rough idea, the number of Access Points could be in the order of hundreds of thousands or even millions, the Far Edge COs of the order of hundreds and the Edge COs of the order of tens.

In a national-wide network, there are typically several tens of Access-Metro domains, all of them interconnected to a single Backbone network spanning the considered nation.

Considering all the Access-Metro domains together, the number of Far Edge COs could be of the order of several thousand, while there could be hundreds of Edge COs for a medium-sized European country. These figures are just illustrative and can increase/decrease (e.g., according to the country size, economy and other aspects).

The drivers that bring SEASON in considering this specific “flat” network segment is based on the following motivation (that also identifies its main characteristics):

- Availability of high performance, high capacity and low cost, footprint and power consumption coherent pluggable modules.

  The OSNR and sensitivity of coherent 400/800G pluggable as currently specified, for example, by OpenROADM and OIF allow to cover distances of the order of 300-400 km, while crossing several transparent nodes, in a metro environment. In future, 1.6 Tb/s and higher data rate pluggables are expected to comply with similar performance specifications. The specified power sensitivities seem appropriate also to enable using these modules in the access network. This potentially allows a transparent interconnection from Access Points generating huge traffic flows to the Service point (where Telco and/or Service functions are located) within the Access-Metro segment.

The continuous decrease of cost, footprint and power consumption, combined with the expected increase of the traffic needs from access end points, may allow these modules to become competitive also in the more cost-sensitive access segment.

The increased effectiveness of real time DSP and the strong optical integration inside modules are allowing new advanced functionalities including time and frequency digital multiplexing, high range of tunability, paving the way to new advanced capabilities in the "optical domain" including coherent PON, digital P2MP (one to many, but potentially also many to many) and "sliceability" of optical signals. These new functionalities may lead to a simplification of the optical transport infrastructure and new architectural topologies for the metro segment.

The integration of these modules in packet switches/routers, or even inside servers, allows new combined packet/optical networks with higher layer Telco or Service locally distributed and strongly integrated with the transport infrastructure.

The interoperability among modules from different vendors (within a specified standard) and open optical specifications allow a full-disaggregated environment in the metro segment, potentially reducing vendor lock-in.

- New services for advanced clients requiring locally low latency and high computation capacity.

  Potentially, if economically sustainable, this computation capability could be served locally in the Far Edge or Edge COs instead of in the Cloud. This may assist in slowing the traffic growth in the Backbone.

  Far Edge CO with Telco and Services could be moved toward access to a small, dedicated data center using integrated new high capacity NICs for interconnection.

- Reduction in the amount of COs with active equipment and, in particular, packet aggregation within the metro transport network.

  The increased performance of coherent interfaces and new functionalities like P2MP capabilities, potentially allow the optical bypass of intermediate aggregation switches/routers that are typically segmenting this network domain. It will result in an extended "flat" optical metro domain.

- Low cost and power footprint in environments characterized by huge, non-uniform and continuously increasing traffic needs.

  In a future perspective, possibly dominated by innovative residential and business use cases, traffic locally generated is expected to increase significantly and be difficult to predict. A "flatter" Access-Metro paradigm should better fit in serving these new requirements than existing architectures. New band and fiber switching technologies, together with other advancements of coherent transceiver technologies, could potentially allow a simplification of transport metro network leading to cost and power reductions while preserving a significant degree of flexibility.

The **Backbone Domain** or "Segment" remains substantially unchanged with respect to the existing networks architecture (the SoA is described in Section 3), and it performs the transport of traffic collected by the Edge nodes over long distances, typically inter-regional or towards external destinations (i.e., other peer networks or the Internet). It includes Cloud COs hosting all the needed pieces of equipment for transport, interconnection with Access-Metro and the “Big Internet”, Telco and IT services delivery.

Here, the goal is to maximize the traffic capacity of the infrastructure maintaining a high level of flexibility and resilience. Key technologies (all considered in SEASON) are: Coherent high capacity and performance transceivers capable of multi band operation; optical switches with optical frequency, sub-band and fiber/core switching capabilities with a large number of node degrees; flexible optical Add/Drop; multi band line operation; transport optical systems employing bundles of conventional or multicore fibers.

Interconnection to the Access-Metro domains should allow, at least, partial optical transparency and provide all the needed flexibility to steer independent optical flows to the desired destination.

4.2 Reference Time Periods for SEASON architecture

The proposal in SEASON is to consider at least two periods as reference time target for the high-level SEASON architecture view. The reasons for this proposal are:

- SEASON is Stream A, so mostly mid-term outlook, not necessarily long-term.
- Considering more than one reference period for the network architecture allows to map the different technologies considered in the project, which are at very different maturity stages. In addition, the same technology could still be considered at different stages of development, e.g., coherent P2MP support of up to 400 Gb/s in the short-term, scaled up to 800 Gb/s in the medium-term.
- Looking at the architecture only in its long-term target version would be a limitation for the Operators. In fact, from Operators business perspective, the higher interest is in solutions targeted for short- and medium-term, since they exploit the existing deployed fiber and potentially other infrastructure elements (e.g., optical amplifiers), while new fiber deployments and more innovative and disruptive technologies (e.g., SDM based on multicore) are seen as interesting opportunities to look at, but only for long-term.

Due to the above reasons and to avoid considering too many scenarios that could create confusion and indeterminacy, two target periods for SEASON architecture are proposed:

- **Medium-term** (≈ 5 years from now, i.e., around 2028) with certain brownfield constraints (i.e., use of existing fibers) and the use of technologies/systems already available or in a phase of advanced R&D.
- **Long-term** (≈ 9 years from now and beyond, i.e., around 2032 and beyond) with higher flexibility to adopt more innovative technologies and new fiber types, and with technologies/systems not yet mature enough to be in roadmap as products (e.g., still undergoing research or at their early prototype stage).

These two periods are indicative and should be interpreted with a certain flexibility as some technologies may, for example, be available shortly before or shortly after the years indicated above.

The main characteristics identified for these two periods are listed in the following.

The **Medium-term period** is characterized by:

- **Targeted for ≈ 5 years from now, i.e., around 2028.**
- **Traffic offered to the network growing by a maximum factor x 5 compared to today's traffic (i.e., traffic in 2022-23 at project start time).** This statement is generic and does not consider specific traffic growth by access type (i.e., fixed vs. mobile, within mobile small cell vs. macro cell) or segment (Access-Metro vs. Backbone).
- **No relevant deployment of new optical fibers, neither single nor multi core.**
- **Use of a limited set of bands in transport systems, i.e., (C+L), eventually (C+L+ another one).** The technology for exploitation of such bands is assumed to become commercially mature for medium- and long-distance optical networking.
- **Use of P2MP and semi/ filterless solutions in the Access-Metro domain** to exploit low cost solutions and allow the bypass of some IP hierarchical level.
- **Partial sharing of the access passive infrastructure with existing or advanced PON** to direct interconnect “capacity hungry” Access Points to Edge COs (thus realizing the paradigm of “flat” access-metro).
- **Use of SDM only with the meaning of parallel single core fibers on topology edges** (node to node, e.g., parallel links/systems between two ROADMs).
- **Widespread use of the paradigms of partial and full optical disaggregation and packet/optical convergence.**
- **PONs operating at a rate of 50 Gb/s or greater (early introduction of 200G coherent PON) but not SDM PONs.**
- **Coexistence of traditional PON and Coherent P2MP** on the same passive distribution access network.
- **Open RAN for 5G.** 5G system is widely and fully deployed in 5G Advanced version (even in its Stand-Alone version, with features of 3GPP Rel. 18 implemented), while 6G will not yet be deployed or at least not to significant extents. **O-RAN standard** is considered as reference for the radio access architecture.
- Radio frequencies already assigned will be fully exploited (refarmed where not yet used by 5G Advanced radio units) with new assignment of 1 sub GHz band, 1 more 3-7 GHz band for mobile services and one band at 24-26 GHz for FWA (in suburban and rural areas mainly). Significant deployment of small cells in urban areas at 3-7 GHz and 24-26 GHz will be expected. This will require significant transport capacity in the access at capillary level.
- A particularly interesting use case in the RAN consists of a **third-party transport service operator that offers the connectivity service to multiple mobile and FWA operators** which share the same radio site location by transporting aggregate traffic from radio sites to the first central office or beyond.
- **Limited decentralization/devolution of Telco and Service functions that are currently centralized.** From Cloud up to Edge for most of the functions, to Far Edge only for a few functions, e.g., UPF is not expected to be moved to it. The degree of decentralization will be strongly dependent on the strategic choices of each Operator.
- **Pervasive Telemetry** is expected to play a significant role supporting the partial and total optical disaggregation and packet/optical convergence, for example in simplifying alarm and defect correlation.

- **AI/ML techniques and Digital Twin** to assist in designing, monitoring and operating multi-vendor IP/optical disaggregated networks.

The **Long-term period** is characterized by:

- **Targeted for ≈ 8 years from now, i.e., around 2032, and beyond.**
- **Traffic offered to the network increasing by a factor in between x 10 and x 30 compared to today's traffic (i.e., traffic in 2022-23 at project start time).** As for the Medium-term period, this statement is generic and does not consider specific traffic growth by access or network segment types.
- **Traffic is expected to become more dynamic and less predictable.**
- **Expansion of technological advanced geographical area (large campus, ports, large industrial areas, etc.);** 6G, High capacity PON, P2P and P2MP together with decentralization of Data Center are expected to be key technologies to provide connectivity and elaboration capacity to these areas.
- **No restrictions on deployment of new fibers including multicore.**
- **Use of all bands, namely C, L, E, S, O and U.** The technologies to exploit such bands are assumed mature at that stage; it should be noted that the compatibility in terms of performance deterioration due to the co-presence of optical power on several bands can limit the use to only a subset of bands, to be evaluated on a case-by-case basis. The use of multi-band is not intended for the purpose of increasing the total traffic between the two end points of a link only. Having more than one band is viewed as an opportunity to have a better utilization of the same fiber infrastructure sharing it among different transport systems with different scopes or reaches among its end points (for example: O band for local point to point interconnection, together with C+L+(partial)S for long haul).
- **Use of SDM in its full meaning.** Optical networking can rely on fiber/fiber-core switching.
- **PONs operating at rates of 200 Gb/s or greater, 200G coherent PON is mature and SDM PON is used in some part of the access.**
- **Strong coexistence of multi-band, SDM, P2P and P2MP in the Access-Metro Domain.**
- **Open RAN for 6G** (3GPP Rel. 20 will be assumed available, implemented in commercial products and deployed by operators).
- All the band already assigned refarmed to radio for 6G. Further increase in available radio bands (for example, new 7-15 GHz bands) and further growth of small cell deployment. This will imply additional quantities of traffic to be collected by the access.
- **Transition to the metaverse complete**. 6G use cases can be performed without restrictions (sub-ms latency and data rate beyond 1 Gb/s per mobile user also in crowded contexts).
- **Extended decentralization/devolution of Telco and Service functions** (network and service functions are located where they are needed and where it is convenient to place them, even in the Far Edge).
- **Massive use of AI/ML solutions in support of network operations.**

4.3 SEASON HIGH-LEVEL ARCHITECTURE

Figure 4-2 and Figure 4-3 show the overall view of the network architecture for the medium- and long-term, respectively. The **Access Area** is schematically depicted in grey color in these figures. According to the general idea of "flat" Access-Metro Domain, the borders of the Access Area are, on the side facing the "user", well identified by the Access Points; on the side facing the "server", they are only defined on an optical flow basis, to be the Far Edge or Edge COs.

As described in section 4.1, SEASON uses the term **Access Point** to collectively identify any termination point of any Access technology, including Mobile and Fixed, to the **Optical Distribution Network (ODN)**. The ODN is traditionally the part of the optical network between the Access Points and the first CO, where the optical access flow is terminated. We believe that this same term could be effectively used in the context of SEASON Access-Metro architecture with the foresight to consider it referring primarily for the underlying fiber infrastructure, whose cables and fibers are shared by all access technologies. Typically, ODN fiber cable infrastructure is made of standard ITU-T G.652 single mode fiber (SSMF) apart from the very last part of the connection, that sometimes uses the so-called bend-insensitive G.657 fibers. In a long-term perspective, new fiber types, such as Multi Core Fibers, could be deployed alongside traditional fibers.

The **Mobile Access Points** are made of sites hosting macro cells (sparser, with coverage extended to the whole territory) or small cells (denser, in urban or dense urban areas or in few geographically limited technological advanced areas). The SEASON architecture will see in the Medium-term (Figure 4-2) a mature and fully deployed 5G network (in terms of both RAN and Core in Stand Alone version), while in the Long-term (Figure 4-3) the next generation 6G system is assumed to be mature and widely deployed. In this latter time frame, the size and number of advanced geographical areas, with strong densification of cells (large campus, ports, large industrial areas, etc.), is expected to gradually increase.

For **Fixed Access Points,** it is expected, in the Medium-term, a complete FTTH for residential clients and business premises. In the Long-term, this traffic is expected to continue increasing, forcing the introduction of new technologies. Dedicated high-capacity interconnection is foreseen for Big Clients and, in future, for technological advanced geographical area (large campus, ports, large industrial areas, etc.).

Both Mobile and Fixed Access Points are served (i.e., the generated/received traffic is transparently transported) by the same fiber infrastructure ODN, in the specific Access-Metro segment, potentially using several different network technologies, all of them considered by SEASON in the selection phase of the "SEASON solution". Therefore, the ODN could see the presence of PONs at rates exceeding 50G (e.g., coherent 200G PON [Far21]) already in Medium-term and the possible introduction of new solutions, including DWDM multiplexing and P2P and P2MP on the same infrastructure to bypass Far Edge nodes, and some degree of optical flexibility. Enhanced optical flexibility and SDM PON are expected in the long-term, at least in some areas. Of course, a direct interconnection at high capacity for specific clients is also considered.

The identification of the mix of technologies proposed for the "SEASON solution" in the two considered time frames is the goal of the architectural, technical, and economic analysis to be performed jointly in WP2 and WP3 (it is outside the scope of this document.) At this stage of the analysis, no technological constraint is considered for the Access area.

Each Access-Metro Domain is in principle conceived as an area without hierarchical internal borders. The assumption here is to have two main types of available Central Office as introduced in Subsection 4.1.

The first type of CO, referred to as **Far Edge CO**, has some constraints in terms of space and power supply and, for these reasons, it can host only a limited amount of computing capacity for Telco and Service functions, as well as switching and optical equipment.

The second type of CO, i.e., the **Edge CO,** is typically an upgrade of the already existing legacy metro-regional exchanges suitably adapted to the new needs (see Figure 2-1, Access CO and Regional CO). In this case, there are no major limitations to the deployment of compute and communication equipment. Therefore, an extended set of telco functionalities and services, together with high communication capacity (both packet and optical levels), can be accommodated in these Edge COs.

Both types of COs, which collect the traffic deriving from mobile and fixed access, are interconnected in the Access-Metro Domain by a network whose details, in terms of topology and packet over optical layer, are within the objectives of the SEASON project.

The optimal dimensions of the Access-Metro Domain will also be evaluated, considering the geography, extension, the population served, the business premises, Big Clients and technological advanced geographical areas density and, consequently, the number of mobile cells and fixed access points required.

Within Access-Metro segment, it will also be necessary to establish the capillarity of Far Edge COs and the amount of Edge COs. This is an optimization objective, which means pursuing the best trade-off between communication costs and costs of the infrastructure hosting the service and telco functions (which may be more or less decentralized), guaranteeing the service requirements in terms of bandwidth, latency and reliability. The enabling technologies, together with the constraints and requirements of network and services, play a fundamental role in the optimization.

Given the quite large number of COs, needed to cover a whole country, technology for interconnecting Far Edge COs with other Far Edge and Edge COs, and Edge COs with other Edge COs, will be driven by a trade-off between capacity, reach and flexibility, from one side, and low cost, low power consumption, and simplicity of deployment, of operation and of fiber infrastructure on the other side. Several technological candidates are expected to address this trade-off, and a mix of them is foreseeable, including Multi Band, with ROADMs or (semi)-filterless. Parallel fibers and systems and full SDN are expected to play also an important role, providing the needed optical flexibility on a channel, sub-band and fiber/core basis. The network environment is expected to be a multi-vendor one from the Medium-term onwards. Partial and Full disaggregation and integration of control of advanced pluggable modules (SBVT and P2MP for example) on board of packed devices by a transport network controller, are expected to be key technologies. To allow the coexistence of P2P and P2MP on the same infrastructure a key characteristic is, at least, the partial support for Drop & Continue and Continue & Add optical node architectures.

As aforementioned, which mix of technologies is expected for the “SEASON solution” in the two considered time frames, is the goal of the architectural, technical and economic analysis to be performed jointly in WP2 and WP3, and it is outside the scope of this document. At this stage of analysis, no technological constraint is given.

Telco functions like Mobile Core UPF and BNG/PE can, by default, be placed anywhere in the Access-Metro domain, but it is expected that they will be placed mostly in the centralized nodes, i.e., Edge COs. In this regard, the medium-term architecture envisages a limited decentralization/devolution of the Telco end Service functions that are today in the cloud, while the long-term architecture does not establish these limits. Functions like virtualized RAN (vDU and vCU) or the virtualized fixed access (vOLT, the SW component of the OLT) can, by default, be hosted anywhere, i.e., both in Edge COs and in Far Edge COs. Concerning the RAN, the positioning of the vDU function (at antenna site or at CO) implies very high data rate FH flows between RU at site and vDU at Access CO or high data rate MH flows between vDU at the antenna site and vCU at Metro CO.

Technological advanced geographical areas (large campus, ports, large industrial areas, etc.) served internally with dense 6G cells will presumably require a huge amount of local elaboration of Telco and Service data to be managed in a mix of data centers hosted in client premises, Far Edge and Edge COs.

SEASON's final architecture will have to be able to guarantee, in addition to the growth of traditional services, the needs of new verticals and new paradigms such as Computer Power Networking (CPN) [Sun22], that can be seen as an evolution of MEC (Multi access Edge Computing), in which computing resources are not only decentralized but also coordinate with each other to allow synergy and resource sharing. As a matter of fact, CPN can connect ubiquitous and heterogenous resources through networking to flexibly realize computing power scheduling. An example of application scenario is the Internet of Vehicle (IoV), which is a system that utilizes sensors, software, and technology to connect vehicles to their relative environment (entities such as pedestrians, traffic management equipment, other vehicles, parking lots, and so on) and that require not only a reliable low-latency and high-capacity mobile network (i.e., 6G access), but also a huge distributed compute capacity to process the information received from the field and send control instructions to vehicles and to the other involved players listed above. An example of a generic service, not limited to a specific vertical or application scenario, is Machine Learning (ML) as a service [Rib15], which requires high distributed computational capacity and low latency, for which CPNs offer a powerful delivery infrastructure.

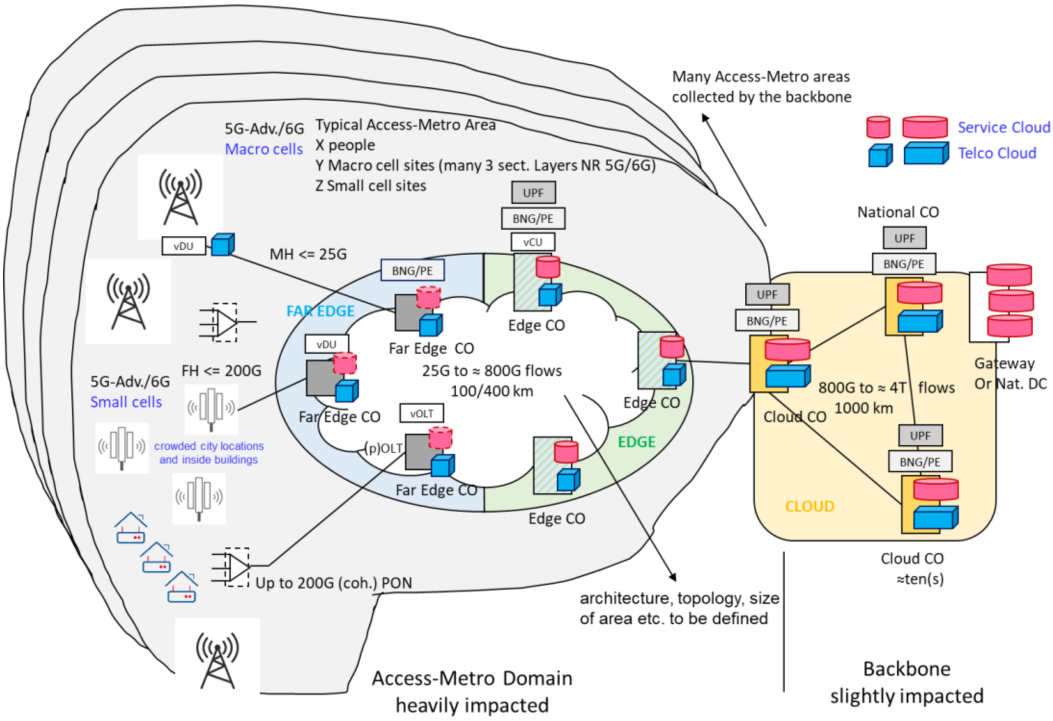


Figure 4-2 – Overall high-level view of the SEASON architecture for the Medium-term.

The expected capacity needs (albeit roughly approximate) for the FH/MH and fixed access based on PON, together with a rough estimation of data rate ranges for flows to be carried in the Access-Metro and Backbone segments in the two target periods, medium- and long-term, are illustrated in Figure 4-2 and Figure 4-3. These values approximately scale by a factor of 5 and between 10 and 30 compared to the values indicated in the drawings of the state of the art architectures (Figure 2-1, Figure 2-2 and Figure 2-3), according to traffic scale factors specified for the two target timeframes.

As indicated in Figure 4-2 and Figure 4-3, an Access-Metro area can extend from about 100 to 300-400 km and can be characterized by flows ranging between 25 Gb/s and 800Gb/s or even between 100 Gb/s and 1.6-3.2 Tb/s, depending on the target period. Such a high variability of unitary flows could be effectively managed with a suitable mix of high capacity P2P, sub-carrier multiplexing P2MP and SBVT. Higher data rate flows are expected between Far Edge CO and Edge CO or between pairs of Edge COs; in case of CPN involving compute resources sharing high data rate flows, they can be expected also between Far Edge COs.

These data (distances, covered population and traffic) for the Access-Metro area are taken as a reference only. They may change depending on each nation and operators' networks. Additionally, the values shown in Figure 4-2 and Figure 4-3 are subject to changes during the project timeframe, since they will be further investigated through formulation of scenarios and quantitative studies.

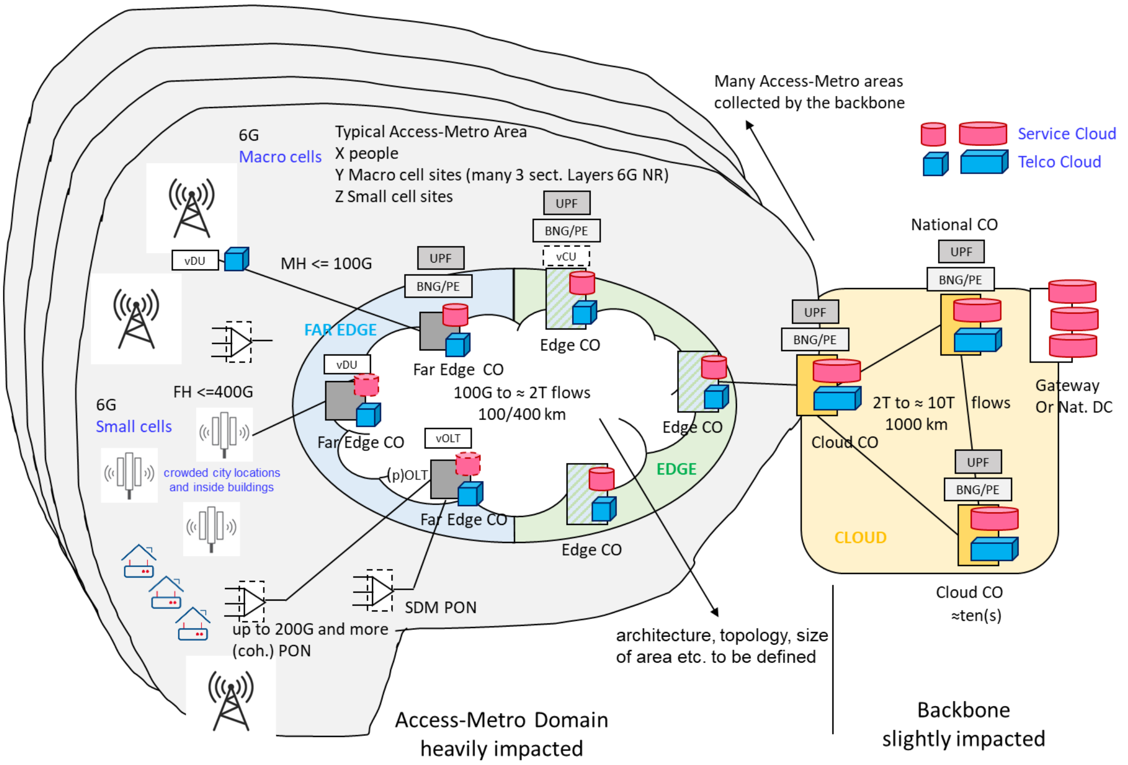


Figure 4-3 – Overall high-level view of the SEASON architecture for the Long-term.

The **Backbone Segment** is shown on the right side of Figure 4-2 and Figure 4-3 (yellow area). In it, the required enhanced cloud functions continue to carry out their task, while the capacity requirements for nodes interconnection at national level are growing (flows of the order of Tb/s and up to ten Tb/s in long-term are estimated). From an architectural point of view, this network segment has the least impact on the data plane, because it substantially envisages only a technological upgrade of nodes and transmission systems in the direction of the introduction of multi-band and SDM solutions. On the other hand, important innovations are foreseen in the control plane, with the introduction of pervasive telemetry and massive use of AI/ML solutions to support network operation. Another requirement is the coordination of the cloud resources of the Backbone with those of Access-Metro (Edge and Far Edge), which is put into practice with an overreaching orchestrator that coordinates the control entities of the various network domains.

4.4 SEASON NODE ARCHITECTURE

Different node architectures should be used in each network segment because of the dissimilar requirements of each segment (as described in section 4.3). Indeed, while a colorless, directionless and (preferably) contentionless ROADM architecture is desirable, especially in the backbone segment, achieving it may be too costly, particularly when several dimensions come into play (such as in the case of multi-band and SDM). The analysis of such an architecture shows that, even for a 3rd order nodal degree exploiting two parallel fibers and 2-band transmission, the dimension and number of optical components that may be required can be very high. Consequently, such architecture should be avoided unless there is a clear benefit resulting from its deployment. Alternatively, a smaller number (or smaller size versions) of these individual building blocks may be exploited to provide a more limited set of functionalities and capacity, but also at a fraction of the cost and operational complexity. Additionally, optical cross-connects and splitter/combiners may also be exploited to further reduce the cost and/or complexity of the node. In summary, finding the node architecture that better suits the offered traffic load and the network functionality required in the different time frames of the network operation depends on a large number of variables that impact its design, and no single solution will be optimal for all scenarios. Indeed, the optical node design is impacted by:

- Number and size of traffic demands.
- Required flexibility.
- Routing requirements.
- Number of fibers/cores and or transmission bands to be used.

As an example, and to simplify the node architecture (reduce complexity/cost), specific transmission bands may be exploited for single-hop transmission or specific optical fibers may be assigned for point-to-point transmission, effectively creating a tunnel between two end-nodes in a network with limited re-routing capability and without the possibility of adding or dropping traffic in intermediate nodes.

The type of optical interfaces to be used, according to the SEASON vision, play a fundamental role in the design of the SEASON node architecture also because they impact the requirements of both the express (line) and the add/drop parts of the node. Thus, there is a clear dependence of the node architecture on the selected transceivers type (i.e, using cheaper and smaller capacity transceivers may lead to costlier and more complex node architectures).

4.5 Enabling Technologies

This section presents an overview of the technologies proposed by SEASON only. A general indication of the characteristics of SEASON technology and main envisioned solutions are given to highlight where and when it will be introduced in the high-level network architecture. A detailed and more technical description of each technology is left to the specific work packages (i.e., WP3 for Data Plane, WP4 for Control-Orchestration Plane).

SEASON leverages the SoA of optical and digital technologies already commercial or in the roadmap of transport system solutions in all analyses and techno-economic evaluations. Anyhow, since SEASON is a research project, the list of proposed solutions may change and be updated during the lifetime of the project as new analyses or ideas might be considered. How this mix of technologies is put in a system wide perspective to provide a “SEASON solution” is the scope of the joint work in progress in WP2, WP3 and WP4.

4.5.1 White Boxes and Coherent Pluggable Transceivers

4.5.1.1 White box switches with pluggable transceivers, EDFAs and VOAs

For the packet switching network layer, and for the Access-Metro Segment, SEASON is considering, for experimental evaluation, the usage of L2/L3 white box switches, equipped with coherent pluggable optical transceivers (100G/400G ZR or Open ZR+). The main objective of this approach is to provide insight into new and not yet available higher capacity pluggable needed in the future with capacity up to 800Gb/s or 1.6-3.2 Tb/s, depending on the target period. This disaggregated paradigm and the proposal of high-performance interoperable standards (for example vendor independent optical and digital specifications in OIF and OpenROADM) seem to indicate that this approach is effective in the Access-Metro for the inherent low cost and power consumption. For Backbone, SEASON assumes that transponder cards will still be employed, since they can be designed with a "no compromise" approach in mind, together with pluggable transceivers on switch/routers.

The state of the art for L2/L3 white box comprises switches capable of hosting up to 32 100G/400G QSFP-DD pluggable transceivers; an example is the Edgecore DCS510 switch [Edg23]. This switch is provided with Open Network Install Environment (ONIE), which supports the installation of a compatible Network Operating System (NOS); among the available options, SEASON will investigate the usage of the open-source NOS Sonic. Moreover, among the pluggable modules that can be hosted by L2/L3 switches, high output power (up to 0dBm) 400G coherent QSFP-DD transceivers are becoming available (e.g., Coherent [Coh23], Acacia [Aca22], and XR Optics [OpenXR forum]), enabling their usage in a service provider network by direct interconnection with an Open Line System (OLS), in alien lambda configuration. This approach allows avoiding the usage of a standalone transponder box, with a consequent reduction of overall costs, footprint and power consumption.

Another interesting type of component becoming available, which can be hosted by L2/L3 switches, are EDFAs and VOAs in pluggable form factor. Their usage will be investigated in the contest of low cost P2MP and filter-less architectures especially suitable for the Access-Metro segment. Specifically, Jabil [Lig23] has recently announced the availability of a QSFP-DD dual pluggable EDFA that works seamlessly inside the same Ethernet switch used for Ethernet connectivity. Also, LiComm [LiC17] provides a QSFP EDFA (named QOA), available in booster or pre-amp configuration, working in the C-band for single- or multi-channel, in this last case supporting a flat-gain filter.

4.5.1.2 Data Processing Unit with coherent pluggable transceivers.

A Data Processing Unit (DPU), also called Smart Network Interface Card (SmartNIC), is a specialized hardware component designed to provide high-speed data processing. Although typically used in data centers, within servers and supercomputers, DPUs are attracting relevant interest in edge networking scenarios due to their ability to handle data movement, storage, and processing for large datasets: performing calculations at high speed and enabling real-time analytic and acceleration of data-intensive applications. Traditional Network Interface Cards (NICs) offer low-level protocol acceleration (e.g., Ethernet) and rely on server Central Processing Units (CPUs) to perform other networking functions. On the contrary, DPUs allow programmability at higher layers and can directly perform advanced in-network functions, freeing processing resources for tenant and application services. The current generation of DPUs includes up to 4 interfaces operating at up to 400 Gb/s, advanced timing and synchronization, hardware encryption, and embedded security features, as well as up to 16 ARM CPUs for embedded computing operations. In SEASON, we will consider scenarios where DPU/SmartNIC are equipped with P2P (e.g., 400ZR+, XR optics) and P2MP coherent pluggable transceivers (XR optics), enabling high-performance packet and optical networking within compact and power-efficient edge computing solutions. These solutions are expected to be of particular interest in pushing elaboration capacity in the Edge and Far Edge Central Offices (see Section 4).

4.5.1.3 White-boxes for DU baseband pooling in Far Edge

In a disaggregated RAN, distributed units are resource intensive components of a wireless network. To save cost, energy and increase performance, DU pooling can be a solution where many cell sites are pooled together in a cloud of general-purpose processors in the far edge data centers. Resources can be allocated and released depending on the network load. Unused processors can be switched off or allocated to other processes to optimize computing resources in data centers.

Further optimalization of DU baseband processing can be achieved by distributing each user device across multiple servers. These techniques allow the RAN to dynamically adapt resources in the most efficient way where performance is key.

These techniques can be investigated in the general architecture towards the "SEASON solution" but are currently not in the scope of 5G SEASON experimental evaluation.

4.5.2 Multi Band Transceivers

In order to explore multiband transceiver technologies, SEASON presents an S+C+L-Band transceiver prototype that enables S- and L-band transmission by employing standard C-band off the shelf components, such as a LiNbO3 dual-polarization IQ modulators and coherent receiver frontends comprising free-space 90° optical hybrids. Thulium-doped fiber amplifiers (TDFA) are used for amplification in the S-band and Erbium-doped fiber amplifiers (EDFA) for the C- and L-bands, enabling the use of an optical bandwidth of ~150 THz. To improve optical performance, Volterra based system identification and nonlinear digital predistortion are employed.

P2MP solutions are paramount to achieve cost and energy-efficient dynamic "flat" Access-Metro networks as the ones envisaged by SEASON (see Section 4), due to their high adaptability to dynamic traffic patterns and low footprint characteristic. P2MP solutions fit well in an environment with no filtering elements (like access PON), as they enable sharing the total cost of the system by several end-nodes. Anyway, it is possible and efficient to use them also in the metro aggregation segment (the most peripheral area of the optical network) in trees or horseshoes amplified filterless or quasi-filterless architectures. This architecture could employ band, or better, sub-bands (400 GHz for example) filters together with optical splitter/combiners in crossing and Add/Drop nodes to create the filterless environment on a sub-band basis. This could be even made compatible with Multi-Band environments. This solution matches quite well with coherent interfaces but, if fixed filters are used on the drop side, simple low-cost intensity-modulated with direct detection (DD) receivers could also be employed (if OSNR and dispersion are within their tolerances, and the bandwidth requirement is small).

The comparison between DD based optical interfaces and coherent ones is ongoing. As expected, preliminary results indicate that DD provides a cheaper solution on a transceiver basis if the required throughput is low enough. This is certainly true in actual PON solution. However, as the total capacity increases, DD based P2P solutions require a much higher interface count, with the corresponding higher footprint and energy consumption and much smaller flexibility to handle dynamic traffic. It is therefore expected that, for a total capacity exceeding a certain value (yet to be determined by a comprehensive cost analysis), coherent P2MP solutions prove to be a better solution.

Two P2MP flavors are considered within SEASON:

A **modular and programmable MB(oSDM) sliceable bit rate/bandwidth variable transceiver, S-BVT,** based on multicarrier modulation (MCM) capable of P2P and P2MP operations. This transceiver is proposed as key enabler to meet future network stringent requirements in terms of capacity/bandwidth and cost/energy efficiency. This solution based on a pay-as-you grow architecture will be particularly relevant in the metro/aggregation segment, enabling to cost-effectively transmit a high-capacity flow composed of multiple slices that can operate in different bands (such as C-, L-, O-, E-, S- or U-bands). Additionally, the different slices can be transmitted within different spatial channels to enhance overall capacity by considering an SDM scenario. Thanks to the modular and scalable approach of the proposed MB(oSDM) S-BVT, flexible bandwidth allocation can be enabled providing an efficient management of the network resources and adapting the transmission to the changing needs and traffic demand. Different transceiver implementations/configurations can be considered including, for example, external or direct modulation (at the transmitter) and direct detection or coherent reception (at the receiver) trading off cost-effectiveness and performance.

Coherent DSCM based P2MP

P2MP can be realized by creating digital subcarrier channels within the Digital Signal Processing (DSP) unit. This block can subdivide the transmission and reception of a given wavelength spectrum into a series of smaller-frequency channels called digital subcarriers. The digital subcarriers can be independently managed and assigned to different destinations, enabling direct low- to high-speed optical transceiver connectivity both in P2P and P2MP mode. As the subcarriers are generated in the digital domain, only one laser is needed. With DSCM, for example, a 400G P2MP transceiver acts as a transmitter in a downstream scenario, transmitting flows from the hub site to leaf nodes: the multi-carrier signal is broadcast to multiple leaf nodes (e.g., antennas), each of which can extract a single subcarrier or a group thereof, according to the traffic characteristics. This allocation of resources at the transmitter opens the door to dynamic adjustments for subcarriers to better match the flow of traffic patterns during the day, as there are times when networks need to address more critical scenarios. By operating in this fashion, the hub node can utilize a single transceiver to communicate with up to 16 leaf nodes simultaneously, with each node receiving a single 25G subcarrier [Wel21].

4.5.3 MBoSDM Switching Technology and Network Capability for Backbone

A **multigranular MBoSDM modular and flexible Optical Switch** architecture is envisioned within SEASON to simplify the node design and enhance switching capabilities towards meeting future capacity targets/requirements within the backbone segment. Specifically, spectral (in terms of wavelengths and bands) and spatial switching granularities can be enabled (WDM, MB and SDM) with key technology within each granularity level. The proposed node architecture under evaluation will be capable of dynamically route and add/drop traffic while potentially increasing the switching capacity in a flexible manner. Mainly, each layer can include different technology options such as WSSs and/or passive filters for band/spatial multiplexing and demultiplexing which will offer different levels of flexibility.

Motivated by the above-mentioned need to simplify conventional ROADM architectures when multiband and multi-fiber processing is required, in Figure 4-4, we present an implementation of a node architecture exhibiting two levels of switching: at the spectral band and at the wavelength channel level. A modular approach is adopted for its design, whereby band filters, spatial optical cross-connects (OXC) and WSS are interlinked so that the node can switch a large number of optical dimensions in a more straightforward and agile manner than in conventional ROADM architectures. In the figure we depict a 3rd order nodal degree, covering three directions (North, East, and West), in each of which three pairs of optical fibers and three spectral bands (S, C, and L) per fiber are rolled out. This design enables switching at the spectral band level as well as at the wavelength level, facilitated by individual-band WSSs. We assume that each band will be amplified by a separate fiber amplifier. Therefore, a band filter is placed at each of the ingresses and egresses of the node, so fiber switching as such is not allowed. If full fiber switching is desired, an S-OXC can be placed at the node ingress/egress, but, given that band amplification is assumed, it does not appear to bring any benefit. However, if (multiband) Raman amplification is considered, this may be an option to explore. The node shown in Figure 4-4 integrates all essential optical components, including band filters (BF), amplifiers, spatial Optical Cross-Connector (S-OXC) switches, WSSs, and A/D modules. These components are interconnected to establish a modular colorless-directionless (CD) MBoSDM node architecture, but a colorless-directionless-contentionless (CDC) architecture could be easily implemented by just removing the 1x20 WSS connected to the contentionless NxN WSS or substituting it with additional contentionless MxN WSS. It is important to note that, for simplicity, we only depict one pair of 1x20 WSS; however, the number of A/D modules could increase depending on the number of channels that need to be added/dropped to/from a given node and the capabilities of the NxN WSS (the actual implementation will determine the constraints in switching channels, e.g., across spatial dimensions, as detailed in section 4.3.1 of D3.1). The programmable S-OXC switches enable dynamic switching of each band within the spatial layer, directing it toward a specific orientation (i.e., North, East, or West), or switching it to the WSSs when wavelength-level processing is needed. In the design shown in Figure 4-4, each individual-band WSS processes the corresponding band across all spatial layers. We depict the contentionless WSSs as NxN modules, receiving bands from each spatial layer and from various directions (i.e., North, East, or West) through independent input ports. These modules seamlessly combine the wavelengths, directing them towards independent spatial layer output ports that are switched to specific directions through the S-OXC switches. On the other hand, band filters serve the purpose of separating or combining different bands, while amplifiers are located at the output of the node to compensate for the attenuation introduced by the fiber span. Note that the necessity (or not) of these amplifiers, as well as the configuration of the amplification gain, depends on the specific requirements of the network segment. There may be no need to consider a pre-amplification stage at the input of the S-OXC, in particular for bands that only undergo band filtering and spatial switching, but pre-amplifying the signal before WSS processing is essential due to the high insertion loss of the WSSs.

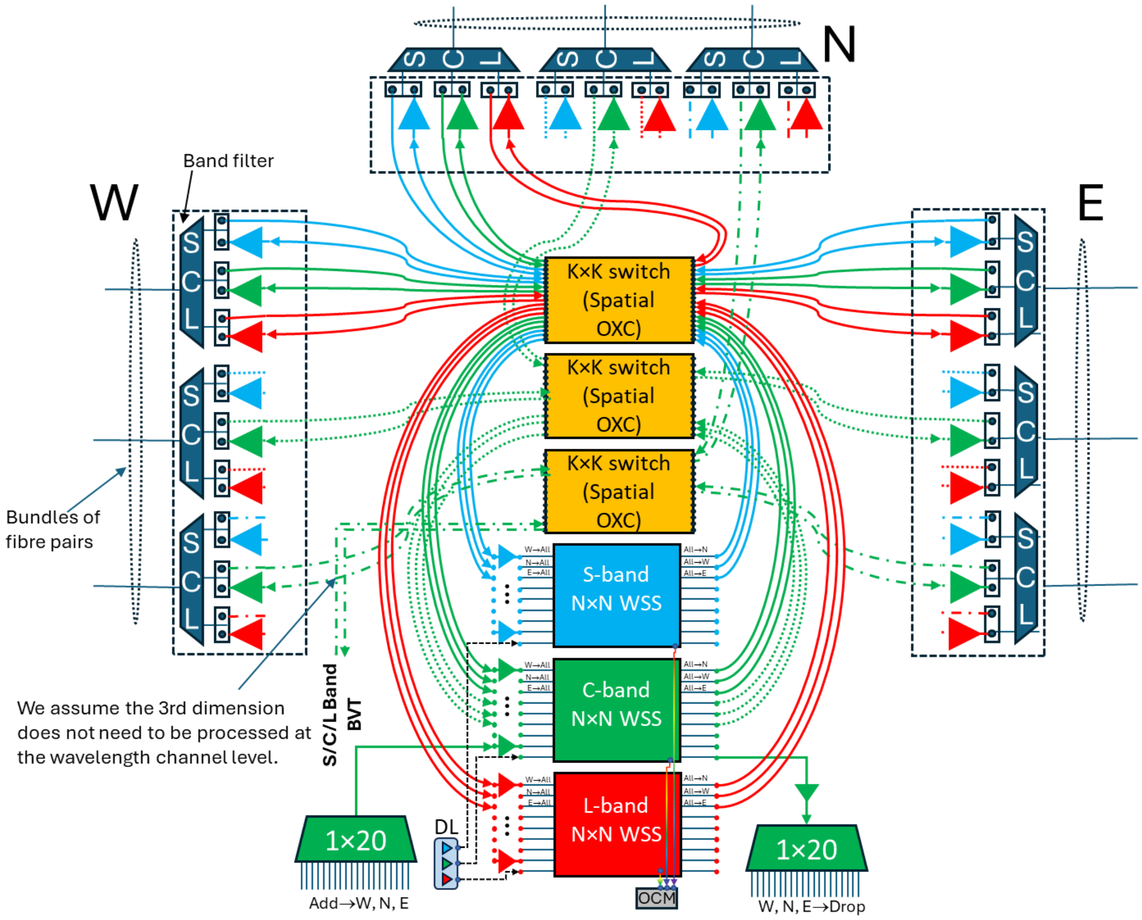


Figure 4-4 – Example of a modular high-capacity MBoSDM node architecture designed for SEASON. We represent a node with three degrees, three spatial dimensions and three spectral bands, assuming amplification per band and the possibility of band and wavelength switching. The 1x20 WSS are used for CD A/D functionality. If removed, the architecture would be CDC, but fiber shuffling, depending on the contentionless NxN WSS technology used, might not be allowed.

In Figure 4-4, as explained above, we assume one K×K S-OXC per fiber and one N×N contentionless WSS per band. However, several variations of the proposed architecture can be contemplated, e.g. one S-OXC per band and MB N×N contentionless WSS, which will be further evaluated in T3.1. The S-OXC is required for directionless functionality in the case of S/C/L band BVTs. It also enables L0 restoration of bands not processed at the wavelength level. If neither of these node capabilities is needed by the operator, it can be skipped and replaced with, e.g., non-programmable direct fiber connections. Dummy light (ASE loading) is considered to keep the effect of SRS under control. This is only necessary for bands processed at the wavelength level. The fact that some bands are switched by the S-OXC without passing through the WSS has the drawback that, compared with a conventional R&S ROADM architecture based exclusively on 1xN WSS, the MBoSDM node architecture under evaluation in SEASON does not allow channel equalization within bands not processed at the wavelength level.

Depending on the implementation of the NxN WSSs, it may be advantageous not to allow switching among spatial dimensions, i.e. Fiber 1 in degree W is only connected to Fiber 1 in degrees N and E, but not to Fiber 2 or 3. This is also true for the conventional ROADM architecture, as allowing for fiber shuffling may impose a heavy burden on the number of required ports and, consequently, the number of components, while the benefits that can be reaped from this additional flexibility may not necessarily compensate for the added cost. However, at this stage we do not impose any restrictions on the potential use of fiber shuffling. The N×N contentionless WSS illustrated in Figure 4-4 is vendor-agnostic and not restricted to any given technology. Networking and techno-economic studies will assess the advantages of incorporating additional flexibility into the node and the necessary trade-offs between performance and increased complexity. Further details about the MBoSDM node design are included in D3.1 and the work on the node design and its modelling is ongoing in T3.1.

Consistent with the above-mentioned architecture relying on different levels of switching, SEASON proposes two different modular implementations of **multi-granular optical switching node prototypes** that aim at increased cost-efficiency in scenarios of interest to SEASON. The first prototype focuses on fiber and whole-band switching (S-, C- or L-band), keeping the intra-band channel processing to the minimum required, whereas the second prototype also exploits WDM granularity together with MB and SDM. Networking studies in this work package will investigate the extent to which this processing can be reduced without impacting performance. The proposed prototypes aim to simplify the network architecture in specific use-cases and scenarios, where switching one entire band among fibers could be desired within metro/core segments, thus permitting high-capacity switching and improved scalability. Additionally, since different transmission bands are characterized by quite different optical performances, different bands can be explored to different applications. As an example, O-band can be explored for single-hop transmission only, thus simplifying the switching architecture. Moreover, simpler optical interfaces can be explored for this application.

Raman amplification may also play a fundamental role in simplifying the network management in the MB transmission scenario. In this case, Raman amplification may be explored to guarantee similar optical performance in all transmission bands without compromising the optical performance of existing bands. In case of a pay-as-you-grow approach, where transmission bands are added sequentially, Raman amplification may be explored to guarantee that optical performance of existing bands (e.g., C-band) does not change significantly due to the stimulated Raman effect when additional transmission bands are enabled. In SEASON, we will explore the Raman pump configurations leading to the best compromises between optical performance, network capacity and cost.

Simpler and more cost-effective switching architectures with lower degree of flexibility will also be considered within the project as a solution for the Access-Metro segment, where relaxed requirements are expected trading-off capacity versus cost/complexity.

4.5.3.1 (Flexible)Filtered-Filterless Hybrid MB and Multi Fiber Line Systems for Access-Metro

In the Access-Metro segment of SEASON architecture (see section 4.3), it is expected the coexistence of P2P and P2MP, Multi Band and a degree of fiber parallelism within the same network area. This is mainly due to: 1) the typical hubbed traffic flows from peripheral nodes (Far Edge COs) together with the traffic coming directly from Access Points (in case of Far Edge bypass), that feeds the metro aggregation and partially the metro core network areas; 2) the strong inhomogeneity of the traffic generated in different COs or high-capacity Access Points in the same area; 3) the continuous increase of traffic that, at a certain time, will exceed the C-band capacity. All these aspects are pointing toward higher capacity optical transport systems including Multi Band and fiber parallelism, with high flexibility and granularity mainly in the

Add/Drop, and potentially less need of optical flexibility for node passthrough (of course to be verified).

These traffic needs seem to fit well with filterless amplified systems allowing P2P and P2MP based on and DSC for low granularity and MCM for higher granularity traffic to coexist. Local laser oscillator and DSP are employed to filter the desired optical flows. This approach works up to a certain degree that depends on the specifications of the employed interfaces (out of band OSNR): typically, 4 or 16 optical carriers could be added together without adding filters.

To allow more capacity it is necessary to introduce sub-band filters (for example 400GHz or 600 GHz) to separate blocks of coherent channels. This architecture could be designed to allow Multi Band (C+L +…) parallel systems on the same fiber, adding sub-bands filters together with optical splitter/combiners in crossing and Add/Drop nodes to create the filterless environment on a sub-band basis.

More flexibility could be also obtained by adding, in selected locations, sub-band or fiber switching, and adding sub-band and fiber flexibility at the Add/Drop side. On the opposite, having ROADMs allowing efficient and multigranular optical switching supporting P2P and P2MP DSC and MCM functionalities, is expected to be a big challenge and possibly not economically viable for use in the Access-Metro segment.

4.5.4 SDM PON

The extension of traditional TWDM-PON architectures through spatial multiplexing is envisioned within SEASON. SDM-PON architectures recently proposed in [Fan18] allow up to 300/120 Gb/s (downstream/upstream respectively) providing a low-cost high-speed candidate solution for interconnecting both residential, mobile and business users, mainly in the access but also in the aggregation and metro segments. Such aggregated capacity is achieved by combining multi-core fiber (MCF) and WDM, in particular, 3x cores, 4x wavelengths and 25/10 Gb/s per wavelength, using simple intensity modulation with DD (without DSP).

While the introduction of the spatial dimension allows to increase PON capacity, it enables at the same time flexible aggregation of spatial channels to enforce energy-saving schemes through transceiver activation/deactivation. Such aggregation of spatial channels will be achieved through the re-design of traditional central office architecture and exploiting spatial switching/aggregation technology. The envisioned approach will be exploited in line-card based TWDM PON, pluggable PON, and Point-to-multipoint systems.

4.5.5 Front/Mid-haul solutions

Coherent "lite" for FH

Coherent "lite" has consolidated as a trend towards cost/performance optimization for shorter reach. In the data center segment, the trend is motivated by DC-interconnect needs (e.g., the 800G-LR activity at OIF). With 1.6 Tb/s transmission on the radar, coherent technology will be pushed even further in the short distance domain. In telecom, the historical trend of reduction of cost/performance/power consumption of coherent optics has already produced optimized "coherent lite" solutions at 100G to cover the so-called metro-access edge.

From the above considerations, we believe "coherent lite" might play a fundamental role in future 6G RAN and RAN transport.

Coherent DSCM based P2MP

Coherent P2MP DSCM enables single fiber operation and is a key element in RAN transport including Far Edge optical bypass on an optical flow basis. As stated previously, this technology provides a significant simplification of the network architecture by reducing the number of needed transceivers, reducing the total cost of ownership, and significantly increasing the capacity and flexibility in the RAN.

Pluggable Optical Line Systems (POLS)

The **POLS** play an important role in the evolution of the RAN transport scenarios. In fact, the needs of the RAN optical infrastructure will be covered with the ultimate step of disaggregation. Today's simple P2P solutions will be complemented over time by an increasing number of elementary functionalities like EDFAs, splitters, OCMs, and OTDRs in pluggable modules, which can be composed into full optical line systems tailored to the specific RAN transport scenarios.

4.5.6 SDN-based infrastructure configuration and control

SEASON includes the design of a scalable control plane for truly self-managed and autonomous networks, addressing the following aspects:

- A control and orchestration plane following SDN principles for an overarching control of the RAN, PON and Transport Segments (Aggregation/Metro/Backbone);
- The applicability of new control paradigms based on NetDevOps approaches jointly with AI/ML in support of network operation and network orchestration;
- An optical monitoring and telemetry platform using open interfaces;
- The use of digital twins for use cases such as fault localization.

Macroscopically, AI/ML will be applied for the near-real time control of network resources and services aiming at reducing energy consumption and ensuring performance, including moving intelligence as close as possible to the data plane, and devising a distributed system based on multiple communicating agents.

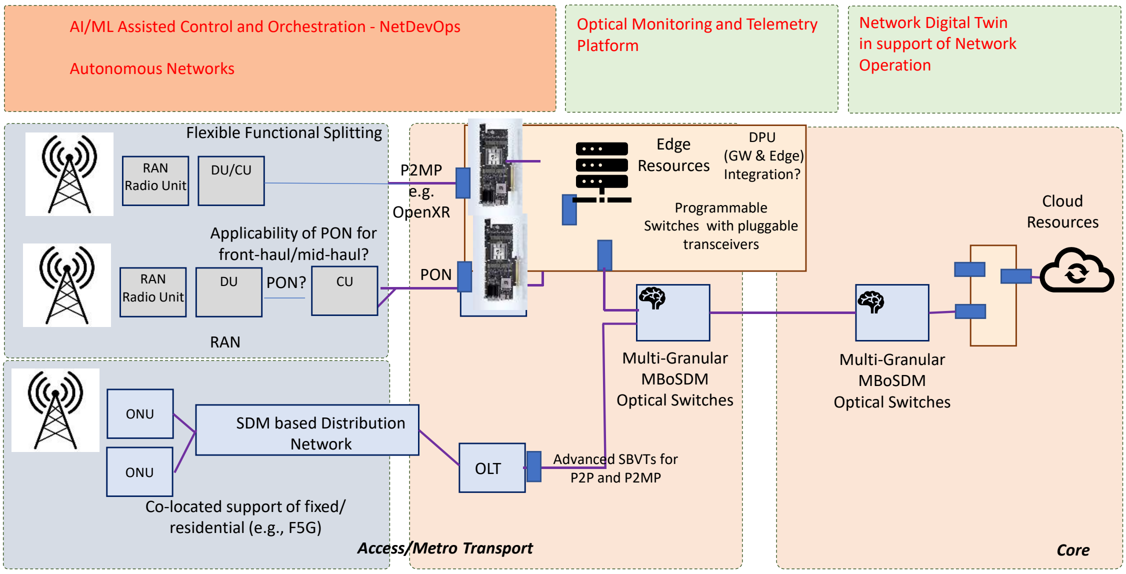


Figure 4-5 – Macroscopic overview of SEASON Control Plane key aspects over the SEASON data plane infrastructure.

There are several key innovation technologies addressed in the project:

- Infrastructure Control for MBoSDM optical network, including New Paradigms for SDN based Control (based on NetDevOps and Continuous Integration/Continuous Development);
- The usage of secure AI/ML techniques in support of network orchestration and Optical Layer Digital Twin including Multi-Agent Systems (MAS);
- Monitoring, Streaming Telemetry and Intelligent Data Aggregation in support of the previous aspect;
- RAN Intelligent Controller (RIC) and access/metro SDN Control Integration.

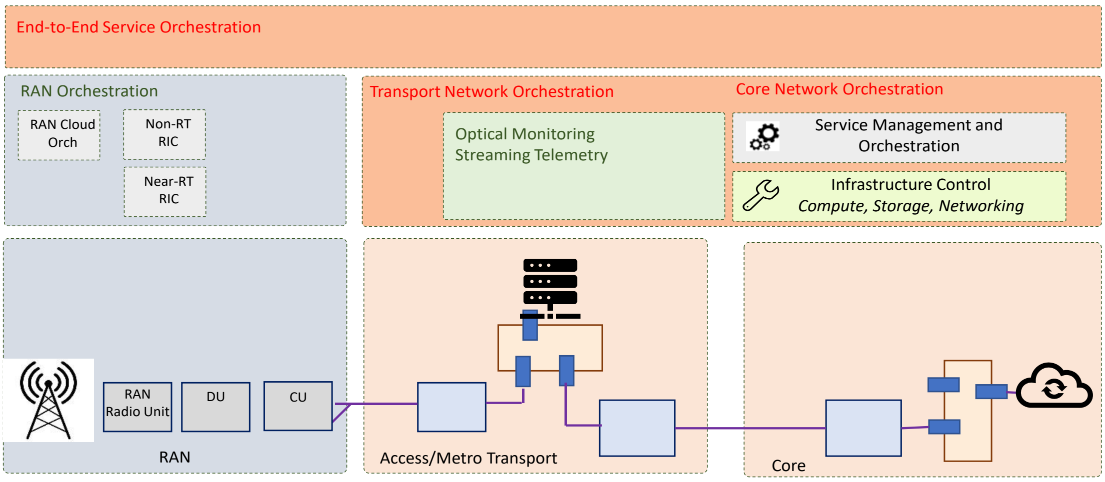


Figure 4-6 – End-to-End service orchestration and overarching control, including RAN/Transport orchestration.

Infrastructure Control for MBoSDM optical network

A key aspect is to design and develop an SDN control plane for a single optical domain where nodes encompass flexi-grid switching and SDM. The SDN control plane will rely on a single SDN Controller offering a standard Northbound interface (NBI) based on TAPI.

Part of the work is the design and development of SDN agents that rely on device data models to be designed during the project. The purpose is to be able to remotely configure and monitor the devices conceived in WP3.

SDN Control of PON

An enabling element in SEASON is the SDN control of PON infrastructure. SDN control will be enforced via NETCONF as southbound interface (SBI) API. NBI APIs will be developed to control envisioned mechanisms for spatial aggregation/disaggregation and deactivation/activation of active components at the OLT. The envisioned mechanisms require the joint control of OLT components (linecards, transceivers, and bandwidth allocation) and spatial switching elements envisioned in SEASON central office architecture.

Furthermore, the ability to control PON via SDN enables efficient integration between the optical and RANs thanks to the cooperation with O-RAN near Real Time and Non-Real Time Radio Intelligent Controllers. PON SDN control will offer the capability to implement ad-hoc resource allocation strategies for VLANs devoted to serve specific slices in the mid-haul segment of the mobile network. This will enable efficient end-to-end network resource usage as well as integrated optical and radio latency control.

Network Orchestration using TeraflowSDN

TeraflowSDN (TFS) Controller is an open source cloud native SDN controller hosted by ETSI and led by the Open Source Group for TeraflowSDN (OSG TFS) [TFS23]. TFS architecture is depicted in Figure 4-7:

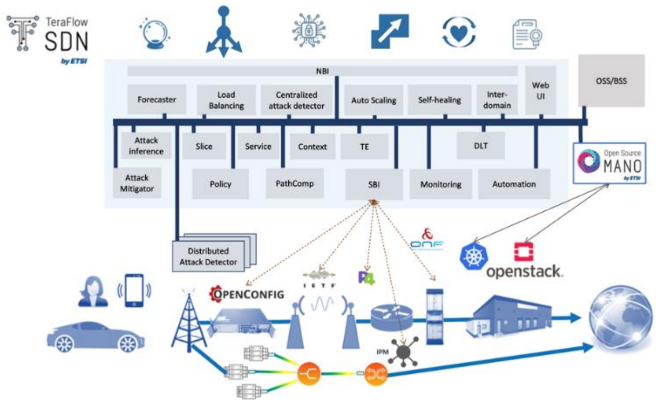


Figure 4-7 TFS architecture.

In SEASON, the TFS framework will be used for 2 roles. The first one is as an IP/MPLS (packet) controller. The second one is as a Transport Network Orchestrator.

TFS as packet layer controller

The current version of TFS controller (release 2) has the capabilities of Layer 3 VPN service provisioning, L2 VPN, ACL management for security and inventory information using

Netconf/Openconfig as SBI and standard L3NM / L2NM in the northbound. It is also able to collect, via gNmi/Openconfig, telemetry data from packet devices.

The Opendevice SBI driver module is in charge of connecting to network devices and/or network controllers. This driver will be enhanced to control the SEASON packet/optical/DPU and colored pluggable modules. The NBI, currently residing in the compute component, will be enhanced to cover the necessary interactions to create optical connectivity from the packet/optical devices. Different scenarios will be studied in SEASON regarding the control of the pluggable interfaces. In particular, effort will be addressed to investigate the SINGLE management MANTRA scenario, in which the packet controller is the sole entity accessing the packet box [Gon22] where the necessary workflow will be taken to standardization in IETF [IET23]. This does not exclude other architectures and scenarios, including the use of different controllers.

TFS as Transport Network Orchestrator

Multi-domain, multi-technology context: The TFS context component is the single-entry point to the necessary operations for reading, updating, or removing elements from the TeraFlowSDN controller database. Context handles objects such as topologies, devices, links, services, and connections. In SEASON, the context component will be enhanced to include the necessary information to connect the different transport domains.

The TAPI SBI driver is responsible for connecting to the optical controller. In SEASON, the driver will be enhanced to be able to retrieve the enhanced TAPI context exposed by the MBoSDM optical controller. Moreover, a new SBI driver will be required in SEASON to connect to the PON domain, and include the necessary abstract representation of the access domain in the Context module.

As per NBI requests, the TFS has an OSM-TFS interface based on IETF L2VPN Yang service model. The use of IETF Slice model, which is more generic, will be investigated to be used as the SEASON Orchestrator NBI. This will allow customers to request intent-like connections, which will be translated into the necessary domain-specific resources needed.

RAN Control

Figure 4-8 shows the service management and orchestration (SMO) interfaces to manage, monitor and deploy various network functions in the RAN network segment. The telemetry data (3GPP 28.552 stats) is available at both the near RT RIC for xApps via the E2 interface and in the non-RT RIC for rAPPS via the ONAP High Volume-VES interface.

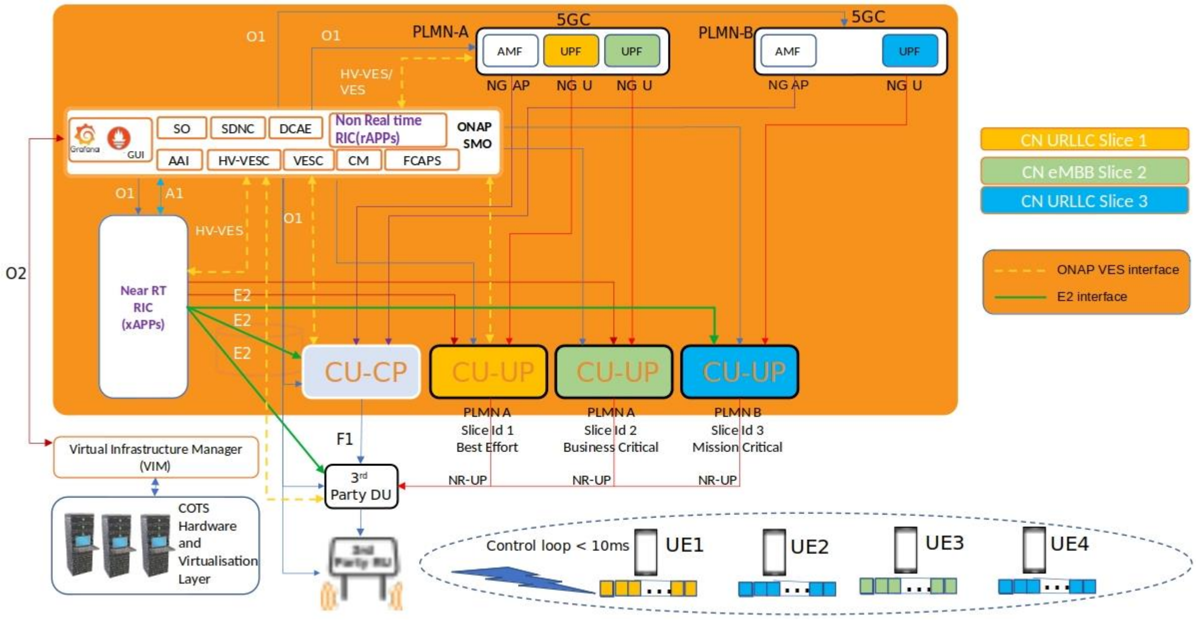


Figure 4-8 – Example ONAP and mobile network slicing architecture.

Based on the telemetry data, the machine learning rAPPs instruct the SMO to optimize the configuration of compute resources or network functions, the RAN nodes (RU's) and the transport network resources via the SDN controller to save energy and improve network resources.

Data Processing Unit (DPU) Control

SEASON will investigate the use of a new generation of SmartNICs, called DPUs, equipped with coherent pluggable transceivers. Two main innovations will be addressed:

- Introduce OpenConfig control within the DPU. So far, OpenConfig control of optical parameters has been applied to switches or transponders only, while no work has been done at the level of NICs. The goal is to enable the SDN configuration of the main optical parameters of the coherent transceiver equipped within a DPU when it is connected to an OLS. SDN control refers to main optical parameters such as wavelength, power levels, and operational modes. The MANTRA scenarios like DUAL and SINGLE will be also considered for DPU applicability;
- Investigate the main functionalities that DPUs equipped with coherent modules can provide to 5G/6G use cases. For example, this includes leveraging on HW-acceleration capabilities on encryption/decryption, cyber security, and deep packet inspection.

4.5.7 NetDevOps and Continuous Integration / Continuous development

NetDevOps ensures that network changes are small and frequent but also performed in a much more automated, efficient, and reliable way. DevOps is a software development strategy and culture that bridges the gap between the Development (Dev) and Operational teams (Ops), to build, test and release software faster and more reliably. NetDevOps is applying tools, concepts, and methodologies from DevOps and Infrastructure-as-Code (IaC) to network operation, allowing network devices and infrastructure configuration and operation a Network-as-Code (NaC) paradigm.

The approach also increases automation and monitoring to increase efficiency and reduce errors. NetDevOps applies several strategies from DevOps to address this issue, such as:

- Automation: It takes what traditionally are manual procedures in network infrastructure and applies the principles of automation and scalability.
- Frequent but smaller updates. They are incremental and make each deployment less risky.
- Reduce manual intervention with IaC: Under this paradigm, network devices are provisioned using machine-readable definition files rather than physical configuration files.
- Continuous Integration (CI) and Continuous Delivery (CD) or CI/CD: this makes iteration times very small.

Use cases:

i) device provisioning: the first step is to create the configuration file and then pushing the configuration onto the device;

ii) data collection and telemetry using NETCONF and gRPC or custom-built code using various libraries;

iii) configuration management: it involves actual deployment and management of configuration files to networking devices, e.g., for configuration of flexible transponders with optimal modulation format;

iv) service provisioning and service lifecycle management.

What is CI/CD Pipeline:

- A pipeline is a series of steps to facilitate the CI/CD of the application.
- Initially, it creates the compilation environment in the "Runner machine" according to the nature of the application (Java/Python/Docker).
- The typical pipeline has processes like code compilation, artifact generation, deployment, testing, monitoring and feedback.

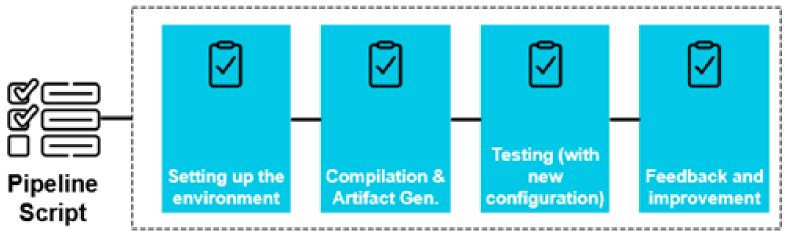


Figure 4-9 –CI/CD pipeline example.

4.5.8 AI/ML Empowered Network Operation

AI/ML empowered control plane utilizes the operation data of the NEs and deployed services and enforces a predictive management of the network**.** End-to-end management of the optical services incorporating the intelligence which results from the learning of the deployed services and NE behaviour in the past. The main function of the AI/ML in control plane is to effectively configure/re-configure the service requests satisfying the requirements. This also helps to provide a study on the controller scalability study having Digital Twin based data plane. The benefit lies in: i) ensuring SLA compliance to optical service requests, ii) Effective resource utilization, iii) Conservation of energy with proper resource utilization, iv) and predictive actions based on ML algorithm.

1. One technical insight of AI/ML empowered control plane is the monitoring of performance data of optical channels (or optical services), where the increase in the number of channels in the link affects the channel performance due to noise, interference, etc. This can be predicted using suitable ML algorithms and managed efficiently with the increase/decrease in service requests.

2. Suitable protocols and technologies to retrieve operational data from data plane is part of the pervasive telemetry.

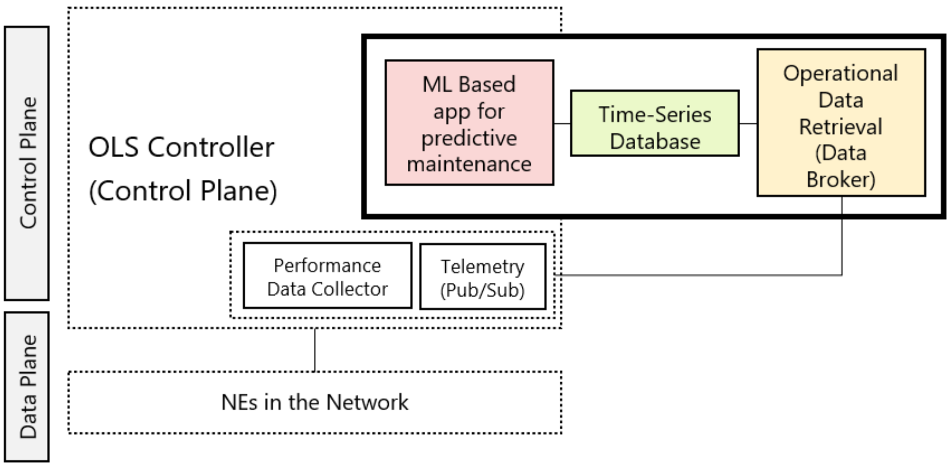


Figure 4-10 – Basic reference diagram for AI/ML assisted Network Operation.

Multi-Agent systems and Digital Twin

A key element in SEASON control plane is **the Multi-Agent System (MAS)**, that comprises a set of individual agents that share knowledge and communicate with each other to solve a problem that is beyond the scope of a single agent. It is oriented to deal with near real-time resource management across different segments, e.g., involving both RAN and optical transport. Several use cases are devised, e.g., to reduce energy consumption by dynamically managing P2MP transponders in support of RAN transport. This distributed negotiation of resources liberates centralized SDN-based control and management layers from critical near-real time autonomous operation tasks.

Another important element is the **optical layer Digital Twin (DT)** built on top of the current OCATA framework. This DT, that will be named OCATA-MBC, will include main features such as time and frequency-domain modelling of MB and SDM technologies. OCATA-MBC will improve current automatized mechanisms from soft-failure detection, localization, and identification, as well as lightpath provisioning by producing accurate QoT analysis. Both use cases are expected to lead to OPEX savings.

AI/ML Service Orchestration

The AI/ML empowered control plane is designed to adaptively manage and optimize network operation across diverse segments. It replaces the manual, traditional control methodologies with AI/ML-driven solutions for increased efficiency and dynamism. Its primarily placement is within the **end-to-end service orchestration platform**, integrating with the various network segments such as RAN, access/metro transport and core by making use of components such as Cross-Domain resource management and Inter-Domain Service Orchestration. It brings several benefits, including reduced operational expenses (OPEX), improved decision-making and enhanced network resource management.

For the aforementioned to be realized, AI/ML techniques can be deployed, such as Support Vector Machines (SVM), Deep Neural Networks (DNN), Reinforcement Learning (RL), and Long Short-Term Memory (LSTM). These techniques are adept at addressing complex tasks, such as failure detection, traffic monitoring and analysis, anomaly detection, and modelling traffic patterns. The integration of these technologies aims to enhance the overall Quality of Service (QoS), by ensuring optimal availability, reliability, and performance, while simultaneously reducing the consumption of resources such as energy and computing/communication resources. Besides this Multi-Agent Systems approach, Federated Learning (FL) can also be utilized as a key approach for distributed data processing and collaborative model training. The latter holds because FL aligns with the distributed nature of the multi-agent system, with each agent operating as a node in the FL network, learning from its local data while maintaining its privacy, as well minimizing the data overhead transmitted over the various channels, as in centralized architectures. This cooperative framework promotes shared learning across the network, contributing to the development of more comprehensive and context-aware models that boost overall system performance. By receiving inputs such as service demand and infrastructure capabilities and, through the application of the aforementioned robust AI/ML algorithms, the system will provide optimized outputs that guide resource allocation decisions and management and orchestration across communication domains. The data-driven decision-making process will not only promote efficiency but also enhance the adaptability of the network, allowing for a more resilient and reliable communication infrastructure.

Regarding the architecture of such an AI-driven orchestration framework, well-established and state-of-the-art architectural frameworks and techniques will be followed, Cloud-native approaches will be followed for the architecture of the orchestration capabilities of SEASON. For the management of the various network services, along with the configuration, instantiation, scaling, termination, etc. of the various VNFs/CNFs/KNFs, capabilities from container orchestration platforms such as Kubernetes will be considered, potentially following also design principles indicated by well-established orchestration frameworks such as the OSM. Besides the service and network function orchestration and lifecycle management, the execution environment and lifecycle of the required AI/ML workloads will be managed, offering a reliable, scalable, and robust infrastructure. Inherent features like auto-scaling, self-healing, and automated rollouts and rollbacks will be leveraged.

To conclude, incorporating the O-RAN, metro/access transport, core, and other infrastructure into this AI-driven framework is crucial for a harmonized network operation. Cross-domain orchestration challenges will be explored, while also various reference architectures such as the ETSI ZSM's integration fabric component will be considered. AI/ML functionalities are deemed of utmost importance in optimizing resource orchestration and service management in such complex contexts; using AI/ML techniques and achieving seamless interoperability and integration, the considered system will attempt to give rise to an adaptive and intelligent network by optimizing performance, improving QoS and efficient, scalable, and resilient communications across its entities.

4.5.9 Pervasive Telemetry

This enabling technology targets the continuous and secure optical performance monitoring of the end-to-end packet and optical transport (i.e., link load, latency, OSNR, pre-FEC BER) network. Specifically, it will be achieved by a common telemetry platform across the different segments, including the RAN (via the RAN Controllers), PON systems (via dedicated controllers) and the aggregation and metro segments and the 5G core, such as the 5G network data analytics function (NWDAF). Furthermore, the packet and computing resources within DPUs/SmartNICs will be specifically considered as key elements of the pervasive monitoring platform, not only as producer of computing, packet and optical monitoring data, but also as consumer, directly performing advanced in-network monitoring functions.

Specific functions that are envisioned for pervasive telemetry include: *i*) enhanced signal processing techniques for fiber link characteristics estimation, *ii*) dedicated monitoring sources for signal identification and characterization, *iii*) adaptive AI-based methods for sampling, aggregation, compression, and analysis of optical signal samples, *iv*) characterization of individual fiber sections by means of interrogators, *v*) amplifier control and link monitoring by embedded OSAs, vi) monitor O-RAN components to optimize performance between RAN elements, vii) increase energy efficiency by dynamically manage RAN resources.

Since pervasive telemetry is one of the essential pillars for AI/ML empowered control plane, some expected benefits include cost-effective and energy-efficient self-managed network operation.

4.6 Technology Mapping for Data Plane

This section provides a tentative and very preliminary mapping of the technologies considered in SEASON. It is to be intended as a guideline only, not excluding different applications or even new ideas that could arise during the project. The section is divided into two subsections, one dedicated to the mapping of data plane technologies, the other to the mapping of control plane technologies; for each of them the mapping is done for both periods defined in section 4.2, i.e., for the medium- and for the long-term. Part of the content of this section has already been anticipated in the previous sections. In this sense, this section recapitulates and completes the previous ones and presents a preliminary proposal summary for the use of technologies within SEASON high-level network architecture.

4.6.1 Medium-term

In the medium-term, the SEASON data plane technologies could be introduced according to the following scheme:

- Extended use of L2/L3 switches or whiteboxes capable of hosting pluggable transceivers and use of compatible pluggable modules in the Access-Metro. Pluggable modules includes transceivers (up to 800G) compliant with high-performance interoperable standards (e.g., OIF, OpenROADM), but also EDFAs and VOAs to be plugged in optical whiteboxes (systems that are capable of hosting modules from different manufacturers to create an open line system) or even in L2/L3 switches; any control and management issue in hosting pluggables (any type) in L2/L3 switch/whitebox or optical whitebox is assumed addressed and solved.
- Use of DPU/Smart NIC with interfaces at up to 800G and support of P2P and P2MP at Edge and Far Edge: at the Far Edge mainly for providing Telco functions (e.g., vDU) and also providing Service functions (e.g., AI tasks) at the Edge.
- 50G PONs as solution to collect end points in the access and possible early introduction of coherent PON at 200G; possible introduction of WDM PON to multiply the fiber capacity.
- Coherent DSCM based P2MP and P2P transceiver (up to 800G) as a possible solution in the Access-Metro segment, including transport of FH flows (<=200 Gb/s) in the RAN.
- Pure filterless or hybrid filtered-filterless optical line systems in combination with DSCM and MCM based P2MP and P2P transceiver.
- Possible coexistence in the same fiber network of PON (including coherent and WDM PON) and coherent DSCM based P2MP and P2P in the Access-Metro segment.
- Exploitation of P2P transceivers operating on C+L bands, eventually extended to include S-band. To be used in the Metro part of Access-metro or in the Backbone.
- Exploitation of MBoSDM sliceable bit rate/bandwidth variable transceiver in a subset of bands and for flows of the order of 1 Tb/s or higher, to be used in the Metro part of Access-metro or in the Backbone.
- Implementation of radio access according to the O-RAN architecture providing double split 2 (MH) and 7.2 (FH) with open solutions (distributed or centralized) regarding the positioning of the vDU and vCU functions. Reference to functionality available with 5 G Advanced (3GPP Rel. 18 and 19).

4.6.2 Long-term

In the long-term, the application of SEASON data plane technologies could evolve according to the following items:

- Application in the Access-Metro of evolution of whiteboxes and pluggables (hard to predict in which form) to reach data rates per flow of up to 2 Tb/s, preferably with the same form factor as today's 400G; evolution of other type of pluggable, EDFA and VOAs, with their higher level of integration and lower cost power consumption and footprint.
- Massive use of DPU (or its evolution) with interfaces at 800G or higher data rate (up to 2 Tb/s) at Far Edge to support both Telco and Service functions (e.g., not only vDU but, for instance, also massive AI tasks to support services according to the Compute Power Networking paradigm).

- Coherent PON at 200G and higher, WDM PON and SDM PON as solutions to cope with traffic demand growth from Access Points in the Access-Metro domain. The pros and cons of these different solutions, depending on specific application scenarios, are to be evaluated.
- Use of coherent DSCM based P2MP and P2P transceivers in their enhanced version (>= 800 Gb/s, up to 2 Tb/s of total capacity) in the Access-Metro.
- Add a fully meshed connectivity in the fronthaul (exploiting coherent technologies and optical layer flexibility) to allow independent processes to be flexibly managed providing optimization in the cloud RAN.
- Use of coherent "lite" transceivers at >= 400 Gb/s for FH application (with 6G).
- Full exploitation of MBoSDM sliceable bit rate/bandwidth variable transceiver or its evolution, beyond the C+L band and at aggregate bit rates above 1 Tb/s, potentially up to 10 Tb/s. To be used in the Metro part of Access-Metro or in the Backbone.
- Full exploitation of multigranular MBoSDM modular and flexible node or its evolution; specifically, spectral and spatial switching granularities will be fully enabled allowing a three-layer switching capability (WDM, MB and SDM layers). The multigranular node is mainly (or exclusively) candidate for applications in the backbone segment.
- Implementation of radio access according to the O-RAN architecture providing double split 2 (MH) and 7.2 (FH) with open solutions (distributed or centralized) regarding the positioning of the vDU and vCU functions. Reference to functionality available with 5 G Advanced (3GPP Rel. 18 and 19).
- Still implementation of radio access according to the O-RAN architecture but with additional frequencies available and with reference to the features available with 6G (3GPP Rel. 20 and subsequent).

4.7 TECHNOLOGY MAPPING FOR CONTROL PLANE

Regarding the control plane, a two-step introduction of the technological innovations that will be developed and tested in the SEASON project has been identified. The evolution has been formulated by the project with the help of the partners involved in WP4 and evaluated afterwards by the Operators. Even though the innovations themselves are of interest and desired, it is difficult to establish whether they will actually be implemented and, if yes, when.

Before formulating the development plan of the control and orchestration plane in two steps for the medium- and the long-term, let us first express some actions that could be of interest in a shorter time frame as they concern technologies that are mature or almost already available, and do not require disruptive changes.

One of such actions could be the adoption of model-driven development in new systems and in migrations deployments, the consolidation of open device and network data models such as OpenConfig and OpenROADM, and the support of standardization for Transport SDN, covering aspects such as Optical networking or IP router configuration.

Another action to take in short-term could be a gradual migration of old systems for alarm and notification to SDN-compatible frameworks and systems. In addition, a systematic increase in telemetry and optical network monitoring and integration in telcos OSS/BSS (operation support systems and business support systems) can be implemented.

Introduction of devices and sub-systems with open Application Programming Interfaces (API)s into production deployments, based on industry standard, consolidation of partial disaggregation in SDN decoupling control of transceivers and optical line systems are other activities to be promoted. In addition to that, the usage of devices and subsystems with increased programmability, dynamic configuration of operational modes (e.g., transmission capabilities) based on network status should be considered.

Other action points for the short term are the automated provisioning of services upon request (human driven) and basic transmission system dynamic adaptation, and the adoption of AI/ML techniques for aspects such as QoT monitoring, path validation or traffic matrix estimation, but mostly as an off-line tool for validation, planning and forecasting.

4.7.1 Medium-Term

In the medium-term, the main innovations of the control plane identified are:

- Consolidation of SDN principles and best practices for the automation of service provisioning.
- Introduction of some level of autonomy by means of simple rules and AI/ML-assisted network operations.
- Adoption of control and orchestration systems based on composable functions (components) that are interconnected, via open and standard (internal) interfaces, following a Service Oriented Architecture (SOA) and implemented e.g., as distributed systems or microservices benefiting from automated deployment, scaling, and lifetime management.
- Integration and orchestration of different network layers (e.g., packet and optical), increased use of programmable coherent pluggables requiring interlayer coordination.
- Integration of networking control with IT (Computing/Storage) management.
- Deployments of network sharing and network virtualization at the transport level, proof-of-concept in terms of transport slicing. Manual operation of “transport slicing”.
- Increased application of AI/ML solutions in support of network operations beyond expert- or rule- based systems, targeting mostly single domains scenarios and specific applications.

4.7.2 Long-term

In the long-term, the control plane could evolve from what was already achieved in the medium-term according to the following innovation actions:

- Overarching control of multi-domain networks including optical bypass and transparent domain interconnection. Integration of different network domains (access, aggregation, core) and joint orchestration with RAN (e.g., telemetry, resource allocation, dynamic bandwidth allocation).
- Increased dynamicity with improved consideration for Physical Layer Impairments across domains and systems and more efficient capacity management.
- Automated use cases for traffic management and dynamic capacity adjustment with little to no human intervention.
- Network slicing and virtualization across domain boundaries and actors.

- Massive use of AI/ML solutions in support of network operations, extended to work cooperatively across different domains.
- Quantum / Legacy networking coexistence and interworking.

5 REFERENCE TOPOLOGIES FOR NETWORK STUDIES

The reference architecture for The SEASON project outlined in Figure 4-2 for the mid term and in Figure 4-3 for the long term includes an Access-Metro domain and a Backbone. In the next two subsections of this chapter some reference networks are presented. The reference networks are provided by operators based on their real networks in the field and cover both the two domains defined for SEASON architecture, Access-Metro and Backbone. These reference networks can be used, together with considerations on use cases and related generated traffic and on enabling technologies, for dimensioning studies and techno-economic evaluations in SEASON project.

5.1 TOPOLOGY FOR ACCESS-METRO DOMAIN

In the Access-Metro domain of the proposed SEASON architecture, transport solutions will integrate with each other, as well as with network and service functions, to allow the satisfaction of all requirements reported in Section 0, i.e., bandwidth, latency, computational and storage capacity, and others.

In operator networks, network segmentation today includes at least three clearly demarcated segments: **access segment** (fixed fiber component (e.g., FTTH) and mobile radio (4G/LTE and 5G/NR)), **metro or metro-regional segment** (depending on case to case, but typically divided into two sub-segments: aggregation and metro core), and **backbone segment** for long-distance connections on a national scale.

According to SEASON's statement presented in Section 4, the clear demarcation of the access and metro segments is desired to be removed by seeking, as far as possible, optimized solutions throughout the entire part of the network from the access termination (of any type) up to the first national backbone node (Cloud CO).

Starting from the operator networks as they are today, and to use them consistently with the SEASON architecture, an adaptation must be made. What is proposed is to consider the metro-regional networks as they are today, with central offices as possible candidate points to host switching and cloud equipment. Examples of metro-regional networks are provided by TIM (subsection 5.1.1) and TID (subsection 5.1.2).

Furthermore, current fiber topology will be assumed as the baseline for the new optical network and the extension of this typology towards the access areas is done through a categorization of the access areas using regular models based on realistic statistics. Operators, for confidentiality reasons, cannot provide details about their access networks, but they can provide average typical values for modelling the areas in terms of size and collected households and gathered radio sites. The proposed model, described in subsection 5.1.3, involves the categorization of access areas into four geotypes: dense urban, urban, suburban and rural. Each central office (of any level) included in the current network topologies is associated with one of the above geotypes. The access geotype model applies to both the regional metro networks of TIM and TID, and in general also to other situations, being sufficiently generic to be adapted, by attributing appropriate values to the parameters, to many other scenarios.

Traffic collection and aggregation points today are COs (of any type: Local, Regional or National) and, in the SEASON architecture, these points can be a potential candidate to become a Far Edge or Edge point. In addition, Far Edge points under specific needs can be placed also in other more distributed points that today just host cabinets or mobile sites. These additional more peripheral points are provided through regular typical models for the geotypes mentioned above, i.e., Dense urban, Urban, Suburban, or Rural areas. As the market is under evolution, model parameters or the model itself can be changed to consider the evolution in time in the access architecture, especially on potential deployment of small cells in some areas which requires collecting very high amounts of traffic. Fixed technologies are expected to evolve, for instance, in terms of PON technologies with higher capacity than they have today (e.g., from 10 Gb/s PON of today standard deployment to 25/50 Gb/s PON of next deployment, in short term, to 200/400 Gb/s coherent PON or even SDM PON in the long term).

5.1.1 Metro-Regional network of TIM

One of the networks proposed as a reference for SEASON network study is presented hereafter and it is inspired by Metro-Regional networks of TIM. The network has a metro core level made of metro core nodes connected by a mesh of fiber links plus a number of aggregation horseshoes made of a chain of aggregation nodes (leaves of horseshoe structure) and attached to the core in two metro core nodes (hubs of the horseshoe, they can be at Regional or National level). The typical hierarchical structure is depicted in Figure 5-1.

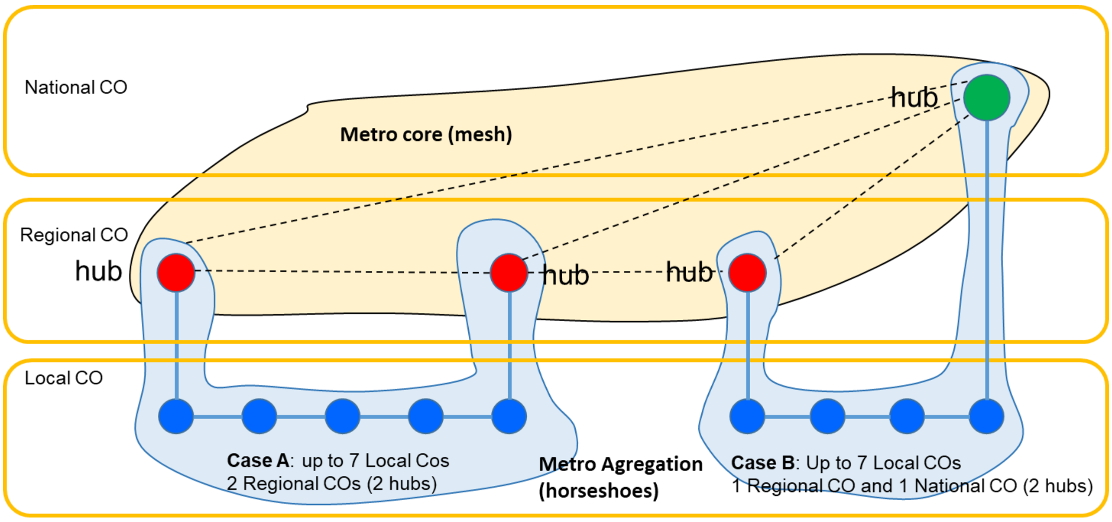


Figure 5-1 – Hierarchical structure of Metro-Regional network of TIM. Metro core mesh is within hubs (a hub can be in a Regional CO or in a National CO): Metro aggregation horseshoes end on hubs that can be both at Regional level (Case A) or one at Regional CO and the other at National level (Case B). The upper limit of Local COs leaves on horseshoes is 7 making 9 the maximum number of nodes in a horseshoe.

The fiber topology of the metro core reference network selected for the project is shown in Figure 5-2, where red nodes (MC01 to MC21) are the nodes that currently take part of the Regional level, while green nodes (BB01 and BB02) are the nodes that are located in National level central offices. In total there are 23 nodes, two of which are National, and 29 links. These nodes can be hubs for aggregation horseshoes.

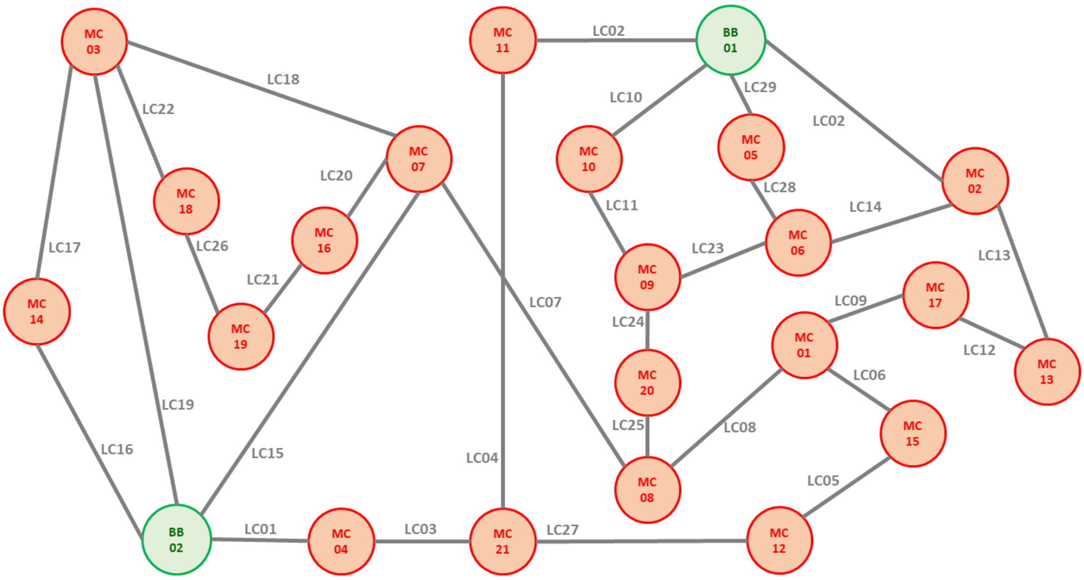


Figure 5-2 – Metro core mesh of the Access-Metro segment proposed as reference topology.

In fact, pairs of nodes of the metro core network collect one or more horseshoes and Figure 5-3 shows the example of the BB02 and MC04 nodes which act as hubs for three aggregation horseshoes, two of them collect four metro aggregation nodes (in blue) each and the remaining one, two metro aggregation nodes.

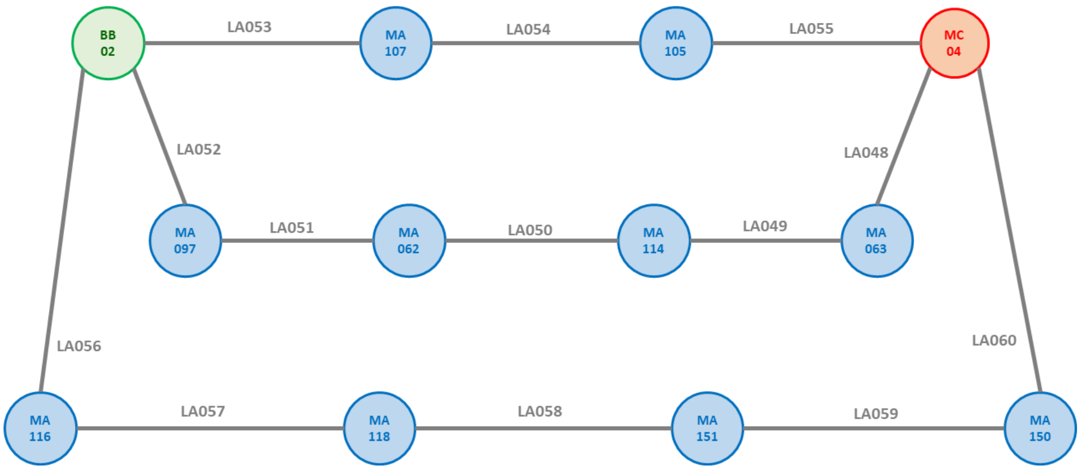


Figure 5-3 – Example of horseshoes collected by a twin of hubs in the Metro-Access segment.

The entire topology (metro core mesh plus all horseshoe structures) appropriately anonymized and with the parameters slightly perturbed for confidentiality reasons is included in an excel file and make available within the consortium for network studies. In addition to link lengths some characterization parameters is provided for each node, i.e., the number of households covered, the number of mobile radio site hosting macro cells and the number of mobile radio sites that, in future, could potentially host a small cell mobile radio site. The macro cell mobile site counts are possible educated guesses but do not constitute at all a TIM deployment plan.

5.1.2 Metro-Regional networks of **Telefónica**

The metro-regional networks proposed by Telefónica consist of a number of HL4 rings multi-homed to two HL3 aggregation nodes belonging to the backbone network, as is explained in the next section. Depending on the region's size and population, five different ring configurations can be observed, which can be illustrated in the five representative models presented in Figure 5-4. The nodes are denoted using the following naming convention: R (for Regional) + two digits (the first one representing the number of rings in the region and the second one serves as the HL4 node ID) + A,B… (only in the case of >1 ring, to differentiate between rings). The terminating HL3 nodes have ID "0" in Figure 6-7, but also have an associated code "Nxy1" or "Nxy2" (or exceptionally, "Nxy0", when there is only one HL3 in a city) in Figure 6-9.

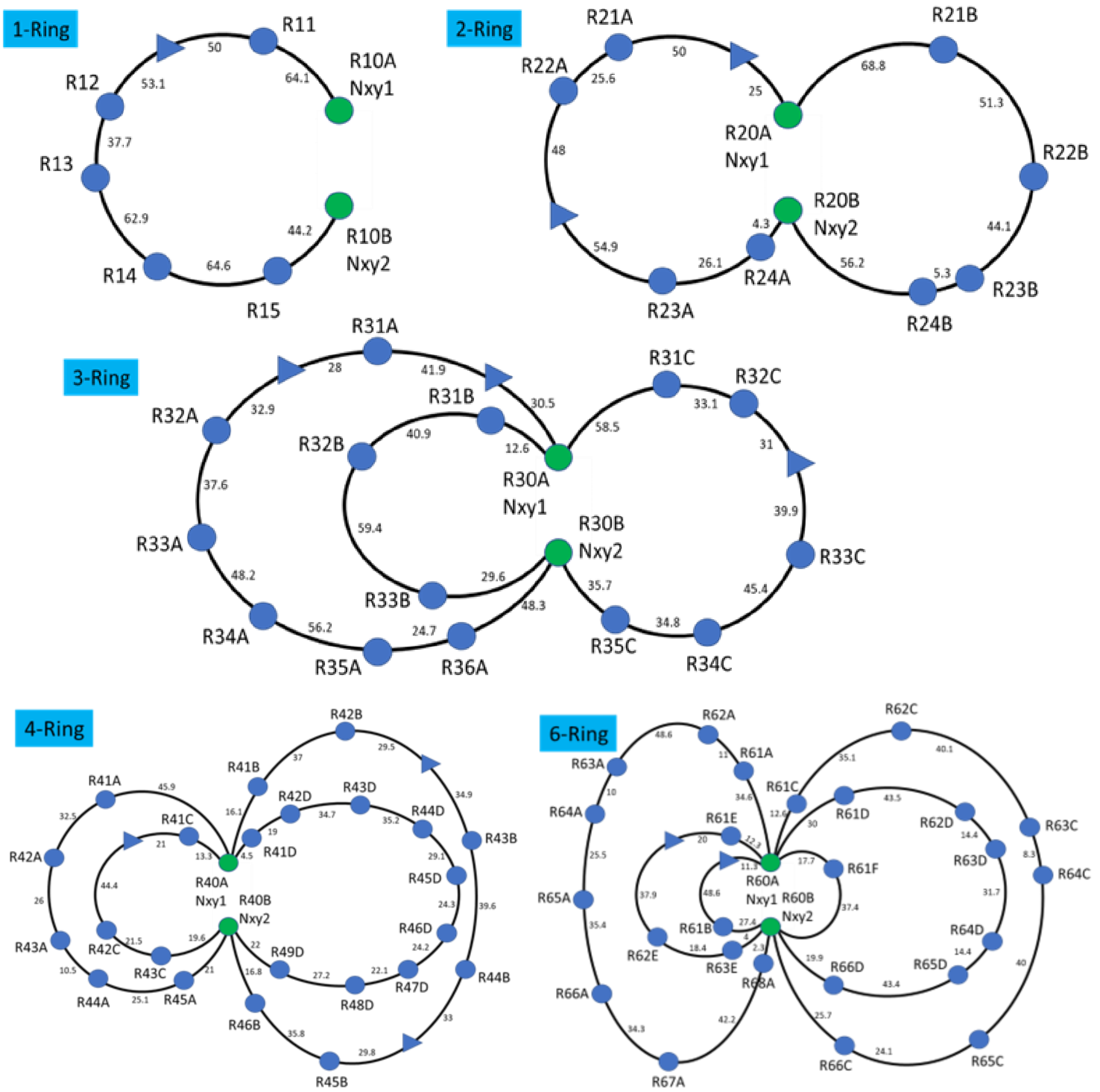


Figure 5-4 – SEASON metro-regional reference network topologies: topologies composed of 1, 2, 3, 4 and 6 rings. The triangle indicates an amplification site.

The most common metro-regional structures consist of two and three rings, representing 47% and 26% of the total, respectively. The highest average number of links occurs for 3-Ring and 4-

Ring structures, but we observe a significantly higher variability in the case of 6-Ring node structures, the standard deviation increasing from roughly ±1.5 links for 1- to 4-Ring structures to ±2.5 links for 6-Ring structures.

The Madrid region deserves special mention due to its high population density and the presence of HL1 interconnection nodes. There are six HL3 sites, four HL2 sites and 3 HL1 sites, meaning that the metro-regional rings can be aggregated at different sites. As a result, in Madrid there are two 1-Ring structures, one 2-Ring structure and two 3-Ring structures terminating at different HL3 node combinations.

The metro-access networks consist of semi-rings composed of HL5 nodes (remote nodes) that are connected to two HL4 nodes (aggregation nodes) belonging to either a common metro-regional ring or different rings. As shown in Figure 6-7, four semi-ring models can be defined in terms of their number of nodes, ranging from three to six nodes. In this case, nodes are named following a code consisting of A (for Access) followed by two digits, the first one representing the number of nodes in the semi-ring and the second one serving as the node identifier. For the aggregation nodes, an alternative code is provided, following the naming convention in Figure 6-6, as these nodes also belong to the metro-regional rings.

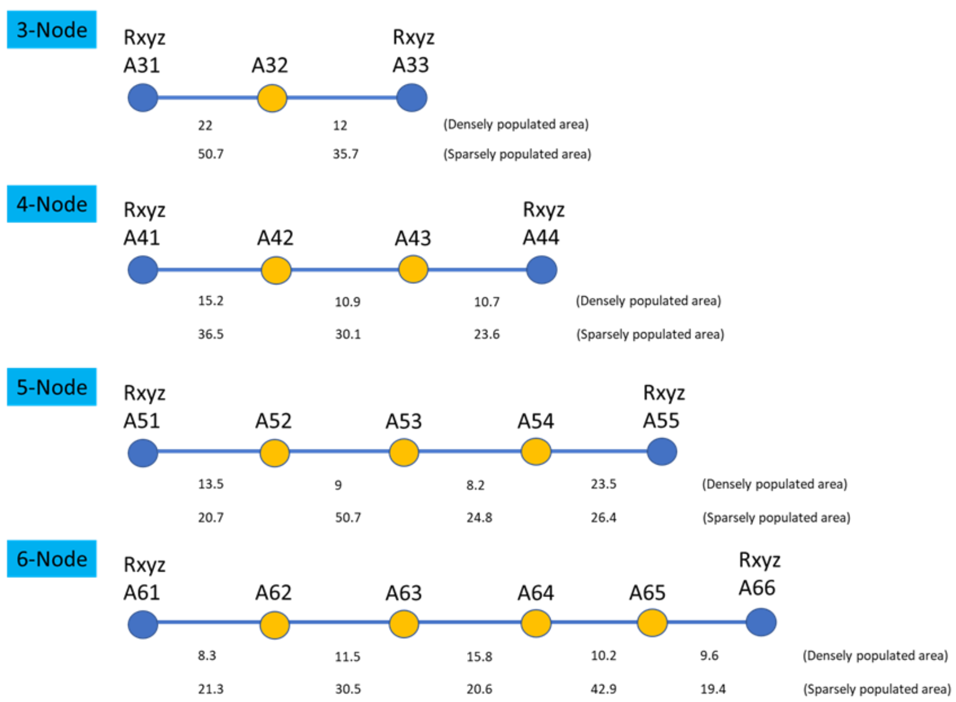


Figure 5-5 – SEASON metro-access reference semi-ring models, formed by a number of nodes ranging from 3 to 6, with link lengths provided for densely and sparsely populated areas. It must be understood that the variable combinations xyz for the aggregation nodes on both ends of each semi-ring model are different.

The different models for the metro-regional/access network topologies are described an Excel spreadsheet where link/span lengths are indicated.

Finally, in Table 5-1, we present the fiber parameters for the metro-regional and metro-access networks.

Table 5-1. SEASON reference metro-regional and metro-aggregation networks fiber specifications.

	Metro-Regional Rings		Metro-Access Semi-rings
Fiber type	G.652.D	G.652.B	G.652.B
Attenuation @ 1310 nm	0.34 dB/km	0.4 dB/km	0.4 dB/km
Attenuation @ 1550 nm	0.20 dB/km	0.3 dB/km	0.3 dB/km
Attenuation @ 1625 nm	0.22 dB/km	0.35 dB/km	0.35 dB/km
CD @ 1550 nm	18 ps/(nm·km)	20 ps/(nm·km)	20 ps/(nm·km)
PMD	0.1 ps/sqrt(km)	0.2 ps/sqrt(km)	0.2 ps/sqrt(km)

The topology illustrated in next session, presented by TIM, regarding the distribution of cabinets, macro, and small cell mobile sites for access, also applies to TID.

5.1.3 Geotype model for access areas

To extend the networks toward the access for a complete coverage of the access-metro domain defined in SEASON, regular structures as the ones shown in Figure 5-6 can be considered. In Figure 5-6 a typical distribution of radio sites and cabinets is depicted. Today radio sites with macro cells are present, in future there will be also radio sites with small cells or combined sites with both macro and small cells. As far as fixed access today a cabinet hosts PON splitters, in future a cabinet will be a potential candidate to become Far Edge points hosting also active equipment. In the model depicted in Figure 5-6 an Urban area a square of 1.6 km side (2.56 km^2) is served by a topological node (blue circle in the center, in current deployment can be host a central office at local, regional or national level). The Urban area includes also a number of cabinets (green circles, covering squares of 200 m each) and radio sites (yellow triangles for macro cell sites and violet diamonds for small cell sites, in the particular case of Urban area of Figure 5-6 the ratio between number of small and macro cells is 2.7). Macro sites can host cells that offer mobile service or FWA service. For simplicity, it is assumed that a cell of a given type (associated with a specific carrier belonging to a given band) provides either mobile service (with mobile terminals, for example smartphones) or FWA connectivity service (with special fixed routers connected to the cells FWA). Cabinets and radio sites are assumed distributed regularly in assigned points of the grid over the area as it is shown in Figure 5-6. Cabinets and radio sites can be co-located (all or part of them) or not, depending on the specific area represented, in the example they aren’t.

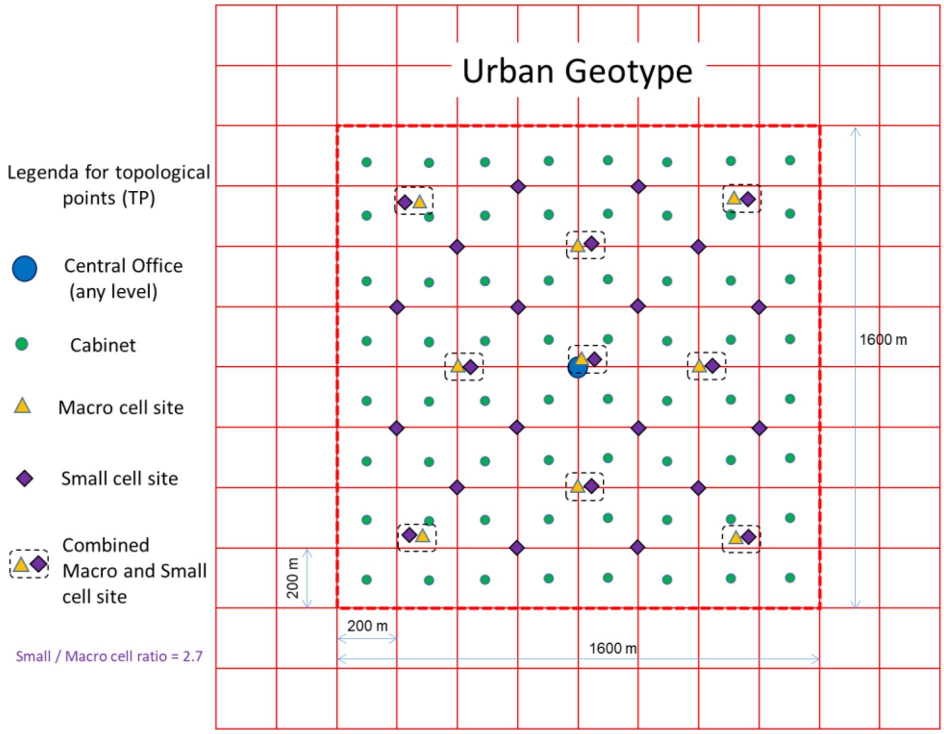
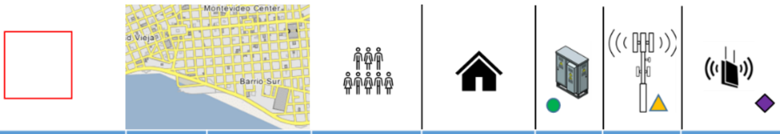


Figure 5-6 – Example of a regular model for the access Urban area geotype collected by a central office based on statistical data from a big city in Italy. (small cell radio sites is a projection not based on operator's plan).

As each topological node (blue circle in Figure 5-6) collects access basins of different type (in terms of amount and sort of access points as well as socioeconomical environment and geographical size) and, potentially, all different from each other. The model proposed for SEASON assumes four categories of areas covered by each topological node, where nodes are those represented in the Figure 5-2 and Figure 5-3. The four geotypes are the Urban (shown in Figure 5-6) the Dense Urban (shown in Figure 5-7 (a)), the Suburban (shown in Figure 5-7 (b)) and the Rural (shown in Figure 5-8) geotype. Although this modeling does not accurately represent the reality on field, it however allows to make realistic assessments given that different areas have different customer and traffic densities. By attributing a geotype to each topological node, it is possible to make evaluations based on the traffic (mobile, FWA and fixed) generated by that node. Furthermore, on the basis of traffic distribution and other criteria, it will be possible to decide which nodes will perform the Far Edge role (it could be a basic and cheaper central office) and which will perform the Edge role (as current Telco grade central office) in the SEASON architecture while the Cloud role is constrained by the national level central office locations in current networks by assumption.

Typical values chosen to characterize each geotype is given in Table 5-2. Within the four geotypes, the four parameters population, households, cabinets and macro sites can be considered stable as they are registry or infrastructural elements that should not vary significantly over time. However, as regards macro sites, their actual number within the geotype may be subject to change as the introduction of small cells could imply a re-deployment of macro cells. Furthermore, as already mentioned, macro sites can host cells for the mobile service and cells for the FWA service (when both are present, the two services are delivered on dedicated cells). Regarding small cells it is very difficult to make predictions because their number in a geotype area (density) will depend on deployment plans. Specific small cell deployment scenarios will be needed for studies to be perfomed in SEASON. For this reason, in Table 5-2 only qualitative indications are provided (“very high”, “high”, “spotted” and “nil or rare spots” for the four geotypes, respectively).

Table 5-2: Values of parameters for the four access-area geotypes. (Size means the edge of a squared area covered by a cabinet; ** density of small cell sites not specified as it depends on development plan and on the period)*



Geotype	Size* [km]	Area [km^2]	Population	Households	Cabinets	Macro Cell sites	Small Cell sites density**
Dense urban	0.8	0.64	10000	6000	36	5	Very high
Urban	1.6	2.56	27500	12500	64	9	high
Suburban	3.2	10.24	13750	6250	36	9	spotted
Rural	12.8	163.48	5500	2500	16	6	Nil or rare spots

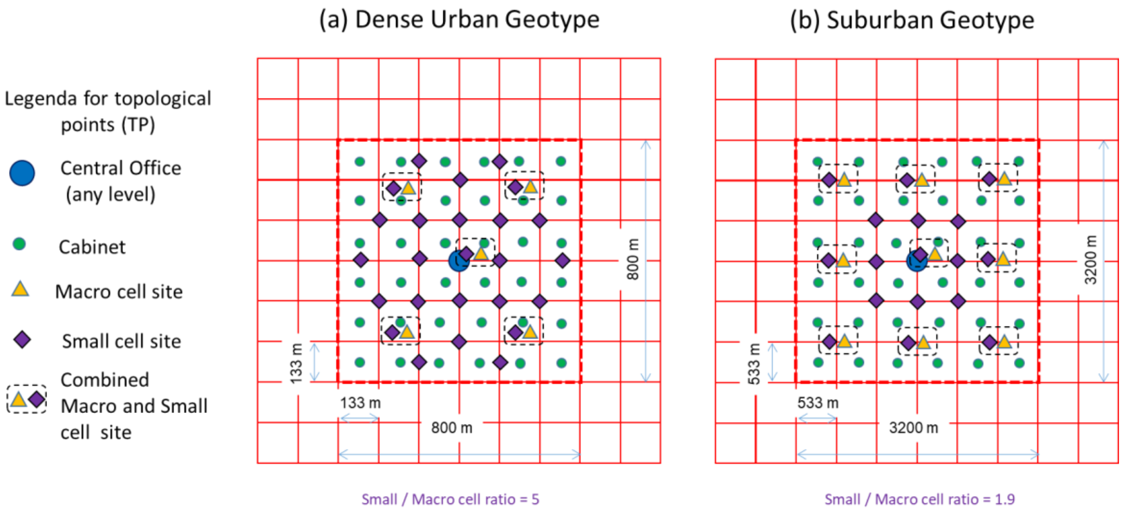


Figure 5-7 – Representation of Dense Urban (a) and Suburban (b) geotypes coherent with numbers of Table 5-2 (except for small cells). The draws on the left ((a) Dense Urban) and on the right ((b) Suburban) are not in the same scale as the smaller red squares that appear identical is smaller by a factor of 4 in Dense urban (side of 133 m) than in Suburban (side of 533m). On the bottom are reported also the ratio between number of Small vs. Macro cells. Number of small cells is assigned to provide a graphic example; they do not coincide with values in Table 5-2 which, in fact, are not reported (the density of small cells is indicated in qualitative terms only).

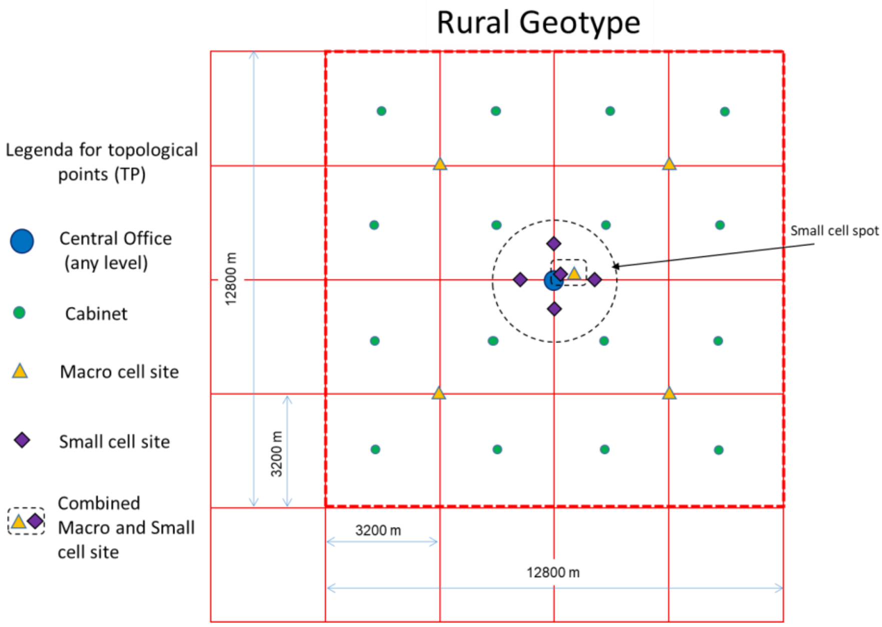


Figure 5-8 – Representation of Rural geotype coherent with numbers of Table 5-2 (except for small cells). Small cell spot is included as example and placed closed to the central office but, if present, it could be anywhere within the area. The possible presence of hot spots in rural areas will be defined in specific study scenarios in the subsequent phase of the project by making detailed hypotheses on the deployment of small cells in rural areas.

Dense Urban, Urban and Suburban access areas can be placed close together to compose a scenario as it is exemplified in Figure 5-9 where the central part is made of four areas of Dense Urban type (it could be the downtown of a big city), surrounded by urban-type areas and then fading into suburban-type area. This is only an example but other patchworks of geotypes can be composed from them to create scenarios to be analysed and taken for dimensioning and techno-economic studies.

Figure 5-9 – Example of an extended area of a city and its surroundings modeled as a chessboard of Dense Urban, Urban and Suburban geotypes. (small cell mobile site not represented).

5.1.3.1 Additional geotypes

The geotypes defined above represent some typical access network situations in more or less populated but generic contexts and without specific characterization and needs in terms of coverage bandwidth and latency requirements. There are also other access scenarios that require specific modeling and for these cases appropriate ad hoc scenarios have or will be defined.

Examples of scenarios of this type can be:

- University or technology campuses;
- Areas where events with high attendance take place (stadiums, gathering places for concerts or sporting events);
- Shopping centers or amusement parks;
- Arterial roads with a high concentration of users.

5.1.3.2 Radio Frequencies, bands, and carriers

In order to model the transport requirement in the radio access part of the network it is necessary to define which radio bands and carriers (how many, carrier width in MHz) will be deployed in mobile radio site in each of the different geotype defined in the previous subsections. To do this it is necessary to start with some definitions.

Bands range

Portion of spectrum containing different bands usable for telco mobile and FWA radio services. The division of the spectrum into bands usable for radio services, including the telco mobile radio service, is decided by international organizations.

Band

Portion of spectrum within a Bands range. For example, the 1-3 GHz Bands range contains the bands known as 1500, 1800, 2100 and 2600 MHz.

Carrier

A portion of radio spectrum assigned to a telco operator within a band. Many carriers can be assigned in a band, usually one at each operator that obtained the license for that band. Carriers are assigned by the State in tenders, at Country or regional level. Example: carrier between 3720 MHz and 3800 MHz licensed to an operator in the 3.4-3.8 GHz band for its use in the entire Country.

Carrier width

Is the width of a carrier assigned to an operator expressed in MHz. In the above example of a carrier between 3720 MHz and 3800 MHz licensed to an operator in the 3.4-3.8 GHz band the carrier width is 80 MHz. Within same band the width of licensed carriers can be all the same or, in some cases, different. For example, in Spain for C Band (24-28 GHz) four carriers are licensed to as many operators with carrier width of 80, 100, 110 and 90 MHz respectively (see Figure 2-11).

Macro cell Site for mobile service and FWA

A Macro cell site is a place where Radio units, Baseband units and Cell site routers can be installed. Usually, it is in elevated place that favors radio propagation. A Macro Cell mobile site includes the mechanical support (e.g., a metal tower) and electrical and communication (e.g., fiber) commodities. It can be equipped with equipment of different generation (2G to 5G today, 5G-A and 6G in perspective). Within a radio mobile generation, it can be equipped with many carriers licensed to an operator (normally no more than one carrier per band). In case of mobile service (for FWA service radio access is set with different criteria), each carrier can propagate the signal from one or more cells, usually 3 cells when the propagation must cover 360^{o} degrees (tri-sectoral site), but there are situations with less or more (very rare) than three cells per carrier in a site. As already mentioned, macro sites can host cells for the mobile service and cells for the FWA service. Radio mobile technology is supposed to be used for FWA even if the user is fixed and does not require functions that allow mobility, such as handover between cells (FWA delivered on LTE or 5G systems is used by many operators, but other radio systems can be used). In multi-mobile operator sites some operators (two to a maximum of four) with equipment belonging to many generations, and for each generation one or more carriers, share the site infrastructure. A macro cell mobile site can host small cells as well, but they are placed in a lower position (e.g., about a few to dozen meters higher than the base of the tower).

Small cell site for mobile service

It is a place where small cells can be placed. It has simpler requirements than Macro cell site, usually it is single-operator, mono-carrier and single cell. It does not require a very high elevated place and electrical and communications commodities are still necessary but with lower requirements than the case of macro cell site.

Concerning the frequency bands for telco mobile radio services they are as the following lists. Bands are used today for services from 2G to 5G. In future they will be increased (more Bands ranges and more Bands in existent Bands range) and assigned to 5G Advanced or 6G. In medium term refarming of bands from 2G-4G to 5G/5G-Advanced and, in long term, from 5G/5G-Advanced to 6G will be very likely.

Bands up to 15GHz suitable for Macro cells (for mobile and FWA) and Small cells (above 3 GHz)

- Sub GHz bands:
  - ✓ 470-700 MHz (new, approved at WRC 2023)
  - ✓ 700 MHz
  - ✓ 800 MHz
  - ✓ 900 MHz
- 1-3 GHz bands:
  - ✓ 1500 MHz
  - ✓ 1800 MHz
  - ✓ 2100 MHz
  - ✓ 2600 MHz
- 3-7 GHz bands:
  - ✓ Lower-3.3-4.2 GHz (typ. 3.4-3.8 GHz)
  - ✓ Middle-4.4-5 GHz
  - ✓ Higher-6.425-7.125 GHz (new, approved at WRC 2023)
- 7-15 GHz bands (potential for WRC 2027 agenda):
  - ✓ 7.125-8.5 GHz
  - ✓ 10.7-13.25 GHz (3 sub bands)
  - ✓ 14-15.35 GHz

The bands up to 15GHz listed above include all the bandwidths available up to now including the new ones (400-700 MHz and 6.425-7.125 GHz) approved at World Radiocommunication Conference (WRC) in December 2023 [WRC23]. WRC takes place every three years, the next will be in 2027. The 7-15 GHz bands are not already approved but have lot of capacity expansion potential and they will be probably proposed for use in telco mobile radio services in WRC 2027.

Bands from 24 GHz to subTHz (Small cells and Macro cells for FWA only)

- 24-52 GHz bands:
  - ✓ ≈26 GHz (typ. 26-27.5 GHz)
- Sub THz Bands (research, maybe potential for WRC 2030):
  - ✓ W-Band (≈100 Thz)
  - ✓ D-Band (≈130 Thz)
  - ✓ Above 175 GHz

In the 24-52 GHz Bands range the 26 GHz band is already assigned in many countries even the deployment hasn't started yet or it's just at the beginning. It is not expected to increase the use of more bands in this bands range. In the medium term, a systematic exploitation of this band is expected, which allows carriers with width up to 1 GHz and above.

As regards the THz band spectrum, the allocation of the spectrum and the applications for communication services are not yet clear and defined, therefore it is decided not to consider it as a source of services and related traffic for the access network in the SEASON project.

Assuming the bands listed above the following assumptions can be made about carriers present at macro and small cell sites in scenarios to be studied in SEASON project. The two reference periods of analysis defined in section 4.2 , medium and long term, are considered.

For the **Medium term** 5G-Advanced is assumed to be the mobile generation in the field. Starting from current frequency assignment (based mainly on Spain and Italy situation) and taking into account new spectrum bands approved by WRC 2023, the bands and carriers involved in radio access are assumed to be the following one.

- Macro cell:
  - ✓ Sub GHz, for mobile service only, up to 4 bands (+1 band compared with current assignment), carrier width 10 or 15 MHz, up to 4 carriers/operators per band
  - ✓ 1-3 GHz, for mobile service only, up to 4 bands, carrier width 10, 15 or 20 MHz, up to 4 carriers/operators per band
  - ✓ 3-7 GHz, for both mobile and FWA, up to 2 bands (Lower and Middle) (+1 band compared with current assignment), carrier width 20 to 200 MHz, up to 4 carriers/operators per band
  - ✓ 24-46 GHz, for FWA only, one band, channel width 200 to 1000 MHz, up to 4 carriers/operators
- Small cell:
  - ✓ 3-7 GHz, for mobile service only, up to 2 bands (Lower and Middle) (+1 bands compared with current assignment), carrier width 100 MHz, up to 4 carriers/operators per band
  - ✓ 24-46 GHz, for mobile service only, one band, channel width 200 to 1000 MHz, up to 4 carriers/operators

For the **Long term** the transition to 6G is considered completed. Additional pieces of spectrum taking into account possible further assignment defined by WRC 2027 are included in the following list of bands and carriers.

- Macro cell:
  - ✓ Sub GHz, for mobile service only, up to 4 bands, carrier width 10 or 15 MHz, up to 4 carriers/operators per band
  - ✓ 1-3 GHz, for mobile service only, up to 4 bands, carrier width 10, 15 or 20 MHz, up to 4 carriers/operators per band
  - ✓ 3-7 GHz, for both mobile and FWA, up to 2 bands (Lower and Middle), carrier width 20 to 200 MHz, up to 4 carriers/operators per band
  - ✓ 24-46 GHz, for FWA only, one band, channel width 200 to 1000 MHz, up to 4 carriers/operators
- Small cell:
  - ✓ 3-7 GHz, for mobile service only, up to 3 bands (Lower, Middle and Higher) (+1 band compared with medium term assignment), carrier width 100 MHz, up to 4 carriers/operators (same of Macro but with lower power and denser)

- ✓ 7-15 GHz, for mobile service only, one band (new Bands range, expected introduction by WRC 2027), channel width up to 2000 MHz.
- ✓ 24-46 GHz, for mobile service only, up to two bands, channel width 200 to 1000 MHz, up to 4 carriers/operators (+1 band compared with medium term assignment)

Using the availability of bands and carriers specified above the Table 5-3 gives a hypothesis on carriers used in a typical mobile site of both cell categories, macro and small, and for each geotype specified. Values of carriers in Table 5-3 hold for a single operator and it is reported for both medium and long term. For carriers in bands of bands ranges other than 25-56 GHz the carrier width is the same within the same band for all operators. For the bands in bands range 24-26 GHz, carrier width for an operator can be Nx200 MHz with N=1 to 5 (1GHz maximum for the width) with the constraint of up to 1400 GHz of maximum total width assigned in a Band (for instance, if there were four operators carrier widths could be 800, 200, 200 and 200 MHz, or if there were three operators and width is the same for everyone, they may have been assigned 400 MHz each: 1400 MHz mustn't exceeded). Specific cases depend on the carriers licensed to the operators. We can assume N=5 (1000 MHz) as the worst case for carrier width in 24-26 GHz band.

Table 5-3: Hypothesis about total number of carriers deployed in a single site for each category of cell (macro and small) and for each bands range for a single operator.

	Radio bands parameters				Number of carriers in a site							
					Dense Urban		Urban		Suburban		Rural	
	Bands range	Number of bands in bands range	Service	Single carrier width	Medium Term	Long Term	Medium Term	Long Term	Medium Term	Long Term	Medium Term	Long Term
Macro cell site (3 cells)	Sub GHz	4	mobile	10 MHz	2	2	2	3	2	4	1	3
	1-3 GHz	4	mobile	20 MHz	3	4	2	4	2	3	1	2
	3-7 GHz	2	Mob.&FWA	100 MHz	2	2	1	2	1	2	1	1
	24-46 GHz	1	FWA	Nx200 MHz N ≤ 5	0	0	0	0	1	1	1	1
Small cell site (1 cell)	3-7 GHz	2 MT, 3 LT	mobile	100 MHz	2	3	1	2	0	1	0	0
	7-15 GHz	0 MT, 1 LT	mobile	2000 MHz	0	1	0	1	0	0	0	0
	24-46 GHz	1 MT, 2 LT	mobile	Nx200 MHz N ≤ 5	1	2	1	1	0	1	0	0

Values in Table 5-3 together with additional hypothesis on RAN architecture (type of split option used and consequent need to carry FH, MH or BH traffic from the equipment in the mobile radio site to the equipment in the central office) can be used to evaluate the requirements for the transport network in an entire access area as the ones defined with geotype model.

Subsection 3.3.3 gives some examples about the data rate required by each carrier (Table 3-7) or by an a entire site (Table 3-8) including macro and small cells site depending on the channel width and on the split option.

The values in Table 5-3 hold for carriers owned by a single operator. In case the mobile sites were shared by many radio mobile and FWA service operators, while transport service were provided by a third party fixed network provider, reference can be made to Table 5-4 where the operators are supposed have the carriers equipment specified in Table 5-3.

Table 5-4: Hypothesis about total number of carriers deployed in a single site (distinguished between Macro and Small cell) shared by four operators.

	Radio bands parameters				Number of carriers in a site							
	Bands range	Number of bands in bands range	Service	Single carrier width	Dense Urban		Urban		Suburban		Rural	
					Medium Term	Long Term	Medium Term	Long Term	Medium Term	Long Term	Medium Term	Long Term
Macro cell site (3 cells)	Sub GHz	4	mobile	10 MHz	8	8	8	12	8	16	4	12
	1-3 GHz	4	mobile	20 MHz	12	16	8	16	8	12	4	8
	3-7 GHz	2	Mob.&FWA	100 MHz	8	8	4	8	4	8	4	4
	24-46 GHz	1	FWA	Nx200 MHz N ≤ 5	0	0	0	0	4	4	4	4
Small cell site (1 cell)	3-7 GHz	2 MT, 3 LT	mobile	100 MHz	8	12	4	8	0	4	0	0
	7-15 GHz	0 MT, 1 LT	mobile	2000 MHz	0	4	0	4	0	0	0	0
	24-46 GHz	1 MT, 2 LT	mobile	Nx200 MHz N ≤ 5	4	8	4	4	0	4	0	0

5.1.3.3 Logical connections mapping on physical topology

The grid model of the geotypes presented in subsection 5.1.3 does not provide information about the actual fiber topology which is essential for carrying out studies on transport solutions. Hypotheses on how the topological points (mobile sites and cabinets) are linked to the reference point where the traffic is collected (the central office assumed at the center of the geotype area) can be made.

Figure 5-10 shows how it is possible to adopt an orthogonal segment model for creating a topology of connections from the mobile radio sites (macro and small) to the central site. The same approach is also possible for cabinet binding. It is possible to find multiple alternatives of collecting trees of the topological points towards the center point. It will be a matter of making a choice on a case-by-case basis to create scenarios for network studies and work with it.

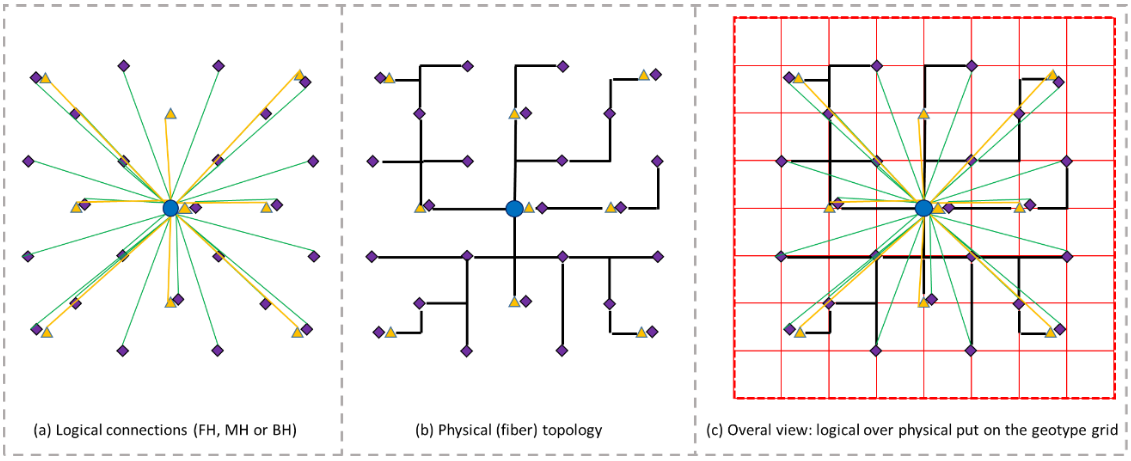


Figure 5-10 – Example of logical connections mapping on physical topology. (a) connections required to interconnect a radio mobile site (macro cell- yellow triangle- or small – violet diamond) to the reference central office. (b) physical layout (fiber three of the area converging in the central office). (c) both logical and physical shown on the geotype grid.

5.2 Topology for Backbone domain

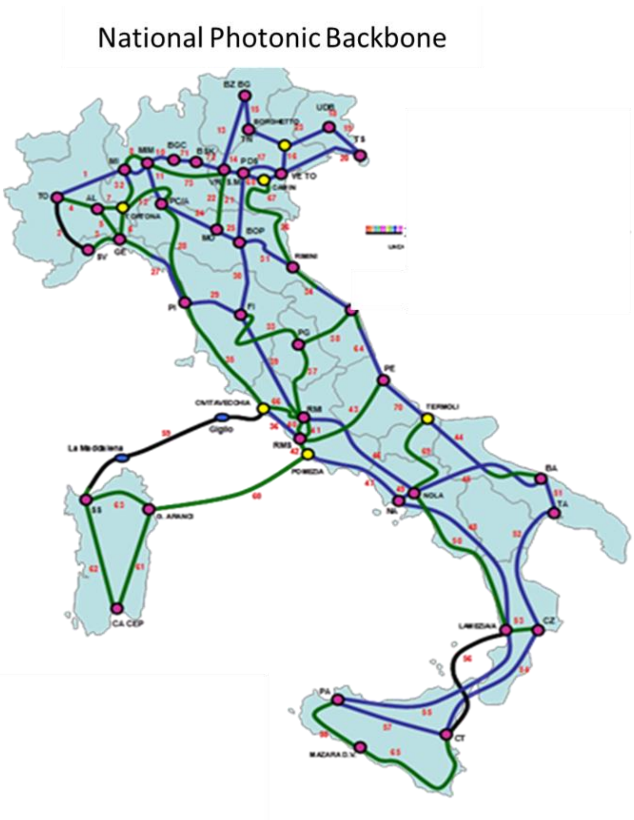
5.2.1 Backbone network model of TIM

As a backbone network, a model inspired by the TIM backbone network is proposed. The TIM photonic network is evolving and includes today a number of nodes equal to approximately 50 and a number of links of about 80. A topological representation of the network is given in Figure 5-11 where some statistics on nodal degree and link length are also reported.

Of the 50 national topological nodes equipped with ROADMs all are National COs, some are Regional COs, and some are pure transit site only (i.e., there are no add and drop features on them). Links are the topology edge between ROADMs.

Concerning the type of fiber used on links, fiber: G.655 is prevalent (≈65%) and G.652 takes the remaining part of the share (≈35%). There are residual quantities of the G.653 (a few %).

OLA are placed at 80 km on average with distances from 40 to 100 km, but there are exceptions for submarine links (in that case distances between OLAs are greater or significantly greater than 100 km).



Topological degree	Occurence
1	0
2	10
3	18
4	12
5	4
6	0

Link length L	% of links
0 < L <= 50 km	15.5%
50 < L <= 100 km	16.9%
100 < L <= 200 km	33.8%
200 < L <= 400 km	25.4%
400 < L <= 600 km	8.5%

Figure 5-11 – Topology of the Italian Backbone of TIM proposed as reference network with some node and link statistics. Network is in evolution (number of nodes and links are still growing) and the topology depicted above does not correspond to the updated version.

The entire topology of the backbone appropriately anonymized and with the parameters slightly perturbed for confidentiality reasons is provided in an excel file and make available within the consortium for network studies.

5.2.2 Backbone network model of Telefónica

The backbone network reference proposed by Telefónica consists of hierarchical levels HL3, HL2 and HL1 whose main function is to connect the different regional networks to data centers, the Internet, and other ISP networks. This network interconnects 50 regions through HL3 nodes, with typically having two HL3 nodes per region located in the most important cities of each region.

The reference topology considered for SEASON is shown in Figure 6-9, where the nodes are denoted using the following naming convention: N (for National) + two digits (representing a city) + 0, 1, 2… (0 meaning that only one HL3 exists in that city, and 1, 2… differentiate between multiple nodes within the same city). When there is only one HL3 node available in a city (e.g. N050), the metro-regional rings (described in the previous section) will be hubbed to two HL3 nodes located in different cities (in this example, to N050 and N060).

There are specific cases that require more than two HL3 nodes per region, which meet the conditions of higher population.

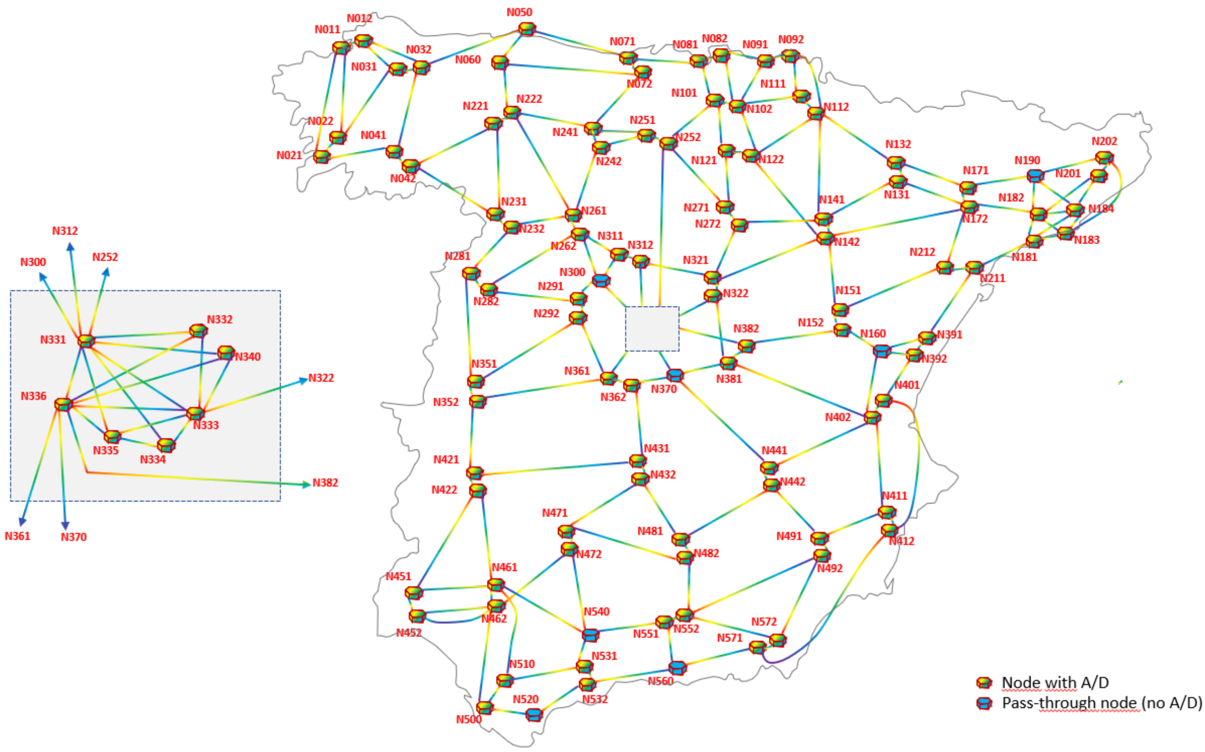


Figure 5-12 – Telefónica's backbone reference topology.

Table 5-5 and Table 5-6 show the fiber parameters, the correspondence between the optical nodes and the IP hierarchical levels, and the spans per link, fiber specifications, as well as a matrix with the link distances are provided in a Excel file made available to project partners to carry out network studies.

The backbone network is composed of 190 links with an average link length of 104.9 km and an average number of amplification spans per link of 2. The average span length is 53.1 km. Other parameters related to the number of nodes and nodal degree are provided in Table 5-5, and the fiber parameters are indicated in Table 5-6..

Table 5-5. Some statistics regarding the nodes and links classified according to the Telefónica IP hierarchy.

Node Level	Nodal Degree Avg. [Min, Max]	Number of Sites
HL1	6.0 [3, 9]	5
HL2	4.8 [3, 9]	16 (5 also HL1)
HL3	3.4 [3, 9]	98 (13 also HL2; 3 also HL1)
Ø (No A/D)	3.6 [2, 4]	7

Table 5-6. SEASON reference backbone network fiber specifications.

Fiber Type:	ITU-T G652.D
Chromatic Dispersion at 1550nm	18 ps/(nm·km)
Attenuation Coefficient:	
1310 nm	0.34 dB/km
1550 nm	0.20 dB/km
1625 nm	0.22 dB/km

6 CONCLUSION

The work carried out by WP2 during the first year of the SEASON Project is reported in detail in the previous sections of this document which constitutes the project deliverable D2.1. This final section of the document will bring the main messages that can be extracted from the content of the deliverable.

The first message concerns service use cases. An analysis of the use cases taken into consideration and researched in the last 10 years was carried out and service requirements were formulated for some significant and representative selected use cases. The reference environment for services projected into the 6G era is that of the Metaverse in its various articulations, i.e., consumer, industrial, and academic/enterprise. Evaluating the evolution in two macro steps, medium (5G Advanced, late twenties) and long term (6G, early thirties), the requirements identified at the service level are 1 ms of latency and data rate of the order of a few Gb/s for the medium term and sub ms latency (0.1 ms) and data rate up to a few hundred Gb/s (in case of holography, otherwise ten Gb/s will suffice) for the long term. Further drivers in addition to the one related to service use cases are also provided. The RAN technical requirements (Table 3-7 with split options and F/M-H data rates included) and a model based on geotypes with radio band/carriers deployment prediction (Table 5-3) are supplied.

The second message concerns architectural aspects at high and general level and the definition of a reference architecture for the SEASON project. Two reference segments have been defined for network analyses, the Access-Metro (the two parts seen as a whole for an optimization of networking solutions) and the Backbone. Three types of central office (physical place where equipment of any layer can be hosted) have been identified: Far Edge CO (very light, for example containers or reinforced cabinets, potentially replacing expensive traditional central offices and functional to their consolidation), Edge CO and Cloud CO. Another aspect defined in the reference architecture definition was the choice of analysis panels. The two periods considered are the medium term (late twenties – 5G Advanced deployed) and long term (early thirties - 6G deployed). Having the above listed as premises, the network architectures were designed (a pictorial view is provided, Figure 4-2 for medium term and Figure 4-3 for long-term), with particular reference to the data plane and the positioning of the telco functions (e.g., RAN, vDU and vCU, vOLT, BNG, and UPF). A rough indication of distances involved in each network segment, and data rate of the interfaces requested in the various network sections are also given. In addition to the pictures a list of characteristics involving architecture, technologies, and traffic volume to be carried, is also provided as guidelines for all the project WPs for implementing the specific solutions. In the context of architecture definition and due to its high relevance, the technologies under development in the project were recalled. An example is the architecture of a large-capacity MS over SDM node which is being defined by the joint task force of WP2 and WP3, but many other technologies are shortly described (white boxes and coherent pluggable transceivers, multi band transceivers, SDM PON, FH/MH solutions, SDN-based infrastructure configuration, NetDevOps, Pervasive Telemetry).

The third message concerns requirements. The approach followed was to start from the KPIs and derive the network and system requirements from them, limiting itself to the general and architectural requirements and including those on the RAN and telemetry, leaving instead the highly specialized system ones (systems and subsystems of the data plane and control plane and experimental phase) to an analysis in the respective relevant WPs (WP3, WP4, and WP5).

While evaluating the requirements arising from the KPIs, we focused on the elements that the project needs to address them. These include actions, introduced technologies, and necessary studies to achieve the desired implementation of the requirements. These guidelines must be kept in WP2 but also in the other WPs during the 2nd and 3rd years of the project.

APPENDIX: REQUIREMENTS TOWARDS SEASON KPIS

This appendix presents a first set of requirements derived from the project objectives and KPIs, such as those relating to the network architecture and to the monitoring system. The project objectives considered at this stage are those relevant for WP2 "Use Cases, Architecture and Techno-economic", namely Obj. 2, Obj. 5 and Obj. 6, to which Obj. 4 was added because of its general relevance and high importance for the project, as it concerns the access architecture and in particular the RAN.

Other requirements, regarding specific aspects of systems and subsystems considered in the project solutions, will be detailed in other WPs, i.e., WP3 (data plane), WP4 (control plane) and WP5 (demonstrators), within which such requirements are relevant.

The analysis done in this appendix reports the work covered by an internal milestone document dedicated to the requirements and is to be considered preliminary work on the actions to be implemented to achieve the project KPIs. The work will continue in the second year of the project.

OBJ 2 - DESIGN AND VALIDATE A SCALABLE, ULTRA-HIGH CAPACITY, AND POWER EFFICIENT MULTI-BAND OVER SPACE DIVISION MULTIPLEXING (MBOSDM) NETWORK INFRASTRUCTURE FROM ACCESS TO CLOUD

KPI 2.1:

Increase the available bandwidth of the fiber from actual C-band (~35 nm) to O, E, S, L, U bands (~415 nm) that, together with the usage of SDM, e.g., with >10 fibers / cores, will make the available bandwidth to grow by a factor x120 compared to current C-band capacity.

Fibers and technologies for ultra-high-capacity transmission based on Space-Division Multiplexing and Multiband

The use of multiple spatial light-paths is an effective approach to scaling available bandwidth and capacity of fiber-optic systems, and its most straightforward implementation is the one based on parallel single-mode fibers (SMF) and systems. However, a major limitation of this solution is that the increase in system capacity comes with the same cost per bit of the individual single-mode systems operated in parallel. Cost-per-bit reduction can be enabled by system-resource integration, in which case the use of multiple spatial light-paths is referred to as Space-Division Multiplexing (SDM) [Ryf20]. An SDM system is a system in which some of the end-to-end (e2e) components are shared among the spatial light-paths used for transmission. However, the cost effectiveness of an SDM system using multi-core fiber, compared to the cost of a multi-fiber system using traditional fiber of the same capacity, will need to be evaluated on a case-by-case basis and it will depend on the maturity and cost of the two alternative technologies at the time of the deployment.

A prominent example of a system based on SDM paradigm is the recently deployed Google-owned Dunant submarine cable, where amplification of 12 fiber pairs relies on a pump-sharing amplifier architecture. A special flavour of spatial multiplexing is the one based on the use of novel fibers, where multiple spatial light-paths are integrated into a single fiber, which we refer to as SDM fibers. In particular, two main types of SDM fibers can be identified:

- Multi-Core Fibers (MCFs), where multiple cores are surrounded by a shared cladding [Mat22, Hay22];
- Few-Mode Fibers (FMFs) (sometimes referred to as Multi-Mode Fibers (MMFs)) where multiple modes are guided in a single, larger-area core [Sil22].

These fiber technologies can provide a considerable increase in cable spatial-channel density, compared to single-mode fiber cables that are available today. Specific advantages and disadvantages entailed by their use are discussed in the following sections.

SDM using Multi-Core fibers

Multi-core fibers are characterized by a multiplicity of cores sharing the same cladding. These can be produced with a cladding diameter of 125 µm, required for long term reliability, tensile strength, and compatibility with existing cabling infrastructures [Mat16]. The individual cores of MCFs are normally single-mode cores of the same kind of conventional single-mode fibers. Multi-Core fibers with Multi-Mode cores have also been proposed to further increase the fiber spatial-mode count [Tak12], however the cladding of these fibers is larger than 125 µm, which makes them less practical for applications in the near future.

The advantage of an SDM optical communication system using MCFs is that the total transmission capacity per fiber is increased by multiplexing independent signals in the fiber cores, without increasing the transmit power per core. Here, optical signal crosstalk between cores is a critical design consideration, and SDM transmission must be implemented according to the fiber design of choice. With a Multi-Core Fiber (MCF) communication system consisting of single-mode cores, such as those used in conventional optical fibers, properly designing the arrangement of the cores, by suitably considering the inter-core crosstalk, allows for an almost linear increase of system the transmission capacity as the number of fiber cores increases. As discussed, some categories of MCFs allow the use of the same type of optical transmitters and receivers used in conventional SMF optic systems.

There are two types of MCFs:

- Uncoupled-Core Multi-Core Fibers (UC-MCFs);
- Randomly-Coupled Multi-Core Fibers (RC-MCFs);

Uncoupled-Core MCFs are designed with the goal of minimizing inter-core crosstalk, so that the individual cores can be addressed by means of conventional transceivers that are used in single-mode systems. Since the crosstalk level primarily depends on the core pitch and it accumulates with propagation distance, the maximum number of cores in a specific transmission band depends on the cladding diameter of choice, as well as on the system reach of interest. As a reference, crosstalk values close to -60 dB/km have been demonstrated for 125-µm cladding diameter four-core MCFs in the C-band [Hay19]. Provided that inter-core crosstalk remains negligible, the capacity of UC-MCFs scales proportionally to the core count.

Randomly-Coupled MCFs (often referred to as Coupled-core MCFs) are designed with the goal of achieving strong and random mixing between the signals propagating in the individual cores. In this propagation regime multiple-input-multiple-output (MIMO) techniques are necessary to disentangle the transmitted signals at the receiver side, thereby increasing the complexity of receiver DSP. Note that the frequency-dependence of the mode coupling process leads to the phenomenon of modal dispersion, which is the predominant factor in setting the MIMO-DSP complexity. It is important to stress that the coupling between the fiber cores must be random in nature. In fact, this propagation regime is beneficial in two ways:

- it reduces the accumulation rate of modal dispersion with respect to propagation distance from linear trend (as it would be in the case of weak and/or deterministic coupling) to propagation distance square-root trend [Ho11] (a record-low modal dispersion of 2.5 ps/√km has been reported in [Hay19]);
- it mitigates the nonlinear signal distortions caused by the Kerr effect [Ryf17].

Strong random mode coupling is attained by reducing the core spacing to an optimal value, for which the eigenstates of the resulting waveguide, known as supermodes, are sufficiently degenerate that the perturbations affecting the fiber structure (manufacturing imperfections and deployment-related issues) can effectively introduce random coupling between the supermodes. Spacing the cores below the optimal value produces non-degenerate supermodes, with the result so that the transmitted signals in the cores quasi-deterministically couple with each other while modal dispersion accumulates linearly with propagation distance. The core pitch optimization limits the number of cores that can be accommodated in a RC-MCF, and the largest number of strongly coupled cores in a 125-μm cladding diameter MCF reported to date is 19 cores [Rad23-2].

The fiber cores are addressed for transmission and reception by means of fan-in/fan-out technology [Fon22], which can be implemented in multiple platforms. Photonic lanterns based on ultrafast-laser inscription have been successfully demonstrated to multiplex 121 cores. However, given the complexity and the demand for extremely high accuracy of these prototype solutions, especially for splicing problems, their translation into commercial systems still appears to be a long way off.

SDM using Multi-Mode fibers

This type of SDM system relies on the use of single-core fibers supporting multiple spatial modes, a transmission regime that is attained by enlarging the core area. Depending on the number of supported modes, these fibers are referred to as either few-mode fibers or multi-mode fibers. In all cases they are characterized by the existence of mode groups, such that modes belonging to the same group are quasi-degenerate and strongly couple with each other, similar to the case of randomly-coupled MCFs, whereas modes belonging to different groups couple weakly and increasingly with propagation distance. MIMO techniques are necessary to recover the signals transmitted in the spatial modes addressed by the SDM transceiver, and two regimes of operation can be identified, typically referred to as *weak coupling* and *full MIMO* [Sil22].

In the weak-coupling regime of operation, the mode groups are received disjointly with independent SDM receivers of lower complexity and the crosstalk between mode groups is treated as noise. In this case suppressing inter-group crosstalk is imperative and step-index fibers are typically the solution of choice, as they support groups with either one or two spatial modes, thereby requiring 2x2 or 4x4 MIMO, respectively. This regime of operation is more suitable for short-reach systems, where inter-group crosstalk remains sufficiently low.

In the full-MIMO regime of operation, all fiber modes are jointly received, and therefore the MIMO complexity scales with the square of the total number of modes. In this case, the receiver DSP complexity is dominated by modal dispersion, which linearly accumulates with propagation distance (because different mode groups are characterized by different propagation), until inter-group coupling becomes sufficiently strong and random. Graded-index fibers are typically the solution of choice in this regime of operation, as they are characterized by lower modal dispersion than step-index fibers. Techniques to artificially induce coupling between modes with the goal of reducing modal dispersion have most recently been demonstrated in a 15-mode long-haul transmission experiment [Hou23].

Mode multiplexing/demultiplexing in FMFs and MMFs is typically performed by means of photonic lanterns or multiplane light conversion technology [Fon22], and a record high mode-count transmission in a 125-µm cladding diameter 55-mode fiber has been recently demonstrated [Rad22].

It should be noted that while strong mode mixing between all spatial modes enhances the tolerance of SDM transmission to nonlinear distortions, partial coupling between modes may be responsible for a non-negligible nonlinear penalty [Fer19].

Summary of fiber types from the literature

By relaxing the 125-µm cladding diameter constraint, a variety of SDM fiber designs for high spatial density can be conceived. A summary of these fiber types is presented in Figure A-1 reproduced from [Miz17].

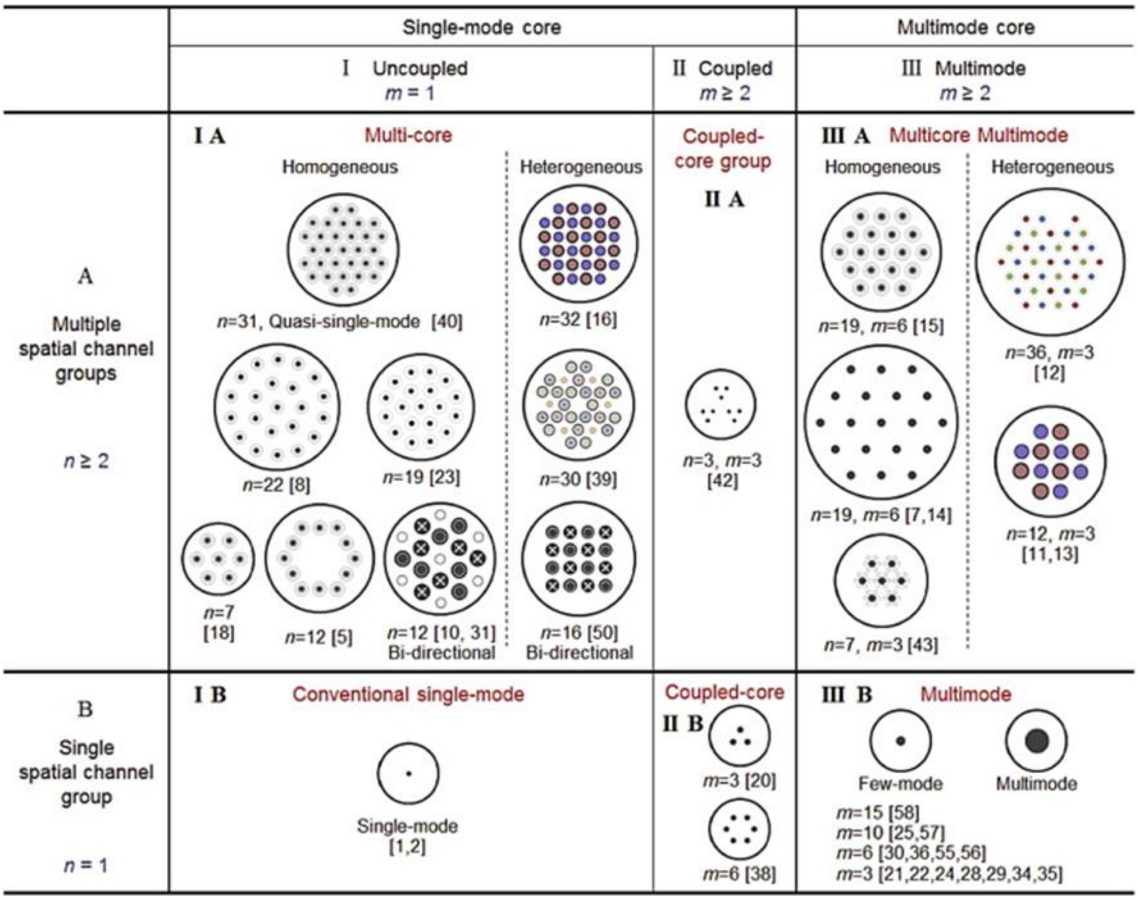


Figure A-1– SDM transmission matrix with various core schemes per fiber [Miz17].

In this figure, the fibers are grouped based on the cores layout and the number of modes supported by each core.

- (IA) multi-core single-mode fibers;
- (IIA) multi-core fibers with uncoupled groups of randomly-coupled single-mode cores;
- (IIIA) multi-core fibers with multi-mode cores.

The family A fibers are the "parallel" version of the family B modules. Family B shows its elementary constituents (elementary groups of spatial channels):

- (IB) single-mode fibers;
- (IIB) randomly-coupled multi-core fibers;
- (IIIB) few-mode/multi-mode fibers.

The parameter n denotes the number of type B elementary modules (groups of spatial channels, with $n = 1$ for type B) while m is the number of modes of each spatial channel group.

High-density fiber cables (HDFC)

The spatial density of transmission channels can be increased not only by using special fibers like MCFs and FMFs/MMFs reviewed in the previous sections, but also by increasing the number of single-mode fibers in a cable.

This approach is based on extreme packing engineering of many fibers inside a classic fiber cable, and it entails a paradigm shift from increasing spectral efficiency to increasing spatial efficiency. Solutions of this type are already commercially available, sometimes leading to the miniaturization of the fiber cables. This evolution was also enabled by the reduction of the fiber coating diameter, from 245µm to 200µm for the latest generation of stranded cables with tubes, as well as by the intensive use of fiber tapes (ribbons) with very large fiber counts, up to 3456 fibers per cable [Sas22].

Therefore, the use of high-density fiber cables is an immediate and effective solution to increase transmission capacity by exploiting the spatial dimension in conjunction with mature telecom technologies.

Performance of different types of fiber

Multiple Pb/s SDM transmission demonstrations have been reported in the literature. In [Put22] 1-Pb/s S+C+L transmission in a 4-core 125-µm cladding diameter 52-km MCF was demonstrated, “showing the potential of combining multi-band and low-core count MCF transmission technologies to enable practical, high throughput optical communication systems.” The limitations to the performance of these systems depend on the fiber type of use. As an example, in the case of coupled-core multi-core fibers, at a fundamental level, transmission capacity is limited by mode-dependent loss [Win11]. On the other hand, modal dispersion is the main factor impacting the system complexity. The interplay between these phenomena and nonlinear distortions, which sets the ultimate limit to performance, has been only partially explored. Intriguingly, [Ser22] shows the existence of an optimal value of modal dispersion in terms of nonlinear-distortion mitigation.

When focusing on single mode fibers, the optical performance is clearly dependent on the fiber type. Although most network operators currently deploy standard single mode fibers (SSMF—G.652.D) [Fer20] only, several other fiber types have been deployed along the years and are still in use. As an example, several network operators have deployed dispersion shifted fibers (DSF – G.653) due to their reduced chromatic dispersion parameter in the C-band, which could benefit intensity-modulated with direct-detection systems. However, the impact of four wave mixing (FWM) is enhanced in this case, due to the small accumulation only of chromatic dispersion. Consequently, the use of DSF is not recommended for wavelength division multiplexed (WDM) transmission systems. Non-zero dispersion shifted fiber (NZDSF – G.655) has been proposed as an alternative to DSF, since it circumvents the main limitations arising when using DSF while still maintaining most of its potential benefits. Nevertheless, NZDSF usually leads to worse optical performance in the C-band than SSMF (when used in combination with coherently-detected modulation formats). Still, the use of existing DSF and NZDSF infrastructure can be interesting for the upgrade of optical systems to multi-band transmission, since they may potentially achieve competitive optical performance when compared with SSMF in transmission bands other than the C-band (due to the decreasing chromatic dispersion parameter of SSMF, which usually attains 0 ps/nm/km in the O-band).

SDM-fiber testbed in L'Aquila

The laboratory of Optics and Photonics of the University of L'Aquila provides access to the unique fiber-optic infrastructure available from the project INCIPICT (http://incipict.univaq.it/). This is the first world-wide deployment of SDM fibers. It consists of two fiber-rings, as shown in Figure A-2.

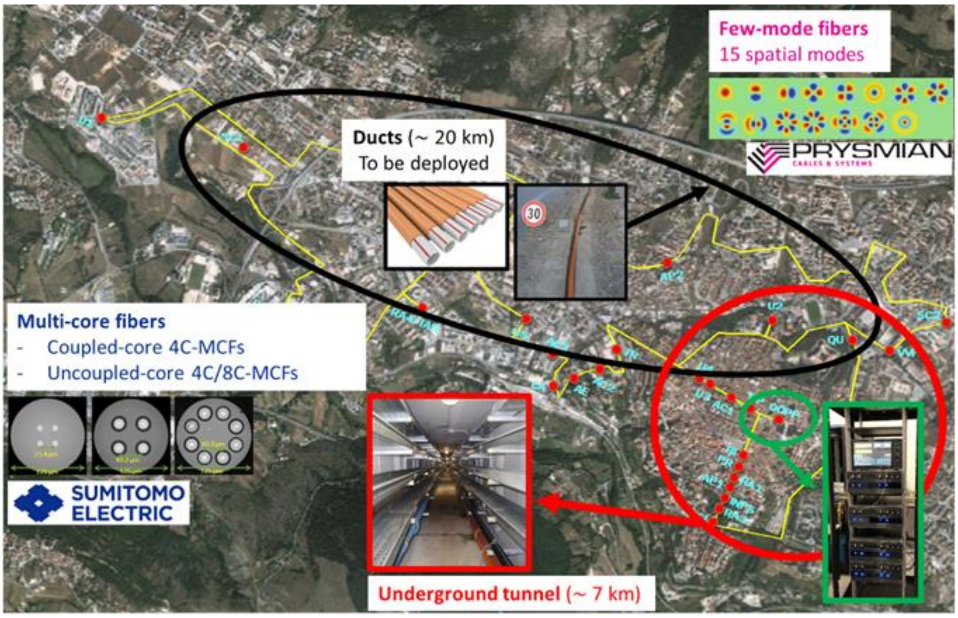


Figure A-2 – SDM-fiber testbed in the city of L'Aquila, Italy.

The shorter ring, including three fiber cables, is about 6-km long and is hosted in the multi-service underground tunnel.

The first cable, supplied by Sumitomo, includes four strands of uncoupled-core 4-core fibers for use in O to L band, 2 strands of uncoupled-core 8-core fibers for use in O band, and 12 strands of randomly-coupled 4-core fibers for use in C to L band. Out of the 12 strands of coupled-core MCFs, 11 are spliced to each other, so as to form a span of about 70 km. All the deployed MCFs are equipped with FIFO and multi-core connectors. Details on the fiber characteristics are available in [Hay19].

The second cable, supplied by Prysmian, includes 8 strands of 15-mode graded-index fibers for use in C and L bands, as demonstrated in [Sil16]. A characterization of the deployed fibers is available in [Rad23-1]. The fiber strands can be concatenated or individually used. Two pairs of mux/demux devices, based on multiplane light conversion technology, are available in the lab.

The third cable includes 24 standard single-mode fibers, which can also be concatenated or individually used.

The longer ring is about 20 km long and relies on the use of conventional ducts for the deployment of additional SDM fibers and standard fibers. This part of the fiber-optic infrastructure is expected to be operational in early 2024.

Multi-band transmission

Multi-band transmission (MBT) has a high potential to enable the cost-effective upgrade of optical networks since it maximizes the usage of the existing infrastructure, potentially postponing new fiber roll-out and maximizing the return-on-investment. This is the fundamental advantage of MBT when compared with the remaining SDM approaches. Particularly, MBT aims at expanding the transmission spectrum beyond the currently utilized C-band only, by considering the complete low-loss bandwidth of single-mode fibers (SMF). Therefore, MBT has the potential to increase the offered bandwidth by a factor exceeding 10x, as shown in Figure A-3 and Table A-1.

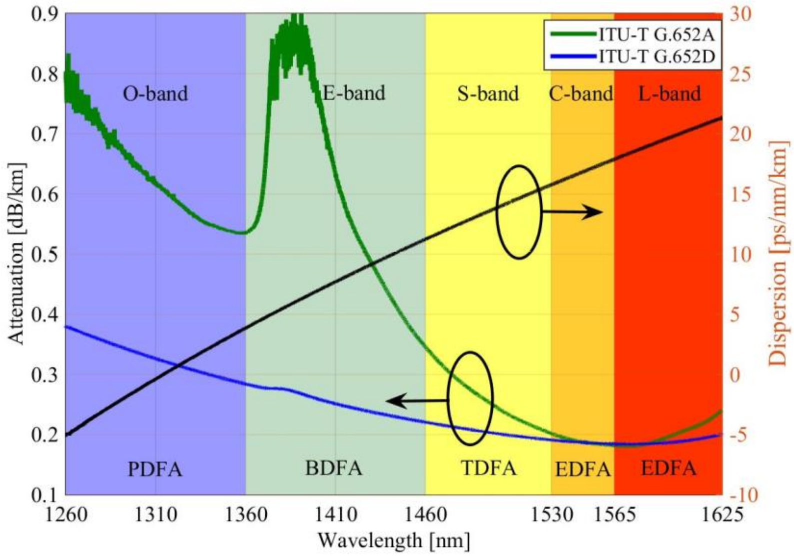


Figure A-3 – Fiber parameters for ITU-T G.652A and G.652D fibers [Fer20]. DFA: doped fiber amplifier; possible doping materials for each band are: Praseodymium for O-band; Bismuth for E-band; Thulium for S-band; and Erbium for C- and L-band.

Table A-1. ITU-T band definition for single-mode fiber [Fer20].

Band	O	E	S	C	L
Wavelength (nm) [9]	1260-1360	1360-1460	1460-1530	1530 - 1565	1565 - 1625
C-band				35 nm	
C+L-band				95 nm	
All bands	365 nm				

An early form of MBT is already a reality, since commercial systems exploiting C+L-band for data transmission have become available and have been deployed in live networks [Inf18]. A significant number of contributions have been recently published in the major journal and conferences of the area, covering MBT systems exploiting different combinations of the O-, E-, S-, C-, L- and U-bands [Sad22]. A key aspect to consider with MBT is the difference in performance that may be expected across the different bands. For instance, O-band shows quite poor optical performance when compared to the remaining bands [Fer20], mainly due to its higher fiber attenuation and stimulated Raman scattering which causes power depletion toward the other bands, making it suitable for short-reach applications only, particularly when E- and S-bands are not used. On the other hand, reasonably good signal-to-noise ratio (SNR) can still be achieved in both E- and S-bands, in particular when one of them is not used. For instance, it has been shown that, by deploying counter-propagating Raman pumps, similar performance as the one obtained in C-band only systems can be achieved in MBT systems using the C-, L-, and part of the S-band [Sou22].

Since the S-band is the one showing better optical performance from the available ones when upgrading a C+L MBT system, extensive analysis has been carried out considering transparent and translucent solutions, regular or super (extended) transmission bands as well as pay as you grow (brown) and green field deployments. For these cases, the trade-off between number of interfaces required and amplifier count as well as impact on the power consumption were evaluated. As main results, it was shown that using an S+C+L MBT system solution leads to a small increase of interface count only for the same system capacity when compared to a C-band only solution using multiple fibers. Moreover, for the less loaded parts of the network, the enabling of the additional transmission bands (by deploying the required optical amplifiers and optical cross-connects – see Figure A-4) may be postponed with respect to the most heavily loaded fiber links. This result further highlights the high potential of MBT for optical networks capacity upgrade when combined with a pay as you grow approach. Noteworthy, MBT can be combined with the previous mentioned approaches (SDM) or with hollow core fibers, to further increase the system capacity [Mon20], [Pog22].

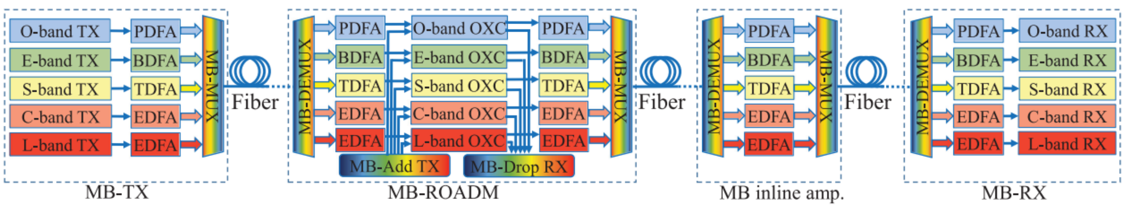


Figure A-4 – Multi-band transmission system with band separation. Transmitter (MB-TX); optical cross-connect (OXC); Receiver [Fer20].

Operators view on evolution of fibers deployment in different network contexts

Operators' perspective on fibers in Access Network

Fiber in TIM access network is rapidly progressing towards its deployment at end users' facility/home, especially in suburban and rural areas, supported by the European fundings for the increase of telco high bandwidth connectivity, available after the pandemic event. Specifically, low water peak ITU-T G652.D fibers are installed, allowing low attenuation from O to L band, and thus introducing the possibility to apply MBT. Also, the replacement of radio links with fiber links is presently a driver for new installations.

On the other hand, the already deployed single-mode fiber assets, very extended especially in urban areas, will be fully exploited in next years before choosing to install new fiber types, but their long-term saturation time point is not yet predictable because of today fibers abundancy in cables, where 250 fibers are normally hosted. Furthermore, in Italy there is also a quite consistent installation of rollable ribbon cables, each one hosting more than one thousand fibers (high count cables).

The drivers for long term installation of new fibers could be cell sites or service points densification, different additional fixed access points with respect to residential ones, and traffic needs coming from new services like Metaverse, Telesourveillance, Volumetric Video, Holoconferencing, Digital Twin, etc.

Multi-Core Fibers (MCF) are not used in the access, partly because of the already discussed high single mode fiber availability, but even because of difficulties on connectors and fan-in/fan-out settings with respect to present equipment ports.

Regarding transmission technologies, in the next 2-3 years a 100G Fiber To The Access (FTTA) connectivity for mobile 5G RAN will be massively deployed, while for residential and business users the today already available Fiber To The Curb (FTTC)/Fiber To The Home (FTTH) GPON and XG(S)-PON technologies, respectively serving a 64 client tree at 1 Gbit/s and 10 Gb/s, could be enriched by 25G/50G solutions available with HS-PON (ITU-T G.9804.x), which is presently a prototype under test in TIM laboratories, or with 50G-EPON (IEEE 802.3ca). The covered distances generally range from 10 to 12 km, because of reduced power budget, sensitivity and dynamic range. In long term perspective i.e., beyond 2030, mobile networks will be served by 400G B5G O-RAN FTTA, while Next-Generation Coherent PON at 200G will be employed in FTTC/FTTH for home/factory customers. Figure A-5 provides a tentative roadmap for the PON technology up to 2030 and beyond [Far21].

Alternatively, or in synergy with the PONs, smart transceivers capable of providing data-rates according to the services and/or end-users – such as coherent point-to-multipoint (P2MP) transceivers enabled by digital subcarrier multiplexing (DSCM) technique – could be employed in all these scenarios starting from the short term.

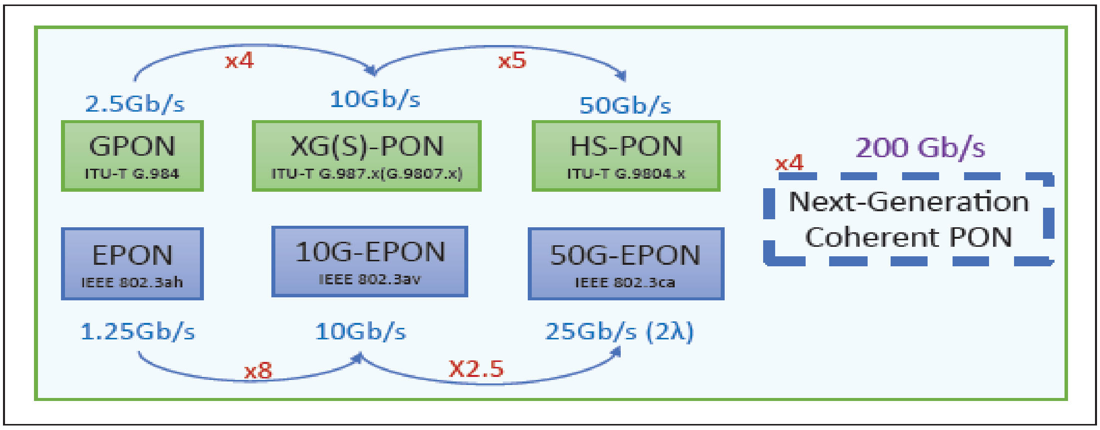


FIGURE 1. The line-rate progression in different PON standards of ITU-T and IEEE.

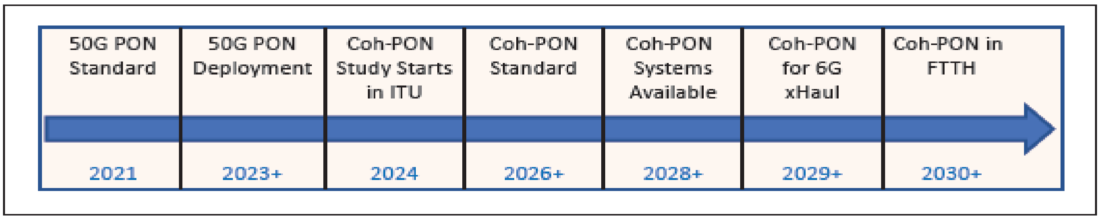


FIGURE 2. Possible PON technology evolution timeline.

Figure A-5– PON evolutionary diagrams [Far21].

Operators' perspective on fibers in Metro Network

Fiber exploitation in TIM and Telefónica reference Metro Aggregation/Core network has been optimized to reduce the amount of COs at the border between access and metro segments, from more than ten thousand to a few thousand, making a by-pass of the Access COs candidate to be eliminated because they were usually connected by copper links to higher hierarchical COs. Moreover, legacy C/DWDM structures are being replaced by modern DWDM transport solutions. The few thousand selected COs host the OLT equipment, are connected via fiber to customers' ONUs and can be at different metro network levels, i.e., at Local, Regional, or even Core.

Each cable in metro network hosts about one hundred of G.652 single mode fibers (from 8 fibers/cable in rural areas to 512 fibers/cable in urban areas). About one half of the new COs has still quite enough fibers available in the short term, while the other half has more limited assets at its disposal, but the WDM capacity is not yet saturated. In the case of Telefónica's reference metro networks, the most substantial cable occupancy takes place in densely populated urban areas, where more than two-thirds of fibers are currently in use, but where, due to the proximity between COs, the majority of connections rely on dark fibers, indicating that, in the case of fiber unavailability, the deployment of transport solutions could be a way to exploit the fiber infrastructure more efficiently. In small urban areas, over half of available fibers are already in use. Furthermore, TIM and TID's PDH/SDH decommissioning plans will release fibers for short-term transmission systems. Only a very limited number of COs (about one hundred) is presently connected by radio links and therefore will require new fiber connections/installations in the short run.

Currently network capacity per flow amounts to up to 100 Gb/s in Metro Aggregation segment and up to 400 Gb/s in Metro Core one. As traffic increases at a rate of 20% to 40% per year, in the short term, traffic volumes collected at access and aggregation levels may saturate the system's capacity at Metro Core level. The solution to cope with such saturation can be exploiting existing fibers by means of parallel line systems installation in the Metro Core.

The long-term scenario is unpredictable, even if fibers aging could be a strong driver for their replacement in the 2030s (as a matter of fact, fibers lifetime is estimated at around 30 years, but they could also last much longer in practice). In addition, the possible high bandwidth increases due to transmission of brand-new services, to DC/CO interconnection and to access points densification, would suggest the deployment of fibers for Multi-Band (MB) and /or SDM. The MB solution could be based on extension from actual C-band to C+L-band in the Aggregation segment and to multi-band, i.e., one or more bands or sub-bands in addition to C and L, taking into account the transmission performance constraints of the whole system, in the Metro Core. The SDM solution could be based on the complete use of available fibers where cables will not be replaced yet, or on an open choice between new bundles of SMF, MCF or even the very promising Hollow Core Fibers (HCF) (if this technology will reach maturity in the 2030s), when and where new cables will be deployed.

Operators' perspective on fibers in Backbone Network

The TIM Backbone consists of technological evolutions over time that gave rise to two overlayed networks, named Kaleidon and Kaleidon Evolution. The former, which supports connections at 40 Gb/s and 100 Gb/s, has almost reached its capacity saturation, while the latter has been developed in 2016 with flexible-grid ROADMs and transponders at 200 Gb/s and 400 Gb/s of line side capacity (transponders at 600 Gb/s will be available in the short-term). Backbone fibers are a mix of G.655 (about 70%) and G.652 (30%), also with a few G.653 cables still present.

Regarding Telefónica, the availability of fiber in its backbone network is highly variable and contingent upon the country in question. However, in the reference network being considered for the SEASON project, cables generally containing over a hundred ITU-T G.652.D fibers, with average fiber availability in the region of 65%, can be counted on. Network modernisation has also been carried out to enable flexible grid transport of optical channels with capacities over 100G, as well as optical restoration. Currently, the reference flexible backbone network is based on the transport of optical channels with capacities of 400 Gb/s, but capacities of 600 Gb/s, or even 800 Gb/s for short-haul connections from large urban areas towards the interconnection nodes.

For what it concerns SDM, both presently and in the near future, fiber exploitation will be based on the available assets, since the foreseen bandwidth capacity needs per link could be supported either with single fibers pair or with bundles of fibers already available in cables, that can host a huge number of G.655 or G.652 fibers (i.e., from 100 to 144). As regards MB, an extension to L-band in addition to C-band could be necessary in some network parts, where traffic is more concentrated, if technology improvements will soon be offered to the market and will be economically viable as well.

In the long-term scenario, the MBoSDM solutions could be driven by huge traffic increases (as discussed for Metro and Access networks), particularly at peer and international gateways interconnections, and by fibers replacements due to their aging even if, as already stated, the fiber end of life cannot be predicted with accuracy. Regarding MB, a full MB solution could be a solution (if technically viable), while for SDM either Multi-Fibers and/or Multi-Core fibers could be deployed if technically available and economically sustainable. A combination of the two solutions, i.e., MB over SDM, could be another possibility.

KPI 2.2:

50% CAPEX reduction by (1) designing an architecture that jointly leverages on parallel fibers (where fiber resources are abundant), multiple bands (where fiber resources are scares), and\ multi-core fibers (where fibers are not present, e.g., for cell densification); (2) limiting intermediate aggregation in routers thanks to the ultra-high capacity of MBoSDM and by exploiting smart coherent pluggable to remove aggregation layers and unnecessary O/E/O conversions.

Operators view on innovative architectural solutions for achieving CAPEX reduction

There are multiple innovative architectural solutions, both in the data and control planes, that can be added to next-generation telco networks and that all together could allow important CAPEX reductions, at 50% percentage or even more. Some of these architectural innovations include:

<u>Network softwarisation (including SDN/NFV and disaggregated network equipment)</u>

This will allow multiple cost savings, in different ways. First, SDN and NFV will allow network functions to be centralized, managed and reconfigured without requiring expensive hardware upgrades; also, NFV can further reduce costs by allowing multiple functions to be consolidated onto a single physical device (namely COTS or Commercial Off-The-Shelf hardware). In addition, using open-source software in disaggregated optical networks, instead of proprietary software, can reduce CAPEX by eliminating licensing fees and reducing the need for expensive hardware [Her20, Her21-2].

<u>Intelligent control plane and network automation</u>

Automating network management tasks can decrease CAPEX by reducing the need for manual operation and by increasing the network efficiency. This also includes network infrastructure sharing with other telcos or vendors, namely network slicing, which can decrease CAPEX by reducing the need for duplicated infrastructure and by sharing costs across multiple telcos.

<u>Efficient data-plane hardware like P2MP coherent transceivers and packet-optical with SmartNICS (</u>Smart Network Interface Cards)

Packet-optical nodes with SmartNICs can potentially reduce CAPEX investments by enabling the operators to deploy a more flexible and scalable network infrastructure, e.g., optimized and adaptable for current needs. SmartNICs are specialized network interface cards that offload processing tasks from the host CPU, allowing for more efficient data processing and improved network performance. When combined with packet-optical nodes, SmartNICs can help reduce CAPEX investments because of hardware consolidation (it is a smarter and cost-efficient way to deploy edge computing), improved efficiency (since smartNICS can offload processing tasks from the host CPU, live network VNFs and AI/ML tasks) and reduced energy cost (smartNICS are more efficient than micro-datacenters).

Concerning the use of P2MP transceivers and tree topologies (i.e., XR optics), instead of multiple pairs of P2P transceivers, it can reduce equipment costs since multiple points (leaf nodes) can communicate with a central point (hub node) using a shared communications channel, thus reducing complex routing and switching equipment, which can be costly to deploy and maintain [Bäc20, Nap22, Her23]. In addition, reduced fiber usage – also thanks to single fiber transmission – and improved scalability are two other benefits of P2MP tree-based architectures [Wel21].

Multiband and SDM

In a medium long term perspective telecommunication operators can decrease CAPEX with MB and SDM in several ways. Thanks to optical MB, which allows for the transmission of multiple optical channels over a single fiber, important CAPEX reductions can be achieved since the operator can consolidate the required network equipment. Even SDM technologies leveraging on bundles of SMF fibers can increase network capacity, resulting in increased revenue without additional fiber deployments, but the hardware at the optical endpoints and at intermediate points must be replaced (and consolidated, as in the case of MB systems, which should be more cost-effective than deploying parallel SMF-based networks).

Finally, the benefit of reusing existing fiber infrastructure in the case of MB (not in SDM though) is that it can reduce the amount of fiber deployments and therefore of fiber investments, which typically amount to about 100 USD per meter, including digging, trenching and civil works.

Overall, Optical Multiband and SDM technologies can help telecommunication operators to reduce CAPEX by increasing network capacity, improving efficiency, and reducing the amount of additional equipment or infrastructure.

Capex reduction by the use of PtMP in combination with DSCM

A way to reduce the Capital Expenditure (CAPEX) is to reduce the number of needed transceivers and consequently the points of opto-electronic conversions is to use coherent P2MP transceivers – realized by using DSCM, as it enables, e.g., to remove layer of electronic aggregation in metro access [Bäc20]. This concept has been also reported in [Wel21] where the full chain from an antenna to a data center has been compared with traditional point-to-point (P2P) transceiver and P2MP ones. Further applications of the technology were reported in [Nap22], where in the Telefonica network hierarchy, a layer of router was removed by using optical aggregation and DSCM and in [Cas23] where the authors exploit the possibility of optically aggregating channels to simplify highly complex network topologies of Telecom Italia. In all these mentioned studies, the savings in CAPEX have been ranging between 30% – 75% depending on the initial assumptions, use case, and network topology. The authors in [Her23] also demonstrated that aggregating nodes with uncorrelated daily traffic patterns on the same P2MP tree can lead to a reduced number of transceivers, say 20%.

Coordination of Radio Access and Optical Transport

The support of 5G and beyond use cases requires bringing the optical network to the very edge, not only to increase capacity but also to guarantee e2e quality of service (QoS), e.g., delay. Such e2e QoS requires that both 5G radio access network (RAN) and optical transport operate under strict QoS constraints [Ber20]. However, establishing fixed capacity optical connections to connect RAN to 5G Core entails large capacity overprovisioning, increasing thus the total cost of ownership for network operators.

Figure A-6 shows the analysed e2e scenario, where user equipment (UE) in a RAN requests 5G services, that are virtualized and placed in a remote location in the fixed network, e.g., a metro/core site. Without loss of generality, we assume that UEs and 5G core are the endpoints of e2e traffic and that some maximum e2e delay needs to be ensured. Hence, the e2e traffic flow consists of two components for the RAN and the optical network. The component of such e2e traffic flow, that traverses the RAN, is represented by a blue thick arrow. Moreover, RAN configuration (e.g., gNB parameters) are conveniently set up to support capacity and latency requirements. This configuration has a direct impact on the actual QoS (see inset graph with delay measured at the RAN).

Let us assume that a cell site gateway (CSG) is the boundary between the RAN and the fixed optical transport network. For the sake of simplicity, we assume that traffic flow at the fixed network (green thick arrow) transparently traverses single or multiple optical domains inside a single e2e lightpath. The capacity of such lightpath can be properly dimensioned e.g., by dynamically activating/deactivating subcarriers (SCs) to provide the required QoS. In line with [Vel21], autonomous optical capacity management with QoS guarantees can be realized in the fixed transport network segment by means of the control architecture sketched in Figure A-6 (a), where different entities are considered (from bottom to top): i) the transponder (TP) agent that is in charge of collating telemetry data, e.g., traffic and measured delay from the TPs, as well as to manage SCs to ensure the committed QoS; ii) the capacity manager that uses telemetry to run policies, models, and rules to find the required capacity that better satisfies the target QoS; iii) the SDN controller that is in charge of the initial lightpath setup and of communicating the capacity manager key parameters, such as the required QoS.

It is worth noting that both RAN, and optical network domains operate without any coordination among them, which entails overprovisioning capacity in the lightpath to meet a fixed target optical network delay component that absorbs delay variations introduced by the RAN. This is illustrated in Figure A-6 (left), where the optical capacity is dynamically adjusted to keep the optical network delay component under control. Although this uncoordinated strategy can guarantee e2e QoS and provide some dynamic capacity adaption, it results in large overprovisioning if the RAN delay is far from the maximum.

In view of the above, we propose studying the coordination of RAN and optical network operation to dynamically adjust the target optical network delay component to the current traffic conditions. We claim that overprovisioning can be greatly reduced while guaranteeing e2e delay (as sketched in Figure A-6 (b)), thus achieving CAPEX reduction.

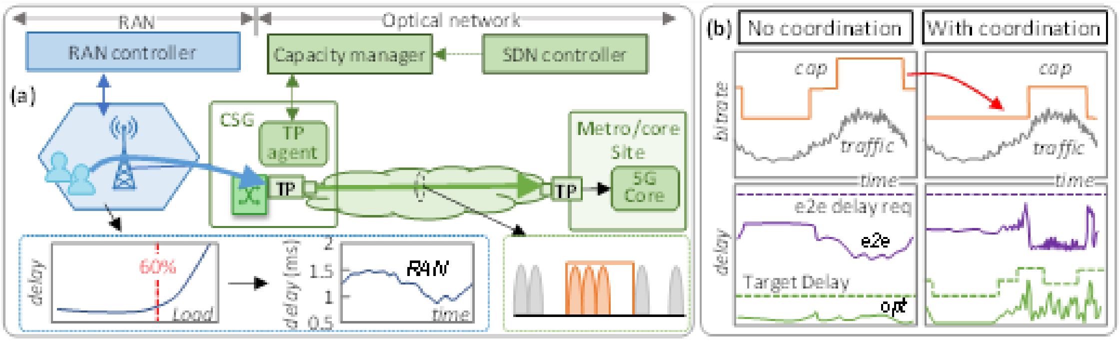


Figure A-6 – (a) Reference e2e scenario; (b) autonomous capacity management performance.

KPI 2.3:

Network connectivity service with creation time < 3 min combining control and data planes. In [Sha21], 3 mins were needed for network connectivity in the metro segment only, mainly due to laser configuration. In SEASON, connectivity will be extended to cover end-to-end, including front-haul, PON and metro/core.

Aspects involved in creation of a network connectivity service

While SEASON encompasses the provisioning of B5G/6G "services" at large (related to the interconnection of *generic network and application functions*) located at variable sized datacenters and computing storages distributed across the SEASON infrastructure, this KPI focuses on the sub-problem of setting up a *network connectivity service,* understood as a data connection across multiple network elements.

As a key innovation of SEASON, the *network connectivity services* span multiple network segments (for example, the access, metro, and core segments) and the interconnection at the segments' demarcation may be transparent (optical connection) or may require electrical conversion and electrical switching. As a consequence, services are multi-layer (combining packet switching and optical switching).

The successful provisioning of a network connectivity is a process that involves different (sub)systems, and the *creation time* is defined overall provisioning delay (measured as the time between the initial request sent to the system entry endpoint and the successful reporting to the user of the provisioning operation). Note that, in general, the time of the successful reporting of the provisioning operation may differ from the time when the data plane is actually able to carry traffic, since the data connection may require additional post-validation out of scope of the control plane. In the following, we assume a synchronous approach.

In this context, the creation time macroscopically depends on different factors: i) processing of the provisioning request at the control, management and orchestration level, including aspects such as path computation, function placement and resource allocation; ii) the actual provisioning of the connectivity services, encompassing the configuration of reconfigurable hardware such as sliceable bandwidth variable transceivers, cross-connections and related forwarding operations at the network elements, and iii) the posterior validation of aspects such as QoT, given the important transients that take place related, for example, to power equalization.

It is complicated to provide a general KPI bound that can be applied across many scenarios and network sizes. However, by adopting state-of-the-art techniques and ensuring that the system can handle the required latency, throughput, and distance requirements, the KPI should be reachable. These techniques include, but are not limited to, efficient control and management architecture, AI/ML integration and decoupled telemetry.

KPI Requirements and Relevant Use Cases

As of today, such targeted dynamicity is not commonly required, except in a set of reduced use cases. In the scope of the past 10-15 years, there has been a migration from processes oftentimes exceeding multiple hours to operations in the order of minutes. That said, the evolution towards 6G will imply increase dynamicity and more efficient use of resources, so that reducing the setup latency is of increasing importance. Use-cases are essential for understanding the specific scenarios and requirements that the network must support, ensuring that the network architecture meets the users' needs. By identifying relevant use-cases, we can determine the necessary network features and functionalities, validate the network's ability to meet these requirements, and guide network development and optimization.

In the context of the service provisioning KPI, it is essential to consider various use-cases to ensure that the system can cater to different scenarios and requirements effectively. The use cases requiring <3min service creation time is not explicitly mentioned in 5GPPP white paper.

Some possible use-cases could include:

- fast network provisioning: ensuring rapid service setup for various scenarios, including different network segments and multi-layer services;
- dynamic network adaptation: providing the ability to quickly adapt to changing network conditions and traffic patterns, ensuring efficient resource allocation, and minimizing service setup time;
- fault detection and recovery: Identifying and addressing potential issues in the network, ensuring the fast and efficient provisioning of network connectivity services.

Incorporating use-cases in the design and validation process is essential to ensure that the network architecture and solutions are tailored to the specific needs and requirements of the targeted applications and services. Moreover, use-cases help in evaluating the effectiveness and efficiency of the implemented solutions in real-world scenarios.ù

Effect of Control, Management and Orchestration Architecture

The adoption of SDN for the control and management of transport networks implies the adoption of a centralized control model in which multiple functional elements may be combined to perform specific tasks, and their interconnection by means of typical open and standard interfaces may introduce latency in the provisioning of services. In most cases, such software systems are logically distributed but co-located in a single place, thus reducing the impact compared to a monolithic software system.

Latencies introduced by multiple software systems/modules are characterized in terms of the order of tens of milliseconds, but this is highly dependent on the actual workflow and modules interdependencies.

To meet the given KPI requirements, a state-of-the-art reference architecture that merges Software-Defined Networking (SDN) and Network Functions Virtualization (NFV) can be utilized as this combination allows for a highly dynamic, programmable, and scalable network infrastructure that is particularly well-suited for the outlined metro and core domain scenarios with O(10) nodes involved in service provisioning. The SDN controller(s) manage the overall DCN, PON system, and the transport network for front-haul, as well as the provisioning of connectivity services across both metro and core domains, while the NFV orchestrator manages the virtual network functions and service chaining for flexible network operations. To satisfy KPI 2.3, the reference architecture should also include a Multi-Domain Orchestrator (MDO) which ensures seamless coordination across different domains and network segments.

A first case of this interconnection of systems is seen in the design of *hierarchical control systems*, in which multiple controllers are arranged in a hierarchical setting, in which controllers at a given level perform a set of tasks. For example, a parent controller may perform domain sequence selection using abstracted topological information, while children controllers perform per domain/segment path computation.

SEASON will consider state-of-art architectures when defining the overall control, management, and orchestration systems, along with telemetry platforms. Notably, in TIP-OOPT (Telecom Infra Project-Open Optical and Packet Transport), network architectures with different technologies including Ethernet, Microwave and Optical Transport networks are being discussed. It comprises domain, multi-domain and hierarchical controllers. The domain and multi-domain controllers are specific to technologies while the hierarchical controller controls multi-domain controllers coming from various technologies (for example, Ethernet/Microwave and Optical) as shown in Figure A-7Figure A-7 .

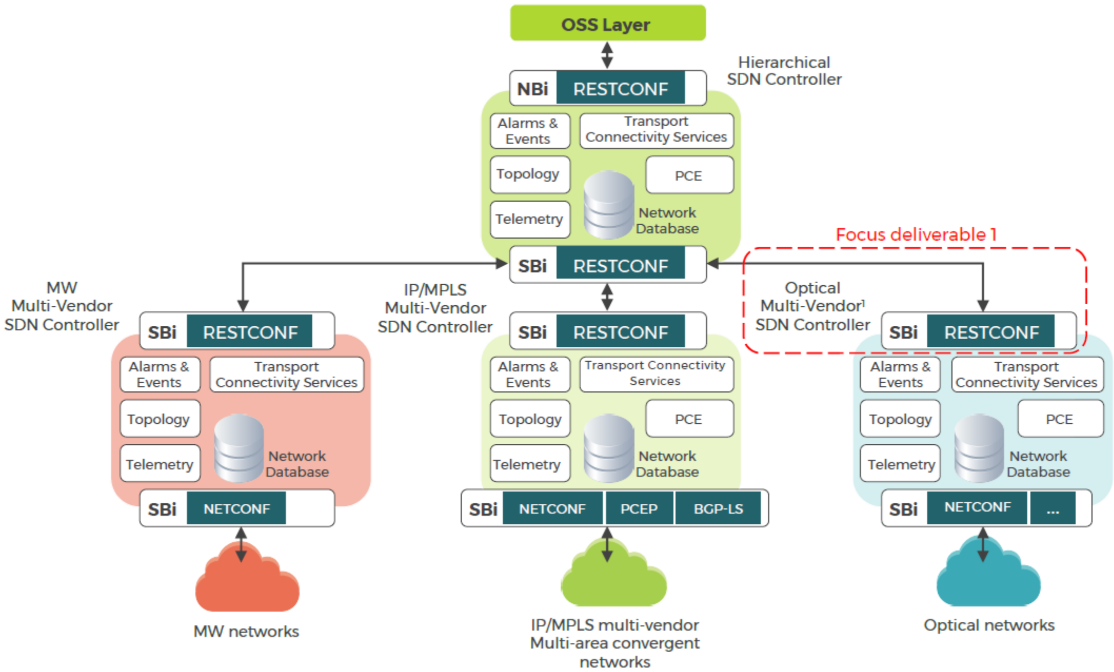


Figure A-7 - Image From: TIP-OOPT-MUST-Optical SDN Controller NBI Technical Requirements.

The design and dimensioning of the Data Communications Network (DCN) that supports the SDN control plane will impact the latency as well, in particular related to the physical distance between the controllers and the underlying hardware.

Macroscopically, such networks are characterized by latencies in the order of hundreds of milliseconds.

Effect of Control Protocol Stack

For a given DCN, a subsequent consideration concerns aspects related to the chosen transport protocol stack. SEASON will align with industry-adopted protocols such as NETCONF or REST(CONF), each of them with their own specific characterization in terms of encoding efficiency, protocol exchanges including handshake and error management.

The usage of open and standard data models and transport protocols imposes a penalty with regards to highly efficient, ad hoc defined transport protocols, that can be optimized for latency (reduced roundtrips, binary encoding, etc). The benefits of industry adopted frameworks outweighs such optimized protocols for many reasons (software tool availability, debugging facilities, etc.). It is assumed that such penalty is minimal overall.

Effect of AI/ML

The adoption of AI/ML is considered a key innovation in aspects related to control and operation of the transport network. However, this adoption will be done progressively and up to well past the time frame that the SEASON project targets. The usage of AI/ML shall be seen as adoption of AI/ML models *in support of* network operation, and it will not be, by any means, essential. It is expected that AI/ML will be deployed in selected scenarios and use cases. AI/ML can be used normally to forecast and manage the dynamic network scenarios. However, the influence of AI/ML for reducing the service creation time is novel and requires more investigation.

In such cases, the assumption is that long-running operations such as training should, as much as possible, be decoupled from the provisioning (as a side process). Nonetheless, using the trained models with real data, for aspects like classification, introduces a delay.

In the following, different architectures of AI/ML are presented in order to compare their capabilities and examine the applicability of each.

- (Deep) Reinforcement Learning (RL) for network optimization: RL algorithms can learn optimal network policies for resource allocation (to minimize congestion and maintain QoS), for traffic routing (path computation by taking into account various factors and network constraints to determine the most efficient routes), and for load balancing, can identify patterns and bottlenecks in the provisioning process (LSTM could be exploited) and suggest improvements to reduce the overall service setup time (by minimizing cross-connection latency and BVT configuration time), leading to reduced latency and improved network performance.
- Deep Learning (DL) for anomaly detection: Convolutional Neural Networks (CNNs) or Recurrent Neural Networks (RNNs) can be used to identify unusual patterns or behaviors, enabling proactive fault detection and prevention.
- Transfer Learning for dynamic network configuration: By leveraging pre-trained models, AI/ML can quickly adapt to network changes and adjust configurations, ensuring optimal network performance even as conditions change.

Telemetry role

In modern networks, telemetry plays a critical role in monitoring and diagnosing network performance. In principle, aspects related to configuration and control are designed to be separated from telemetry aspects, at least in terms of “open loop” configurations. Decoupling telemetry from control enables the use of streaming telemetry, which allows real-time data collection (network performance, configuration times, and device states) on network conditions. Even if the KPI is defined in such terms (as stated in the Introduction) we cannot, in general, not include also closed loop aspects. For example, the configuration of S-BVTs may include multiple iterations in BER calculus and the telemetry aspects are clearly relevant. That said, closed loops at network level should be minimized, at least for baseline operations. Its importance is also clearly stated when we consider the posterior validation in terms of service QoT.

The involvement of telemetry in service creation time seems to be significant. The monitoring of performance indicators in Optical Transport Network, including SNR, BER, Q-factor, is performed periodically for the existing channels or optical services. This helps in making decisions while deploying the additional service/channel on the existing path, based on the required SLA. This monitoring of the KPI margins helps in reducing the planning costs during the service creation.

Data collected using telemetry systems can be processed by advanced data analytics and machine learning techniques, such as time series analysis or clustering algorithms, to provide actionable insights for a centralized controller (which communicates with the SDN controller and NFV orchestrator). The controller can make informed decisions based on actual network performance rather than solely relying on predefined policies. This approach allows for better scalability, flexibility, and the ability to integrate with various network components and data sources.

Workflows and Control plane functions

The control plane takes into consideration aspects such as path computation and device configuration. For the simplest path computations (e.g., Yen k-shortest paths with FF or random allocation) for networks in the order of tens or hundreds of nodes, modern hardware implementations of such algorithms accomplish running times of the order of nanoseconds or microseconds. The higher the network complexity, also in terms of number of slots (e.g., over 300 for C-band flex grid network) and implemented functions, the higher the path computation latency.

Path computation functions and RSA can range from a few microseconds in simple scenarios to several minutes in complex scenarios with multiple validations. In particular, workflows may not be fully automated and computed paths may be subject to further approval and validation.

The actual provisioning latency depends on whether the device configuration is sequential, or it can be parallelized. For example, the establishment of N cross-connections where each cross-connection consumes K iterations (roundtrips) in a Netconf device, and each iteration takes T milliseconds can be O(N x K x T). If the process can be executed in parallel (e.g., multiple threads or asynchronous processes) this can be reduced to O(K x T), at the expenses of additional complexity in systems programming.

Hardware Configuration

It is quite common that, given the previous orders of magnitude, the overall service setup configuration comes determined by the hardware configuration delay and posterior validation. In this case, let us note for example:

a) S-BVT configuration time prototype. Experimentally, the prototype can be configured in the order of seconds/minutes (30 s for Tx and 155 s for Rx). In this case, we may need to reduce the number of 10 iterations for BER estimation.

b) Node cross-connection. In the simplest passive cases, this is limited by the matrix configuration. For example, a reference value is approximately 60 ms. More complex devices have this setup time increased.

c) PON system configuration. As previously highlighted, the time required for PON configuration is partially impacted by the burden related the utilization of open industry standards such as NETCONF. A major contribution to the time required to apply configuration in the PON is represented by bandwidth allocation operations. In [Cen22] the time to provision via NETCONF a new service with dedicated bandwidth on an XG(S)-

PON has been shown to be around 1s. Further experiments measured the time required to update the configuration of an already provisioned service (e.g., variation of reserved bandwidth) in between 100ms and 200ms depending on the size of the XML content.

Overall Assumptions for KPI service provisioning

Note that the previous sections have defined the underlying considerations for the evaluation of the Provisioning delay. However, there are a set of underlying assumptions on the deployment models of an SDN Control plane as well as used models and network sizes. The following list provides a basic set of such assumptions.
Fully dedicated DCN with rates > 100 Mb/s for centralized Control.

- Overall DCN with up to a few hundreds of Km distance nodes/controller.
- A single PON system with a dedicated agent.
- Simple transport network for Front-haul.
- Service spanning a Metro domain with O(10) nodes involved in the provisioning of the connectivity service.
- Service spanning a Core domain with O(10) nodes involved in the provisioning of the connectivity service.
- Quasi-parallel node configuration with < 1 min cross-connection latency.
- BVT configuration < 2 minutes. This can be achieved by reducing the number of iterations or postponing BER estimation (alternatively, reducing the quality of the estimator to have a less accurate profile and reduce configuration time)
- Open Loop operation provision

OBJ. 4: DEVELOP AN INNOVATIVE ACCESS AND FRONT/MID-HAUL TRANSPORT SOLUTION SUPPORTING POWER-EFFICIENT FUNCTIONAL SPLIT IMPLEMENTATIONS AS WELL AS COST-EFFECTIVE SMALL/FREE CELLS SOLUTIONS

KPI 4.1:

<1ms mobile user latency via coordinated resource allocation at optical access and mobile network for SDM-PON mid-hauled RU/DU as a result of SEASON's target integration against >5ms delay in non-integrated approach [Li18].

Reference disaggregated sliced open RAN architecture

The solution from Accelleran adopted in SEASON, shown in Figure A-8
follows disaggregated RAN architecture as proposed by O-RAN. It consists of the DU (Distributed Unit), CU-CP (Control Plane Centralised Unit), CU-UP (User Plane Centralised Unit), Near Real Time RIC (RAN Intelligence Controller) and Non-Real Time RIC realised as virtual network functions implemented in docker containers. The CU-CP supports MOCN (Multi Operator Core Network) feature with NSSF (Network Slice Selection Function). The disaggregated network functions are deployed in a cloud native Kubernetes cluster via SMO (Service Management and Orchestration) function and communicate using standard 3GPP, ORAN or proprietary interfaces. The CU-CP and the DU communicate using standard 3GPP F1AP interface for control plane

signalling. The DU and RU communicate using O-RAN compliant open fronthaul interface that supports 3GPP split 7.2x. The DU implements standard O-RAN E2 interface to support KPM (Key Performance Measurement) and RC (RAN Control) service models. The CU-CP supports E2 like proprietary interface (E2*) that uses cloud native NATS and Kafka bus to publish the KPM stats, UE measurements, Control plane events and to facilitate the RAN control commands. The RIC will support RNIB (Radio Network Information Base) and UENIB (UE Network Information Base) that capture the cell specific information and the RIC UE id mappings. The telemetry data received from all RAN nodes via E2 interface can help in pervasive monitoring of performance and resource usage. The O1 interface is used to configure the RAN nodes using Netconf protocol. The O2 interface is used to deploy the network functions on a Kubernetes cluster from SMO using a proprietary REST API towards the Service Orchestrator infrastructure that implements the kubectl API.

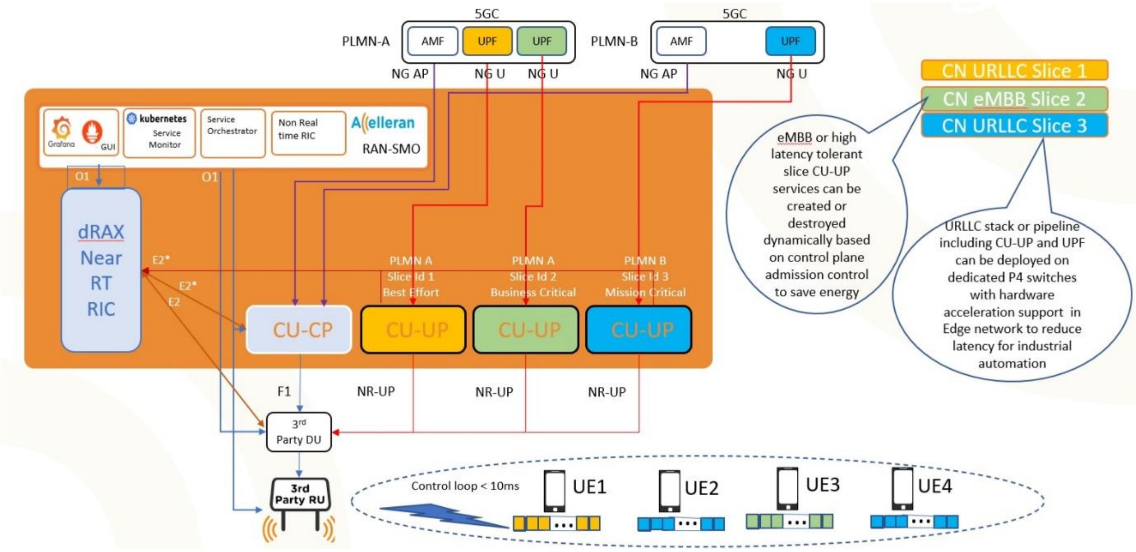


Figure A-8 - SEASON network slicing architecture.

The SMO layer can be provisioned with configuration templates and rAPPs that perform SON (Self Organizing Network) functions to facilitate zero touch provisioning of CUs, RUs and DUs. The virtualised user plane functions including core network UPF (User Plane Function) can be deployed on Edge cloud servers and use eXpress Data Path (XDP) to run user plane processing directly in Linux kernel space. The SMO can deploy virtual networks functions that handle xURLLC (Extreme Ultra Reliable Low Communications Latency) slice traffic as part of isolated pipelines to accelerate user plane processing. This can have the effect of reduced latency and processing time compared to traditional network deployments that are CPU based.

Additional features enabling sub ms latency

The following additional 5G features must be supported in the DU to facilitate xURLLC service that offers latency below 1ms, in particular:

- lower latency by supporting:
  - higher subcarrier spacing, with shorter transmission durations;
  - mini-slots with fewer number of symbols;
  - frequent PDCCH (Physical Downlink Control Channel) monitoring reducing the latency of the layer-1 control information;

  - configured-grant, which allows the UE to autonomously transmit uplink data without having to send a scheduling request and wait for the uplink grant;
  - downlink pre-emption.
- Higher reliability by supporting:
  - multi-slot repetition;
  - low spectral efficiency MCS/CQI (Modulation and Coding Scheme/Channel Quality Indicator) tables;
  - PDCP duplication.

The CU-UP and transport network resources for high latency network slices can be dynamically switched ON and OFF by rAPPs in Non-Real Time RIC. The resources can be switched OFF when there are no calls and switched ON when there are active calls admitted for a slice by control plane during Admission Control. This can result in significant energy and cost savings during quite periods when user plane activity is very low for such slices. In dual frequency networks with umbrella coverage provided by the Macro, small cells (DU and RU) can be completely switched OFF based on activity patterns during certain time of the day to save energy.

KPI 4.2:

>50% contribution in energy saving via dynamic spatial channels aggregation and deactivation of unused transceivers or spectrum at the OLT side basing on traffic conditions over total 70% energy saving targeted by [SRIA].

Dynamic resources allocation in TDM and TDWDM PONs

Current PON technologies rely on the allocation of transmission opportunities to different Optical Network Units (ONUs) at fixed line rate (1.25G, 2.5G, 10G, 25G or more depending on the adopted technology). The amount of transmission opportunities given to a specific ONU determines the offered throughput. Dynamic allocation mechanisms can be implemented in a Time Division Multiplexing (for TDM PONs) or frequency division multiplexing or both with Time and Wavelength Division Multiplexing (for TWDM PONs) fashion.

PONs, due to their large capillarity, represent a good transport technology to support mobile networks front/mid/back-hauling, and softwarization of both optical (via e.g., NETCONF) and radio (via O-RAN) access networks allows high cooperation between such network infrastructures with consequent advantages in terms of network efficiency and savings in cost of ownership for operators.

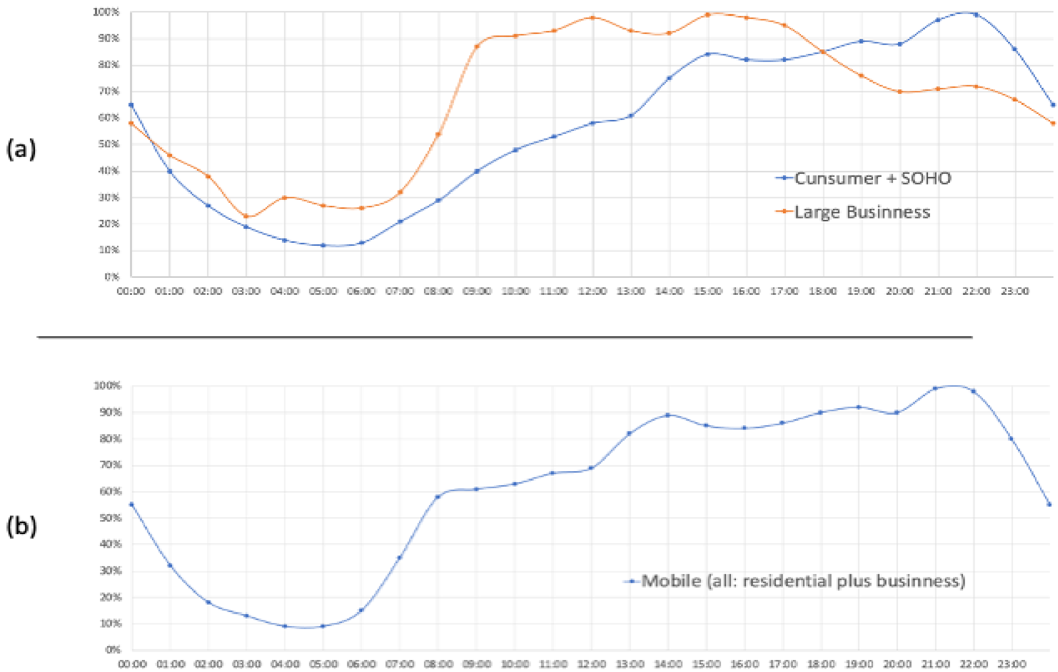


Figura A-9 - Traffic variations during the day for (a) fixed and (b) mobile connectivity services (data provided by TIM).

It is worth notice that aggregated traffic by the users in PON and RAN is characterized by substantial fluctuations during the day as shown in Figure A-9. However, considering traditional PON architectures, such fluctuations leave unchanged the number of utilized transceivers at the Optical Line Terminal (OLT) side since multiple users (active and non-active) share the same wavelength both in upstream and downstream.

The envisioned SEASON architecture aims at leveraging the spatial degree of freedom (for example through MCFs or multiple SMFs) in conjunction with the exploitation of the dynamic nature of the traffic as one long term approach to help reaching the targeted >50% energy savings.

As shown in Figure A-10, SEASON architecture extends the traditional central office architecture by introducing the possibility to dynamically aggregate and disaggregate spatial channels through spatial switching controlled via SDN. Note that this architecture could be employed using several different flavours of SDM including MCF, as shown in Figure A-10 or bundle of fibers; the approach is agnostic to the SDM technology employed allowing its deployment even for short -medium term scenarios if needed.

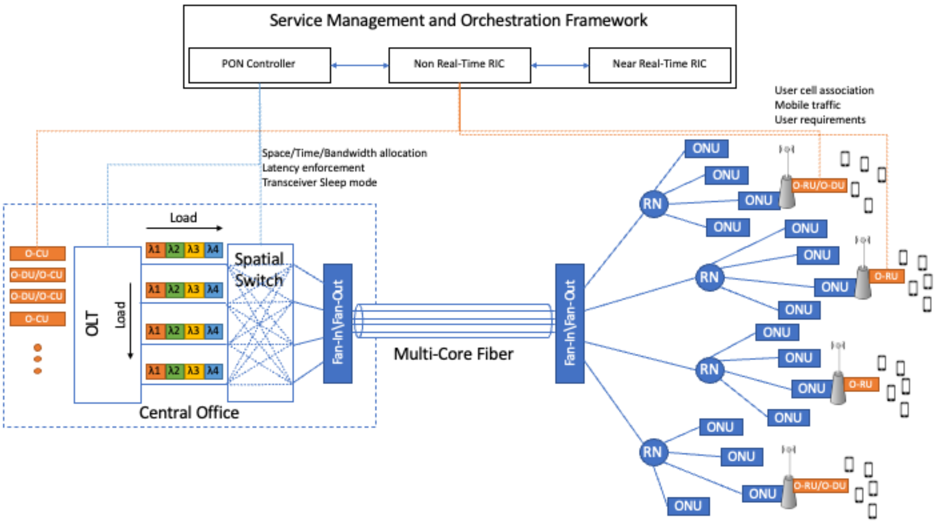


Figura A-10 - Reference SDM WDM PON access architecture reported in the project proposal.

As in the central office, OLTs for multiple optical distribution networks (ODNs) are co-located, via spatial aggregation it will be possible, in case of low traffic conditions, to aggregate multiple ODNs over a single spatial channel and deactivate unnecessary transceivers and line cards at the OLTs, consequently achieve significant energy savings. As shown in Figure A-10, the PON infrastructure is considered as x-haul infrastructure for a mobile network based on the emerging O-RAN paradigm. Decision on spatial channel aggregation will be based on the expected traffic in the PON, which can be forecasted by leveraging software controllability of O-RAN. Expected traffic variation in mobile network as well as user-specific constraints can be shared between the Radio Intelligent Controller (RIC) and the PON controller. This allows to enforce latency policies for specific x-haul traffic, bandwidth allocation strategies, aggregate spatial channels, and put unutilized transceivers in sleep mode to reduce power consumption.

A graphical example of the intended spatial aggregation is given in Figure A-11 for an NGPON-2 with 4 wavelengths per direction (down/upstream) on each spatial channel. In high load conditions the spatial switching element is configured to utilize all the spatial channels separately, and all the available transceivers are utilized (Figure A-11 (a)). In contrast, when the traffic is low on all the ODNs, the proposed architecture allows to aggregate all the ODNs on a single spatial channel. Consequently, all the unnecessary transceivers and line cards hardware can be deactived to reduce power consumption. Deactivated transceivers in (Figure A-11 (b)) are grey-coloured.

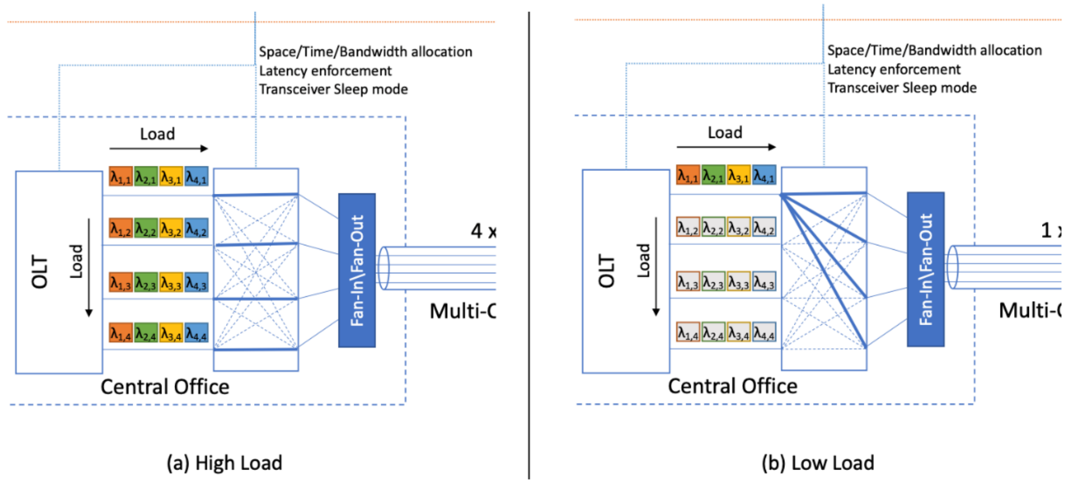


Figure A-11 - Spatial aggregation and transceiver deactivation in SDM-PON.

Line-card based solution vs. pluggable PONs

It is worth mention that the proposed architecture can be applied to many PON technological solutions. For example, instead of NGPON-2 based on WDM MUX/DEMUX, also pluggable-PONs solutions for both GPON and EPON families can be considered, as shown in Figure A-12. While for TWDM PONs (in Figure A-12 (a)) each spatial channel requires WDM Mux/DeMux and performs Dynamic Wavelength and Bandwidth Allocation (DWBA), in pluggable PON based solution (in Figure A-12 (b)) the central office architecture is simplified, and simpler Dynamic Bandwidth Allocation (DBA) is performed. Finally, other point-to-multipoint technological solution explored in SEASON can be utilized in conjunction with the proposed energy saving mechanism.

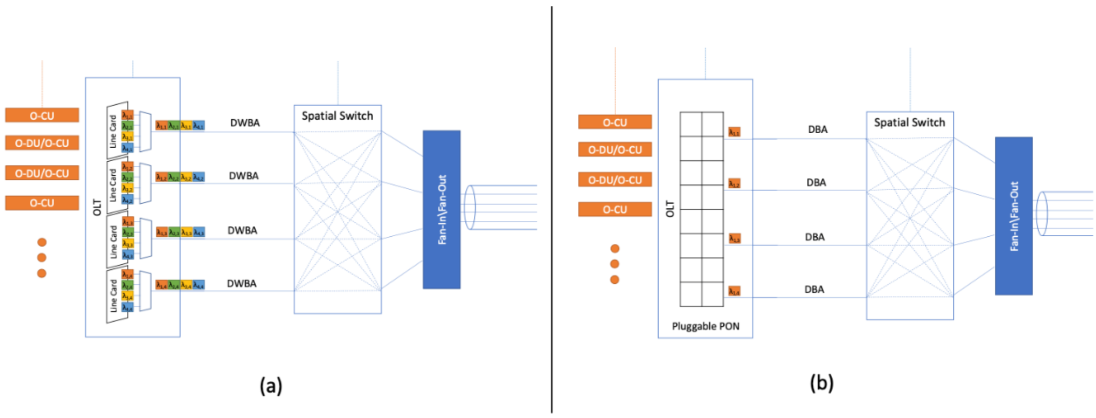


Figure A-12 - Pluggable-PONs solutions for GPON and EPON.

KPI 4.3:

400Gb/s RAN fronthaul ports capacity.

Trends in use of coherent transmission for x-hauling in the RA

Current radio transmission leverages on 25G pluggable transceivers per port, and 50Gb/s is the next step. The enormous bandwidth growth driven by future 6G applications (e.g., holographic communication) will further increase bandwidth requirements in the RAN transport. Coherent is gaining momentum on shorter distance applications and market is following consequently (see the success of Open ZR with wide supplier base), as shown in Figure A-13 where a metro access ring based on coherent pluggable is identified to interconnect core DC with edge nodes (source: DELL).

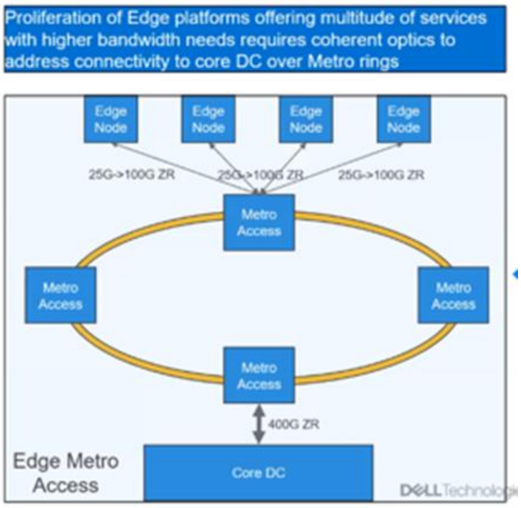


Figure A-13 - Core DC to Edge Nodes interconnections through 400G coherent based technology (Source: DELL).

The above scheme can be mapped similarly to the RAN use-case (FigureA-14), provided suitable cost for coherent technology will meet RAN requirements.

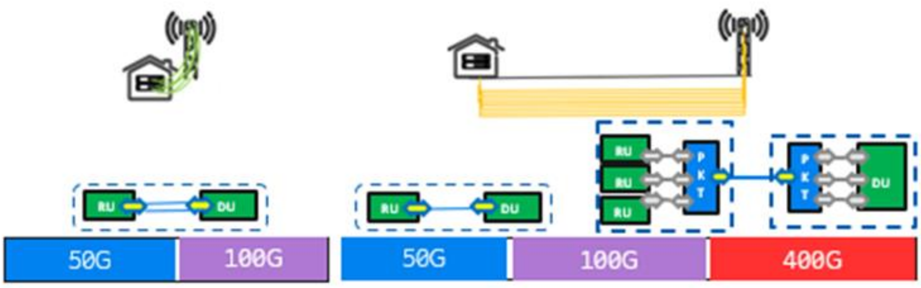


Figure A-14 - 400G coherent-lite opportunity in RAN.

Coherent “lite” trends are ongoing to optimize costs for shorter reach (Figure A-15). The trend is motivated by DC-interconnect needs (e.g., the 800G-LR activity at OIF). The 1.6 Tb/s transmission is in the radar, confirming the trend that higher rates requirements push coherent technology further in the short distance applications.

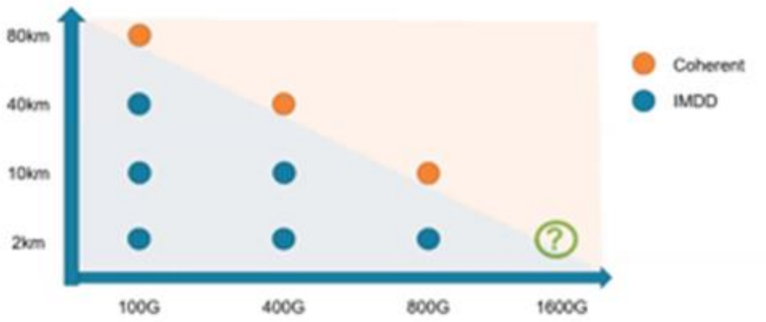


Figure A-15 - Transition from IM-DD to Coherent (Source: Acacia).

From the above considerations we believe “coherent lite” or other coherent solutions such as the one based on digital subcarrier multiplexing which enable high capacity point-to-multipoint transmission, might play a fundamental role in future 6G RAN and RAN transport.

Even if today’s coherent technology has been designed for metro and is too expensive for RAN, Data centers are pushing to reduce the cost of coherent pluggable, cause the same technology ingredients for 800G/1.6T will generate **“coherent lite” solutions at 400G** and below, which could fit the RAN in the 2026-2030 timeframe. This wouldn’t be the first time that metro technologies are adapted to the different cost/performance RAN sweet spot (today’s 10G/25G DWDM transceivers in use in optical fronthaul are a good example). In any case, adaptation to mobile transport implies addressing temperature and synchronization requirements, and single fiber operation would also be a desirable feature. Alternatively, coherent point-to-multipoint enables a significant simplification of the network architecture which reduces the number of needed transceiver thus leading to a considerable reduction of the total cost of ownership, and a significant increase capacity and flexibility in the network design and management.

Proposed 400G WDM architecture for fronthaul

The following network architecture, represented in Figure A-16, will be investigated in SEASON as a parallel track with respect to SDM. A physical ring implements a logical full mesh between DUs and RRUs. 400G coherent technology provides the required capacity scaling expected by 6G. This topology exploits WDM and is suitable in fiber-scarce environments. Furthermore, it can be deployed in shorter terms in an evolutionary path toward the further capacity growth addressed by multi-band and spatial multiplexing.

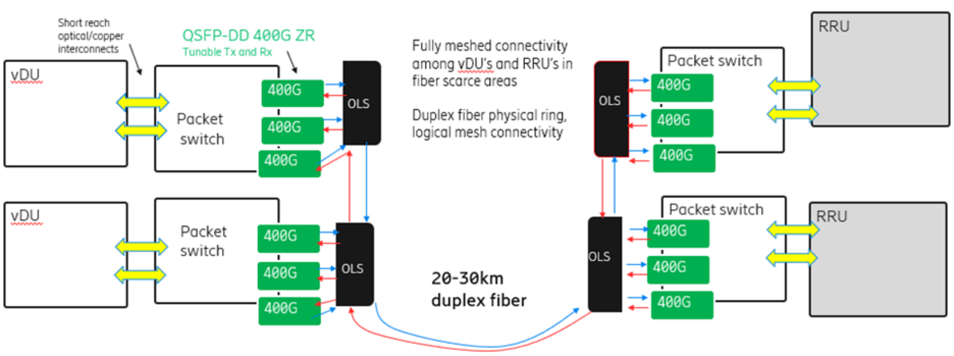


Figure A-16 - WDM based full meshed connectivity with 400G coherent in a horseshoe/ring topology.

The optical infrastructure is based on Optical Line System (OLS) that can be implemented with Pluggable solutions (POLS): double EDFAs in a single QSFP-DD form factor are already available. Coherent demultiplexing will be explored to realize simple colourless ROADM nodes based on passive splitters, as alternative to WSSs. Furthermore, coherent P2MP technologies and single fiber operation (either full or half duplex) is an option that will be explored in the context of SEASON.

The WDM ring architecture with optical bypass avoids OEO conversion in routers/switches when not required, leading to significant power efficiency. The use of simple colourless ROADM based on splitters further improves the power efficiency, the flexibility being achieved through coherent technology (tuning).

The latency contributions of this solution will be assessed in the Ericsson lab to verify the fulfilment of the KPIs. Our proposed architecture is not based on TSN (Time Sensitive Networking); however, latency asymmetry contributions to synchronization time error will be addressed. Cable asymmetry can be compensated down to few nanoseconds using fiber monitoring tools like a high precision OTDR (Optical Time Domain Reflectometer).

KPI 4.4:

High accuracy profile for IEEE 1588-2019 or better, evolving ±1.5 µs of LTE and Release-15 Standalone, aiming to ns with target IEEE P802.1CM A+ networks, demanding an accuracy better than 12.5 ns.

At this early stage of the project the requirements from this KPIs cannot be defined yet but will be evaluated in a next step.

OBJ 5 - DEVELOP A PERVASIVE MONITORING INFRASTRUCTURE FOR SECURE AND TRULY SELF-MANAGED NETWORKING

The requirements related to Objective 5 are analysed in the following section in a general perspective, without specifically referring to the related KPIs, that are just listed in the following, with the exception of KPI 5.4 that is commented in a specific sub-section:

- KPI 5.1: Achieve sub-km (<500 m) and sub-dB (<0.5) resolution in the estimation of longitudinal fiber attenuation points and optical amplifier gain, respectively, using DSP-based monitoring scheme.
- KPI 5.2: Performance improvement achievable with an OSA embedded in the amplifier setup and control identified for different link designs and applications.
- KPI 5.3: OTDR Interrogator for latency / position measurement with 4 ns / < 1 meter accuracy respectively
- KPI 5.4: Applicability of modulation format insensitive OSNR measurement techniques in different scenarios determined, sources of inaccuracy identified, impact of signal *disto*rtions worked out.

Requirement analysis

Telemetry data is a collection of data from many different sources and can be described by means of a number of characteristics [Lan01], known as the 5 V's, standing the five V for volume, velocity, variety, veracity, and value. Such characteristics can be seen as different tiers of a pyramid: i) at the bottom of the pyramid, volume refers to the size and amount of data that needs to be collected and analysed; ii) velocity refers to the speed at which data is collected, stored and managed. Volume and velocity together impose requirements that need to be carefully considered, e.g., sometimes it is better to have limited data in real time than lots of data at a low speed; iii) variety refers to the diversity and range of different data types and data sources; iv) veracity is related to the quality, accuracy, trustworthiness of data and data sources and it is the most important factor of all the five V's for business success; and v) value, at the very top of the pyramid, refers to the ability to transform data into useful insight. Indeed, operators can capture value from telemetry data by, among others, reducing network margins, automating service provisioning, improving resource utilization, and extending the working life of network equipment, which might lead to CAPEX savings (KPI 2.2).

From the analysis of typical measurements that can be collected from real optical network equipment (e.g., see [Pes22] for an exhaustive list), we can extract the requirements of the proposed pervasive telemetry architecture in support of the 5 V's.

1. Different measurements should have different collection periodicity, which can be variable, or even being collected asynchronously. For instance, the configuration of the Tx happens at setup time or upon some event, and the temperature of the laser would not significantly change that fast.
2. In general, it is not useful to store all the measurements when no significant changes happen. However, to determine whether a significant variation in one measurement has happen, some analysis needs to be carried out, and that should be done earlier in the telemetry pipeline, e.g., at the node level, to reduce volume of data being conveyed to the centralized telemetry system.
3. Compression techniques, which can be either lossy or lossless, can be explored to reduce bandwidth requirements.
4. From the two previous issues, telemetry systems be somehow decentralized. Some processing and data analysis might be needed at the node level. However, such analysis might be orchestrated by some entity running at a centralized level, which can have global network vision.
5. Data veracity should be checked along the telemetry pipeline and it should be discarded from the main pipeline whenever there is evidence that such data is somehow contaminated. For instance, a sample data that does not follow statistically last measurements can be either an outlier or an anomaly. However, the detection point can be local if it refers to the gain of an amplifier or it needs to be in the centralized system if it requires correlation with other measures, e.g., in the case of spectrum measurements in the route of a lightpath;
6. Value should be extracted from data as soon as possible in the telemetry pipeline. E.g., we should not wait to detect degradations from the data collected from a network node in the centralized telemetry system, if this can be done directly in the node. However, sometimes, it is necessary to perform correlation among data collected from different network nodes to extract value from data.

Key concepts related with monitoring/telemetry architecture

The following concepts need to be taken into account when designing the monitoring architecture:

1. Intelligent data aggregation needs to be a key component in the monitoring architecture: it is intended to greatly reduce the impact of both volume and velocity of telemetry, as well as add value for self-adaptive networking purposes. Techniques to be explored include monitoring data summarization, supervised feature extraction, and compression using auto-encoders [Rui22]. These techniques could be exploited for any monitoring/telemetry data, including those more complex measurements such as optical constellations and optical spectrum data.
2. Digital twin (DT) is as key component for self-managed networking that needs to be continuously fed with monitoring data: DTs have been proposed as a key tool for network automation, as they can provide a holistic representation of the network with high accuracy and, simultaneously, low computational complexity [Vel23]. A DT should generate, among others, expected signals that can be compared with those obtained from the network by monitoring. In that way, deviations between the monitored and the expected signals can be detected and used for, e.g., soft-failure and anomaly detection.
3. Telemetry is an essential component of the multi-agent system (MAS): telemetry data are consumed at the intelligent control plane, where a MAS controls the infrastructure. The MAS consists of several transport agents running as part of node agents that communicate among them. Transport agents might include: i) a telemetry processor to collect from the local node and process telemetry data, including intelligent data aggregation; ii) an inter-agent communication module, which is used for telemetry data distribution and state and model sharing; and iii) technology-specific intelligence for autonomous decision making based on local and remote observations.

KPI 5.4:

Applicability of modulation format insensitive OSNR measurement techniques in different scenarios determined, sources of inaccuracy identified, impact of signal distortions worked out.

OSNR from OTs (Related to telemetry listening)

One of the goals of deploying a monitoring architecture is to make the network self-managed or self-adaptive. A Self-adaptive network possesses a monitoring framework for control-loop automation with adaptive decisions, promptly reacting to the dynamic network scenarios.

This self-managed network helps to automatically configure/terminate the network resources, resulting in effective resource usage. This is possible with the inclusion of AI/ML in the monitoring framework for network automation, to create new services or scale the existing ones. Requirement from different vendors is the enablement of fundamental parameters for self-managed networking. This is however tedious as due to security concerns; some parameters are not accessible by customers or service providers.

The use of standard protocols (gRPC/gNMI) for telemetry functionality, providing them as an input to the management functions, is encourage. Figure A-17 show a simplified scheme of an architecture suitable for OSNR monitoring.

Details on data model (YANG) for OSNR data retrieving from the equipment will be provided in WP4.

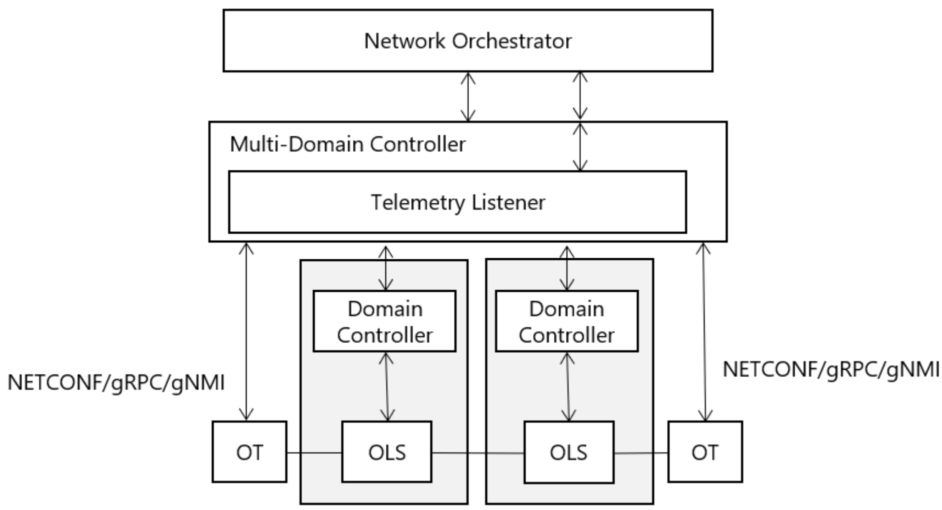


Figure A-17 - Monitoring Architecture – OSNR.

OBJ 6 PROVIDE AND VALIDATE SMART EDGE NODES FOR PACKET/OPTICAL INTEGRATION WITH COMPUTING RESOURCES

Expected benefits from functionalities integration in a smart edge node

SEASON will design and develop a smart edge computing node based on the latest generation of SmartNICs, also called Data Processing Units (DPUs), enhanced with coherent intelligent pluggable modules.

Two main benefits are expected.

The first benefit is the reduction of active standalone nodes and intermediate O/E/O conversions. Figure A-18 (left) shows a traditional edge computing scenario where computing and networking resources are implemented in different platforms and multiple O/E/O conversions (highlighted with red dots) are required to provide edge-cloud services. Figure A-18 (right) shows the innovative SEASON scenario where an edge computing node equipped with SmartNIC/DPU and enhanced with coherent pluggable is providing both networking and computing resources in a single platform (right).

Figure A-18 - Today's reference scenario supporting edge computing through separated networking and computing resources (left); Edge computing node equipped with SmartNIC/DPU enhanced with coherent pluggable providing both networking and computing resources in a single platform (right).

The second benefit consists in reduced latency. Indeed, the aggregation of computing and optical networking resources in a single platform with less O/E/O conversions also contributes to reducing the e2e latency. Furthermore, the adoption of point-to-multipoint high-speed transceivers directly plugged in SmartNICs/DPUs has the potential to better support ultra-low latency services towards the access, avoiding/limiting aggregation nodes while leveraging on hardware-accelerated in-network functions implemented in the SmartNICs/DPUs (e.g., encryption).

The innovative edge computing node equipped with SmartNIC/DPU and coherent pluggable modules is expected to improve the performance of two main types of services. First, enhance the service level for ultra-low latency user applications. Second, effectively enable the deployment of 5G functions closer to cell-sites (e.g., CU/DU).

Issues to be addressed for KPIs achievement

The expected KPIs of Obj. 6 are:

KPI6.1: 40% CAPEX reduction by collapsing computing, IP networking, and usage of high-speed intelligent coherent optical transmission in a single element (i.e., DPU) not designed for the Telecom market but for much wider computing markets and verticals (e.g., automotive).

KPI6.2: >40% reduction of O/E/O conversions in edge-edge and edge-cloud communications by developing smart edges with high-speed coherent intelligent pluggable and by moving 5G functions closer to the cell sites.

KPI6.3: Supporting traffic adaptation/monitoring at μs granularity on innovative HW-accelerated networking smartNICs/DPUs (including computing, networking, and optical resources) for selected low-latency services.

To achieve these objectives and KPIs the following aspects need to be addressed:

- Analysis of technology gaps (e.g., QSPF-DD coherent transceivers not supported within SmartNIC/DPU) and definition of potential solutions to overcome such limitations during experimental validations (use of external switch/board encompassing the coherent transceiver and controlled by the SmartNIC as being its pluggable module).
- Analysis and definition of the underlying working software platform including the operating system and tools for the deployment of containerized applications (e.g., Sylva platform).
- Analysis of the most relevant acceleration capabilities provided by the SmartNIC/DPU that are of specific interest for the SEASON Project (e.g., CU/DU functions, security).
- Definition of specific technical activities to provide a proof of concept of the proposed packet-optical and computing integrated solution.

GLOSSARY

Acronym	Description
2G	*Second Generation*
3GPP	*Third-Generation Partnership Project*
4G	*Fourth Generation*
4T4R	*Four Transmit Four Receive*
5G	*Fifth Generation*
6G	*Sixth Generation*
ACL	*Access Control List*
AI	*Artificial Intelligence*
AP	*Access Point*
API	*Application Programming Interface*
ATSSS	*Access Traffic Steering, Switching and Splitting*
BER	*Bit Error Rate*
BH	*BackHaul*
BNG	*Broadband Network Gateway*
BSS	*Business Support Systems*
BTS	*Base Transceiver Station*
BVT	*Bandwidth Variable Transponder*
CD	*Continuous Delivery*
CD/CDC	*Colourless Directionless/Colourless Directionless Contentionless*
CDN	*Content Delivery Network*
CI	*Continuous Integration*
CN	*Cloud Native*
CNF	*Cloud Native Function*
CO	*Central Office*
CPN	*Computer Power Networking*
CPU	*Central Processing Unit*
CSI	*Channel State Information*
CU	*Centralized Unit*
DD	*Double Density*
DDDSU	*one type of LTE frame*
DMC	*Dual Mode Core*
DNN	*Deep Neural Network*
DPU	*Data Processing Unit*
DSC	*Digital Signal Controller*
DSCM	*Digital Sub-Carrier Multiplexing*
DSP	*Digital Signal Processing*
DSUDD	*one type of LTE frame*
DT	*Digital Twin*
DU	*Distributed Unit*
DWDM	*Dense Wavelength Division Multiplexing*
eCPRI	*enhanced Common Public Radio Interface*
EDFA	*Erbium Doped Fiber Amplifier*
EPC	*Evolved Packet Core*

EPG	*Evolved Packet Gateway*
ETSI	*European Telecommunications Standards Institute*
FDD	*Frequency Division Duplexing*
FEC	*Forward Error Correction*
FH	*FrontHaul*
FL	*Federated Learning*
FOADM	*Fixed Optical Add Drop Multiplexer*
FTTA	*Fiber to the Antenna*
FTTCab	*Fiber to the Cabinet*
FTTCurb	*Fiber to the Curb*
FTTH	*Fiber to the Home*
FWA	*Fixed Wireless Access*
GE	*Gigabit Ethernet*
gNmi	*gRPC Network Management Interface*
GPON	*Gigabit Passive Optical Network*
gRPC	*google Remote Procedure Call*
GTP	*GPRS Tunneling Protocol*
HSI	*High Speed Internet*
HW	*HardWare*
I/O	*Input/Output*
IAB	*Integrated Access and Backhaul*
IaC	*Infrastructure as Code*
ICAS	*Integrated Communication And Sensing*
IETF	*Internet Engineering Task Force*
IoV	*Internet of Vehicle*
IP	*Internet Protocol*
IQ	*In-phase Quadrature*
ITU-T	*International Telecommunications Union – Telecommunications sector*
JCAS	*Joint Communication And radar/radio Sensing*
KPI	*Key Performance Indicator*
L2	*Layer 2*
L2NM	*L2VPN Network Model*
L2VPN	*Layer 2 VPN*
L3	*Layer 3*
L3NM	*L3VPN Network Model*
LSTM	*Long Short-Term Memory*
LTE	*Long Term Evolution*
MAN	*Metropolitan Area Network*
MAS	*Multi-Agent System*
MB	*Multi-Band*
MBoSDM	*Multi-Band over Space Division Multiplexing*
MCF	*Multi-Core Fiber*
MCM	*Multi Carrier Modulation*
MEC	*Mobile Edge Computing*
MH	*MidHaul*
MIMO	*Multiple Input Multiple Output*
ML	*Machine Learning*
mMIMO	*massive MIMO*
mmWave	*millimeter Wave*

MPLS	*Multi-Protocol Label Switching*
MW	*MicroWave*
N3IWF	*Non-3GPP Interworking Function*
NaC	*Network as Code*
NBI	*NorthBound Interface*
NE	*Network Element*
Near-RT	*Near-Real Time*
NETCONF	*NETtwork CONFiguration protocol*
NetDevOps	*Network Development Operations*
NFV	*Network Function Virtualization*
NGMN	*Next Generation Management Network*
nGRG	*next Generation Research Group*
NIC	*Network Interface Card*
Non-RT	*Non-Real Time*
NOS	*Network Operating System*
NR	*New Radio*
NRUPP	*NR User Plane Protocols*
NSA	*Non-Stand Alone*
NWDAF	*5G NetWork Data Analytics Function*
OCM	*Optical Channel Monitoring*
ODN	*Optical Distribution Network*
OFDM	*Orthogonal Frequency Division Multiplexing*
OIF	*Open Internetworking Forum*
OLS	*Optical Line System*
OLT	*Optical Line Terminal*
ONAP	*Open Network Automation Platform*
ONIE	*Optical Network Install Environment*
ONT	*Optical Network Termination*
OPC	*Optical Packet Core*
OPEX	*OPerational EXpenditure*
O-RAN	*Open RAN*
OSA	*Optical Spectrum Analyzer*
OSM	*Open Source MANO*
OSNR	*Optical Signal-to-Noise Ratio*
OSS	*Operations Support Systems*
OTDR	*Optical Time Domain Reflectometer*
OTN	*Optical Transport Network*
OTT	*Over The Top*
P2MP	*Point-to-Multipoint*
P2P	*Point-to-Point*
PDCP	*Packet Data Convergence Protocol*
PE	*Provider Edge*
POLS	*Pluggable Optical Line System*
PON	*Passive Optical Network*
POP	*Point of Presence*
QAM	*Quadrature Amplitude Modulation*
QOA	*QSFP-DD Optical Amplifier*
QoS	*Quality of Service*
QoT	*Quality of Transmission*

QSFP-DD	*Quad Small Form Factor-Double Density*
RAN	*Radio Access Network*
rAPP	*APP for Non-Real Time RAN*
RIC	*Radio Intelligent Controller*
RL	*Reinforcement Learning*
RLC	*Radio Link Control*
ROADM	*Reconfigurable Optical Add/Drop Multiplexer*
RU	*Radio Unit*
Rx	*Receiver*
SA	*Stand Alone*
SBI	*SouthBound Interface*
S-BVT	*Sliceable Bandwidth Variable Transponders*
SC	*Small Cell*
SDAP	*Service Data Adaptation Protocol*
SDM	*Space Division Multiplexing*
SDN	*Software Defined Networking*
SLA	*Service Level Agreement*
SMO	*Service Management and Orchestration*
SOA	*Service Oriented Architecture*
SoA/SotA	*State of the Art*
SSMF	*Standard Single Mode Fiber*
SVM	*Support Vector Machine*
SW	*SoftWare*
TAPI	*Transport API*
TDD	*Time Division Duplexing*
TFS	*TeraFlow SDN*
TNGF	*Trusted Non-3GPP Gateway Function*
TRL	*Technology Readiness Level*
TWDM	*Time and Wavelength Division Multiplexing*
Tx	*Transmitter*
UNI	*User Network Interface*
UPF	*User Plane Function*
URRLC	*Ultra Reliable Low Latency Communications*
UWB	*Ultra-Wide Band*
vCU	*virtual CU*
vDU	*virtual DU*
VES	*Virtual-function Event Streaming*
VLAN	*Virtual Local Area Network*
VNF	*Virtual Network Function*
vOLT	*virtual OLT*
VPN	*Virtual Private Network*
WDM	*Wavelength Division Multiplexing*
WSS	*Wavelength Selective Switch*
xAPP	*Extended APPlication for Near-RT RAN*
xG(S)-PON	*10G (Symmetrical) PON*

REFERENCES

[3GP24]	"Release 18", 3GPP official site. [online] https://www.3gpp.org/specifications-technologies/releases/release-18 .
[5GT20]	5G-TOURS - Horizon 2020 project. [online] https://5gtours.eu/ .
[Aca22]	Acacia 2022, Acacia Introduces Two New 400G QSFP-DD Pluggable Coherent Optical Modules That Further Expand Optical Transceiver Applications, 03/2022, [online] *https://acacia-inc.com/blog/acacia-introduces-two-new-400g-qsfp-dd-pluggable-coherent-optical-modules/* .
[Bäc20]	J. Bäck et al., "CAPEX Savings Enabled by Point-to-Multipoint Coherent Pluggable Optics Using Digital Subcarrier Multiplexing in Metro Aggregation Networks," 2020 European Conference on Optical Communications (ECOC), Brussels, Belgium, 2020, pp. 1-4.
[Bar19]	A. Baratè, G. Haus, L. A. Ludovico, E. Pagani, N. Scarabottolo, 5G TECHNOLOGY AND ITS APPLICATION TO E-LEARNING, Proceedings of EDULEARN19 Conference 1st-3rd July 2019, Palma, Mallorca, Spain. ISBN: 978-84-09-12031-4.
[Bar22]	Barba, P., Stramiello, J., Funk, E.K. et al. Remote telesurgery in humans: a systematic review. Surgery Endoscopy 36, 2771–2777 (2022). https://doi.org/10.1007/s00464-022-09074-4.
[Ber20]	A. Bernal et al., "Near real-time estimation of end-to-end performance in converged fixed-mobile networks," Comp. Comm., 2020.
[Bha21]	J. R. Bhat and S. A. Alqahtani, "6G Ecosystem: Current Status and Future Perspective," in IEEE Access, vol. 9, pp. 43134-43167, 2021, doi: 10.1109/ACCESS.2021.3054833.
[Bha21]	J. R. Bhat and S. A. Alqahtani, "6G Ecosystem: Current Status and Future Perspective," in IEEE Access, vol. 9, pp. 43134-43167, 2021, doi: 10.1109/ACCESS.2021.3054833.
[Cas23]	C. Castro et al., "Scalable filterless coherent point-to-multipoint metro network architecture," in Journal of Optical Communications and Networking, vol. 15, no. 5, pp. B53-B66, May 2023.
[Cen22]	C. Centofanti, A. Marotta, D. Cassioli, F. Graziosi, N. Sambo, L. Valcarenghi, C. Bernard, and H. Roberts, "Slice Management in SDN PON Supporting Low-Latency Services," in European Conference on Optical Communication (ECOC) 2022, Optica Publishing Group, 2022, paper Tu5.64.
[Coh23]	II-VI Coherent Corp., "Coherent Corp 400G ZR+ QSFP-DD-DCO High Tx Output Power Optical Transceiver", 2023. [online] https://ii-vi.com/product/400g-zr-qsfp-dd-dco-high-tx-output-power-optical-transceiver/,
[Cou23]	Counterpoint Technology Market Research, Global XR (AR & VR Headsets) Market Share: Quarterly, Dec 18, 2023. [online] https://www.counterpointresearch.com/insights/global-xr-ar-vr-headsets-market-share/ .
[Dux22]	Simon Dux, TIM uses 5G to support remote eye surgery at Bari Polyclinic in Puglia. Mobile Europe, Sept. 2023. [online] https://www.mobileeurope.co.uk/tim-uses-5g-to-support-remote-eye-surgery-at-bari-polyclinic-in-puglia/.
[Eck19]	T. Eckert, Network 2030 Focus Group at ITU-T for SG13, Presentation at 2nd Visions for Future Communications Summit Lisbon, Portugal, Nov. 27, 2019 . [online] https://futurecomresearch.eu/previous/2019/slides/Toerless_Eckert.pdf.
[Eco21]	Connecting learners: Narrowing the educational divide, The Economist Intelligence Unit Limited 2021, [online] https://connectinglearners.economist.com/data/EIU_Ericsson_Connecting.pdf.

[Edg23]	"Edgecore Networks", [online] *https://www.edge-core.com/*, 2023.
[Eri23]	Ericsson 2023, "6G spectrum - enabling the future mobile life beyond 2030", white paper on Ericsson company site, March 2023. [online] https://www.ericsson.com/en/reports-and-papers/white-papers/6g-spectrum-enabling-the-future-mobile-life-beyond-2030 .
[Eri24-1]	Using 5G to bring digital access to students in India, Ericsson Company site, accessed Jan. 2024. [online] https://www.ericsson.com/en/about-us/new-world-of-possibilities/imagine-possible-india/using-5g-to-bring-digital-access-to-students-in-india.
[Eri24-2]	5G Can Redefine Education & Remote Learning In India, Ericsson Company site, accessed Jan. 2024. [online] https://www.ericsson.com/en/about-us/new-world-of-possibilities/imagine-possible-india/5g-can-redefine-education--remote-learning-in-india.
[ETS22]	European Telecommunications Standards Institute (ETSI) 2022, "5G; Service requirements for Video, Imaging and Audio for Professional Applications (VIAPA)", ETSI Specification. [online] https://www.etsi.org/deliver/etsi_ts/122200_122299/122263/17.04.00_60/ts_122263v170400p.pdf .
[ETS23]	European Telecommunications Standards Institute (ETSI) 2023, "Summary of 3GPP 5G Release 17 Feature", ETSI Technical Report. [online] https://www.etsi.org/deliver/etsi_tr/121900_121999/121917/17.00.01_60/tr_121917v170001p.pdf
[Far21]	Md S. Faruk, Xiang Li, D. Nesset, I. N. Cano, A. Rafel, and Seb J. Savory, "Coherent Passive Optical Networks:Why, When, and How", IEEE Communications Magazine, December 2021.
[Fer19]	Filipe Marques Ferreira, Christian S. Costa, Stylianos Sygletos, and Andrew D. Ellis, "Nonlinear Performance of Few-Mode Fiber Links With Intermediate Coupling," J. Lightwave Technol. 37, 989-999 (2019).
[Fer20]	A. Ferrari et al., "Assessment on the Achievable Throughput of Multi-Band ITU-T G.652.D Fiber Transmission Systems," in Journal of Lightwave Technology, vol. 38, no. 16, pp.4279-4291, Aug. 2020, doi: 10.1109/JLT.2020.2989620.
[Fio15]	Fiorani, M., Skubic, B., Mårtensson, J. et al. On the design of 5G transport networks. Photon Netw Commun 30, 403–415 (2015). [online] https://doi.org/10.1007/s11107-015-0553-8.
[Fio15]	Fiorani, M., Skubic, B., Mårtensson, J. et al. On the design of 5G transport networks. Photon Netw Commun 30, 403–415 (2015). *https://doi.org/10.1007/s11107-015-0553-8.*
[Fon22]	N. K. Fontaine et al., "Photonic Lanterns, 3-D Waveguides, Multiplane Light Conversion, and Other Components That Enable Space-Division Multiplexing," in Proceedings of the IEEE, vol. 110, no. 11, pp. 1821-1834, Nov. 2022, doi: 10.1109/JPROC.2022.3207046.
[Gho17]	A. Ghosh, "Massive MIMO for the New Radio - Overview and Perfor- mance", IEEE 5G Summit, June 2017.
[Gig30]	UNICEF and ITU's Giga initiative, in Ericsson company site. [online],https://doi.org/10.1007/s00464-022-09074-4.
[Gig30]	UNICEF and ITU's Giga initiative, in Ericsson company site. [online] https://doi.org/10.1007/s00464-022-09074-4.
[Gon22]	O. Gonzalez de Dios et al., J. "IPoWDM convergent SDN architecture - Motivation, technical definition & challenges", Mantra Whitepaper, [online] *https://telecominfraproject.com/wp-content/uploads/ TIP_OOPT_MANTRA_IP_over_DWDM_Whitepaper-Final-Version3.pdf.*, 08/2022.

[GSM20]	GSMA, “5G TDD Synchronisation Guidelines and Recommendations for the Coexistence of TDD Networks in the 3.5 GHz Range”, [online] https://www.gsma.com/spectrum/wp-content/uploads/2020/04/3.5-GHz-5G-TDD-Synchronisation.pdf , 04/2020.
[Hay19]	T. Hayashi, T. Nagashima, T. Nakanishi, T. Morishima, R. Kawawada, A. Mecozzi, and C. Antonelli, “Field-Deployed Multi-Core fiber Testbed,” in Proc. of 24th OptoElectronics and Communications Conference (OECC 2019), Fukuoka (Japan), 07 – 11 July 2019 (Paper PDP3). DOI: 10.23919/PS.2019.8818058.
[Hay22]	T. Hayashi et al., "Randomly-Coupled Multi-Core Fiber Technology," in Proceedings of the IEEE, vol. 110, no. 11, pp. 1786-1803, Nov. 2022, doi:10.1109/JPROC.2022.3182049.
[Her20]	J. A. Hernandez, M. Quagliotti, E. Riccardi, V. Lopez, O. G. d. Dios and R. Casellas, "A Techno-Economic Study of Optical Network Disaggregation Employing Open Source Software Business Models for Metropolitan Area Networks," in IEEE Communications Magazine, vol. 58, no. 5, pp. 40-46, May 2020, doi: 10.1109/MCOM.001.1900756.
[Her21-1]	J. A. Hernández, G. Otero, D. Larrabeiti, O. González de Dios, “Dimensioning Flex Ethernet Groups for the transport of 5G NR fronthaul traffic in C-RAN scenarios”, in ONDM 2023.
[Her21-2]	J. A. Hernández, M. Quagliotti and L. Serra, "On the cloudification of Metropolitan Area Networks: impact on cost and energy consumption," 2021 IEEE 7th International Conference on Network Softwarization (NetSoft), Tokyo, Japan, 2021, pp. 330-338,doi: 10.1109/NetSoft51509.2021.9492662.
[Her23]	J. A. Hernández, F. Arpanaei, G. Martínez, Ó González de Dios, J. P. Fernández-Palacios, A. Napoli, Clustering-based dynamic bandwidth allocation for point-to-multipoint coherent optics, in Optical Fiber Conference (OFC) 2023.
[Hex22]	Deliverable D1.3 Targets and requirements for 6G – initial E2E architecture, Hexa-X project, Feb. 2022. [online] https://hexa-x.eu/wp-content/uploads/2022/03/Hexa-X_D1.3.pdf.
[Hex22]	Deliverable D1.3 Targets and requirements for 6G – initial E2E architecture, Hexa-X project, Feb. 2022. [online] https://hexa-x.eu/wp-content/uploads/2022/03/Hexa-X_D1.3.pdf.
[Ho11]	K. -P. Ho and J. M. Kahn, "Statistics of Group Delays in Multimode Fiber With Strong Mode Coupling," in Journal of Lightwave Technology, vol. 29, no. 21, pp. 3119-3128, Nov.1, 2011, doi: 10.1109/JLT.2011.2165316.
[Hol19]	O. Holland et al., "The IEEE 1918.1 “Tactile Internet” Standards Working Group and its Standards," in Proceedings of the IEEE, vol. 107, no. 2, pp. 256-279, Feb. 2019, doi: 10.1109/JPROC.2018.2885541.
[Hou23]	Menno van den Hout et al. “273.6 Tb/s Transmission Over 1001km of 15-Mode Fiber Using 16-QAM C-Band Signals,” OFC23, PDP Th4B.5.
[HTe21]	“Chirurgia robotica: cosa ci riserva il futuro?”, Health Tech 360°, Oct. 2021. [online] https://www.healthtech360.it/salute-digitale/robotica/chirurgia-robotica-stato-dellarte-e-cosa-ci-riserva-il-futuro/.
[Hua17]	Video Big Data. The Top 10 most demanding video on the Net, Huawei iLab report, 2017. [Online] https://www.huawei.com/~/media/CORPORATE/PDF/white%20paper/Big-Data-Video-Top-Ten-Most-Demanding-Videos-en.
[Hua18]	Technical White Paper on the SmartWi-Fi 4K Video Transmission Solution. Huawei Technologies Co., Ltd. 2018. [online] https://www-file.huawei.com/-/media/corporate/pdf/ilab/smart-wifi-4k-video-transmission-solution-en.pdf.
[IET23]	“Applicability of Abstraction and Control”, IETF Iternet Draf, 30 June 2023. [online] https://datatracker.ietf.org/doc/html/draft-poidt-ccamp-actn-poi-pluggable-02 .

[Inf18]	Infinera, "Windstream Deploys Infinera C+L Solution, Sets Foundation to Double Fiber Capacity", Press release, 2018, https://www.infinera.com/press-release/windstream-deploys-infinera-c-l-solution-sets-foundation-double-fiber-capacity/ .
[Int24]	Intuitive Surgical 2024, Da Vinci Robot Surgical Systems. [online] https://www.intuitive.com/en-us/products-and-services/da-vinci .
[IOW21-1]	2021 Innovative Optical Wireless Network Global Forum, "Cyber-Physical System Use Case Release-1", IOWN Global Forum Approved Reference Document, 2021. [online] https://iowngf.org/wp-content/uploads/formidable/21/IOWN-GF-RD-CPS_Use_Case_1.0.pdf .
[IOW21-2]	2021 Innovative Optical Wireless Network Global Forum, "AI-Integrated Communications Use Case Release-1", IOWN Global Forum Approved Reference Document, 2021. [online] https://iowngf.org/wp-content/uploads/formidable/21/IOWN-GF-RD-AIC_Use_Case_1.0.pdf .
[IOW23]	2023 Innovative Optical Wireless Network Global Forum, "Metaverse Use Cases", IOWN Global Forum Positioning Document, 2023. [online] https://iowngf.org/wp-content/uploads/formidable/21/IOWN-GF-RD-Metaverse_Use_Case-1.1.pdf
[ITU12]	Detailed specifications of the terrestrial radio interfaces of International Mobile Telecommunications-Advanced (IMT-Advanced), Recommendation ITU-R M.2012-6, Jan 2024. [online] https://www.itu.int/rec/R-REC-M.2012-6-202312-I/en.
[ITU20-1]	ITU-T Technical Report, "FG-NET2030 – Focus Group on Technologies for Network 2030; FG-NET2030-Sub-G1 - Representative use cases and key network requirements for Network 2030", [online] *https://www.itu.int/dms_pub/itu-t/opb/fg/T-FG-NET2030-2020-SUB.G1-PDF-E.pdf*, 01/2020.
[ITU20-2]	ITU-T Technical Report, "FG-NET2030 – Focus Group on Technologies for Network 2030; Network 2030 - Additional Representative Use Cases and Key Network Requirements for Network 2030", [online] *https://www.itu.int/en/ITU-T/focusgroups/net2030/Documents/Additional_use_cases_and_key_network_requirements.pdf*, 06/2020.
[JPR24]	"Global XR Market Set for Record Growth in 2024 with Apple's Vision Pro Leading the Way", on Jon Peddie Research site, January 15, 2024. [online] https://displaydaily.com/global-xr-market-set-for-record-growth-in-2024-with-apples-vision-pro-leading-the-way/ .
[Kra17]	J. Krause, 3GPP TS38.801, version 14.0.0, "Study on new radio access 36 technology: Radio access architecture and interfaces" [online] *https://panel.castle.cloud/view_spec/38801-e00/pdf/*, 03/2017.
[Lan01]	D. Laney, "3D Data Management: Controlling Data Volume, Velocity, and Variety," META Group Technical Report, 2001.
[Li18]	J. Li, et al, "A Flexible Low-Latency Metro-Access Converged Network Approach Based on Time-Synchronized TWDM-PON," OFC18.
[LiC17]	LiComm, "LiComm QOA (QSFP Optical Amplifier) Data Sheet", [online] *https://www.licomm.com/qoa*, 2017.
[Lig23]	Lighthwave, "Jabil: QSFP-DD Dual Pluggable EDFA", [online] *https://www.lightwaveonline.com/data-center/data-center-interconnectivity/article/14289198/jabil-qsfpdd-dual-pluggable-edfa*, 02/2023.
[Mat16]	S. Matsuo et al., "High-spatial-multiplicity multicore fibers for future dense space-division-multiplexing systems," J. Light. Technol. 34, 1464–1475 (2016).
[Mat22]	T. Matsui, P. L. Pondillo and K. Nakajima, "Weakly Coupled Multicore Fiber Technology, Deployment, and Systems," in Proceedings of the IEEE, vol. 110, no. 11, pp. 1772-1785, Nov. 2022, doi: 10.1109/JPROC.2022.3202812.

[Met24]	Metaverse Standard Forum 2024, “Metaverse Standard Forum”. [online] https://metaverse-standards.org .
[Miz17]	T. Mizuno and Y. Miyamoto “High-capacity dense space division multiplexing transmission - Optical Fiber Technology,” Optical Fiber Technology 35, pp. 108-117, 2017.
[Mon20]	D. Moniz, V. Lopes, and J. Pedro, “Design strategies exploiting C+L-band in networks with geographically-dependent fiber upgrade expenditures”, OFC20, M2G.3
[MS2.1-23]	Milestone MS2.1 of SEASON project, “Requirements, KPIs, and Specifications”, 04/2023.
[Nap22]	A. Napoli, Z. Stevkovski, J. D. Jiménez, E. J. Zuleta, J. Bäck, J. Pedro, J. Rodriguez, R. Diaz, J. Carrallo, A. Mathur et al., “Enabling router bypass and saving cost using point-to-multipoint transceivers for traffic aggregation,” in Optical Fiber Communication Conference, (Optica Publishing Group, 2022), pp. W3F–5.
[NGM22]	Next Generation Mobile Networks (NGMN) 2022, “6G Use Cases and Analysis”, NGMN white paper, March 2022, [online] https://www.ngmn.org/wp-content/uploads/220222-NGMN-6G-Use-Cases-and-Analysis-1.pdf .
[Nok23-1]	Nokia 2023, “Metaverse at work”, Nokia Research Report, accessed January 10th, 2024. [online] https://www.nokia.com/metaverse/industrial-metaverse/the-metaverse-at-work-research/ .
[Nok23-2]	Nokia 2023, “Spectrum for 6G explained”, June 2023, in Nokia company site. [online] https://www.nokia.com/about-us/newsroom/articles/spectrum-for-6G-explained/
[Nok24]	Nokia 2024, “Envisioning a 6G Future”, Nokia Bell Labs white paper, 2032. [online] https://d1p0gxnqcu0lvz.cloudfront.net/documents/Nokia_Bell_Labs_Envisioning_a_6G_future_eBook_EN.pdf .
[NVI24]	2024 NVIDIA Corporation, Nvidia Omniverse technology applied in Siemens plants, promotional video, [online] https://www.nvidia.com/en-us/omniverse/digital-twins/siemens/ .
[OMA22]	OMA3 2022, “Open Metaverse Alliance for Web3 (OMA3). [online] https://www.oma3.org/ .
[ORA21]	O-RAN ALLIANCE Specification O-RAN.WG9.XTRP-REQ-v01.00, O-RAN Open Xhaul Transport Working Group 9, Xhaul Transport Requirements, Feb. 2021. [online] https://orandownloadsweb.azurewebsites.net/specifications.
[Ote18]	G. Otero Perez et al: ”Fronthaul Network Modeling and Dimensioning Meeting Ultra-low Latency Requirements for 5G”, J. Opt. Comm. Netw. 10 (6), 573-581, 2018.
[Ote19]	G. Otero D. Larrabeiti and J. A. Hernández, ”5G New Radio Fronthaul Network Design for eCPRI-IEEE 802.1CM and Extreme Latency Percentiles,” in IEEE Access, vol. 7, pp. 82218-82230, 2019.
[Par17]	S. Parkvall, E. Dahlman, A. Furuskar and M. Frenne, "NR: The New 5G Radio Access Technology," in IEEE Communications Standards Magazine, vol. 1, no. 4, pp. 24-30, Dec. 2017.
[Pes22]	Pesic, M. Curtol, L. Abnaou, A. E. Imadi and S. Morganti, “SDN Automation for Optical Networks Based on Open APIs and Streaming Telemetry,” in Proc. Int. Conference on Optical Network Design and Modelling (ONDM), 2022.M2.1 SEASON - GA 101016663.
[Pog22]	P. Poggiolini, and F. Poletti, “Opportunities and challenges for long-distance transmission in hollow-core fibers”, in Journal of Lightwave Technology, vol. 40, no. 6, pp. 1605-1616, Mar 2022, doi: http://dx.doi.org/10.1109/JLT.2021.3140114.

[Put22]	B. J. Puttnam, R. S. Luis, G. Rademacher, Y. Awaji, and H. Furukawa, "1 Pb/s Transmission in a 125μm diameter 4-core MCF," in Conference on Lasers and Electro- Optics, Technical Digest Series (Optica Publishing Group, 2022), paper JTh6B.1.
[Qua24]	"What's next in 5G Advanced? A first look at 3GPP Release 19", Qualcomm official site. [online] https://www.qualcomm.com/news/onq/2023/12/whats-next-in-5g-advanced
[Rad21]	J. Radoff, "The Metaverse Value-Chain". [online] https://medium.com/building-the-metaverse/the-metaverse-value-chain-afcf9e09e3a7.
[Rad22]	G. Rademacher et al., "1.53 Peta-bit/s C-Band Transmission in a 55-Mode Fiber," 2022 European Conference on Optical Communication (ECOC), Basel, Switzerland, 2022, PDP Th3C.3.
[Rad23-1]	G. Rademacher et al., "Characterization of the First Field-Deployed 15-Mode Fiber Cable for High Density Space-Division Multiplexing," in European Conference on Optical Communication (ECOC) 2022, PDP Th3B.1.
[Rad23-2]	G. Rademacher et al. "Randomly Coupled 19-Core Multi-Core Fiber with Standard Cladding Diameter," OFC23, PDP Th4A.4.
[RHC22]	"Scopriamo la Robot-Assisted Surgery (RAS). La sicurezza è al primo posto", Redazione RHC (in Italian), 2022, [online] https://www.redhotcyber.com/post/scopriamo-la-robot-assisted-surgery-ras-la-sicurezza-e-al-primo-posto/.
[RHI24]	"VNF and CNF, what's the difference?", article on Red Hat Inc. official site, 2024. [online] https://www.redhat.com/en/topics/cloud-native-apps/vnf-and-cnf-whats-the-difference
[Rib15]	M. Ribeiro, K. Grolinger and M. A. M. Capretz, "MLaaS: Machine Learning as a Service,"2015 IEEE 14th International Conference on Machine Learning and Applications (ICMLA), Miami, FL, USA, 2015, pp. 896-902, doi: 10.1109/ICMLA.2015.152.
[Rui22]	M. Ruiz et al., "Deep Learning -based Real-Time Analysis of Lightpath Optical Constellations," IEEE/OPTICA JOCN, 2022.
[Rui23]	M. Ruiz, J. A. Hernandez, M. Quagliotti, E. Hugues Salas, E. Riccardi, A. Rafel, L. Velasco, O. Gonzales De Dios, "Network Traffic Analysis under Emerging Beyond-5G Scenarios for Multi-Band Optical Technology Adoption", Accepted to be published on JOCN, SI on Multiband, expected date of publication: oct/dec 2023.
[Ryf17]	R. Ryf et al., "Long-Haul Transmission over Multi-Core Fibers with Coupled Cores," 2017 European Conference on Optical Communication (ECOC), Gothenburg, Sweden, 2017, pp. 1-3, doi: 10.1109/ECOC.2017.8345874.
[Ryf20]	Ryf, R., Antonelli, C. (2020). Space-Division Multiplexing. In: Mukherjee, B., Tomkos, I., Tornatore, M., Winzer, P., Zhao, Y. (eds) Springer Handbook of Optical Networks. Springer Handbooks. Springer, Cham. https://doi.org/10.1007/978-3-030-16250-4_10.
[Saa19]	Saad, Walid & Bennis, Mehdi & Chen, Mingzhe. (2019). A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems., [online] https://www.researchgate.net/publication/331396903_A_Vision_of_6G_Wireless_Systems_Applications_Trends_Technologies_and_Open_Research_Problems.
[Sad22]	R. Sadeghi et al., "Transparent vs translucent multi-band optical networking: capacity and energy analyses", in Journal of Lightwave Technology, vol. 40, no. 11, pp. 3489-3498, June 2022, doi: doi.org/10.1109/JLT.2022.3167908.
[Sas22]	T. Sasaki, F. Sato, B. G. Risch and P. A. Weimann, "Ultrahigh Fiber Count and High-Density Cables, Deployments, and Systems," in Proceedings of the IEEE, vol. 110, no. 11, pp. 1760-1771, Nov. 2022, doi: 10.1109/JPROC.2022.3199645.

[Ser22]	P. Serena, C. Lasagni, A. Bononi, C. Antonelli, and A. Mecozzi, "The ergodic GN model for space-division multiplexing with strong mode coupling," J. Lightw. Technol., vol. 40, no. 10, pp. 3263–3276, May 15, 2022.
[Sha21]	B. Shariati, et al "Demonstration of latency-aware 5G network slicing on optical metro networks," JOCN 2022.
[Sil16]	P. Sillard et al., "Low-Differential-Mode-Group-Delay 9-LP-Mode fiber," in Journal of Lightwave Technology, vol. 34, no. 2, pp. 425-430, 15 Jan.15, 2016. doi: 10.1109/JLT.2015.2463715.
[Sil22]	P. Sillard et al., "Few-Mode Fiber Technology, Deployments, and Systems," in Proceedings of the IEEE, vol. 110, no. 11, pp. 1804-1820, Nov. 2022, doi: 10.1109/JPROC.2022.3207012.M2.1 SEASON - GA 101016663.
[SMT24]	SMTA bv - the Netherlands 2024, "Global Mobile Frequencies Database", accessed 15th January 2024. [online] https://www.spectrummonitoring.com/frequencies.php?market=E.
[Sou22]	A. Souza, N. Costa, J. Pedro and J. Pires, "Benefits of counterpropagating Raman amplification for multiband optical networks," in Journal of Optical Communications and Networking, vol. 14, no. 7, pp. 562-571, July 2022, doi: 10.1364/JOCN.456582.
[Spe24]	Spectrum-tracker 2024, "Frequency spectrum database, spectrum-traker.com" , accessed 15th January 2024. [online] https://www.spectrum-tracker.com/Spain/Telefonica.
[SRIA]	Strategic Research and Innovation Agenda 2021-27, European Technology Platform NetWorld2020 "Smart Networks in the context of NGI" https://bscw.5g-ppp.eu/pub/bscw.cgi/d367342/Networld2020%20SRIA%202020%20Final%20Version%202.2%20.pdf
[Sun22]	Y. Sun, B. Lei, J. Liu, H. Huang, X. Zhang, J. Peng, W. Wang, "Computing Power Network: A Survey"; *https://arxiv.org/pdf/2210.06080.pdf*, 11/2022.
[Tac14]	The Tactile Internet, ITU-T Technology Watch Report, 2014. [online] https://www.itu.int/dms_pub/itu-t/opb/gen/T-GEN-TWATCH-2014-1-PDF-E.pdf.
[Tak12]	K. Takenaga et al., "Large Effective-Area Few-Mode Multicore Fiber," in IEEE Photonics Technology Letters, vol. 24, no. 21, pp. 1941-1944, Nov.1, 2012, doi:10.1109/LPT.2012.2219618.
[TFS23]	TeraFlowSDN by ETSI, "ETSI Open Source Group for TeraFlowSDN (OSG TFS)", [online] *https://tfs.etsi.org/*, 2023.
[Tie20]	Tien Wan et al., Telerobotic Spinal Surgery Based on 5G Network: The First 12 Cases, Neurospine, No 17, 2020 Mar. 31. doi: 10.14245/ns.1938454.227.
[TIM21]	TIM 2021, "3GPP: the evolution of 5G towards 6G", Notiziario tecnico TIM , No 3, 2021, pp 8-15, [online] https://www.gruppotim.it/content/dam/gt/notiziario-tecnico/pdf/Notiziario-Tecnico-TIM-2021-n3.pdf.
[TIM22]	TIM 2022, "Metaverse", Notiziario tecnico TIM , No 3, 2022, pp 1-91, [online] https://www.gruppotim.it/content/dam/gt/notiziario-tecnico/articoli/2022-n3/pdf-3-2022/Notiziario_Tecnico_TIM_3_2022_Metaverso.pdf.
[Tou17]	I. Toufik, 3GPP TR 38.816 3GPP Technical specification, "Study on CU-DU lower layer split for NR; (Release 15)" [online] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3364 , 09/2017.
[Tri24]	TrialsNet 2024, EU financed project TRIALSNET, [online] https://trialsnet.eu/
[Vel21]	L. Velasco et al., "Autonomous and Energy Efficient Lightpath Operation based on Digital Subcarrier Multiplexing," IEEE J. on Selected Areas in Communications, vol. 39, pp. 2864-2877, 2021.

[Vel23]	L. Velasco, M. Devigili, and M. Ruiz, "Applications of Digital Twin for Autonomous Zero-Touch Optical Networking [Invited]," invited in International Conference on Optical Network Design and Modeling (ONDM), 2023.
[Vet23]	Peter Vetter, "6G getting into next gear", keynote speech at EuCNC 2023, [online] https://www.youtube.com/watch?v=XGJ0XobGDqc .
[W3C24]	W3C Metaverse Interoperability Community Group 2024. [online] https://www.w3.org/community/metaverse-interop/ .
[Wel21]	D. Welch et al., "Point-to-Multipoint Optical Networks Using Coherent Digital Subcarriers," in Journal of Lightwave Technology, vol. 39, no. 16, pp. 5232-5247, 15 Aug.15, 2021.
[Win11]	Peter J. Winzer and Gerard J. Foschini, "MIMO capacities and outage probabilities in spatially multiplexed optical transport systems," Opt. Express 19, 16680-16696 (2011).
[WRC23]	World Radiocommunication Conference 2023 (WRC-23), Provisional Final Acts. [Online] https://www.itu.int/dms_pub/itu-r/opb/act/R-ACT-WRC.15-2023-PDF-E.pdf.
[Wub14]	D Wübben, et al, "Benefits and Impact of Cloud Computing on 5G Signal Processing: Flexible Centralization through Cloud-RAN", in IEEE Signal Processing Magazine, vol. 31 no. 6, pp. 35-44, 2014.
[Zhe20]	Zheng, J., Wang, Y., Zhang, J. et al. 5G ultra-remote robot-assisted laparoscopic surgery in China. Surgery Endoscopy, No 34, 5172–5180 (2020). https://doi.org/10.1007/s00464-020-07823-x.