Network Traffic Analysis under Emerging Beyond-5G Scenarios for Multi-Band Optical Technology Adoption

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The recently created ITU-T Focus Group Network 2030 is leading network operators to identify the requirements and use cases that networks are expected to fulfill for short, medium, and long-term within the current decade. Essentially, network operators need to evolve their networks to meet strict performance requirements in several dimensions, including large bandwidth to support foreseen beyond 5G (B5G) services, such as digital twins (DT) and volumetric video (VV). In order to provide such bandwidth requirement in a sustainable and scalable way, multi-band (MB) optical networks are expected to gradually extend legacy optical networks capacity by exploiting bands beyond C+L. In this paper, we present a traffic analysis methodology to help network operators to compute expected traffic demand to be supported in their networks as a result of combining well-known mass market services with foreseen B5G services scenarios. Numerical results based on inputs and forecasts from major European network operators show that MB will be required at all network segments, including metro-aggregation, metro-core and backbone, by the end of this decade.

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1. INTRODUCTION

According to Cisco's Visual Networking Index, data traffic keeps growing at a steady pace of between 30 and 40% per year [1]. Video streaming is still the dominating type of traffic nowadays, but other applications and services have appeared in the past years to stress networks even more, e.g., Machine-to-Machine (M2M) applications and Online Gaming, with 46% and 59% Cummulative Annual Growth Rate (CAGR) respectively [2, 3].

To address future network demands and emerging B5G services, the ITU-T Study Group 13 has established a Focus Group entitled FG-NET2030 to investigate the capabilities of networks and establish a road map toward year 2030 and beyond. This road map includes envisioned use cases and requirements (sub-group 1), capabilities and technologies (sub-group 2) and architectures and frameworks (sub-group 3) [4]. Examples of new capabilities and services intended for 2030 include: Qualitative Communications, Holographic Teleport and High-Precision Communications, where the support of futuristic applications like Digital Reality, Holographic Twin, Holographic Education and Holographic Healthcare are examples of services expected to come. This ITU-T document further elaborates on the use cases and their network requirements in five *dimensions*, namely:

- *Bandwidth*, including: bandwidth capacity, Quality of Service (QoS), Quality of Experience (QoE), flexibility, and adaptable transport.
- *Time*, including: latency, synchronisation, jitter, scheduling, coordination, and geolocation accuracy.
- *Security*, including: privacy, reliability, trustworthiness, resilience, traceability, and lawful intercept.
- *AI*, including: data computation, storage, modelling, collection and analytics, autonomy, and programmability.
- *Manynets* (i.e., seamless coexistence of heterogeneous network infrastructures), including: addressing, mobility, network interface, and heterogeneous network convergence.

In this regard, both telecommunication operators (telcos) and research community started the process of re-designing transport networks and prepare them for the next decade, e.g., see [5–7]. Following the guidelines of FG-NET2030 focus group, the operators and research groups participating in EU-funded

H2020 B5G-OPEN (Beyond 5G – OPtical nEtwork coNtinuum)[1] have identified a number of key research directions and innovations [8] intended to fulfil the above-mentioned dimensions. With the participation of three major operators within EU, namely, Telefonica (TID), Telecom Italia (TIM) and British Telecom (BT), B5G-OPEN has proposed to build open and domain-less, yet high capacity and smart optical networks [9–12].

In the data plane, Multi-Band (MB) optical transmission and switching technologies have the potential to boost network capacity by more than 12 times the current bandwidth offered by the classical C-band. Essentially, MB advocates to squeeze existing optical fibre infrastructure, by using all available optical bands (O+E+S+C+L), that is the 365 nm ranging from 1260 to 1625 nm, accounting for a total of 53.4 THz [13, 14]. That MB network upgrade requires considering physical layer effects that are not present in traditional C-band systems. For instance, not all the bands are suitable for all connection lengths (e.g., O-band performance significantly worsens with distance, making it practically usable only for typical metro distances). Moreover, the energy transferred from high to low frequencies due to Raman scattering modifies and worsens the performance of MB systems compared to single band ones (see [15, 16] for further details about these physical layer aspects).

The advantage of extended MB networks over Space-Division Multiplexing (SDM) is the continued use of the existing fibre resources minimizing the need to deploy new fibres, since a majority of fibre deployments are based on low-loss G.652D fibers [17]. Among different options, in this paper we assume that SDM is achieved by means of parallel fibers to implement multiple line systems capable of exploiting available spectrum resources with the mature multi-fiber technology. Although the use of multi-fiber SDM parallel fibers is limited by the port count of Wavelength Selective Switches (WSS) used in Reconfigurable Optical Add/Drop Multiplexers (ROADMs), few (e.g., 4) parallel fibers are typically considered.

The availability of MB transmission systems, including transceivers, amplifiers and switching elements [18–21], will also lead to a complete redesign of the e2e architecture. By removing boundaries between network domains and reducing electronic intermediate terminations, network continuum from data center to B5G access will be provided [22, 23]. Moreover, MB also requires rebuilding the control plane to support such novel MB elements, as well as domain-less e2e network operation. In particular, a new physical layer abstraction and impairment modeling along with the necessary telemetry data to monitor the network and feed Artificial Intelligence / Machine Learning (AI/ML) algorithms for network automation and zero-touch operation is needed [24–26].

Hence, in light of the expected Beyond-5G (B5G) scenarios to come, migration towards MB/SDM networks is in the road map of network operators. Typically, migrating from legacy to emerging technologies requires a large effort in planning gradual upgrade of network operator infrastructures [27]. However, to the best of our knowledge, there are no available studies evaluating *when*, *where*, and *how* traffic is expected to increase because of the advent of new B5G services thus, stressing capacity of current operator networks in such a way that MB/SDM technologies will be required. These open questions need to be solved to properly plan affordable hardware fabrication, software development, and on-time deployment plans to smoothly migrate from legacy C band to optical MB/SDM technologies.

[1]See B5G-OPEN website, available at https://www.b5g-open.eu/, last access April 2023.

Table 1. Acronyms

ACO	Access Central Office
AP	Access Point
AI	Artificial Intelligence
B5G	Beyond 5G
BBN	Backbone Network
BNG	Border Network Gateway
CAGR	Cummulative Annual Growth Rate
CO	Central Office
CCO	Cloud Central Office
CDN	Content Delivery Network
DIRC	DIRect Communications
DL	Down-Link
DT	Digital Twins
DU/CU	Distributed Unit / Centralized Unit
e2e	End-to-End
FTTA	Fiber To The Antenna
FTTH	Fiber To the Home
GW	Gateway
HD	High Definition
HH	Household
IPTV	Internet Protocol Television
IT	Information Technology
M2M	Machine-to-Machine
MB	Multi-Band
MAN	Metro-regional Aggregation Network
MCN	Metro-regional Core Network
MCS	Macro Cell Site
ML	Machine Learning
NCO	National Central Office
QoE	Quality of Experience
QoS	Quality of Service
RCO	Regional Central Office
RTT	Round-Trip Time
SCS	Small Cell Site
SDM	Space-Division Multiplexing
SDN	Software Defined Networking
UL	Up-Link
UPF	User Plane Function
VNF	Virtual Network Functions
VV	Volumetric Video
WB	Web Browsing

In this paper, we present a holistic traffic study suited for a nation-wide operator network where current mass market and foreseen B5G use cases co-exist and share the optical layer infrastructure. The main purpose of this contribution is to identify in which network segments (metro-aggregation, metro-core, or backbone) and when the adoption of MB and SDM technologies will be required to increase optical networks capacity. For the sake of simplicity, we assume that optical interfaces (transponders) can be gradually installed according to traffic needs and therefore, the available C-band spectrum and its exhaustion is the bottleneck to support foreseen scenarios. The study is performed assuming different functional architectures, expected growth of mass market services, and different penetration scenarios for B5G use cases. The considered network and its architectural and functional assumptions describe (in an anonymous way) a typical European operator infrastructure and therefore, the conclusions extracted from this study can be made extensive and suitable for many other national-wide network operators. Moreover, as requirement for the presented traffic study, the paper also describes a methodology to quantify traffic volumes that combine the activity of well-known mass market services and expected future B5G services, including Digital Twins (DT) and Volumetric Video (VV), which present unprecedented bandwidth requirements. Note that this methodology allows performing further studies assuming e.g., different network topologies, B5G use cases, and other parameters.

The remainder of this work is organised as follows: Section 2 briefly overviews the architecture of current telco networks. Then, Section 3 introduces mass-market services as well as DT and VV as reference emerging B5G services. Section 4 briefly reviews the methodology used in this paper to perform traffic dimensioning studies, including the characterisation of traffic per node and the resulting final traffic datasets. Then, Section 5 presents the reference topology and traffic parameters used to conduct the numerical evaluation presented in Section 6 for short, medium and long-term adoption scenarios. Finally, Section 7 concludes this work with a summary of its main findings and discussion of future work.

For the sake of clarity, Table 1 defines the acronyms that are going to be consistently used along this manuscript.

2. REFERENCE OPERATOR NETWORK SCENARIO

A. High-level Network Architecture

Fig. 1 presents the considered high-level fixed network architecture, highlighting where terminations are located, how locations and cloud domains are interconnected, and what typical distances are involved at each network segment. This high-level view is agnostic with respect to the actual technologies used for its implementation (optical, packet and IT-datacenter). As shown, the infrastructural boundary points (blue rectangles) allow identifying the three major domains of a national fixed transport network, namely: i) *far edge*, including fixed access networks; ii) *edge*, including metro networks; and iii) *cloud*, including backbone networks.

Although the contributions presented in this article focus on the edge and cloud domains, a brief definition of far edge domain is provided. Thus, the AP is the physical entity acting as a 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. Typically, the Access Point (AP) is closely connected to (or integrated with) more specific devices enabling fixed, nomadic, and mobile users to be connected to any kind of digital services, such as: residential gateway, customer edge routers, 5G site equipment, etc. The cabinet is a protected space, typically placed outdoor in the street, where fibres can transit or can be terminated on a device. It can host passive devices (e.g., splitters) and, if power supply is available, active devices (switches, mini servers, etc.).

The Access Central Office (ACO), which represents the major end point of our traffic studies, is a small size building that can host telco applications, such as Distributed Unit / Centralised Unit (DU/CU) functions, that typically run close to the end user, and possibly (but not necessarily), IT applications. It includes packet and optical equipment and some servers for telco Virtual Network Functions (VNFs) and IT applications. The Metro-regional Aggregation Network (MAN) interconnects ACOs together and with one or, preferably, more (usually two) Regional Central Offices (RCOs). MANs can be organized at optical transport layer in a mesh, ring, or horseshoe topology. At packet/IP level, the logical connections are typically dual-homed from the ACOs to a couple of RCOs.

The RCO is a medium-size building that hosts telco applications and possibly IT applications. It includes many servers for telco VNFs and IT applications. An RCO is an important network node and requires high degree of physical and logical security and also a high level of reliability and survivability. The Metro-Core-Network (MCN) interconnects RCOs among them and with one or, preferably, more (usually two) National Central Offices (NCOs). It is organized as a meshed network at the optical transport layer, whereas at packet/IP level the logical connections are predominantly hubbed, from the RCOs to the NCOs. IP survivability is maintained by ensuring dual-homed flows that do not share common optical links.

A NCO is a big building that hosts telco and IT applications. It typically holds hundreds of servers for telco VNFs and IT applications, as well as dedicated packet and optical equipment to ensure the interconnection of the Backbone Network (BBN) with the MCNs. Hence, it comprises the neuralgic point of the network and requires very high levels of physical and logical security and very high reliability and survivability. The BBN interconnects NCOs among them and is organized as a flat mesh network at the optical transport layer, while at the packet level it can be logically organized into one or more tiers. Gateways (GWs) to interconnect the BBN with peers (other operators' networks) or to the Internet are co-located with BBN nodes.

Finally, the Cloud Central Office (CCO) is a very large and complex infrastructure that hosts national-level datacenters. It often includes thousands of servers and provides IT applications for the operator and services to both residential and business customers, as well as telco services for the network operator. It is a strategic point of the telco network infrastructure and requires extremely high levels of physical and logical security and reliability. Normally, but not necessarily, it is co-located with a BBN node.

Table 2 provides relevant parameters of each mentioned CO type, including: i) number of COs in a typical European national operator network, ii) population covered by each CO, iii) maximum distance from AP to COs, iv) degree of reliability/availability, and v) Round-Trip Time (RTT) from/to APs.

B. Assumptions and Considerations

Although not depicted in Fig. 1, COs can hold two types of functions in the form of virtualized/containerized nodes. On the one hand, COs host telco functionalities in a containerized *telco nodes*, comprising functions like DU/CU, from 5G func-

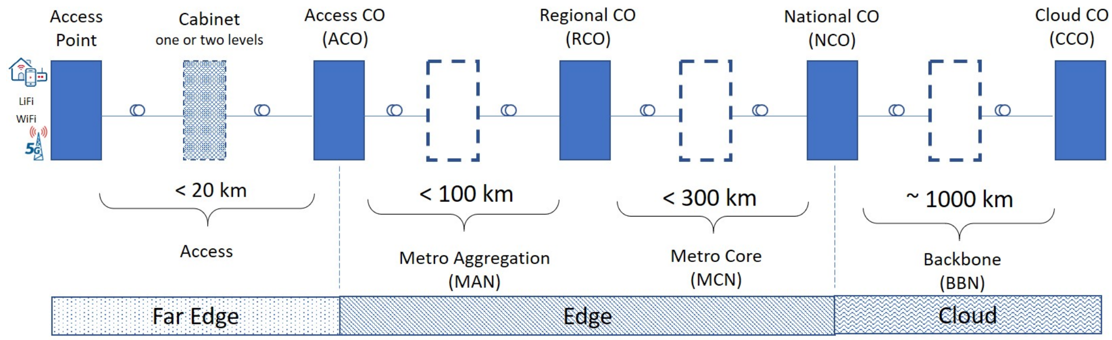

Fig. 1. High-level network architecture

Table 2. Hierarchical telco network parameters

	ACO	RCO	NCO	CCO
Number of COs	∼10K	∼1K	∼100	∼10
Population covered	∼10K	∼100K	∼1M	∼10M
Max. dist. from AP (km)	20	120	420	1420
Reliability	High	Very High	Extreme	Extreme
Downtime (min/year)	600	120	26	26
RTT (ms)	1	∼5-10	20	50

tional split, User-Plane Function (UPF) and Border Network Gateway (BNG). On the other hand, service functionalities are containerized in *service nodes*, containing functions like processing, access to contents, and caching capabilities, just to mention a few. Among telco functionalities, BNG/UPF are those that terminate user sessions and enable traffic to be routed toward destinations (service applications or other users). Therefore, its placement (hereafter referred as $break-out\ point$) is critical to determine which traffic flows (and their magnitude) are generated in the network. In this work, we assume three different scenarios for the potential location for the break-out point:

- *Centralized*: the break-out point is located at NCO level.
- *Semi-distributed*: the break-out point is located at RCO level.
- *Distributed*: the break-out point is located at ACO level.

For the sake of simplicity, we will target traffic studies where either only one or two of the scenarios are simultaneously running to differentiate services. Otherwise, the number of flows that can be generated can increase up to an unmanageable dimension if several break-out points are considered at the same time. In addition to the described break-out point placement, the following extra assumptions are also necessary to fully define such scenarios:

- Each ACO has its own reference RCO plus one additional for backup.
- Each ACO has its own reference NCO plus one additional for backup.
- For the traffic generated by a given ACO, the reference NCO and the reference RCO are the locations where break-out is performed in the cases of centralized and semi-distributed scenarios, respectively.

3. SERVICE DEFINITION

Three mass market services are going to be considered as main generators of background network traffic, namely, Direct Communications (DIRC), Web Browsing (WB), and Content Delivery Network (CDN). Moreover, as already introduced, DT and VV services have been chosen as representative of the B5G use cases that are foreseen to greatly impact on network traffic increase in the coming years.

A. Mass Market Services Definition

The DIRC service concerns the direct interaction of customers who communicate with each other to either exchange data or for multimedia communication such as videoconferencing. In this case, the hypothesis is that the uplink (UL) and downlink (DL) flows are balanced. Note that regardless of the position of the interlocutors, the traffic is typically processed at the closest break-out point of the network. Independently from the position of break-out point, all traffic exchanged outside the MCN is assumed to be processed at packet level in the reference NCO (i.e., no bypass allowed). This simplifies the model and can also be considered reasonable from a general point of view for traffic management between metro domains.

In the WB service case, a user (fixed or mobile) benefits from various types of content (web pages, text, sound, images) that can be accessed on servers at various network levels. The accessibility of the contents depends on the content caching strategy, which is modelled through the percentage of content accessible at various levels. Traffic flows seen from the user's side are quite unbalanced, i.e., DL component is typically much larger than the UL one. Without loss of generality, we can assume that traffic can be exchanged (when needed) with local caches in the reference RCO only. On the contrary, at national level, traffic is exchanged with caches in all the NCOs. Moreover, web traffic is exchanged also with external networks through the GW. The amount of traffic will depend on the percentage exchanged at different levels (local, regional national, and/or external).

The CDN service is the typical service for accessing multimedia contents (today mainly high-definition video) from caches placed at various levels of the network. The CDN service adopts a model similar to that of WB and differs from it essentially in parameter values (Web and CDN cache have specific distributions and also the flow is markedly at a higher bit rate and more unbalanced in favour of DL stream for the CDN case).

B. B5G Services Definition

A DT is the representation of a physical asset, process or system that spans its lifecycle being updated from near real-time data provided by different objects, such as historical records and/or sensors [28]. DT traffic is bidirectional as any change to the physical asset should be reflected in the DT and vice versa. One specific example of how a DT can be implemented is by integrating VR/AR devices to generate data which is gathered and sent towards a model to process the information received. Once processed, the data is retransmitted towards the equipment to achieve the optimisations required. If a large number of these devices is used (e.g. >50), the amount of traffic generated will be in the order of Gb/s for a single node.

VV is a technique that captures a three-dimensional space, such as a location or performance. Rather than having a flat image built using two axis, VV captures the light from all angles to compound 3D video captured along X, Y and Z axis [29]. VV involves setting cameras or sensors at different positions to a capture stage (known as video rig sources), covering the capture stage from as many different views as possible. The reconstruction process uses algorithms to produce a set of 3D models that can then be arranged as a sequence. There are multiple different workflows that can be used to generate VV. Although equipment used to produce a volumetric capture can vary on different factors (quality, cost, storage space, etc), VV typically generates large amounts of data, from hundreds of Mb/s to Tb/s.

4. TRAFFIC CHARACTERIZATION METHODOLOGY

The proposed methodology is intended to generate a network traffic flow dataset F for scenarios supporting a mix of well-known mass market services and emerging B5G services. Specifically, we define the data descriptor of each traffic flow in F as a pair of source-destination COs that define the flow and a reference traffic volume defined in terms of bitrate (e.g., Gb/s). The traffic volume can be either the expected average traffic or maximum, depending on the specific case study. By simple post-processing actions (e.g., aggregating) of generated traffic flow data, different outcomes can be produced such as traffic conveyed by each network segment, traffic traversing across domains, and traffic switched/terminated at each CO.

Let us consider the network layer $G_N(V, A)$ that represents the operator network under study, where V represents the set of ACOs, RCOs, NCOs, and CCOs locations along different MAN, MCN, and BBN segments. In addition, every $v \in V$ contains the set $U(v)$ with the amount of users per type (e.g, household, mobile, business, factories, etc). Moreover, set A represents flow adjacencies between COs, i.e., the adjacency $a =< i, j >$ indicates that a directed traffic flow from CO i to CO j can exist. Therefore, we can formally define a flow $f \in F$ as a tuple $< a, d >$ containing the adjacency $a \in A$ that defines the flow and the traffic volume d.

The traffic F to be conveyed at network G_N is generated by a set S of services. Thus, it is essential to define the upper service layer $G_S(N, E)$, where N contains the service end-points and set E the adjacencies between those end-points. Thus, we can define the dataset of service traffic flows Q where every flow $q \in Q$ is a tuple $< e, d >$ containing the adjacency $e \in E$ and traffic volume d. Therefore, the traffic conveyed in flows in F will be the result of the aggregation of flows in Q which, in turn, will depend on the mapping of node sets N and V, and adjacencies sets E and A. Then, the mapping between G_V and G_N layers is defined in Δ, where $\delta_{nv} \in \Delta$ is a binary parameter equal to 1 if service end-point n is mapped into CO v, and $\delta_{ea} \in \Delta$ is a binary parameter equal to 1 if service traffic in adjacency e needs to be groomed in flow adjacency a.

In this work, we consider the following end-point types in N: i) *service input/output* (IO), representing where service user traffic is injected/consumed by end users, ii) *processing node*, where intermediate processing/caching is performed, iii) *service GW*, in case a target end-point (service IO or processing node) is out of network operator premises, and iv) *telco node*, where BNG/UPF is performed. Without loss of generality, we assume that service IO and GW have a clear and predefined location based on network operator infrastructure (typically ACOs for service IO and CCO for service GW), whereas telco and processing nodes can be deployed in different locations depending on network operator policies such as break-out point location and caching/processing deployments.

Every service $s \in S$ is characterized by a set of workflows $W(s)$, where each workflow $w \in W(s)$ is defined as an ordered set of adjacencies $E(w) \subset E$. Fig. 2 depicts the three main workflows that better represent the basic components for each of the services considered in this work. All of them are defined in both UL and DL directions. The first identified workflow defines communication between service IO nodes within the same operator network (labelled as $w1$). This workflow requires sending traffic from service IO nodes to their respective reference telco nodes, as well as connectivity between telco nodes. The second workflow describes the communication between a service IO node and a processing node ($w2$); note that passing through reference telco node for both request (UL) and delivery (DL) flows is needed. Finally, connecting to and from a remote end-point through a service GW is depicted ($w3$).

The dimensioning (traffic volume) of each of the flows in a workflow is a prior essential step to determine the network flow traffic. To facilitate this task, we consider that service s has assigned a set of dimensioning parameters $P(s)$ containing: i) p_{in}, p_{out}: with the traffic generated and received per user, respectively, at every service IO node or service GW; ii) $p_e, \forall w \in W(s), e \in E(w)$: with the percentage of traffic that is conveyed in adjacency e. Therefore, given a number of users u, the volume d of adjacency e is simply computed as the product between u, p_{in} or p_{out} (in case of UL and DL, respectively), and p_e. Fig. 3 shows an example where 500 users of a CDN service access through service IO A endpoint. This service example has been characterized by means of P parameters in the following way: i) input traffic is largely unbalanced (DL is 10 times larger than UL), ii) 50% of total traffic demand requires local processing at the BNG/UPF level, iii) 30% of total traffic demand access to remote contents within the same network (e.g., located in a NCO), and iv) 20% of total traffic requires accessing external processing/contents through the service GW.

In a nutshell, the procedure used to generate traffic flows set F follows the next set of steps:

Step 1 (Initialization): Create set F containing $A \in G_N$ and traffic volume equal to 0. Create set Q containing $E \in G_S$ and traffic volume equal to 0.

Step 2 (Build node mapping): Set to 1 all required $\delta \in \Delta$ referring to nodes. Node mapping includes mapping service IO and GW with the physical location they belong according

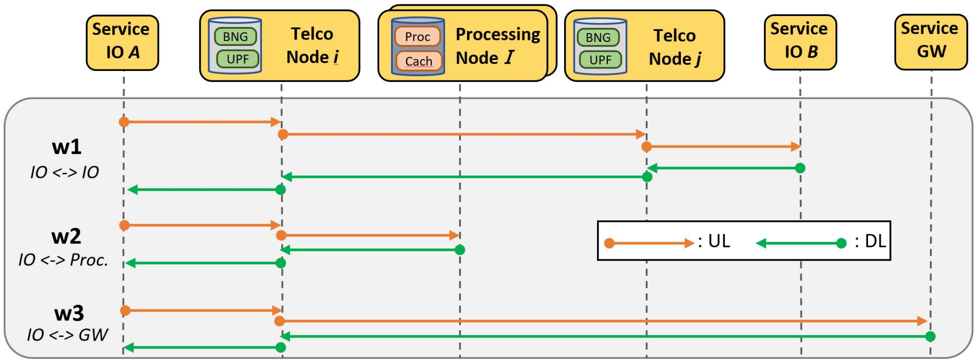

Fig. 2. Service workflows

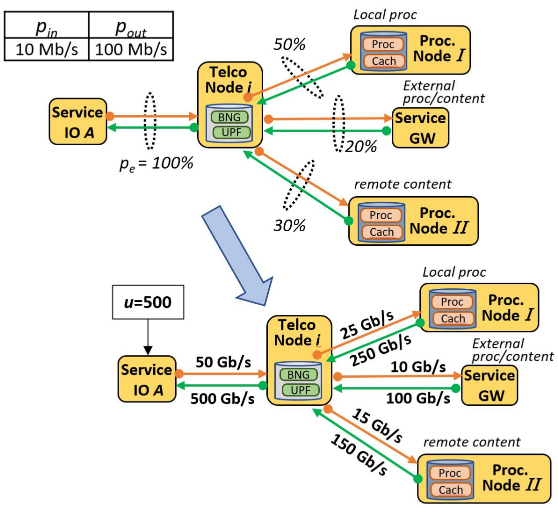

Fig. 3. Service traffic example

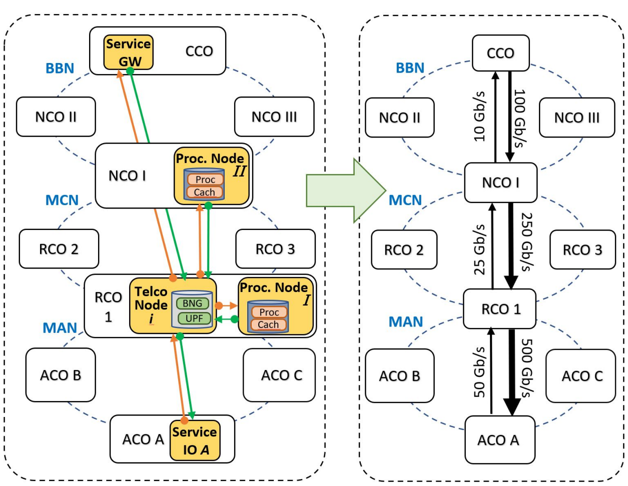

Fig. 4. Example of mapping service into network traffic

to network topology, and telco and processing nodes depending on network operator policies for break-out placement and caching/processing node deployment.

Step 3 (Build adjacency mapping): Set to 1 all required $\delta \in \Delta$ referring to adjacencies. For instance, those service adjacencies that, after Step 2, connect a service IO in an ACO and a service GW in a CCO, might be mapped with several network adjacencies, e.g., from reference ACO to reference RCO, from reference RCO to reference NCO, and from reference NCO to gateway CCO.

Step 4 (Update set P): Given the previous node and adjacency mapping and for each service $s \in S$, update those parameters in $P(s)$ that are related with that mapping.

Step 5 (Compute set Q): for each service $s \in S$, increase the corresponding $q \in Q$ with the service traffic that can be computed from the number of users u (known after mapping in step 2) and the set of parameters $P(s)$.

Step 6 (Compute set F from Q): for each flow $q \in Q$, retrieve the mapped adjacencies $A' \in A$ and, for each $a \in A'$, increase the traffic of the corresponding $f \in F$.

Fig. 4 shows the result of applying the procedure above with the service example illustrated in the example of Fig. 3. Specifically, left side shows the results after Step 2, whereas right side shows the obtained flow set F after step 6. Thus, the service traffic flows Q are mapped into network traffic flows F considering that the break-out point follows a semi-distributed location. As can be observed, the traffic that requires local processing is not traversing any network segment since it remains within reference RCO. Moreover, the flow traversing MCN from RCO to NCO aggregates both the traffic requiring remote contents within the NCO and the traffic targeting an external function/content through service GW.

5. REFERENCE NETWORK AND SERVICE SCENARIO

This section presents the details of the reference realistic national-wide network operator scenario used in this work. The numbers presented in this section have been obtained from current available information provided by TID, TIM, and BT operators, properly anonymized.

A. Network Topology and Dimensioning Parameters

Fig. 5 shows the topology used for the ongoing numerical study, in line with the description and assumptions in Section 2 [30, 31]. Specifically, it consists of four regions, each consisting of: i) 6 horseshoe MANs connecting a number of ACOs with both ends in either a RCO or NCO; ii) a mesh MCN interconnecting RCOs and NCOs. The interconnection between areas is assumed to be done at the core network segment by means of a mesh BBN connecting NCOs (now relabelled as BB). Details in terms of number of nodes, links, and network diameter are provided in Table 3.

Table 3. MAN and MCN parameters

Subnetwork	#COs	#Links	Diameter (km)
Dense Urban	7	6	15.1
Urban	9	8	34.0
Suburban 1	8	7	55.8
Suburban 2	10	9	85.1
Subruban 3	12	11	105.3
Rural	11	10	163.6
MCN	6	9	21.6

Table 4 shows an extract of input parameters characterizing a few representative COs in Fig. 5 in terms of its role, geotype, number of households (HH) for fixed access networks and number of cell sites for mobile networks, divided between macro (MCS) and small cell sites SCS). The number of HH associated with a node drives the amount of fixed traffic generated by the node. To compute the traffic generated by mobile users, we define the number of cell sites collected by a node and the mobile active users per site. Mobile active users represent the mobile users registered on a mobile site that potentially generate traffic in the busy hour. As an example, 200 and 50 active users are considered for each MCS and SCS services, respectively. The percentages of active users, defined for each service (Table 5), allow to compute the active users that generate traffic for the specific service.

Table 4. Example of CO characterisation

Code	Class	Geotype	HH	MCS	SCS
BB_01	NCO	Dens Urban	14,700	13	52
CR_01	RCO	Urban	17,500	9	36
DU_01	ACO	Dense Urban	10,600	11	44
S1_06	ACO	Suburban	8,800	7	28
RU_04	ACO	Rural	4,100	4	0

B. Mass Market Services Parameters

Table 5 presents the traffic generated and received per user (p_{in} and p_{out}), depending on its type and according to current available measurements. Without loss of generality, we consider that these values characterize current mass-market service demand per user.

Table 6 lists the values of the p_e parameters needed to define each of the selected mass-market services. We have distinguished five blocks grouping different components already illustrated in the workflows of Fig. 2. These blocks are: i) the percentage of traffic between service IO and reference telco node (which is 100% for all services and scenarios); ii) the percentage of traffic a telco node exchanges directly without transiting another telco node. Note that this component, that is only valid for DIRC service when both end users are registered under the same UPF/BNG function, is not depicted in Fig. 2; iii) the percentage of traffic between reference telco node and other telco nodes located at the same or different segments of the network; iv) the percentage of traffic between reference telco node and processing nodes that can be placed either locally (i.e., in the same location that the telco node) or remote at different network segments; and v) the percentage of traffic between telco nodes and service GW. Note that the selected break-out scenario impacts on the values of some of the parameters, whereas others are independent of reference telco node placement.

Table 5. Mass market service parameters

Service	Access type	% users	p_{in}[Mb/s]	p_{out}[Mb/s]
DIRC	HH	10%	10	10
	MCS	20%	5	5
	SCS	30%	5	5
WB	HH	20%	1	5
	MCS	50%	0.4	2
	SCS	75%	0.5	2.5
CDN	HH	25%	0.2	20
	MCS	15%	0.075	7.5
	SCS	10%	0.1	10

C. B5G services characterization

Contrarily to mass market services, emerging B5G services are foreseen as future services and hence, their characterization cannot be based on current network operators data. As a consequence of this, in order to setup a reasonable configuration, we assume different levels of service penetration by considering different demand scenarios. In particular, we are going to define *low*, *medium*, and *high* penetration scenarios for characterizing P parameters for both DT and VV services. The numbers obtained from the analysis performed in the next subsections are summarized in Table 7

C.1. DT

In this service, we consider video-cameras in factories as reference traffic generator devices. Thus, the number (density) of factories and quality of the streams generated by the cameras are used to quantify p_{in}. Specifically, we considered the following penetration and video streams definition levels of the DT service:

- *Low*: one digital factory per 10,000 inhabitants, each factory with 300 cameras operating and recording video 24x7, that is, generating and injecting 300 x 8 Mb/s video streams (Full HD quality, 1080p) into the network, i.e. p_{in} = 2.4 Gb/s constant (no variability) per factory. This implies 0.24 Mb/s per inhabitant.
- *Medium*: one digital factory per 1,000 inhabitants, each factory with 500 cameras operating and recording 24x7, that is, generating and injecting 500 x 40 Mb/s video streams (4K

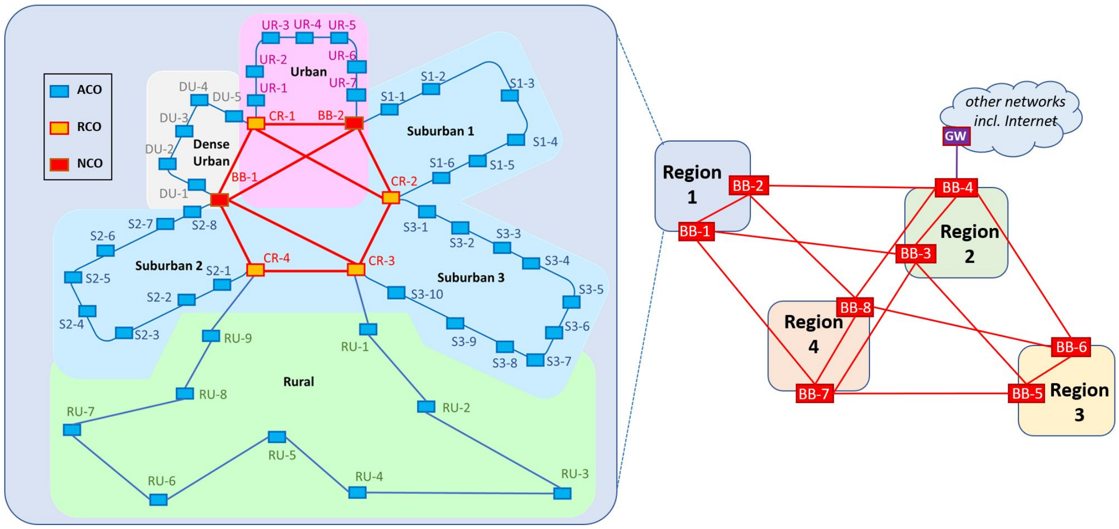

Fig. 5. Reference topology for evaluation

Table 6. Scenario parameters

	Centralized			Semi-Distributed			Distributed		
p_e	DIRC	WB	CDN	DIRC	WB	CDN	DIRC	WB	CDN
Service IO A <-> Ref. Telco Node i	100%	100%	100%	100%	100%	100%	100%	100%	100%
Ref. Telco Node i <-> Service IO B	25%	-	-	10%	-	-	50%	-	-
Ref. Telco Node i <-> Telco Node j [MAN]	0%	-	-	40%	-	-	0%	-	-
Ref. Telco Node i <-> Twin Telco Node i' [MCN]	25%	-	-	0%	-	-	0%	-	-
Ref. Telco Node i <-> Telco Node j [MCN]	30%	-	-	30%	-	-	30%	-	-
Ref. Telco Node i <-> Ref. Proc. Node I [Far Edge]	-	0%	0%	-	0%	0%	-	30%	20%
Ref. Telco Node i <-> Ref. Proc. Node I [MAN]	-	0%	0%	-	40%	50%	-	10%	30%
Ref. Telco Node i <-> Ref. Proc. Node I [MCN]	-	50%	70%	-	10%	20%	-	10%	20%
Ref. Telco Node i <-> Other Proc. Node I [MCN]	-	30%	30%	-	30%	30%	-	30%	30%
Ref. Telco Node i <-> Service GW	20%	20%	0%	20%	20%	0%	20%	20%	0%

quality) into the network, i.e. $p_{in} = 20$ Gb/s constant (no variability) per factory. This implies 20 Mb/s per inhabitant.

- *High*: one digital factory per 1,000 inhabitants, each factory with 2500 cameras operating and recording 24x7, that is, generating and injecting 2500 x 80 Mb/s video streams (8K quality) into the network, i.e. $p_{in} = 100$ Gb/s constant (no variability) per factory. This implies 100 Mb/s per inhabitant.

For both scenarios, we assume that DT traffic is highly unbalanced towards the UL direction and therefore, p_{out}=$p_{in}/100$. Moreover, for the sake of simplicity, we consider that p_e parameters are the same as those of DIRC service, since it requires communication among geographically distributed factories.

C.2. VV

In order to characterize this service, we assume that VV behaves similarly to other well-known entertainment video services, such as IPTV. Following EU estimates[2], the average amount of IPTV content watched per household is 235 minutes per day (i.e. 4 hours), or one sixth of the day (i.e. 1/6 is also the probability that a user is active in that service). Under the assumption that users are uncorrelated and may be using that service at any time, and following the assumption of an ON/OFF process which is active (ON) with probability 1/6 and inactive (OFF) with probability 5/6, the average and standard deviation for IP Television (IPTV) traffic per user (DL) would be 0.8 Mb/s and 1.86 Mb/s, respectively.

Similarly to the DT case, three combinations of penetration and definition levels of VV services are considered:

- *Low*: users on 10% of the households benefit the service, 10 minutes of VV per day per user on average, with a service bitrate of 1,000 Mb/s (high-quality VV with 32 cameras recording at 4K). This implies 7 Mb/s per VV user ($p_{out} =$ 0.7 Mb/s per household).

- *Medium*: users on 20% of the households benefit the service, 100 minutes per day per user on average, with a service bitrate of 1,000 Mb/s (again high-quality VV with 32 cameras recording at 4K). This implies 70 Mb/s per VV user ($p_{out} = 14$ Mb/s per household).

- *High*: users on 30% of the households benefit the service, 100 minutes per day per user on average, with a service bitrate of 2,850 Mb/s (now very high-quality VV with 46 cameras recording at 8K). This implies 200 Mb/s per VV user ($p_{out} = 60$ Mb/s per household).

For all the three scenarios, we assume that VV traffic is highly unbalanced towards the UL direction and therefore, p_{in}=$p_{out}/100$. Similarly to the DT case, we assume that p_e parameters are the same as those of CDN services.

6. NUMERICAL EVALUATION

This section applies the methodology presented in Section 4 in the realistic national-wide network operator scenario detailed in Section 5. Specifically, the network traffic flow set F has been computed according to the proposed procedure. For the sake of clarity, illustrative results have been properly aggregated and analyzed to perform a quantitative case study to identify the traffic handled by nodes at various network levels and considered scenarios. As introduced, the traffic offered to the network is assumed to be generated by a mix of mass market services, along with DT and VV services. With respect to the mass market traffic, the reference numbers presented in Section 5 are considered for the short-term period. Aiming at generating traffic increasing beyond that short-term, a reasonable CAGR of 30% is considered. For DT and VV, the parameters used are the ones presented in Table 7.

Table 7. B5G service parameters

Service	Penetration	p_{in} (Gb/s)	p_{out} (Gb/s)
DT	Low	2.4	0.024
	Medium	20	0.2
	High	100	1
VV	Low	0.007	0.7
	Medium	0.14	14
	High	0.6	60

Adding mass market with DT and VV scenarios, we considered the following three adoption scenarios for different years:

- Short-term (Short-T) Adoption Scenario [year 0]
  - Mass market year 0, i.e., values in Section 5
  - VV: Low Penetration
  - DT: Low Penetration
- Mid-term (Mid-T) Adoption Scenario [year 3]
  - Mass market year 3 = year 0 x $(1.30)^3$
  - VV: Medium Penetration
  - DT: Medium Penetration
- Long-term (Long-T) Adoption Scenario [year 6]
  - Mass market year 6 = year 0 x $(1.30)^6$
  - VV: High Penetration
  - DT: High Penetration

Table 8 shows the amount of traffic generated at each ACO. With the assumptions made in the three scenarios and for the services considered, the nodes will collect from access between 0.07-0.3 Tb/s of total traffic (DL+UL) in short-term, 0.6-2.5 Tb/s of traffic in the mid-term and 2.6-10.2 Tb/s in the long-term. Between UL and DL the dominant component is the DL one (about 80% of the total) since the services that have the greatest impact on the overall traffic are WB and CDN for mass market and VV for B5G services, and all of them are very unbalanced in favour of the DL component.

To show the impact of the adoption scenarios on the entire network architecture, some aggregated results are reported in Fig. 6. The diagram shows the amount of traffic exchanged at access, regional, national and gateway level for the two architectural options characterized by centralized and semi-distributed breakout location for the mid-term adoption scenario.

In Fig. 6a, the values of total traffic processed by the nodes in centralized case are represented. As can be observed, the traffic

[2]See https://www.statista.com/statistics/422719/tv-daily-viewing-time-europe/, last access June 2023.

Table 8. Adoption scenarios

	Short-T		Mid-T		Long-T	
Geotype	DL + UL [Tb/s]	% DL	DL + UL [Tb/s]	% DL	DL + UL [Tb/s]	% DL
Dens Urb.	0.21	83%	1.75	80%	7.00	78%
Urban	0.30	83%	2.54	80%	10.22	78%
Suburban	0.15	84%	1.25	80%	5.04	78%
Rural	0.07	87%	0.63	81%	2.56	79%

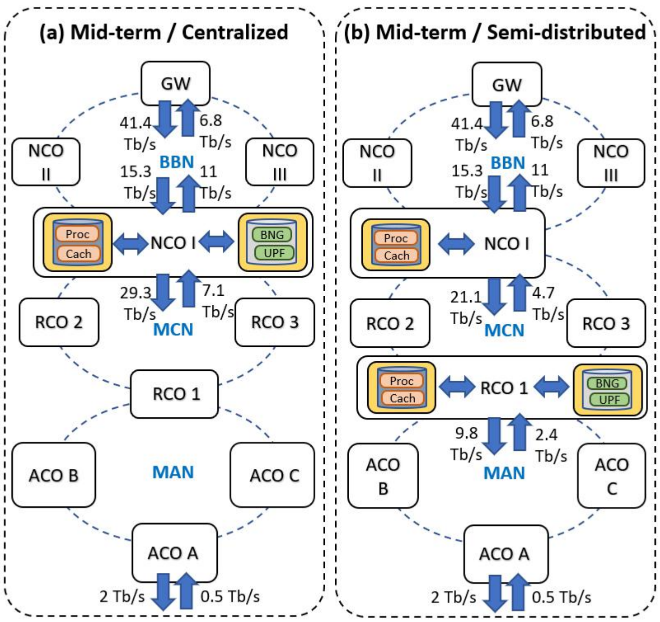

Fig. 6. Diagram for mid-term scenario

Table 9. Node traffic (in Tb/s) for centralized scenario

CO	Side	Direction	Short-T	Mid-T	Long-T
ACO	Access	UL	0.05	0.5	2.2
ACO	Access	DL	0.25	2.0	8.0
NCO	MCN	UL	0.7	7.1	31.7
NCO	MCN	DL	3.6	29.3	114.8
NCO	BBN	UL	1.6	15.3	56.5
NCO	BBN	DL	1.3	11	44.1
GW	BBN	UL	1	6.8	27.7
GW	BBN	DL	3.2	41.4	171.7

Table 10. Node traffic (in Tb/s) for semi-distributed scenario

CO	Side	Direction	Short-T	Mid-T	Long-T
ACO	Access	UL	0.05	0.5	2.2
ACO	Access	DL	0.25	2.0	8.0
RCO	MAN	UL	0.2	2.4	10.6
RCO	MAN	DL	1.2	9.8	38.3
NCO	MCN	UL	0.5	4.7	21.2
NCO	MCN	DL	2.5	21.1	111.1
NCO	BBN	UL	1.6	15.3	56.5
NCO	BBN	DL	1.3	11	44.1
GW	BBN	UL	1	6.8	27.7
GW	BBN	DL	3.2	41.4	171.7

collected in the multi access network including fixed and mobile for residential and business customers is 0.5 Tb/s at UL and 2 Tb/s at DL (for urban node geotype).The traffic collected in ACOs in this case must reach the NCO where it is processed before being forwarded to the destinations. In this case, the RCO does not process the traffic and it must ensure only the switching of the transiting flows. The switching can be done at the electrical or optical layer, depending on the amount of traffic and networking implementation choices (not considered here). In this scenario, the traffic processed by NCOs, on average, is about 29 Tb/s DL and 7 Tb/s UL on the MCN side and 15.3 Tb/s UL and 11 Tb/s DL on the BBN side. In total, the gateway pushes into the BBN about 41.4 Tb/s and receives 6.8 Tb/s of traffic.

In Figs. 6b, the traffic values for flows in the semi-distributed case are shown. The traffic collected by the ACOs is the same than that of the centralized case. However, the traffic is now processed at the RCO before reaching its destination. The amount of traffic exchanged with the ACO by RCOs and to be processed by telco node functions is about 9.8 Tb/s UL and 2.4 Tb/s DL. Part of the traffic processed by RCOs is not forwarded to the NCOs (it is served by the processing and/or caching components of the local service node) and this is the reason why the NCOs exchange about 21 Tb/s DL traffic (4.7 Tb/s UL) instead of 29 Tb/s of the centralized case. The values of traffic exchanged by in the BBN by NCOs and GW are the same as in the centralized case because traffic flows in the backbone do not depend on position of telco and service functions.

In Table 9 and Table 10, the values of total traffic at different levels of the topology are reported for centralized and semi-

Table 11. Required technologies at different network segments and periods

Network Segment	Short-term	Mid-term	Long-term
MAN	C-band	C-band	(C+L)-bands / SDM($\leq$ 4)
MCN	(C+L)-bands / SDM($\leq$ 4)	MB (S+C+L or E+C+L) / SDM($\leq$ 4)	MB (O+E+S+C+L) / SDM (>4)
Backbone	(C+L)-bands / SDM($\leq$ 4)	MB (S+C+L or E+C+L) / SDM($\leq$ 4)	MB (O+E+S+C+L) / SDM (>4)

distributed scenario, respectively, for each of the identified flows in Figs. 6. For centralized scenario, the value of DL traffic of NCOs at the MCN side grows from 3.6 Tb/s (short-term) to 29.3 Tb/s (mid-term) and 114.8 Tb/s of Combination 3 (long-term). Similarly, the UL traffic at the NCO BBN side grows from 1.6 Tb/s (short-term) to 15.3 Tb/s (mid-term) and 56.5 Tb/s (long-term). This means that NCOs should be able to switch and process traffic of the order of some Tb/s in the short-term, few dozens Tb/s in the mid-term and a few hundred Tb/s in the long-term. For a semi-distributed scenario, the values of traffic switched and processed by NCOs are slightly lower since RCOs switch and process about one or few Tb/s for short-term, one or a few dozen of Tb/s for mid-term, and less than one hundred of Tb/s for long-term.

Finally, Fig. 7 shows the maximum node traffic for the semi-distributed scenario detailed in Table 10, as well as indicative levels for network upgrading towards MB and SDM. In order to setup such levels, we have made different assumptions for MAN, MCN, and BBN. For the MAN segment (Fig. 7a), we assumed a typical example where 8 ACOs are connected to a RCO, e.g. following a ring topology. Thus, assuming enhanced C-band of 24 Tb/s, migration to C+L bands and/or SDM will be required as soon as ACO nodes generates 3 Tb/s (and RCOs aggregate 24 Tb/s each). The limit of this option is considered to be reached when 4 parallel fibers (assumed to be available nowadays) are fully occupied with C+L bands, which would trigger the migration to MB and more parallel fibers. That limit is 24 Tb/s for ACOs and 192 Tb/s for RCOs. In view of the figure, is clear that C+L along with SDM with current fiber deployment is sufficient for MAN in all adoption scenarios.

For the MCN and BBN (Fig. 7b), we assume 2.5 Tb/s per node as a reasonable limit for enhanced C-band capacity. This number is indicative and has been estimated assuming a typical mesh network with a few dozen of nodes and paths from three to four hops (on average) to route traffic flows. Then, going beyond that level requires upgrading to C+L and SDM, while 12 Tb/s per node will be sufficient to exhaust 4 parallel fibers, thus requiring MB solutions. As can be observed, MB and more than 4 parallel fibers will be required in some segments event for mid-term adoption scenarios. Next section goes beyond these results and provide the final conclusions of this work.

7. CONCLUDING REMARKS

We discuss hereafter the impact of the traffic calculated with the model presented in the previous sections on the upgrade of the optical transport systems required in the different network segments and in the three target periods considered (summarized in Table 11). The presented conclusions are closely linked to the assumptions made in both the services and network architecture. However we believe that, given that the assumptions of the study derive from the experience and information shared by three major network operators, the considerations listed in

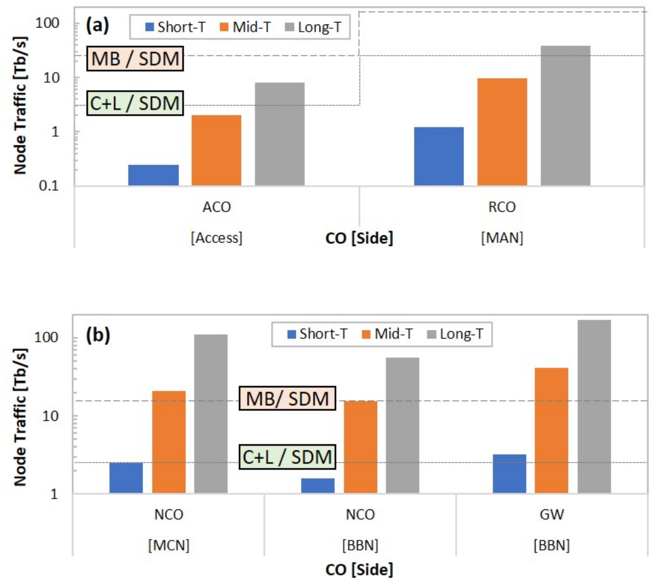

Fig. 7. Adoption of MB and SDM for semi-distributed scenario

this section can give useful insights about where and when MB and/or SDM would be required in an operating nation-wide network.

A. MAN

In short-term, the aggregated flow exchanged by an ACO is of the order of a few hundred Gb/s (at maximum, in the Urban geotype) and so, they are far from causing the saturation of state-of-the-art C-Band systems.

In mid-term, aggregated flows exchanged by ACOs could induce the saturation of C-Band systems as ACOs reach 2 Tb/s of DL traffic in case of urban geotype (lower or significantly lower values for suburban and rural). This would happen in rare combinations with many nodes in the same metro aggregation network all offering very high traffic; in such case, the use of parallel fibers (SDM) or the introduction of C+L band systems will be the most economically viable solution. Apart from these exceptions, the use of enhanced high spectral efficient coherent systems in C-Band should be sufficient. No significant differences between semi-distributed and centralized scenario can be noticed, while in case of the distributed scenario, which lightens the traffic leaving the ACO, the need for overcoming C-Band systems in critical situations could result delayed in time.

In long-term, flows exchanged by ACOs with RCO (semi-distributed scenario) or directly with NCO (centralized scenario) reach values of little less than 10 Tb/s in urban geotype (order of 2 Tb/s for rural). Then, the introduction of C+L or even the full MB band systems, possibly in combination with the SDM, will be required in most cases.

B. MCN

In short-term, flows exchanged within MCN should be of the order of few Tb/s at most and this approaches the limit for C-band systems. Thus, the use of C+L bands and the targeted use of parallel fibers only where necessary can constitute a strategy to address the capacity need in the MCN in this time frame. Semi-distributed scenarios, which lightens the traffic injected in the metro core by RCOs, could delay for a while the introduction of C+L and parallel fibers in the MCN.

In mid-term, traffic flows in MCN become of the order of ten or a few tens of Tb/s. Use of C+L band systems and targeted use of parallel fibers can be the solution in some cases; however, it might be not sufficient for situations where traffic is particularly high. Then, full MB capabilities can be required in any functional distribution scenario.

In long-term, traffic flows exchanged in the MCN (especially the ones terminated at NCOs) will be of up to 100 Tb/s and in some case even higher. In consequence, they significantly exceed C+L systems capacity limit and therefore, MB will be definitely required in any functional distribution scenario, probably in combination with SDM as using all bands on a single fiber at the higher spectral efficiency may not be sufficient.

C. BBN

In short-term, traffic exchanged by NCOs each other or with the GW is of the order of one to few Tb/s and once routed in the BBN, line systems could easily reach maximum C-band capacity. The use of C+L bands or SDM (multi-fiber) begin to become necessary, independently from the telco and service functions distribution scenario.

In mid-term, traffic exchanged by NCOs and GW are of the order of dozens TB/s, significantly exceeding C-band and even C+L capacity limits. Then, MB or SDM (or a combination of the two in most critical cases) is definitely required in any functional distribution scenario.

In long-term, traffic exchanged by NCOs each other or with the GW require are of the order of few dozens Tb/s (up to two hundred Tb/s for the gateway towards external networks) which will require the synergy and co-existence of both MB and SDM technologies.

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