CONVINcE
D3.1.2

Specification of energy saving mechanisms in the core/metro network

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EXECUTIVE SUMMARY

In the previous deliverable D3.1.1 [1] we presented Sub Lambda Photonically Switched Networks (SLPSN) technologies and showed that they could provide energy savings in the context of content distribution networks within a metro network context. We modelled 4 networks architectures using Optical Circuit Switching (OCS) or SLPSN, assuming different interconnection levels among edge nodes and core node: **hub&spoke** architecture on core node where any communication between edge nodes is routed via the core node and **flat** architecture where edge nodes can have direct adjacency. We compared these scenarios in terms of energy savings based on a more and more distributed traffic evolutions scenario. Results showed that having OCS or SLPSN direct links between edge nodes with the flat architecture provided around 20% energy saving on the transport network compared to the conventional hub&spoke OCS architecture. In addition, SLPSN flat architecture allows flexible adaptation to traffic distribution evolution in an optimized manner. This work however did not include the power consumption of the content servers that generated part of the traffic.

In this deliverable, we complement the previous model including servers' power consumption. Based on the previous work, we only concentrate on the architecture that had best energy efficiency: SLPSN with flat architecture, and use the conventional hub&spoke OCS architecture as benchmark. Then we add two cases on the content placement: at edge nodes (EN) or only at concentration nodes (CN). Consequently, we study and compare three use-cases: **OCS-CN** (the legacy architecture), **OCS-EN**, and **SLPSN-EN**.

We consider the case in which content on demand service is managed by the ISP. The architecture ***OCS-CN*** is the legacy architecture having only OCS interconnections between the CN and the ENs. Architectures ***OCS-EN*** and ***SLPSN-EN*** are characterized by the possibility to locate servers also at the ENs. The first has still OCS interconnections between the CN and the ENs, while the latter has all nodes interconnected by SLPSN logical links. We examined different cases in which servers are characterized by different storage capacity, output bandwidth and power consumption values.

The design of the network and storage architecture is strongly influenced by server characteristics: *i)* the storage capacity, *ii)* the output bandwidth and *iii)* the power consumption. The number of servers has to be sufficiently large to store the entire catalogue and to provide enough output bandwidth to satisfy all content demands. Given that these two requirements are satisfied, the number of servers for architectures ***OCS-EN*** and ***SLPSN-EN*** is determined by the relationship between the server power consumption and the power consumption of transporting data. If the power consumption for storing data is less than the transport power consumption, architectures ***OCS-EN*** and ***SLPSN-EN*** store more data than ***OCS-CN*** and this results in installing more servers, otherwise the same number of servers is installed for all architectures. The distribution of contents at the ENs is advantageous, in particular, when content demands volumes are large. Positioning servers at the network edges reduces indeed the amount of network resources required to transport the traffic and decreases the overall power consumption.

Architectures ***SLPSN-EN*** presents better performance with respect to architecture ***OCS-EN*** at low traffic volumes thanks to the sharing capabilities of the SLPSN interfaces. It is possible to reduce the number of network interfaces since the traffic and content bandwidth exchanged among the nodes can be better aggregated improving the interfaces utilization. At higher traffic demands volume, the efficiency of OCS is improved and the benefits introduced by ***SLPSN-EN*** interfaces are reduced.

All-in-all, depending on the traffic volume and distribution, the energy consumption improvement allowed by **SLPSN-EN** over the legacy architecture ranges between 15% and 20%.

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1 DOCUMENT HISTORY AND ABBREVIATIONS

1.1 Document history

Version	Date	Description of the modifications
v0.1	22/09/16	First draft
v0.2	03/10/16	Part from Esther Le Rouzic on OBS in the metro network
v1.0	07/10/16	Executive sumary, conclusion and introduction added
v1.1	03/11/16	Comments form reviewer integrated

1.2 Abbreviations

CN	Concentration Node
CP	Content Provider
EN	Edge Node
ICT	Information Communication Technologies
IP	Internet Protocol
ITU-T	International Telecommunication Union – Telecommunication sector
ISP	Internet Service Provider
LNC	Linear Network Coding
OBS	Optical Burst Switching
OCS	Optical Circuit Switch
OXC	Optical Cross Connect
PP	Peering Point
ROADM	Reconfigurable Add Drop Multiplexer
RX	Receiver
SLPSN	Sub-Lambda Photonically Switched Network
SLPS	Sub-Lambda Photonically Switched
TX	Transmitter
WDM	Wavelength Division Multiplexing

2 INTRODUCTION

In the previous deliverable D3.1.1 [1] we presented Switching or Sub Lambda Photonically Switched Networks (SLPSN) technologies and showed that under certain conditions they could provide energy savings in the context of content distribution networks within a metro network context. We modelled 4 networks architectures using Optical Circuit Switching (OCS) or SLPSN, assuming different interconnection levels among edge nodes and core node: **hub&spoke** architecture on core node where any communication between edge nodes is routed via the core node and **flat** architecture where edge nodes can have direct adjacency. We compared these scenarios in terms of energy savings based on a more and more distributed traffic evolutions scenario. Results showed that having OCS or SLPSN direct links between edge nodes with the flat architecture provided around 20% energy saving on the transport network compared to the conventional hub&spoke OCS architecture. In addition, SLPSN flat architecture allows flexible adaptation to traffic distribution evolution in an optimized manner. This work however did not include the power consumption of the content servers that generated part of the traffic.

In the current work, we complement the previous model including servers' power consumption. Based on the previous work, we only concentrate on the architecture that had best energy efficiency: SLPSN with flat architecture, and use the conventional hub&spoke OCS architecture as benchmark. Then we add two cases on the content placement at edge nodes or only at concentration node only.

The next section presents the study assumptions and summarizes the most interesting results we obtained.

3 Optical Burst Switching (OBS) in the Metro Network

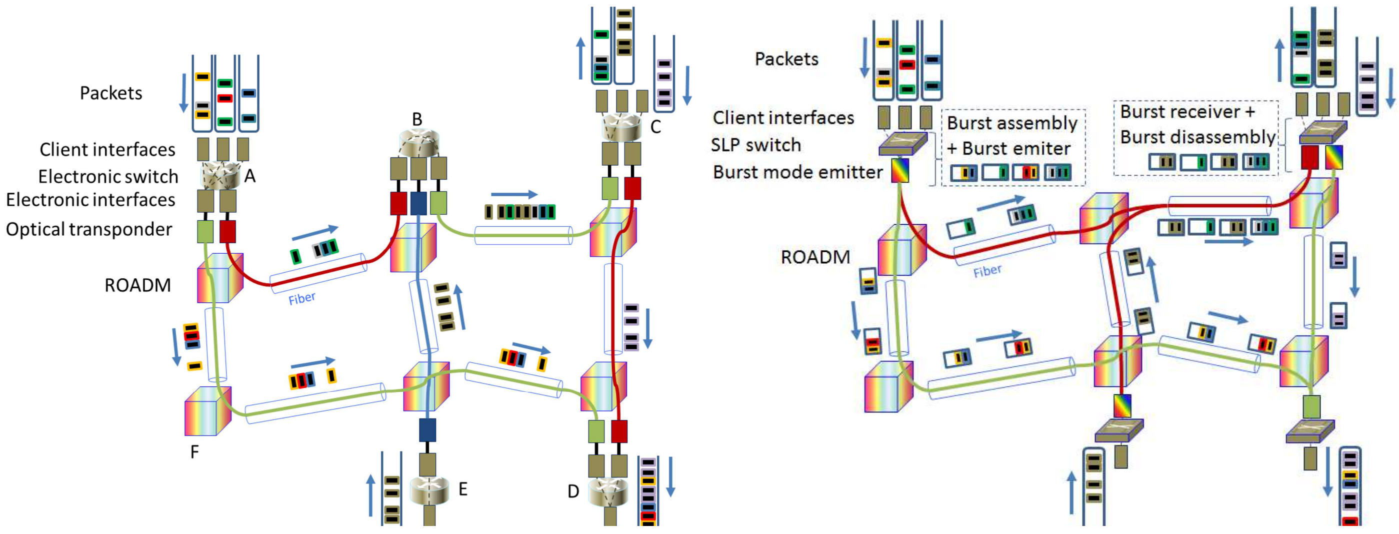
3.1 All-you-need-to-know on OBS

Optical Burst Switching or more precisely Sub-wavelength (Lambda) Photonically Switched (SLPS) techniques have been presented in [1]. The interested reader may find relevant references there. We however prefer to repeat here essential property of the technique that we used for the modelling.

SLPSN gathers several techniques which all share a common constraint: the lack of optical memory and a common will that is to keep the optical containers (made of packets of data) in the optical domain from their source to their destination. Numerous possible implementations have been proposed either by academics or by industrial, often (but not always) grouped under the same term of optical X switching, X being the type of container, for example: packet (OPS) or burst (OBS), or short circuit (dynamic OCS), … [2-3]. The implementation choice in terms of control, synchronisation, reservation and scheduling can induce loss of data (or not) during their transport, which we call lossy or lossless respectively.

Lossy solutions, where the optical containers can be lost due to collision(s) or lack of resources, were the most studied techniques in the literature at the beginning of 2000s because they could appear as cheap solutions. However Loss of data in the transport network of an operator is not acceptable. Considering the Quality of Service level for a transport network, we have based this work on solutions without losses also known as lossless.

SLPSN solutions rely on burst mode transmission. At the emitter, the SLPSN switch assembles (one or) several packets incoming from the electronic client side having the same destination (like the cars of a train) within the SLPSN network into a unique container that we call burst. Then the burst is converted in the optical domain, at a specific wavelength, thanks to a burst mode emitter. As soon it is emitted, it is transmitted towards the destination node and steered (on a wavelength basis), in the optical domain, along the nodes it crosses (without any conversion into the electronic domain). At the receiver side, the burst is detected by a burst mode receiver and packets are extracted towards the client side thanks to the SLPSN switch. This is illustrated in Fig 1.



(a) (b)

Figure 1. <u>(a) conventional OCS network with three flow example (A to C, A to D, C to D); (b) equivalent SLSPN network.</u>

On the one hand, the solutions add some constraints and issues. For example they introduce some latency with the burst assembly process or due to the collision avoidance techniques. Scheduling,

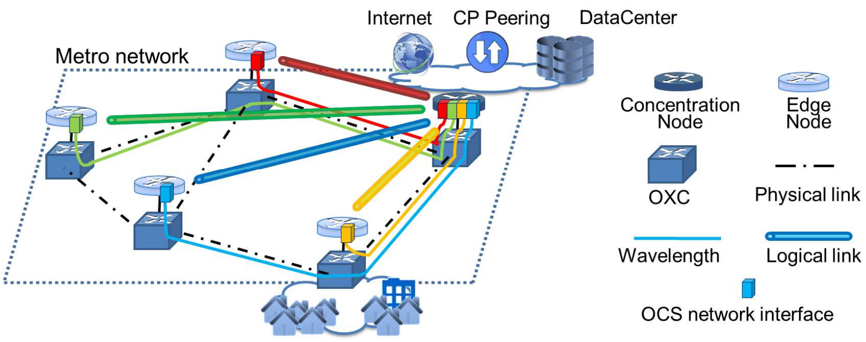


Figure 2. Current OCS metro network scenario

collision avoidance and other method for contention resolution also reduce the throughput of the interfaces. As a result, maximum throughput is estimated around 80 % [4-5] or slightly more on ring topology [6].

On the other hand, SLPSN techniques combine very interesting features: transparency, sharing and flexibility. Fig. 1 b illustrates this: i) a single emitter in A can be used for multiple destinations; ii) a single receiver in D can receive from several sources; iii) a single wavelength (red) can be used for multiple flows; iv) capacity of flows is adapted online according to needs, all this without resorting to electronic switching except at the edge.

In this respect, SLPSN techniques benefit from transparency, which has proven very efficient in current optical networks and fine granular switching with bursts. The challenge is thus to have an implementation which does not give up too much on reach, latency and throughput to benefit from transparency, sharing and flexibility. Cost and power savings are the principal motivation for the introduction of the technique. Flexibility may also be an asset given the growing interest for network programmability. Moreover the SLPSN technique allows to provide on demand bandwidth thus improving the use of the network capacity.

3.2 Assumptions for the study

3.2.1 Metro network architectures

The current metro network scenario is depicted in Fig. 2: one Concentration Node (CN) is connected with several Edge Nodes (ENs) each serving a large group of users. The CN interconnects the metro network to the Internet Service Provider (ISP) core network segments which provide access to Internet, datacenters and to the peering points with the Content Providers (CPs). The metro networks, i.e., the ENs, thus provide to local area users the access to services (Internet, content, …). Typical metro networks rely on a physical infrastructure made of fiber links interconnected by Optical Cross Connects (OXCs). The physical topology of metro networks is usually partially meshed with an average node degree larger than 2.

In this work, we suppose that all traffic is transmitted using IP and that WDM transmission technology is employed at the physical layer. The IP traffic is carried by optical logical links which are established to interconnect the metro network nodes. The whole set of logical links constitutes the logical layer over which traffic demands are routed. Several traffic demands can be groomed in the same logical link. In order to reach the destination node, a traffic demand can use several consecutive logical links. In that case the traffic demand has to be electronically switched between two consecutive logical links.

The logical links are realized by wavelength channels over the physical layer, i.e., fiber links. The logical links are however independent from the physical layer, i.e., their physical realization is transparent to them. Each node of the metro network is thus equipped with an IP router, responsible for switching IP traffic at the electronic layer, and an OXC, which is in charge of wavelengths switching at the optical layer. The wavelength channels are generated by transmitters (TXs) at the source nodes and they are terminated by receivers (RXs) at the destination nodes. The physical path of each wavelength channel can span one or more fiber links. The wavelength channel is thus transparently switched at the intermediate nodes of its path by the OXCs. In this work, we assume that the physical layer is adequately dimensioned to support any instance of the proposed architectures since we focus on the dimensioning of the logical layer.

3.2.2 Optical Circuit Switching metro conventional hub&spoke architecture

Optical Circuit Switching (OCS) is the standard technology that is currently adopted in metro and core network segments. The today's metro network architecture is shown in Fig. 2. We refer to it as ***OCS*** architecture. Each optical logical link in OCS technology is associated to a specific wavelength channel. The OCS network interfaces associated to that logical link operate with this specific wavelength and they can transmit/receive just for that logical link. On a given physical path, i.e., a sequence of fiber links, a wavelength channel is thus reserved for the communication between a specific pair of nodes. The same wavelength can be associated to several logical links only in the case that the physical paths of these logical links are disjoint. The CN is connected to each EN through an OCS logical link, and vice versa and there is no direct logical link between the ENs.

3.2.3 Sub Lambda Photonically Switched Network metro architecture

SLPSN technologies present as main feature the capability of switching at sub-wavelength level. Wavelength channels are shared in the time domain by several logical links in a complete transparent way. In a SLPSN metro network, as the one depicted in Fig. 3, a logical link is thus not strictly associated to a specific wavelength channel.

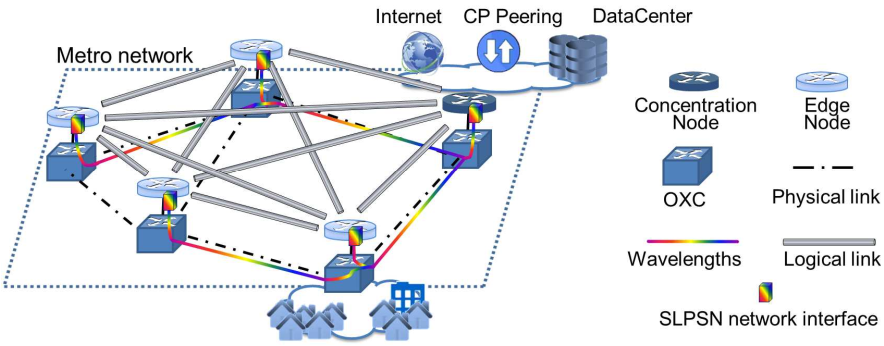


Figure 3. SLPSN metro network scenario

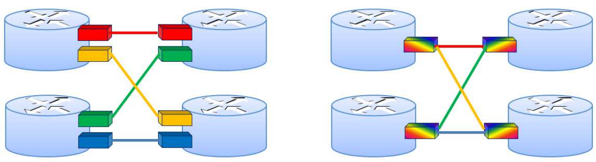


Figure 4. Network interfaces in OCS (left) and sharing in SLPSN (right)

SLPSN interfaces are thus not devoted to a given logical link-wavelength channel pair, but they are shared by several logical links. A single SLPSN interface can thus ensure the communication with all other nodes operating at different time instants on any wavelength, as depicted in the right side of Fig. 4, while an OCS interface is dedicated to the communication between a nodes pair, as shown in the left of Fig. 4. SLPSN technology permits thus to create a logical full mesh with only one network interface per node, as depicted in Fig. 3. This represents a significant advantage since the number of required network interfaces can be reduced decreasing the overall network energy consumption.

Several SLPSN technologies have been already proposed in the literature. In this work, we do not consider any SLPSN technology in particular. We only take into account in our model that SLPSN interfaces can be shared in the communication among several node pairs.

3.2.4 Storage and content models

In this work we consider as storage resources, used to implement the content on demand service, the servers which are in charge of content storage and content delivery. A server is characterized by a storage capacity and an output bandwidth. We assume servers having all the same characteristics. One or more servers can be installed in each node. We define the storage and output bandwidth capacities of the node as the aggregation of the capacities of all the installed servers. We assume that a content item stored in a server is accessible to all the other servers installed in the node.

Servers can be placed at the CN and at the ENs. In particular, we investigate two different cases: i) *CN-storage* case, where servers are only placed at the CN, and ii) *EN-storage* case, where servers can be placed at the CN and/or at the ENs.

The on demand content service offers to users the possibility to download content items from a catalogue of size *C*. Each EN retrieves content items for the users associated to it. The CN does not need to retrieve content as it is not directly serving users, and it only serves content to the ENs and their users. We consider that at each EN any content item is requested at least once. A copy of each content item is thus stored in the network. Several copies of the same content item can be stored in the network in different locations, i.e. at the CN and/or at some ENs (*EN-storage* case). We assume that an EN can retrieve a given content item only from a single location for all its users, even if the content item is present in the network in several copies.

We dimension the resources considering the content traffic demands as the overall amount of bandwidth that is associated to the download of content items and that has to be received at the ENs, i.e., the content items downloads generate a certain amount of bandwidth that has to be reserved at each EN. We denote the overall bandwidth related to the downloads of all content items at EN *i* as λ_i^{Cnt}, while the bandwidth associated to a given content item *c* is named $\lambda_{i,c}^{Cnt}$.

Each content item is characterized by a given popularity, which depends on the frequency that users request it. We assume that the popularity of content item *c* follows a certain popularity distribution ψ_c. A Zipf-like distribution is chosen to represent the content popularity [7]. The frequency, with which the content item *c* is requested by the users, can be computed as $\psi_c = \Omega / c^{\alpha}$ where $\Omega = \left(\sum_{c=1}^{C} 1/c^{\alpha}\right)^{-1}$ with positive real α.

The content items are characterized by different values of download bandwidth depending on their size and their popularity. It is thus possible to compute the value of this bandwidth for each content item *c* at each EN *i* knowing the content related bandwidth λ_i^{Cnt} of the EN, the size δ_c and the popularity ψ_c of the content item. We define ρ_c as the percentage of the overall content bandwidth λ_i^{Cnt} to which bandwidth $\lambda_{i,c}^{Cnt}$ is equal and thus $\lambda_{i,c}^{Cnt}$ can be simply computed as $\lambda_{i,c}^{Cnt} = \rho_c \cdot \lambda_{i,}^{Cnt}$. The percentage ρ_c is also equal to the ratio between the popularity of content item *c* weighted by its size and the sum of the popularity values of all content items weighted by their size. Then, ρ_c can be computed as $\rho_c = \delta_c \cdot \psi_c / \sum_{q=1}^{C} \delta_q \cdot \psi_q$. Notice that the value of ρ_c does not depend on the value of λ_i^{Cnt}, but it depends only on the size and on the popularity values of the content items. Thus, given the catalogue and the popularity distribution, it is possible to compute the value of ρ_c for all content items for any EN.

For example, we consider 3 content items all of size $\delta_c = 1$ GB. The Zipf distribution parameter α is set equal to 0.8. The value of Ω is 1.9896 and the popularity ψ_c of the three items is equal to $\psi_1 = 1.9896$, $\psi_2 = 1.1427$, and $\psi_3 = 0.82617$. The popularity ratios are then equal to $\rho_1 = 0.50262$, $\rho_2 = 0.28867$ and $\rho_3 = 0.20871$ respectively. At EN *i* we have that 50% of the bandwidth λ_i^{Cnt} is due to the download of content item 1, 28% is related to content item 2 and 20% to content item 3. If the EN has bandwidth λ_i^{Cnt} equal to 500 Gbps, the bandwidth related to the download of content item 1 would be equal to about 251 Gbps, the bandwidth of content item 2 to 144 Gbps and content item 3 to 104 Gbps.

We consider the bandwidth related to content download as the bandwidth required to transmit the content to the users. The transmission of content items to the servers (content upload) is not included in this bandwidth. We assume to be in a "steady state" in which content is already stored in the servers. We can suppose that the content transmission to the servers is performed exploiting the overprovisioning present in the network.

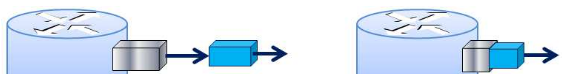


Figure 5. Separated (left) and integrated (right) IP and physical interface

3.2.5 Network power consumption model

The power consumption of the network resources can be divided into the contributions of the physical and of the logical layer. The physical layer contribution consists in the consumption of optical fibre line amplifiers, of WDM terminals and of OXCs. This contribution is not taken into account since the physical layer is the same for all the considered architectures.

At the logical layer, we consider the power consumption of IP routers. The IP routers consumption consists in the contributions of router chassis and of network interfaces, i.e., TXs and RXs. The IP router chassis contribution includes the consumption of the power supply, the switching fabric, the control board, the routing engine and the cooling system. It can be considered as a fixed power consumption independent from the traffic that the router actually processes. The consumption values of routers chassis is based on the datasheets of metro routers of Juniper Networks [8], in particular we refer to the M and MX Series of routers. Seven different types of routers, with switching capacity ranging from few tens Gbps to some Tbps, have been selected. The relative switching capacity and power consumption of the selected routers chassis are reported in Tab. 1.

We assume to use integrated IP-physical network interfaces. A network interface of a router is usually made of two separate interfaces, i.e., an IP and a physical interface, for vendors' interoperability reasons. The "grey" IP interface is used to connect the router to the physical interface which is responsible for the communication on the optical layer (Fig. 5 left). In this work,

Table 1: Relative switching capacity and power consumption of the selected routers chassis

we consider integrated network interfaces, usually named as "colored", which provide direct

Router chassis	r_1	r_2	r_3	r_4	r_5	r_6	r_7
Switching capacity	1	1.5	4	12	34	64	215
Power consumption	1	1.21	1.52	1.73	1.73	3.77	25.89

connectivity among routers, as depicted on the right side of Fig. 5. Furthermore, line cards usually include both a TX and a RX interfaces providing bidirectional communication. Since, in the SLPSN case, the number of required TXs and RXs is usually different, and no hardware is currently available on the market, we consider that SLPSN TXs and RXs interfaces can be installed separately. We thus assume, in order to be fair in the comparison, that it is possible to install separately also OCS TXs and RXs interfaces. The power consumption of OCS TX and RX interfaces are based on confidential data. SLPSN interfaces are instead not yet available on market. We thus estimate possible power consumption values and we only suppose that, due to their additional networking and control functionalities, they are likely to consume more than OCS interfaces. We evaluated that, in the worst case, SLPSN network interfaces can consume 25% more energy with respect to OCS interfaces.

3.2.6 Server power consumption model

We develop a power consumption model based on a Content Delivery Network server employed in Orange network. The considered server is the IBM Server X3550M4. Its power consumption has been estimated using the IBM Power Configurator tool [9]. The following configuration, used in the servers installed in Orange CDN network, has been considered: 64 GB of memory, 8 TB Hard Disk Drives, 2 processors 6C E5-2620 2.0Ghz, 2 x 550W AC Power Supply, I/O 2 x 10 Gbps (Emulex Dual port 10Gbe VFA III board + 2 modules SFP Brocade). The maximum storage capacity of this server configuration is 8 TB and its maximum output bandwidth is 20 Gbps. As additional setting for the IBM Power Configurator, we select as country: France, as operating voltage: 220 V, as ambient temperature: 15 °C and as elevation: 300 m. The resulting maximum power consumption is of 421 W.

3.3 Integer Linear Programming formulations

The objective of our work is to dimension the required network and the storage resources for a metro network (***OCS*** or ***SLPSN***) and storage (*CN-storage* or *EN-storage*) architecture minimizing the overall power consumption. We thus develop Integer Linear Programming formulations to model this dimensioning problem for the previously introduced network and storage architectures.

We define $\mathbf{N}$ as the set of network nodes comprising the CN and the ENs. Traffic demands are given at input. A traffic demand from source node *s* to destination node *d* is denoted as λ_{sd}. The CN is considered as the source/destination of traffic demands from/to the core network segments. The set of content items, i.e. the catalogue, is denoted as $\mathbf{C}$. The bandwidth, generated by the content items download and received at node *i*, is denoted as λ_i^{Cnt}. The bandwidth related to the download of content item *c* is denoted as $\lambda_{i,c}^{Cnt}$. The popularity of content item *c* is indicated with ψ_c and it is in range (0,1]. The size of content item *c* is indicated as δ_c and the percentage of λ_i^{Cnt} that is related to bandwidth $\lambda_{i,c}^{Cnt}$ is denoted as ρ_c. The capacity of a server is C^{Srv} GB and its maximum output bandwidth is B^{Srv} Gbps. A server has a power consumption of P^{Srv} Watt.

The available IP routers are included in the set $\mathbf{H}$. A router of type *h* is characterized by a full duplex switching capacity of C_h^{Rtr} Gbps and by a power consumption of P_h^{Rtr} Watt. OCS and SLPSN TX and RX have a capacity of C_{OCS} and C_{SLPSN} Gbps respectively. We consider that the capacity of TXs and RXs can not be fully used, but a small fraction is kept unused in order to take into account burstiness of the traffic and, in case of SLPSN technology, the control overhead. We thus define the maximum utilization factors α_{OCS} and α_{SLPSN} in the range (0,1). The power consumption of OCS TX and RX is of P_{OCS}^{Tx} and P_{OCS}^{Rx} Watt, while SLPSN TX and RX consume respectively P_{SLPSN}^{Tx} and P_{SLPSN}^{Rx} Watt.

The binary variable $l_{sd,c}$ indicates from which node a content item is retrieved. It is equal to 1 if the content item *c* is sent from node *s* to node *d*. The real variable γ_{sd} indicates the amount of bandwidth that is sent from node *s* to node *d* taking into account the bandwidth due to the traffic demand and the bandwidth due to content. The bandwidth from node *s* to node *d* that is allocated on the logical link from node *i* to node *j* is indicated by B_{ij}^{sd}. Variable f_{ij}^{sd} is equal to 1 if a traffic demand from *s* to *d* is transmitted on the logical link from *i* to *j*. The binary variable $m_{i,c}$ is equal to 1 if content item *c* is stored at node *i*. The number of servers installed at node *i* is equal to g_i. The binary variable $r_{i,h}$ indicates whether or not a router of type $h \in \mathbf{H}$ is installed at node *i*. The number of OCS TXs at node *i* dedicated to node *j* is given by the integer variable Tx_{OCS}^{ij}. The number of the corresponding OCS RXs at *j* is equal to Tx_{OCS}^{ij} since at each OCS RX corresponds an OCS TX. The number of SLPSN TXs and RXs at node *i* are indicated by the integer variables Tx_{SLPSN}^{i} and Rx_{SLPSN}^{i}.

We report an Integer Linear Programming formulation including the constraints for all architectures. In the following, we detail how the constraints related to OCS, SLPSN TXs and RXs are defined depending on the considered architecture.

The objective, in Eq. 1, is to minimize the power consumption of servers, routers, OCS and/or SLPSN TXs and RXs. In Eq. 2 the value of γ_{sd}, the bandwidth required to be allocated from node *s* to node *d*, is constrained to be equal to the sum of the traffic demand and of the content related bandwidth from node *s* to node *d*. The traffic flow conservation constraint is introduced in Eq. 3. In details, Eq. 2 can be directly included in Eq. 3, it has been separated in order to ease the notation. Eq. 4 constrains the variable f_{ij}^{sd} to be equal to 1 if some bandwidth is allocated from *s* to *d* on the logical link from *i* to *j*. In Eq. 4, the sum of the traffic demands and of content download bandwidth is used as positive constant to let the right hand side of Eq. 4 to assume a sufficiently large value, i.e., the "big M" method. In Eq. 5 the bandwidth from *s* to *d* can be allocated on just one logical link exiting node *i*. This constraint is required to ensure single-path routing from node *s* to node *d*. Eq. 6 constrains the ENs to retrieve content only from the CN, it corresponds to the *CN-storage* case. Instead, for the *EN-storage* case, no additional constraints are required since content can be retrieved from any node. Eq. 7 ensures that each content item is retrieved by each EN from only one server location. The CN does not request content as it is indicated in Eq. 8. In the Eq. 9, it is constrained that if content item *c* is retrieved from node *i*, it has to be stored in the node *i*. The maximum case is when all (N-1) ENs retrieve the content item *c* from node *i*. The number of servers located at node *i* is computed considering the contents stored at the node, in Eq. 10, and the required output bandwidth, in Eq. 11. In Eq. 12 the size of router at node *i* is determined taking into account the volume of transit traffic, the traffic volume generated at and destined to that node and the volume of content traffic transmitted by the servers located at the node. Eq. 13 constrains to install only one type of router at node *i*.

In architecture ***OCS***, the number of OCS TXs is computed by Eq. 14 such that the capacity provided by all the OCS TXs on the logical link between *i* and *j* is larger than the volume of all allocated bandwidth flowing on that link. It is also required to constrain the OCS TXs between ENs to be zero, as constrained in Eq. 15. In architecture ***SLPSN***, in Eq. 16 the number of SLPSN TXs is constrained to provide a capacity larger than the volume of all allocated bandwidth from node *i* to all nodes in set $\mathbf{N}$, which is the set containing all nodes using SLPSN. Similarly, Eq. 17 determines the number of SLPSN RXs required at node *i* to receive traffic from nodes in $\mathbf{N}$.

$$P_{TOT} = \sum_{i\in\mathbf{N}} g_i \cdot P^{Srv} + \sum_{i\in\mathbf{N},h\in\mathbf{H}} r_{i,h} \cdot P_h^{Rtr} + \sum_{i,j\in\mathbf{N}} Tx_{OCS}^{ij} \cdot \left(P_{OCS}^{Tx} + P_{OCS}^{Rx}\right) + \sum_{i\in\mathbf{N}} \left(Tx_{SLPSN}^{i} \cdot P_{SLPSN}^{Tx} + Rx_{SLPSN}^{i} \cdot P_{SLPSN}^{Rx}\right) \quad (1)$$

$$\lambda_{sd} + \sum_{c\in\mathbf{C}} l_{sd,c} \cdot \rho_c \cdot \lambda_d^{Cnt} = \gamma_{sd} \qquad \forall\, s,d \in \mathbf{N} \quad (2)$$

$$\sum_{\substack{j\in\mathbf{N}\\ j\neq i}} \left(B_{ji}^{sd} - B_{ij}^{sd}\right) = \begin{cases} -\gamma_{sd} & \text{if } i=s \\ \gamma_{sd} & \text{if } i=d \\ 0 & \text{if } i\neq s,d \end{cases} \qquad \forall\, i,s,d \in \mathbf{N}, s\neq d \quad (3)$$

$$B_{ij}^{sd} \le \left(\sum_{m,n\in\mathbf{N}} \lambda_{mn,c} + \sum_{m\in\mathbf{N}} \lambda_m^{Cnt}\right) \cdot f_{ij}^{sd} \qquad \forall\, i,j,s,d \in \mathbf{N} \quad (4)$$

$$\sum_{j\in\mathbf{N}} f_{ij}^{sd} \le 1 \qquad \forall\, i,s,d \in \mathbf{N} \quad (5)$$

$$\sum_{\substack{s\in\mathbf{N},d\in\mathbf{N}-CN\\ c\in\mathbf{C}}} l_{sd,c} = 0 \quad (6)$$

$$\sum_{s\in\mathbf{N}} l_{sd,c} = 1 \qquad \forall d \in \mathbf{N}-CN, \forall c\in\mathbf{C} \quad (7)$$

$$\sum_{c\in\mathbf{C}} l_{sCN,c} = 0 \qquad \forall s\in\mathbf{N} \quad (8)$$

$$\sum_{d\in\mathbf{N}} l_{id,c} \le (N-1)\cdot m_{i,c} \qquad \forall i\in\mathbf{N}, \forall c\in\mathbf{C} \quad (9)$$

$$\sum_{c\in \mathbf{C}} \delta_c \cdot m_{i,c} \le g_i \cdot C^{Srv} \qquad \forall i \in \mathbf{N} \tag{10}$$

$$\sum_{\substack{d\in \mathbf{N}\\ c\in \mathbf{C}}} \lambda_d^{Cnt} \cdot \rho_c \cdot l_{id,c} \le g_i \cdot B^{Srv} \qquad \forall i \in \mathbf{N} \tag{11}$$

$$\sum_{j\in \mathbf{N}} \left(\sum_{s,d\in \mathbf{N}} \left(B_{ij}^{sd} + B_{ji}^{sd} \right) + \lambda_{ji} + \lambda_{ij} \right) + \sum_{\substack{d\in \mathbf{N}\\ c\in \mathbf{C}}} \lambda_d^{Cnt} \cdot \rho_c \cdot l_{id,c} \le \sum_{h\in \mathbf{H}} r_{i,h} \cdot C_h^{Rtr} \qquad \forall i \in \mathbf{N} \tag{12}$$

$$\sum_{h\in \mathbf{H}} r_{i,h} = 1 \qquad \forall i \in \mathbf{N} \tag{13}$$

$$\sum_{s,d\in \mathbf{N}} B_{ij}^{sd} \le \alpha_{OCS} \cdot C_{OCS} \cdot Tx_{OCS}^{ij} \qquad \forall i,j \in \mathbf{N} \tag{14}$$

$$Tx_{OCS}^{ij} = 0 \qquad \forall i,j \in \mathbf{N} - CN \tag{15}$$

$$\sum_{j,s,d\in \mathbf{N}} B_{ij}^{sd} \le \alpha_{SLPSN} \cdot C_{SLPSN} \cdot Tx_{SLPSN}^{i} \qquad \forall i \in \mathbf{N} \tag{16}$$

$$\sum_{j,s,d\in \mathbf{N}} B_{ji}^{sd} \le \alpha_{SLPSN} \cdot C_{SLPSN} \cdot Rx_{SLPSN}^{i} \qquad \forall i \in \mathbf{N} \tag{17}$$

3.4 Network scenario

In this work, we consider three different network and storage architectures: 1) ***OCS-CN***, the network architecture ***OCS*** in the *CN-storage* case, 2) ***OCS-EN***, the network architecture ***OCS*** in the *EN-storage* case, and 3) ***SLPSN-EN***, architecture ***SLPSN*** in the *EN-storage* case. We do not consider architecture ***SLPSN*** in the *CN-storage* case since storing content only at the CN limits the traffic volumes exchanged among the ENs and thus it reduces the interest of having direct logical links among the ENs. In case 1) the formulation includes Eq. 6, content stored only at the CN, and Eqs. 14 and 15, required to compute the number of OCS TXs and RXs. The case 2) requires only Eqs. 14 and 15, while Eqs. 16 and 17 are only used in case 3) to compute the number of SLPSN TXs and RXs.

We evaluate these three architectures in a real metro network of Orange composed by 9 ENs and by the CN. We consider an evolving traffic scenario and we define a set of planning periods for a total of 6 periods. The i^{th} period is denoted as τ_i. In the first planning period, we assume that the content traffic volume received by an EN, e.g., λ_i^{Cnt}, is 15% of the total traffic volume received by the same EN. In the following periods we consider that the ratio of traffic volume related to content demands is progressively increasing, with percentage values that are respectively 30%, 45%, 60%, 75% and 90% of the total traffic volume received by each EN. We suppose that the total traffic volume growth is of 35% per period.

For each planning period we *i)* dimension the network resources required to support all the traffic volumes exchanged in the metro network, *ii)* locate and quantify the required storages resources and *iii)* decide the content items placement. The dimensioning of the resources is performed independently from a period to the following one.

We select 100 Gbps as bit rate for both OCS and SLPSN interfaces since it is expected to be the next standard in metro networks as it is currently becoming for the core network segments. We set maximum utilization factors α_{OCS} and α_{SLPSN} equal to 0.9 and 0.8. The maximum utilization of a SLPSN link is lower with respect to OCS in order to take into account possible inefficiencies of the medium access control mechanism in SLPSN technologies [10]. We fix the number of content items in the catalogue to 1000. The content items have all size equal to 4.5 GB, which corresponds to the size of a High Definition movie lasting 1.5 hours according to Netflix [11]. The catalogue size is of 4.5 TB. The content popularity has been computed using a Zipf-like distribution with parameter α equal to 0.8.

We consider different server settings in order to perform a sensitivity analysis. We choose as settings for the maximum storage capacity and for the maximum output bandwidth of the server:

a) 8 TB and 20 Gbps, according to the server model used, with a total power consumption of 421 Watt;
b) 2 TB and 20 Gbps having a power consumption of 375 Watt;
c) 2 TB and 100 Gbps without modifying the power consumption with respect to the previous case;
d) 2 TB and 100 Gbps with an estimated power consumption of 1811 Watt.

The power consumption for case *b* has been computed removing the contributions of the Hard Disk Drives, while for the power consumption estimation of case *d* we assume that all the internal components which are load dependent (processors, memory and network interfaces) would have a consumption 5 times greater. This is a rough worst case estimate, a real server with that characteristics could benefit of some engineering integration achieving a lower power consumption. The different server settings are summarized in Tab. 2.

3.5 Results

The dimensioning of the architectures has been retrieved solving the ILP formulations with the optimization software IBM ILOG CPLEX. The solutions are optimal for all the results of architecture OCS-CN. For the other architectures, due to the high complexity of the formulations, CPLEX is not always able to prove that the retrieved solution is optimal, since it is stopped before for memory constraints. In that case, it reports a percentage gap that corresponds to the maximum difference between the estimated optimal power consumption value and the retrieved one. In the following, for any server setting, we report the gaps for the two architectures. However, in any case the percentage gaps are sufficiently small so that the comparison between architectures ***OCS-EN*** and ***SLPSN-EN*** is not impacted by the not proven optimality of the results. For example, if the consumption of ***OCS-EN*** is larger than the consumption of ***SLPSN-EN***, the estimated optimal solution of ***OCS-EN*** is always larger than the consumption of ***SLPSN-EN***.

3.5.1 Server with 8 TB storage and 20 Gbps bandwidth

In the first case we consider a server with maximum storage capacity of 8 TB and output bandwidth capacity of 20 Gbps. The average percentage gaps between the found and the estimated optimal solutions are for architectures ***OCS-EN*** and ***SLPSN-EN*** of 0.5% and 0.6% respectively.

3.5.1.1 Power consumption evolution

Table 2: Server storage capacity, output bandwidth and power consumption settings

Server settings case	Server storage capacity [TB]	Server output bandwidth [Gbps]	Power consumption [Watt]
a	8	20	421
b	2	20	375
c	2	100	375
d	2	100	1811

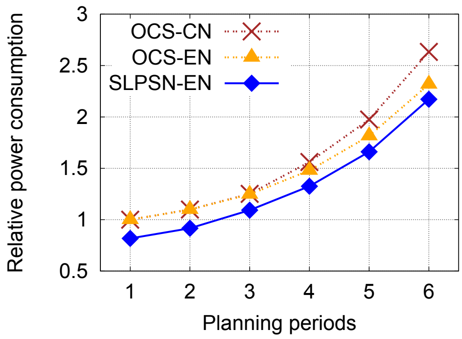


Figure 6. Power consumption evolution

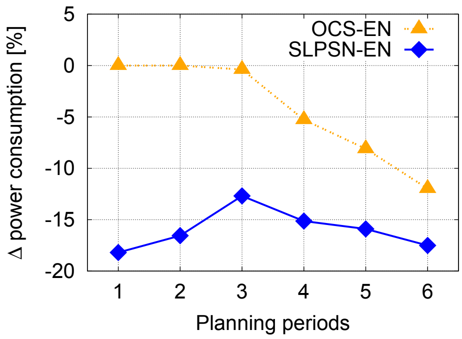


Figure 7. Power consumption percentage difference with respect to architecture OCS-CN

The power consumption evolution for the three architectures is shown in Fig. 6. Architecture ***OCS-CN*** is the most power consuming. Architecture ***SLPSN-EN*** achieves the best results reducing the power consumption in the range of 15 to 20% with respect to architecture ***OCS-CN***, as shown in Fig. 8.

In the first planning periods, until planning period τ_3, only ***SLPSN-EN*** can reduce the power consumption with respect to ***OCS-CN***. Architecture ***SLPSN-EN***, thanks to the sharing characteristics of its network interfaces, can indeed better aggregate the traffic exchanged among the ENs. This gain is slightly decreasing until period τ_3, since the larger traffic volume increases the aggregation efficiency of OCS technology.

From period τ_4, ***SLPSN-EN*** increases again the power savings with respect to ***OCS-CN*** and also architecture ***OCS-EN*** starts to find less power consuming solutions. In the last periods, the content demands volumes are sufficiently large to make advantageous the distributed allocation of storage resources. Indeed, architecture ***OCS-EN*** presents power consumption values similar to architecture ***OCS-CN*** in the first periods, when content demands volume is small.

Note that the solutions of architecture ***OCS-EN*** have power consumption values that are progressively closer to the values of architecture ***SLPSN-EN***. The larger traffic volumes are reducing the difference in the traffic aggregation efficiency between OCS and SLPSN technology. The advantage of SLPSN technology is still present and it can be measured with the gap between the results of ***OCS-EN*** and ***SLPSN-EN***.

3.5.1.2 Analysis of servers deployment

The number of servers and how they are located in the network is depicted in Fig. 8. In particular, for each planning period, referring to the left y-axis, histograms indicate how many servers are required for the three architectures. Each histogram bar indicates also how many servers are located at the CN (blue solid pattern) and at the ENs (green cross striped pattern). Referring to the right y-axis, the lines indicate how many nodes are equipped with servers for the different architectures.

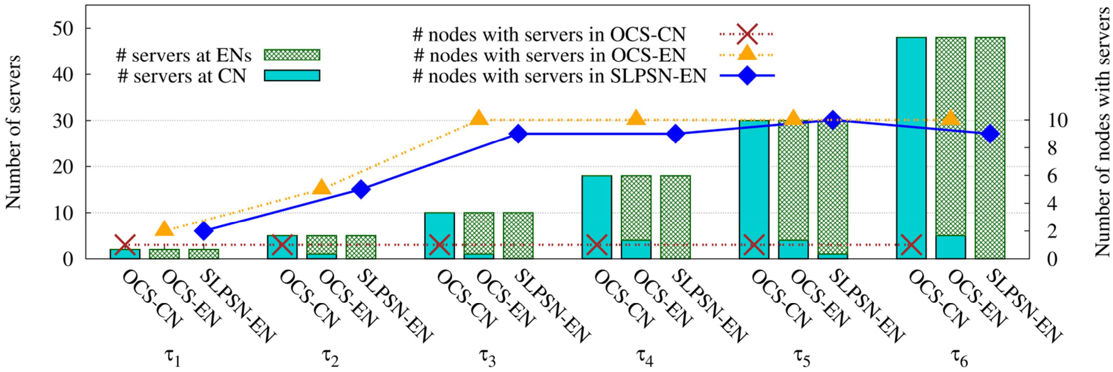


Figure 10. Number of servers deployed and their location

It is possible to notice that the number of servers is the same in each planning period for the three architectures. The number of servers is constrained by the output bandwidth capacity. The storage capacity is not impacting on the results since the entire catalogue (size equal to 4.5 TB) can be entirely stored in just one server (storage capacity of 8 TB). This is confirmed by Figs. 9 and 10 which show respectively the utilization of the server output bandwidth and of the server storage capacity. Note that in Fig. 9 the output bandwidth utilization is always very close to 100% of utilization, while in Fig. 10 the storage capacity utilization is largely below 100%. Furthermore, the utilization of the storage capacity decreases over time since the additional servers installed in the last planning periods are only due to the increase of the content demands volume that has been assumed in the traffic scenario. Furthermore, it is possible to remark that the output bandwidth utilization is the same for all architectures. The output bandwidth is exploited at maximum in order to minimize the number of servers, independently from the architecture considered. It is thus more convenient that the number of servers is minimized in order to minimize the power consumption. **Thus, with the current power consumption values, it is better to transport data than to store more data in the network increasing the number of servers.**

Fig. 8 indicates also how the servers are distributed in the network. In ***OCS-CN*** servers are obviously located at the CN. In architectures ***OCS-EN*** and ***SLPSN-EN*** the servers are instead usually positioned in different ENs. Distributing servers at different nodes permits to the ENs to directly retrieve most of the content from the servers reducing the transport traffic, and consequently the required network resources. In the case that servers are in number smaller than the ENs, we verified that servers are placed at those ENs that are characterized by the higher content demands volumes, ensuring in this way the highest possible reduction of transport traffic.

This analysis is confirmed by the content related traffic volumes that are exchanged in the network as shown in Fig. 10. The values are normalized with respect to the total content demands volume of the corresponding planning periods. In the case of architecture ***OCS-CN***, the content traffic volume is entirely transmitted by the CN to the ENs, while in ***OCS-EN*** and ***SLPSN-EN*** it is possible to notice that the exchanged content volumes decrease over time. As the number of servers in the network increases, the number of ENs with servers increases too and each EN can retrieve most of the content directly from the servers placed within it. Notice that the transit traffic is slightly larger

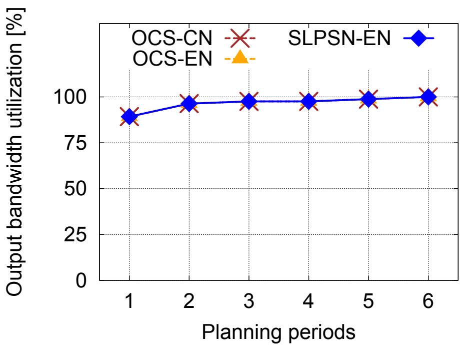


Figure 8. Utilization of the server output bandwidth

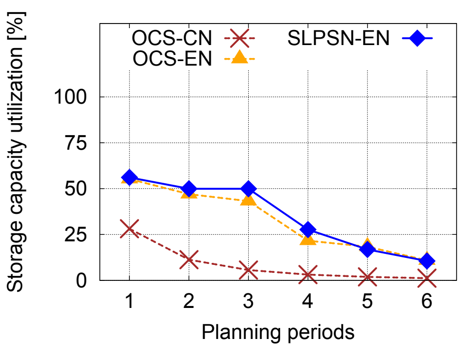


Figure 9. Utilization of the server storage capacity

in ***OCS-EN*** since traffic between ENs has to transit through the CN, while in ***SLPSN-EN*** it can go directly from source to the destination. For this reason, as you can see in Fig. 8, in architecture ***OCS-EN*** few servers are located at the CN in order to reduce the transit traffic at the CN, while in architecture ***SLPSN-EN*** the servers are seldom located at the CN since content can be directly sent

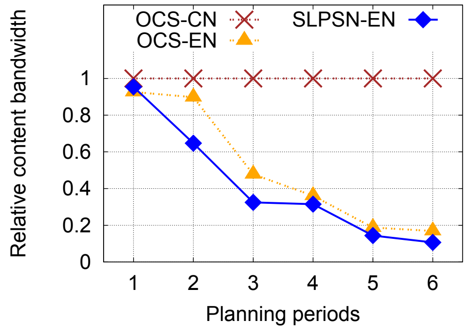


Figure 11. Content related bandwidth exchanged items among network nodes

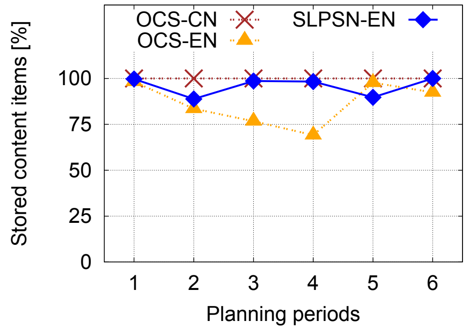


Figure 12. Avg percentage of content items stored in nodes with servers

between two ENs without creating transit traffic. Remember that the CN does not request content since it does not provide direct connectivity to users, but it is the node devoted to interconnect the ENs with the higher layers of the networks.

Some content traffic is however always present, even in the cases in which a server is placed in each node. Indeed, due to the granularity of the content traffic demands volumes, it can be better to retrieve content from other ENs exploiting the available transport capacity without causing an increase of the consumed power. This is confirmed by Fig. 12 which depicts the average percentage of content items stored in nodes with servers. Architecture ***OCS-CN*** has always 100% of content items stored since all content items are required to be stored at the CN. In architecture ***OCS-EN*** and ***SLPSN-EN*** the percentage values are often slightly below 100% since at the ENs some content items are retrieved from other ENs and not from the local servers.

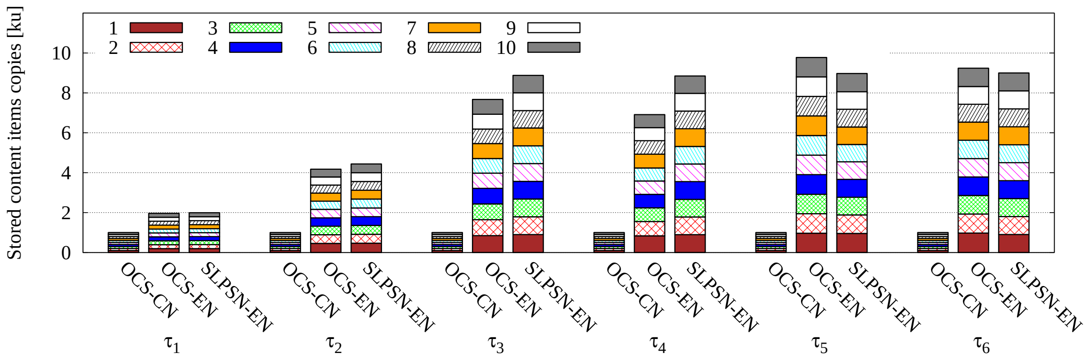


Figure 13. Number of stored content items copies divided in 10 popularity classes

3.5.1.3 Content items and popularity

The total number of content items copies stored in each architecture case is shown in Fig. 13. Each histogram bar divides the content items copies in 10 popularity classes in order to examine the impact of popularity on the content storage. Class 1 contains copies of the first 100 more popular content items, while class 10 contains the copies of the 100 less popular content items.

Architecture ***OCS-CN*** has only one copy stored for each content item, while in ***OCS-EN*** and ***SLPSN-EN*** several copies of the same content items are stored in the network, about one copy for each node with servers. There is not exactly a copy of each content item in each server since, as previously explained, not all content items are retrieved from each storage area.

As the storage capacity is not a constraint with this server configuration (i.e., a server can store the entire catalogue), the popularity is not influencing the storage of content items and the popularity classes have approximately the same number of copies stored, i.e., the number of copies stored for each content item is about the same for all content items.

In summary:

- For servers with 8 TB storage and 20 Gbps bandwidth, we have that
  1. the number of servers is minimized as much as possible; the chosen power consumption model makes more advantageous to transport a content item than to store it more times making to increase the number of servers
  2. The number of servers is constrained by the 20 Gbps output bandwidth and not by the storage capacity; as content traffic volume increases, more servers are installed in order to provide enough output bandwidth
- The distributed allocation of storage resources reduces the power consumption when content demands volumes are sufficiently large
  1. Servers are placed at the nodes with the largest content demands volume and the content related bandwidth exchanged among the nodes is reduced
  2. The required transport resources are thus decreased and energy is saved
  3. The power consumption reduction increases as servers are deployed at a higher number of nodes due to the growth of the content traffic volume
- We can conclude that just the minimum possible amount of data has to be stored in the network and that it is better to store it distributed at the network edges
- Architecture ***SLPSN-EN*** presents larger savings than architecture ***OCS-EN*** thanks to the more efficient traffic aggregation of SLPSN network interfaces, this benefit is larger for low traffic volumes
- The content popularity has no impact because the storage size of a server is larger than the catalogue size

3.5.2 Server with 2 TB storage and 20 Gbps bandwidth

The previous results are conditioned by the large availability of storage capacity. Indeed, a single server was able to store the entire catalogue. We then decide to investigate how the decrease of storage availability impacts on the network and storage resources dimensioning. We thus consider servers with a storage capacity of 2 TB, smaller than the catalogue size. The server power consumption has been modified accordingly, subtracting the power contributions of the exceeding Hard Disk Drives. In this server setting, the optimality percentage gaps are for architectures ***OCS-EN*** and ***SLPSN-EN*** of 1.9% and 1.7% respectively.

3.5.2.1 Analysis of servers deployment

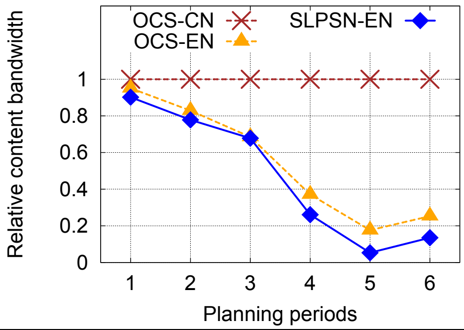


Figure 15. Content related bandwidth exchanged among network nodes

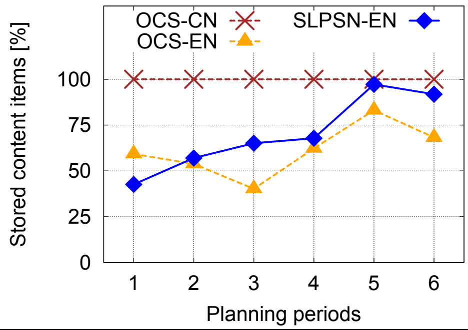


Figure 16. Avg percentage of content items stored in nodes with servers

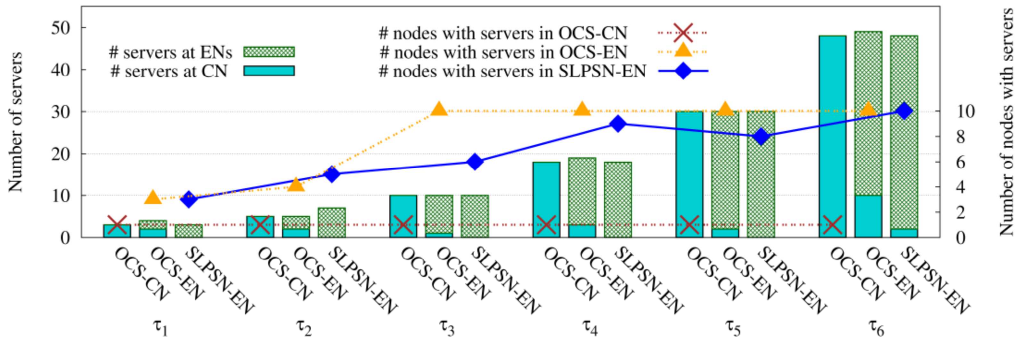


Figure 14. Number of servers deployed and their location

The number of servers employed and their location is shown in Fig. 14. In the first period the number of servers is slightly larger with respect to the previous case since at least three servers are required to store the entire catalogue. In architectures ***OCS-EN*** and ***SLPSN-EN*** the servers are located at different nodes and all the storage capacity is exploited in order to limit as much as possible the transport of content traffic. However, the overall exchanged content bandwidth is still very high in the first periods, as it is possible to notice in Fig. 15. If we compare Fig. 11 and Fig. 15, we can appreciate that the content bandwidth exchanged in periods 2 and 3 is now larger of about 20%. Indeed, in these periods the number of servers is still small and, in addition, the capacity of storage of each server is now very limited, resulting in a scarcer availability of content items and thus in an increase of the exchanged content bandwidth.

In the last planning periods, the number of servers required to satisfy the content related bandwidth becomes so high that there is available a large storage capacity. The server output bandwidth, as in the previous case, determines the number of servers and the results are similar to the previous case.

The average percentage of content items stored in a node with servers is reported in Fig. 16. In this figure, the impact of the reduced availability of storage resources is clear. In the previous case, almost a copy of each content item is stored at each node, while in this case the smaller server storage capacity limits the number of content items stored on average at each node. In the last periods, results are similar to the previous case since the required number of servers is as large as before.

3.5.2.2 Content items and popularity

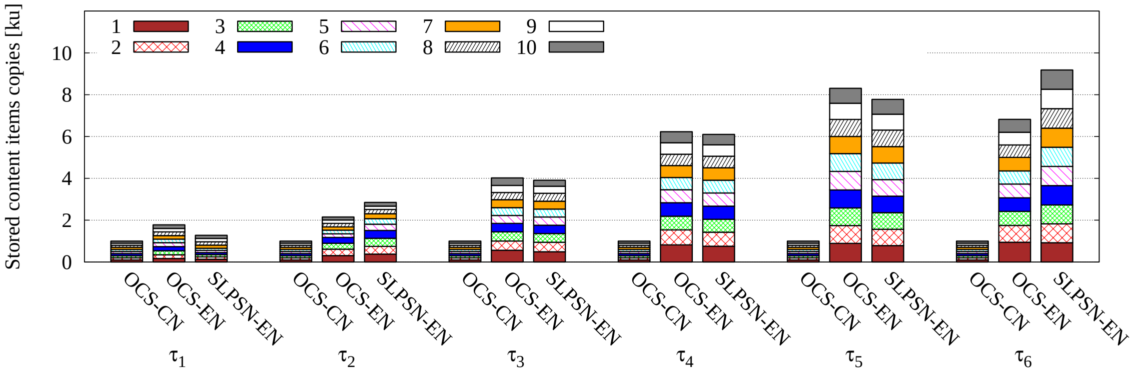


Figure 17. Number of stored content items copies divided in 10 popularity classes

The smaller storage capacity of the network in the first planning periods impacts also on the number of the stored content items copies. As it is possible to see in Fig. 17, the highest popularity class (class 1) has a slightly larger number of copies stored with respect to the less popular classes. In the last planning periods, as storage is not anymore constrained, the classes present almost the same number of stored copies.

In summary:

- In the first planning periods, when the storage capacity of a single server is smaller than the catalogue size
    1. The number of servers is increased to store all the content items
    2. The output bandwidth is not anymore a constraint
- In the following periods, as content demands volume increases, the output bandwidth is again constraining the number of servers
- The less availability of storage capacity in the first periods impacts on
    1. The content related bandwidth exchanged among the nodes, less content items can be stored at each node and the exchanged content bandwidth increases
    2. How content items are stored, the highest popular content items have a slightly larger number of copies stored in the network

3.5.3 Server with 2 TB and 100 Gbps setting and no power consumption update

We continue our analysis selecting a larger server output bandwidth in order to evaluate how the network and storage architectures are affected by increasing server output bandwidth and in the meanwhile keeping constant the content demands volumes. We decide to investigate this case since the previous results show that the server bandwidth was the main responsible for determining the number of required servers. We thus fix the server output bandwidth equal to 100 Gbps. In a first moment, we do not modify the power consumption value of servers in order to not change the relationship between the power cost of transporting and of storing data. In this case, CPLEX found solutions for architectures ***OCS-EN*** and ***SLPSN-EN*** that are respectively at most 2.7% and 5.7% larger on average than the estimated optimal solutions.

3.5.3.1 Power consumption evolution

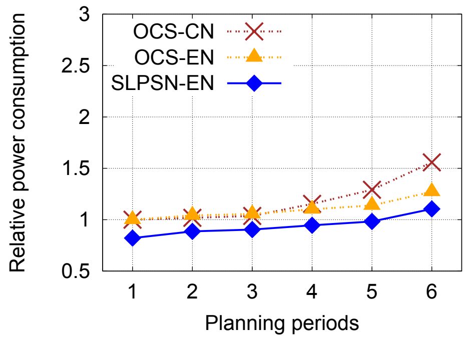


Figure 18. Power consumption evolution

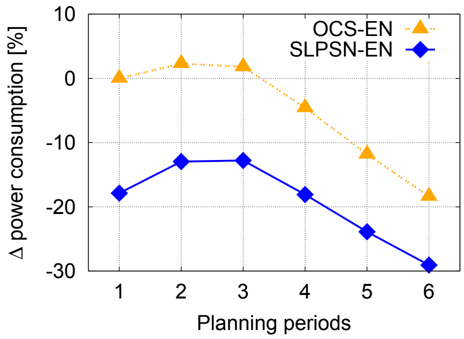


Figure 19. Power consumption percentage difference with respect to architecture *OCS-CN*

The power consumption for the three architectures, shown in Fig. 18, presents a better evolution for architectures ***OCS-EN*** and ***SLPSN-EN*** with respect to the previous examined server setting cases. Indeed, the power savings, illustrated in Fig. 19, are larger than 20% in the last planning periods where content demands volumes are significant.

3.5.3.2 Analysis of servers deployment

The larger server output bandwidth makes the number of required servers to decrease significantly, as shown in Fig. 20. The power contribution of servers is smaller with respect to previous cases making more evident the energy savings that architectures ***OCS-EN*** and ***SLPSN-EN*** can achieve thanks to the reduction of the required network resources.

The utilization of the output bandwidth, shown in Fig. 21, is in this case well below 100% for all planning periods, but the last two. Instead, we can notice in Fig. 22 that the server storage capacity is almost all used for all periods in the case of architectures ***OCS-EN*** and ***SLPSN-EN***. The number of servers is not anymore limited by the output bandwidth, but it is the result of the optimization process and it represents the best trade-off between the requirements of storage capacity and output bandwidth and the power consumed. Indeed, note that in some planning periods the number of servers for architectures ***OCS-EN*** and ***SLPSN-EN*** is larger than in the architecture ***OCS-CN***, meaning that it is better to store more data than to transport it. As the server bandwidth has been increased without changing the server power consumption, **we can consider that the power cost of storing data is now smaller than the cost of transporting data**.

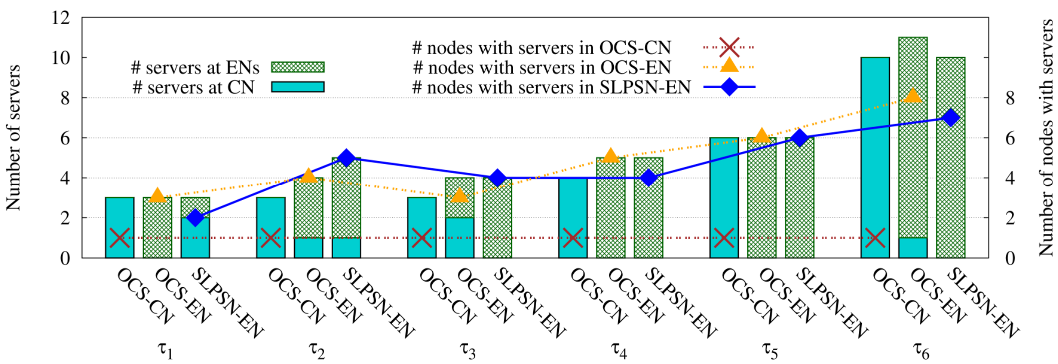


Figure 20: Number of servers deployed and their location

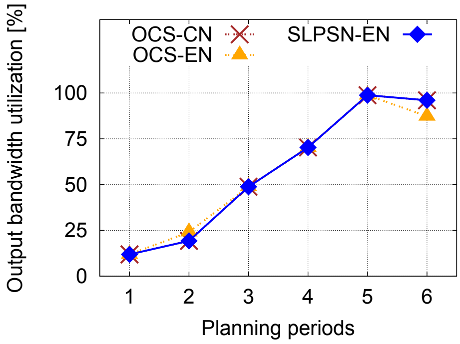


Figure 21: Utilization of the server output bandwidth

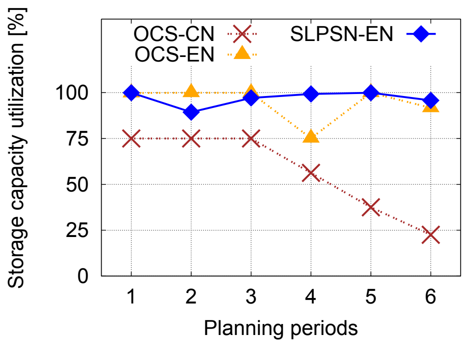


Figure 22: Utilization of the serverstorage capacity

These results are however influenced by the fact that server bandwidth has been increased without changing the server power consumption. In section 3.5.4 we evaluate what happen if the power consumption of servers is updated.

3.5.3.3 Content items and popularity

The limited storage capacity of the network impacts on the number of content items copies stored. In Fig. 23, it is possible to notice that the most popular content classes have a larger number of copies stored with respect to less popular classes. This difference is more evident with respect to the previous cases than before since, before, the storage capacity was not limited.

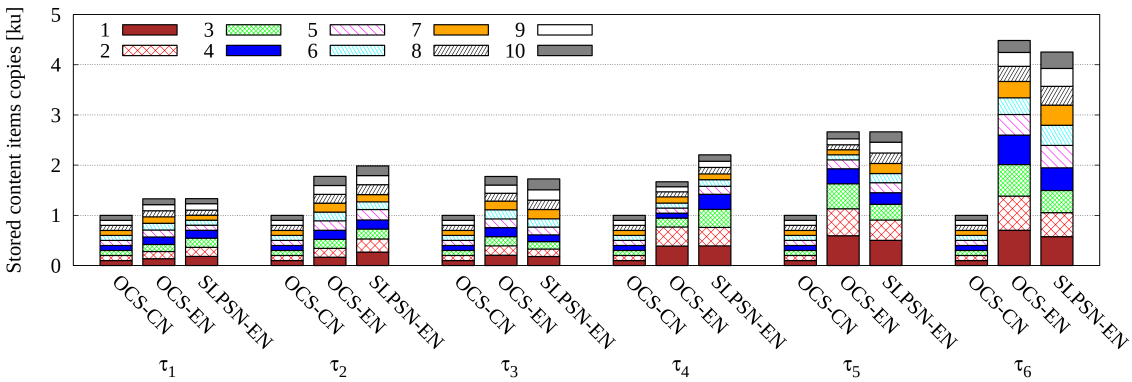


Figure 23: Number of stored content items copies divided in 10 popularity classes

In summary:

- The number of servers have been significantly reduced thanks to the 100 Gbps output bandwidth
- The power consumption model has not been updated to the new server configuration
    1. The relationship between the power cost of transporting and storing data is changed, now it is more advantageous to store more times a content item, at the cost of installing more servers, than to transport it
    2. The number of servers represents thus the best balance between power consumption and storage and output bandwidth requirements
- As the number of servers is significantly reduced for all the planning periods, the network storage capacity is much lower than before
    1. The content related bandwidth exchanged among the nodes is slightly increased due to the lower availability of content items
    2. The impact of the popularity on the number of stored copied is stronger

3.5.4 Server with 2 TB and 100 Gbps setting and new estimation of the power consumption

We then retrieve the results considering the same server setting of the previous case, 2 TB of storage capacity and 100 Gbps of output bandwidth, and updating the server power consumption. We consider that a server, in order to provide an output bandwidth of 100 Gbps, requires more network interfaces, processors and memory. We thus update the power consumption estimating that the load dependent components would consume in the 100 Gbps case five times the power consumed in the 20 Gbps case. Average gaps between retrieved and best bound solutions are respectively of 4.6% and 6.7% for architectures ***OCS-EN*** and ***SLPSN-EN***.

3.5.4.1 Power consumption evolution

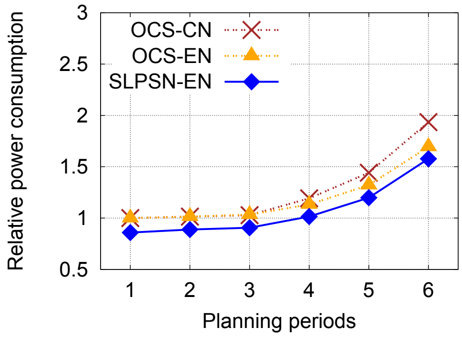


Figure 24: Power consumption evolution

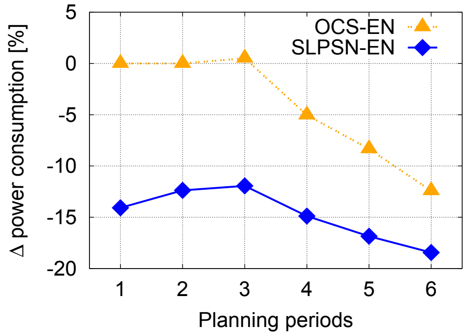


Figure 25: Power consumption percentage difference with respect to architecture ***OCS-CN***

The power consumption evolution for the three architectures presents a significant steeper increase with respect to previous cases, as shown in Fig. 24. The large power consumption of the servers strongly impacts on the overall consumption. The power difference percentages, Fig. 25, are again similar to the cases when power consumption of servers was set to with output bandwidth 20 Gbps.

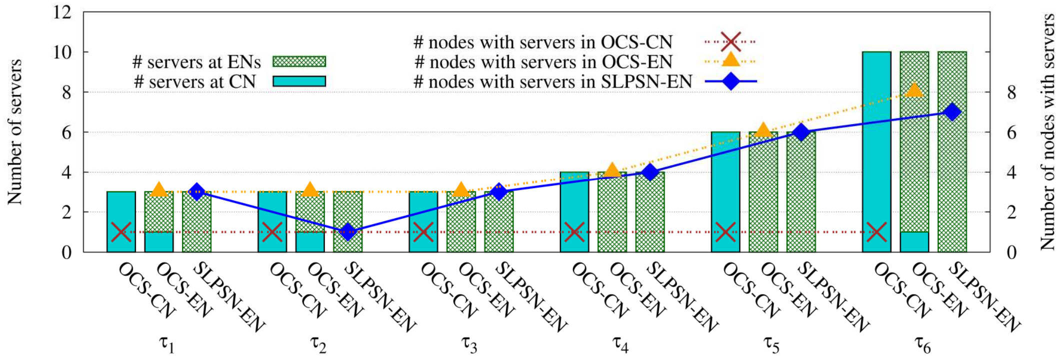


Figure 26: Number of servers deployed and their location

3.5.4.2 Analysis of servers deployment

The number of servers, in Fig. 26, is the same for all architectures in each planning periods. Their number is minimized in order to minimize the power consumption. The minimum number is determined by the requirements of the storage capacity or of the output bandwidth. The power cost of storing data is again larger than the power cost of transporting data, thus it is not any more convenient to store more data.

No significant differences are present for the other results with respect to the case with 100 Gbps server bandwidth and no power update.

3.5.4.3 Content items and popularity

The most popular classes present also in this case a larger number of stored content items copies with respect to less popular classes, as shown in Fig. 27. The difference in number of copies is significant as in the previous case.

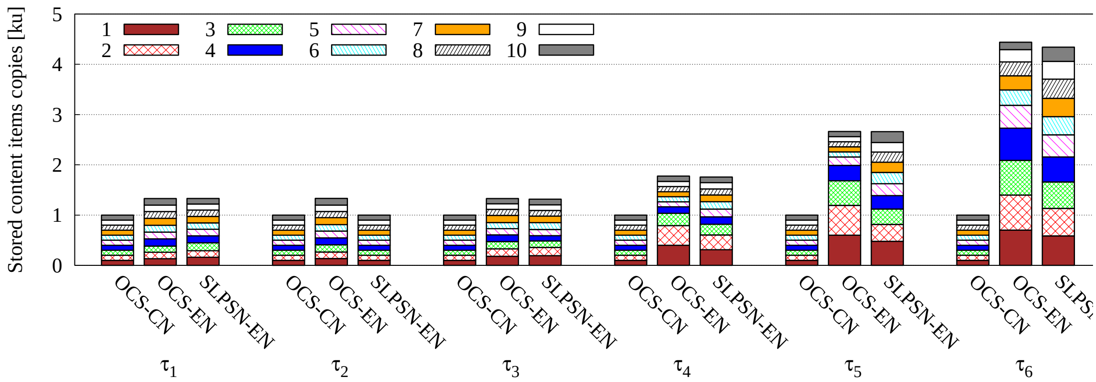


Figure 27: Number of stored content items copies divided in 10 popularity classes

In summary:

- The update of the power consumption model makes again more convenient to transport content items than to store more copies of them
  1. The number of servers is minimized to minimize the power consumption
  2. The storage capacity (first planning periods) or the output bandwidth (last planning periods) constrains the number of servers

3.6 Conclusions

In this study we examine a possible evolution of traffic volumes in metro networks. We consider the case in which a content on demand service is managed by the ISP and we evaluate three different network and storage architectures. The architecture ***OCS-CN*** is the legacy architecture having only OCS interconnections between the CN and the ENs. Architectures ***OCS-EN*** and ***SLPSN-EN*** are characterized by the possibility to locate servers also at the ENs. The first has still OCS interconnections between the CN and the ENs, while the latter has all nodes interconnected by SLPSN logical links. We examined different cases in which servers are characterized by different storage capacity, output bandwidth and power consumption values.

The design of the network and storage architecture is strongly influenced by server characteristics: *i)* the storage capacity, *ii)* the output bandwidth and *iii)* the power consumption. The number of servers has to be sufficiently large to store the entire catalogue and to provide enough output bandwidth to satisfy all content demands. Given that these two requirements are satisfied, the number of servers for architectures ***OCS-EN*** and ***SLPSN-EN*** is determined by the relationship between the server power consumption and the power consumption of transporting data. If the power consumption for storing data is less than the transport power consumption, architectures ***OCS-EN*** and ***SLPSN-EN*** store more data than ***OCS-CN*** and this results in installing more servers, otherwise the same number of servers is installed for all architectures.

The distribution of contents at the ENs is advantageous, in particular, when content demands volumes are large. Positioning servers at the network edges reduces indeed the amount of network resources required to transport the traffic and decreases the overall power consumption.

4 Conclusions and perspectives

In conclusion, architectures ***SLPSN-EN*** presents better performance with respect to architecture ***OCS-EN*** at low traffic volumes thanks to the sharing capabilities of the SLPSN interfaces. It is possible to reduce the number of network interfaces since the traffic and content bandwidth exchanged among the nodes can be better aggregated improving the interfaces utilization. At higher traffic demands volume, the efficiency of OCS is improved and the benefits introduced by ***SLPSN-EN*** interfaces are reduced.
All-in-all, depending on the traffic volume and distribution, the energy consumption improvement allowed by **SLPSN-EN** over the legacy architecture ranges between 15% and 20%.

What about the global network picture?
In a working document [12], we showed that the energy consumption of transport networks increases proportionally with the traffic increase. The absolute values are much lower than what can be observed in the access or for the data center, which makes this segment not so critical today. However the exponential increase of traffic volume observed in this segment may change the situation. It is thus important to keep on improving even in this segment. First this has led to the increase of the switching capacity of machines with huge power consumption and high demand on the electricity supply. In order to make this increase acceptable both for a green and electricity bill issue, equipment makers improve continuously the efficiency of their products. Several other axes of improvement were suggested. Among them technological breakthrough and energy efficient architectures can permit greater network efficiency. This is what we demonstrated in this work. Further improvement may come from optical switching technologies such as burst switching. This could permit to benefit from the capability of optics in terms of high capacity and reach and of statistical multiplexing, resulting in a better usage efficiency of interfaces and in general of resources.

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