Energy-Efficient Baseband Unit Placement in a Fixed/Mobile Converged WDM Aggregation Network

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I. Introduction

ENERGY efficiency is gaining more and more importance as a fundamental driver of the technological progress, for both economic and environmental reasons. During the last decade, thanks to the prominent role that the Internet has gained in our society, the Information and Communication Technology (ICT) have been experiencing an impressive evolution. As a collateral consequence, the impact on human energy consumption has been evolving at the same rate. Today, it is estimated that ICT accounts for roughly 1–2% of the worldwide energy consumption [1]. Today the majority of energy consumption of the Internet is consumed in fixed and mobile access and backhaul (i.e., aggregation) networks, and it is forecast to be dominant also in next years [2]. This represents a relevant issue for network operators, which already have to cope with old infrastructures exhibiting low cost efficiency and capacity bottlenecks. Therefore, such networks must evolve in a disruptive way, in which not only costs reduction, but also energy efficiency must play a central role as design metric.

Fixed/mobile convergence (FMC) is thought to be the most promising paradigm for achieving energy efficiency in access. Although FMC can be generally applied in many different flavors and at various network levels, in this work we intend it as infrastructural convergence. It means that a single network infrastructure becomes a shared facility devoted to the transport of both fixed and mobile access/aggregation traffic towards the metro/core gateway site. Thanks to the mutualization of infrastructure and hardware, like cable plants, cabinets, equipment, sites and buildings, a better utilization of resources can be achieved. This improvement leads not only to a substantial reduction of deployment (CapEx) and operational (OpEx) costs, but also enables higher energy efficiency, because different active (i.e., power-supplied) devices can share housing facilities.

Among the different FMC access/aggregation network technologies under research, optical networks based on Wavelength Division Multiplexing (WDM) are the most promising. Indeed, they ensure a truly future-proof capacity provisioning, but also enable energy efficiency thanks to the employing of transparent wavelength router nodes. In fact, they are able to switch “lightpaths” directly in the optical domain, i.e., without performing power-consuming electronic traffic processing and optical/electro/optical (OEO) conversions. In addition, a common belief is that they will probably follow the same evolutionary steps of core networks, e.g., with more complex nodes architectures and the possibility of efficiently grooming sub-wavelength connections into single wavelengths, towards multi-stage and partially-meshed topologies. As a consequence, they will inherit some powerful features of core networks, like failure resilience, scalability and reconfigurability [3].

An FMC access/aggregation infrastructure is expected to support several mobile backhauling solutions. Among those, BBU hotelling (or hosteling) [4], [5] is a recent solution which radically changes the classical architecture of radio access networks. It consists in separating mobile baseband units (BBU) from corresponding Remote Radio Heads (RRH),

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and consolidating them into common locations, also known as "hotels". Each BBU/RRH pair exchanges Digital Radio-over-Fiber (D-RoF) data, also known as "fronthaul", obtained from the baseband digitization of radio interface signals. Some open interfaces have been specified for transporting such data on optical links. The most popular is the Common Public Radio Interface (CPRI) [6]. Thanks to the sharing of backplanes, power, computational and maintenance resources of BBUs hosted in the same hotel, a relevant amount of energy saving can be achieved by adopting this mobile backhauling architecture.

II. RELATED WORK AND CONTRIBUTION OF THE PAPER

In general, as pointed out in [7], the WDM technology enables to implement energy-efficient network architectures directly at the design stage. An example of this approach is given in [8], where four IP-over-WDM architectures for core/backbone networks are analyzed, showing that the highest energy efficiency is obtained by avoiding electronic processing at intermediate nodes, thanks to the use of transparent architectures, which enable transit traffic to be "bypassed" directly in the optical domain (optical bypass). Shifting the focus on access networks, in [9] the authors show that optical access solutions based on Passive Optical Networks (PON) are more energy-efficient with respect to classical point-to-point active optical networks, in terms of consumption per average access bit rate. For this reason, WDM-PON solutions appear as the ideal candidate for next-generation optical access/backhaul networks. Differently from core/backbone networks, most of ongoing research regarding WDM-PONs focuses on energy savings that are achievable by properly exploiting network adaptation to instantaneous traffic load variations. For instance, in [10] the authors propose some power management schemes that allow to get about 40% of energy savings, by dynamically putting in sleep mode some Optical Line Termination (OLT) cards during low-traffic periods of the day. When dealing with FMC networks, similar considerations can be combined with architectures that are optimized for the particular features required by mobile backhaul networks. For instance, in [11] the energy efficiency of a converged wireless/optical access network is evaluated, where the wireless part coverage is given by LTE femtocells and the optical backhaul consists of PON technology. The results show that relative higher energy savings (around 10–27%) can be achieved by utilizing low-power modes in urban-suburban scenarios. In [12] some energy efficient design schemes and bandwidth-allocation mechanisms are investigated for long-reach converged fiber/wireless networks. Specifically, an evolved dynamic bandwidth allocation scheme is proposed for an architecture based on low-energy states ONUs, that leads to a decrease of the energy consumption up to about 0.3 kWh per day and per ONU belonging to the optical back-end (relative reduction of 25%), with respect to conventional schemes.

As first contribution of this paper, we introduce and describe a FMC aggregation optical network based on WDM, in which the concept of BBU hotelling is employed. As second one, we devise for such architectures a novel energy efficient BBU placement optimization problem. A preliminary work has been carried out in [13], where a simple multi-stage WDM-PON is considered as FMC network and the number of deployed hotels is minimized. In this paper, the aggregation network is optimized by minimizing an ad-hoc performance indicator, the aggregation infrastructure power (AIP), and taking into account that some nodes can perform optical bypass and/or active (electronic) traffic aggregation of sub-wavelength traffic demands. Finally, to quantify the tradeoff among BBU consolidation, optical bypass and active aggregation, we propose three different network architectures and compare them in terms of AIP and other defined metrics.

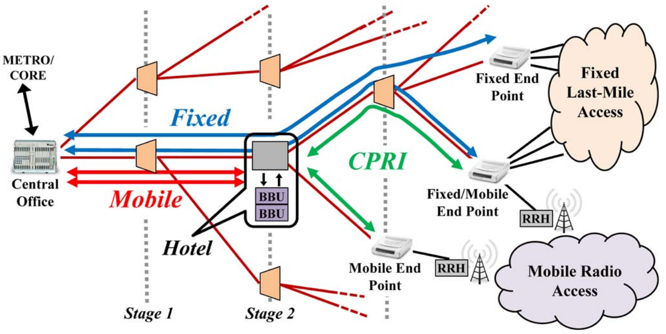

Fig. 1. Illustrative example of a FMC WDM aggregation network, employing BBU hotelling.

The remainder of this paper is organized as follows. In Section III, the network scenario is introduced, three different network architectures are presented and the power consumption model is described. In Section IV, the energy efficient BBU placement problem is described and formalized as an Integer Linear Programming model (ILP), for each architecture. In Section V, the case study is introduced and the simulation results are presented and commented. In Section VI, the conclusion of the paper is given.

III. NETWORK ARCHITECTURE AND POWER MODEL

In this section, we start by giving a description of the basic features of the considered WDM aggregation network. Then, we stress the importance of the Maximum CPRI Route Length constraint, which is fundamental for our problem. We continue by describing in detail three proposed architectures for BBU hotelling on such network. We conclude by detailing the power consumption model which is used in the formalization of the problem.

A. *FMC Aggregation Network Scenario*

As depicted in Fig. 1, our scenario is a metropolitan area that is covered and served by a FMC WDM aggregation network, whose terminal nodes are the "end points" and the Central Office (CO). The end points act as demarcation points between the aggregation network and the access network. We assume three typologies: Fixed End Points, which collect the traffic of various kinds of last-mile fixed access technologies (e.g., xDSL, TDM-PON); Mobile End Points, which collect the traffic generated by cell (or antenna) sites; and Fixed/Mobile End Points, which aggregate both kind of traffic. As a consequence, such end points represent the clients which require to the FMC network the end-to-end transport service toward the CO. Their geographical location is considered given and independent from our problem. We consider an already deployed infrastructure of optical fiber links which provides connectivity between each end point and the CO, through a set of intermediate nodes placed at given locations. Each couple of nodes is connected by one pair of monodirectional fiber links, providing a certain capacity divided among a number of WDM channels, or wavelengths, in both directions. We give no further assumption on the given topology, i.e., the fiber infrastructure may be a common multi-stage tree (also known as branch-and-tree), or a multi-stage ring (ring-and-spur), as well as whatever hybrid partially meshed topology. This choice is due to the fact that, although today typically standard-reach tree-based topologies are considered for the implementation of BBU hotelling architectures, in next future, to ensure greater coverage areas, longer-reach networks might be considered as well. For these kinds of networks, the resiliency to links and node failures has more importance, therefore path- and node-redundant topologies are considered as more valid alternatives. Being the fiber infrastructure given, the degree of freedom is the implementation of nodes, depending on where BBUs are placed and which traffic requests must be satisfied.

In general, a FMC aggregation network offers a transport service for both mobile backhaul and fixed IP traffic. However, since in our case BBUs are in general detached from corresponding cell sites, there are actually two classes of mobile backhaul: IP mobile backhaul, which is the well-known packet traffic between the central office and each BBU uplink interface; and D-RoF backhaul, or fronthaul, consisting in constant bitrate (CBR) CPRI flows among each BBU and the respective RRH located at cell site. For simplicity, from now on we refers to the three classes of transported traffic respectively as: Fixed, Mobile, CPRI (see Fig. 1) For all these kinds of traffic, we assume a common Ethernet-over-WDM transport, therefore each node terminating traffic is equipped with an Ethernet switch featuring both long-reach point-to-point WDM interfaces and short-reach interconnection interfaces. In such a way, switches are also capable of multiplexing different IP and CPRI flows into few wavelengths, pushing toward a reduction of the number of used WDM interfaces and consequently energy savings.

B. Maximum CPRI Route Length

Differently from IP backhauling, CPRI traffic is much less tolerant to jitter accumulated along the transmission chain.[1] For this reason, we impose that each CPRI flow must be routed on a single end-to-end lightpath, therefore it can not be split among parallel paths and it can not be processed by intermediate electronic switches.

Another important feature of CPRI traffic is that each flow can tolerate up to a maximum value of end-to-end latency, as a consequence of the timing constraints imposed on radio interface physical layer procedures [13]. When measured between the transporting WDM circuit endpoints, such value depends on the processing time budget available for the ACK/NACK response of a radio frame (standard dependent), and the elaboration delays due to DAC/ADC, L1/L2, CPRI interface adaptation, and Ethernet switches processing (technology dependent).

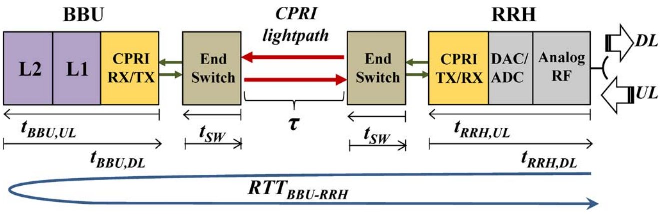

Fig. 2. Delay contributions of $RTT_{\text{BBU-RRH}}$ along the CPRI signal processing chain.

Specifically, considering for instance the LTE FDD radio interface, there is an upper limit of 3 ms [14] to the BBU-RRH round trip latency $(RTT_{\text{BBU-RRH}})$, defined as the sum of all uplink (UL) and downlink (DL) processing times (t) of BBU and RRH, plus the processing times of switches at both endpoints $(4t_{\text{SW}})$, plus the round trip propagation delay (2τ) (see Fig. 2):

$$\begin{aligned} RTT_{\text{BBU-RRH}} = 2\tau + t_{\text{RRH,UL}} + t_{\text{BBU,UL}} + t_{\text{BBU,DL}} \\ + t_{\text{RRH,DL}} + 4t_{\text{SW}} \leq 3\text{ ms} \end{aligned} \quad (1)$$

In this framework, all these processing delays are fixed, because purely technology-dependent. Therefore, the maximum $RTT_{\text{BBU}-\text{RRH}}$ directly translates to a maximum admissible one-way propagation delay for every CPRI flow $(\tau \leq T_D)$, or, equivalently, to a maximum length of its route $(L \leq L_D)$. In such a way, a Maximum CPRI Route Length constraint must be explicitly taken into account in our optimization problem, whenever physical lengths for all links are given.

Values of L_D which typically range from 20 to 40 km are reported in the recent literature [15]. We remark that, when BBU hotelling is applied in our network scenario, the practical values might also be smaller, due to the fact that CPRI flows are transported over the Ethernet layer. Also, physical channel impairments introduced along the optical path can pose further severe limitations to CPRI flows. We argue that, since CPRI flows consist of digital data, the channel impairments basically have impact on the BER, so they can be properly compensated by more complex signal processing, leading to increased processing times, thus lower values of L_D.

C. The Three Network Architectures

In the view of energy analysis, we classify all nodes into two categories: active nodes, which are equipped with at least one power consuming device, and passive nodes. By definition, terminal nodes and intermediate nodes equipped with one or more BBUs are active, because they terminate, route and process traffic in the electrical domain. Intermediate nodes which do not terminate any traffic are made up only of transparent wavelength routers and mu/demultiplexers, hence they are passive. Their specific implementation depends on factors that are out of the scope of the present study (e.g., cost budget, degree of reconfigurability). For sake of simplicity, we model them as capable of routing any wavelength to any output.

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[1] The transport of CPRI flows over Ethernet is a very challenging task today. However, upcoming standard evolutions (e.g., Synchronous Ethernet) and technical advances go towards such direction.

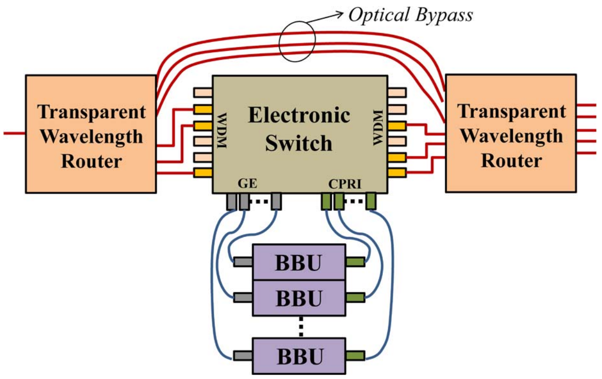

Fig. 3. Implementation detail of an active intermediate node, i.e., equipped with a BBU hotel.

According to the ways BBUs are placed and active intermediate nodes can be implemented, we consider three different network architectures.

1) *Bypass*. Each BBU can be placed in any node. For intermediate nodes, this implies they become active and also equipped with an electronic switch that terminates and aggregates all traffic destined to the BBU hotel. Remaining transit traffic is bypassed directly in the optical domain (the node is optically transparent to transit traffic).
2) *Opaque*. Each BBU can be placed in any node. For intermediate nodes, this implies they become active and equipped with an electronic switch that terminates and aggregates all passing traffic, included traffic which is not destined to the hosted BBUs (the node is optically opaque to all traffic).
3) *No-Hotel*. Hotelling is not performed, i.e., each BBU is placed in its cell site. Therefore, all intermediate nodes are passive and active aggregation can be only performed end-to-end.

The implementation detail of an active intermediate node is depicted in Fig. 3. An electronic switch is equipped with both long-reach interfaces, i.e., WDM, and short-reach interfaces, i.e., Gigabit Ethernet (GE) and CPRI. The incoming lightpaths are mu/demultiplexed by wavelength routers and enter the switch via the WDM interfaces. IP traffic destined to a hosted BBU is extracted and sent over the GE port, while the D-RoF (fronthaul) is collected by the switch from the CPRI interfaces, to be mapped into one or more output lightpaths. In case of Bypass architecture, transit traffic flows can be optically bypassed, by directly connecting the two wavelength routers. In case of Opaque architecture, all incoming lightpaths are terminated and processed by the switch.

D. Power Consumption Model

For the energy efficiency analysis of the proposed FMC architectures, we introduce as performance indicator the Aggregation Infrastructure Power (AIP). It is defined as the sum of the power contributions of solely the equipment that can be considered as part of the aggregation infrastructure. Specifically, the AIP includes two kinds of contributions. The first one comes from all aggregation network devices, i.e., end switches (placed at the CO and at the end points of the network) and intermediate switches (placed in intermediate hotel nodes). The second contribution is caused by the "housing" equipment, which does not perform network functions, but is needed by the infrastructure for guaranteeing the proper operational conditions (mostly, power supplying and cooling systems). The contributions by mobile access devices (BBUs and RRHs), fixed access devices (e.g., DSLAMS, PON OLTs) and CO gateways (interfacing with core network) are not included in the AIP, because they are not part of the aggregation network, but clients of it.

For all the switches, a common power model is adopted, namely a universal scalable switch model. The consumption is modeled as the sum of a baseline (traffic-independent) term, plus a variable quantity which is linearly proportional to the number n_p of ports configured as active.

$$P_S = P_{S,0} + K_S \cdot n_p \tag{2}$$

Only long-reach interfaces (WDM) are considered in the port count (n_p), with a proportionality coefficient equal to $K_S = 15$ W/Port, which includes the term due to the WDM transceiver and an additional allowance for the smaller consumption of short-reach interfaces (GE, CPRI) [16]. The baseline is fixed to $P_{S,0} = 50$ W, including also the term due to embedded cooling systems (typically small fans).

Regarding the power consumption of housing systems, we assume different models, according to the typology of node. Fixed End Points can be deployed as compact premises which do not require external housing resources (beyond that included in the baseline consumption), due to the relatively small size of hosted network equipment, hence we assume zero housing consumption for this kind of nodes. For the same reason, also Mobile End Points with no located BBUs do not require housing power (RRHs are stand-alone devices directly located at the antenna mast). Mobile End Points equipped with BBUs (conventional BS with no hotelling) exhibit a housing contribution which is basically dominated by the BBU. A value equal to $P_{H,\mathrm{BBU}} = 600$ W is assumed, by considering a typical cell-site BBU under mid-to-high load condition, which consumes in average 750 W, and with a PuE (Power Usage Effectiveness) around 1.8.

The housing power model of intermediate hotel nodes is assumed as the sum of a baseline contribution and a variable term.

$$P_{H,I} = P_{H,I,0} + K_{H,I} \cdot n_{\mathrm{BBU}} \tag{3}$$

The baseline contribution is $P_{H,I,0} = 500$ W, needed for the housing of the shared facility in which the BBU hotel and the intermediate switch are located [17]. According to the power model of switches and their relatively lower power consumptions (with respect to BBUs), intermediate switches can benefit from the shared power supplying system of the facility and, since they are typically equipped with built-in cooling fans, their required housing power can be considered as embedded in the 500 W value and fairly independent from their traffic load. The variable term is proportional to the number of hosted BBUs (n_{BBU}), via the coefficient $K_{H,I} = 100$ W/BBU.

TABLE I
SUMMARY OF POWER MODEL PARAMETERS AND THEIR VALUES

Description	Parameter	Value
Switch: baseline	$P_{S,0}$	50 W
Switch: variable	K_S	15 W/Port
Housing of stand-alone BBU	$P_{H,\text{BBU}}$	600 W
Housing of interm. hotel: baseline	$P_{H,I,0}$	500 W
Housing of interm. hotel: variable	$K_{H,I}$	100 W/BBU

It is worth noting that, for each hosted BBU, a considerably smaller amount of power is needed for housing, with respect to the stand-alone case, because the devices can benefit from the shared housing resources whose consumption is already taken into account in the baseline term. The described housing model takes into account the "scale" gain due to the consolidation of network elements into few nodes, which is one of the principles pushing towards infrastructural convergence. Finally, the housing contribution of the CO is not considered in our scenario, because the aggregation switch and the optionally colocated BBUs are placed into an existent equipment room, with a negligible impact on the overall housing power. As a consequence, their power consumption is fixed and independent from the network architectures that we intend to compare. A summary of all the described power model parameters with their values is given in Table I.

IV. ENERGY EFFICIENT OPTIMIZATION PROBLEM

Establishing which of these FMC aggregation architectures is most energy efficient is not a trivial task. In fact, the following observations can be done:

- the No-Hotel architecture has the smallest number of active nodes (only terminal nodes), but with respect to the others, it offers no energy savings deriving from the consolidation of multiple BBUs into single hotels;
- for every intermediate hotel node, the power consumption due to electronic processing in the Opaque case is greater than in the Bypass case, because a greater amount of traffic must be terminated and processed. However, a more efficient aggregation of the traffic towards the CO can be performed, leading to a potential reduction of the number of wavelengths, with a consequent reduction of power.

Therefore the question is: in such FMC network, how and how much do BBU consolidation, optical bypass and active aggregation in intermediate nodes impact on overall energy efficiency? To answer this, for each of the three proposed architectures, we define an optimization problem as follows.

Given: the network topology (nodes connectivity and links lengths), the set of traffic demands, the links capacity (number of wavelengths), the traffic capacity (bitrate) of each wavelength, the maximum number of BBUs that can be hosted in each intermediate active node (hotel capacity), the Maximum CPRI Route Length (L_D), and the power consumption contributions relative to network devices and housing systems;

decide: the placement of each BBU (for Bypass and Opaque architectures), together with the Grooming, Routing and Wavelength Assignment (GRWA) of all traffic demands;

to minimize: the aggregation infrastructure power (AIP), as previously defined.

The defined problem can be interpreted as a non-trivial combination of two well-known network optimization problems, namely the Grooming, Routing and Wavelength Assignment (GRWA) [18], and the Facility Location Problem (FLP) [19]. However, here the two problems are not independent, since the placement of BBUs influences both the source/destination nodes of mobile and CPRI traffic and consequently their routing. In addition, the different transport requirement for CPRI flows makes the problem more complex and valuable.

A. ILP Formulation

For each defined network architecture, we formalize the optimization problem through an Integer Linear Programming (ILP) formulation. It operates on a double-layer network graph, composed by a set N of nodes and two sets, E and V, of directed arcs between couples of nodes. E defines the lower-layer topology of physical fiber links (m,n) laid from node m to node n. V defines the upper-layer topology of virtual links (i,j) representing end-to-end connectivity between nodes equipped with electronic switches, by means of lightpaths established from i to j.

A generic IP (mobile or fixed) traffic demand from a source to a destination node is routed in the upper layer over a sequence of virtual links. Each virtual link provides a certain capacity that can be shared among other requests, thanks to aggregation performed by switches endpoints. Every virtual link is routed in the lower layer over physical links as a number of lightpaths. To reduce end-to-end packet jitter, the routing over virtual links is assumed to be non-bifurcated, i.e., a switch can not split the connection among different virtual links. On the other hand, the routing over physical links can be bifurcated in more lightpaths, because the jitter due to different optical paths can be neglected for this class of traffic.

For CPRI connections, since they are subject to the Maximum CPRI Route Length constraint, we introduce a kind of delay-limited lightpaths, or D-lightpaths. Each D-lightpath has a propagation delay not bigger than a maximum value, derived from the CPRI constraint. Because of the strict synchronization jitter requirements, we impose that every CPRI flow can be directly routed only over a single D-ligthpath, thus it can be neither bifurcated, nor processed by intermediate switches. A very important feature of the proposed model, which pushes towards convergence, is that D-lightpaths are not exclusively reserved for CPRI flows, in fact the spare capacity of D-lightpaths can also be filled by IP requests, improving the overall aggregation efficiency. To reduce the model complexity, the physical paths of all D-lightpaths are pre-computed, and the routing of each CPRI flow simply consists in associating a D-lightpath with it (as for a path formulation).

For sake of simplicity, we assume that each connection request is symmetric, i.e., it requires the same traffic in the downstream and upstream direction. Therefore, we can formalize and solve the problem considering only one direction (e.g., downstream) and the results are straightforwardly replicated in the other one. The case of asymmetric requests can be derived from this formulation with no difficulty.

B. Input Data

- N is the set of nodes, partitioned into: the central office $\{\text{CO}\}$, the subset N_I of intermediate nodes, the subset N_U of network end points. Fixed End Points belong to $N_F \subseteq N_U$, Mobile End Points belong to $N_M \subseteq N_U$, Fixed/Mobile End Points belong to $N_M \cap N_F$.
- E is the set of physical links, indexed by (m, n), with m, $n \in N; m \neq n$.
- V is the set of virtual links, indexed by (i, j), with i, $j \in N; i \neq j$.
- R is the set of connection requests, partitioned into: the subset $R_{\text{IP},M}$ of IP mobile requests, the subset $R_{\text{IP},F}$ of IP fixed requests, the subset R_{CPRI} of CPRI requests. For each request $r \in R$, $k(r) \in N_U$ is the associated end point, $t(r)$ is the requested traffic.
- Λ is the set of wavelengths, indexed by λ.
- C is the traffic capacity of each wavelength.
- B is the BBU capacity of each active node.
- L_D is the Maximum CPRI Route Length, thus the maximum length of D-lightpaths.
- l_{mn} is the length of physical link (m, n).
- $H_{\text{IN}}(n) = \{m \in N | (m, n) \in E\}$ is the set of incoming adjacent nodes of n, with respect to the physical topology.
- $H_{\text{OUT}}(n) = \{m \in N | (n, m) \in E\}$ is the set of outgoing adjacent nodes of n, with respect to the physical topology.
- $H^V_{\text{IN}}(i)$, $H^V_{\text{OUT}}(i)$ are the equivalent sets defined for the virtual topology.
- $\mathcal{M}$ is a very big positive number.

C. Pre-Computed Data

All the D-paths, i.e., physical paths of total length not exceeding L_D, are derived from the physical topology. For each pair of end nodes (i, j), with $i \neq j$, a number Ω_{ij} of D-paths is obtained, which are indexed by $\omega \in \{1, \ldots, \Omega_{ij}\}$. Each triplet (i, j, ω) univocally identifies a D-path, and the set $Q_{ij\omega} \subseteq E$ contains all the physical links composing its route. The set of all enumerated D-paths is denoted by D. Therefore, the following holds:

$$\sum_{(m,n)\in Q_{ij\omega}} l_{mn} \leq L_D; \quad \forall\,(i, j, \omega) \in D \tag{4}$$

D. Decision Variables

- $P^{ij}_{mn\lambda} = 1$, if virtual link (i, j) comprises a lightpath routed over physical link (m, n), on wavelength λ (binary).
- $v_{ij\lambda} =$ number of established lightpaths on wavelength λ composing virtual link (i, j) (integer).
- $Y^r_{ij} = 1$, if the IP request r is routed over virtual link (i, j) (binary).
- $\overline{v}_{ij\omega\lambda} = 1$, if D-ligthpath (i, j, ω, λ) is established, i.e. routed over D-path (i, j, ω), on wavelength λ (binary).
- $\overline{Y}^r_{ij\omega\lambda} = 1$, if the CPRI request r is routed over D-lightpath (i, j, ω, λ) (binary).
- $x^k_i = 1$, if the BBU of Mobile End Point $k \in N_M$ is placed at node $i \in N$ (binary).
- $w_i = 1$, if a hotel is installed in intermediate node $i \in N_I$, i.e., with at least one hosted BBU.

E. Aggregation Infrastructure Power Minimization

The objective is the minimization of the Aggregation Infrastructure Power (AIP), which can be written as:

$$\begin{aligned}\min \Bigg\{ & P_{S,0} \cdot (1 + |N_U|) + (P_{S,0} + P_{H,I,0}) \cdot \sum_{i\in N_I} w_i \\ & + P_{H,\text{BBU}} \cdot \sum_{k\in N_M} x^k_k + K_{H,I} \cdot \Bigg(|N_M| - \sum_{k\in N_M} x^k_k\Bigg) \\ & + K_S \cdot \sum_{i\in N} \sum_{\lambda\in\Lambda} \sum_{j\in H^V_{\text{OUT}}(i)} \Bigg(v_{ij\lambda} + \sum_{\omega\leq\Omega_{ij}} \overline{v}_{ij\omega\lambda}\Bigg) \\ & + K_S \cdot \sum_{i\in N} \sum_{\lambda\in\Lambda} \sum_{j\in H^V_{\text{IN}}(i)} \Bigg(v_{ji\lambda} + \sum_{\omega\leq\Omega_{ji}} \overline{v}_{ji\omega\lambda}\Bigg) \Bigg\}\end{aligned} \tag{5}$$

The four terms of the first two lines are respectively: the total baseline consumption of switches located at the CO and at Fixed and Mobile End Points (constant), the baseline power of switches and housing systems installed in intermediate hotel nodes, the housing contribution due to BBUs placed at Mobile End Points, and the sum of housing contributions in intermediate hotel nodes, proportional to the number of BBUs. The last two lines quantify the switches traffic-proportional power contributions for all nodes originating and terminating lightpaths.

F. Common Constraints for All Architectures

Routing of virtual links' lightpaths over physical links

$$\sum_{m\in H_{\text{IN}}(n)} P^{ij}_{mn\lambda} - \sum_{m\in H_{\text{OUT}}(n)} P^{ij}_{nm\lambda} = \begin{cases} -v_{ij\lambda} & \text{if } n = i \\ v_{ij\lambda} & \text{if } n = j \\ 0 & \text{otherwise} \end{cases} \qquad \forall\, n \in N, (i, j) \in V, \lambda \in \Lambda \tag{6}$$

Routing of IP fixed requests over virtual links

$$\sum_{j\in H^V_{\text{IN}}(i)} Y^r_{ji} - \sum_{j\in H^V_{\text{OUT}}(i)} Y^r_{ij} = \begin{cases} -1 & \text{if } i = \text{CO} \\ 1 & \text{if } i = k(r) \\ 0 & \text{otherwise} \end{cases} \qquad \forall\, r \in R_{\text{IP,F}}, i \in N \tag{7}$$

Routing of IP mobile requests over virtual links

$$\sum_{j\in H^V_{\text{IN}}(i)} Y^r_{ji} - \sum_{j\in H^V_{\text{OUT}}(i)} Y^r_{ij} = \begin{cases} x^{k(r)}_i & \text{if } i \neq \text{CO} \\ x^{k(r)}_i - 1 & \text{if } i = \text{CO} \end{cases} \qquad \forall\, r \in R_{\text{IP},M}, i \in N \tag{8}$$

Routing of CPRI requests over D-lightpaths

$$\sum_{\lambda\in\Lambda} \sum_{\omega\leq\Omega_{ij}} \overline{Y}^r_{ik(r)\omega\lambda} = x^{k(r)}_i \quad \forall\, r \in R_{\text{CPRI}}, i \in N | i \neq k(r) \tag{9}$$

Wavelength occupation (capacity) of physical links

$$\sum_{(i,j)\in V} P^{ij}_{mn\lambda} + \sum_{(i,j,\omega)\in D | (m,n)\in Q_{ij\omega}} \overline{v}_{ij\omega\lambda} \leq 1 \qquad \forall\,(m, n) \in E, \lambda \in \Lambda \tag{10}$$

Capacity of D-lightpaths

$$\sum_{r\in R_{\mathrm{CPRI}}} t(r)\cdot \overline{Y}^{r}_{ij\omega\lambda} \le C\cdot \overline{v}_{ij\omega\lambda} \quad \forall\,(i,j,\omega)\in D, \lambda\in\Lambda \qquad (11)$$

Capacity of virtual links

$$\sum_{r\in R_{\mathrm{IP}}} t(r)\cdot Y^{r}_{ij} + \sum_{r\in R_{\mathrm{CPRI}}}\sum_{\lambda\in\Lambda}\sum_{\omega\le\Omega_{ij}} t(r)\cdot \overline{Y}^{r}_{ij\omega\lambda}$$

$$\le C\cdot\sum_{\lambda\in\Lambda}\left(v_{ij\lambda}+\sum_{\omega\le\Omega_{ij}}\overline{v}_{ij\omega\lambda}\right) \quad \forall\,(i,j)\in V \qquad (12)$$

BBU Capacity of active nodes

$$\sum_{k\in N_M} x^{k}_{i} \le B \quad \forall\, i\in N \qquad (13)$$

One BBU for each cell site

$$\sum_{i\in N} x^{k}_{i} = 1 \quad \forall\, k\in N_M \qquad (14)$$

Identification of hotel nodes

$$\frac{1}{\mathcal{M}}\sum_{k\in N_M} x^{k}_{i} \le w_i \quad \forall\, i\in N \qquad (15)$$

G. Extra Constraints for Opaque Architecture

$$\sum_{m\in H_{\mathrm{OUT}}(n)} P^{ij}_{nm\lambda} + \sum_{m\in H_{\mathrm{IN}}(n)} P^{ij}_{mn\lambda} \le \mathcal{M}\cdot(1-w_n)$$

$$\forall\,\lambda\in\Lambda,\ (i,j)\in V,\ n\in N_I | n\neq i \wedge n\neq j \qquad (16)$$

$$\overline{v}_{ij\omega\lambda} \le (1-w_n)$$

$$\forall\,\lambda\in\Lambda,\ (m,n)\in E,\ (i,j,\omega)\in D|(m,n)\in Q_{ij\omega}\wedge n\neq j \qquad (17)$$

$$\overline{v}_{ij\omega\lambda} \le (1-w_n)$$

$$\forall\,\lambda\in\Lambda,\ (n,m)\in E,\ (i,j,\omega)\in D|(m,n)\in Q_{ij\omega}\wedge n\neq i \qquad (18)$$

H. Extra Constraints for No-Hotel Architecture

$$x^{k}_{i} = \begin{cases} 1 & \text{if } i=k \\ 0 & \text{if } i\neq k \end{cases} \quad \forall\, i\in N,\ k\in N_M \qquad (19)$$

Equations (6)–(15) are common to all the three defined network architectures. Eq. (6) enables the routing of lightpaths composing virtual links over the physical topology, by imposing the flow balancing at each node. Eqs. (7) and (8) enable the routing of IP demands over the virtual topology, taking into account that the hotels are not only an outcome of the optimization process, but also source/destination nodes for mobile flows. Eq. (9) enables the routing of each CPRI flow over a single D-lightpath, thus implicitly imposing the Maximum CPRI Route Length constraint. Eq. (10) ensures that each wavelength in every physical link can be occupied by at most one lightpath. Eqs. (11) and (12) limit the maximum traffic that can be carried by each D-lightpath and each virtual link, where the spare capacity of D-lightpaths (i.e., not used for CPRI traffic) can be exploited by virtual links. Eq. (13) limits the maximum number of BBUs that each hotel can host. Eq. (14) enforces that each Mobile End Point must be associated to exactly one BBU, thus one hotel. Eq. (15) is used to identify hotels as nodes which host at least one BBU.

TABLE II

CASE STUDY PARAMETER VALUES FOR THE THREE GEOTYPES: DENSE-URBAN (DU), URBAN (U), AND RURAL (R)

Geotype	**DU**	**U**	**R**
Cell Sites Density (per km^2) [20], [21]	10	3.5	0.15
Households Density (per km^2) [20], [21]	4000	900	300
N. of Mobile End Points ($\|N_M\|$)	30	20	10
N. of Fixed End Points ($\|N_F\|$)	15	7	25
Hotel Capacity (B)	30	20	10

Equations (16)–(18) are specific for the Opaque architecture. They are needed to prevent any lightpath from transiting through any active node. Specifically, Eq. (16) imposes that, for every intermediate active node $(n|w_n=1)$, any lightpath belonging to a virtual link (i,j) not originated or terminated in n $(n\neq i\wedge n\neq j)$ cannot be physically routed over one of its outgoing or incoming links. Eqs. (17) and (18) act similarly for D-lightpaths, in fact if the route of the D-lightpath (i,j,ω,λ) includes at least one physical link passing through the active node n, i.e., (m,n) or $(n,m)|(m,n)\in Q_{ij\omega}$, then such D-lighpath can not be established $(\overline{v}_{ij\omega\lambda}=0)$.

Eq. (19) is specific for the No-Hotel architecture, and it simply forces all BBUs to be placed at their Mobile End Points, without performing hotelling.

V. CASE STUDY AND SIMULATION RESULTS

As a case study, we estimate the Aggregation Infrastructure Power (AIP) of the proposed network architectures on a multi-stage tree topology.[2] Several multi-stage tree network instances are randomly generated, while keeping fixed the number of stages (equal to 3). As input, the spatial coordinates of Fixed and Mobile End Points are obtained by uniformly scattering their locations over a square coverage area, according to predefined geographical density parameters. Such parameters are differentiated among three typical geotypes: Dense-Urban, Urban and Rural [20], [21], and summarized in Table II. In all cases a small percentage of end points (around 20%) is assumed to be both fixed/mobile.

The infrastructural planning process is simulated by a hierarchical clustering procedure which runs the k-means algorithm, with a city-block (or Manhattan) distance metric. For each stage, it returns the location of intermediate aggregation nodes, such that the average distance towards customer nodes is minimized. The number of clusters is fixed to 4 and 2,

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[2] This is expected to be the dominant kind of topology for the typical coverage areas which are considered in the case study. Moreover, by a proper design, a multi-stage tree network could enable intermediate optical transparent routers to be implemented as cyclic Arrayed Waveguide Gratings (AWG), which are currently the most considered solutions for a practical deployment, because of their lower costs with respect to the more advanced Optical Add/Drop Multiplexers (OADM).

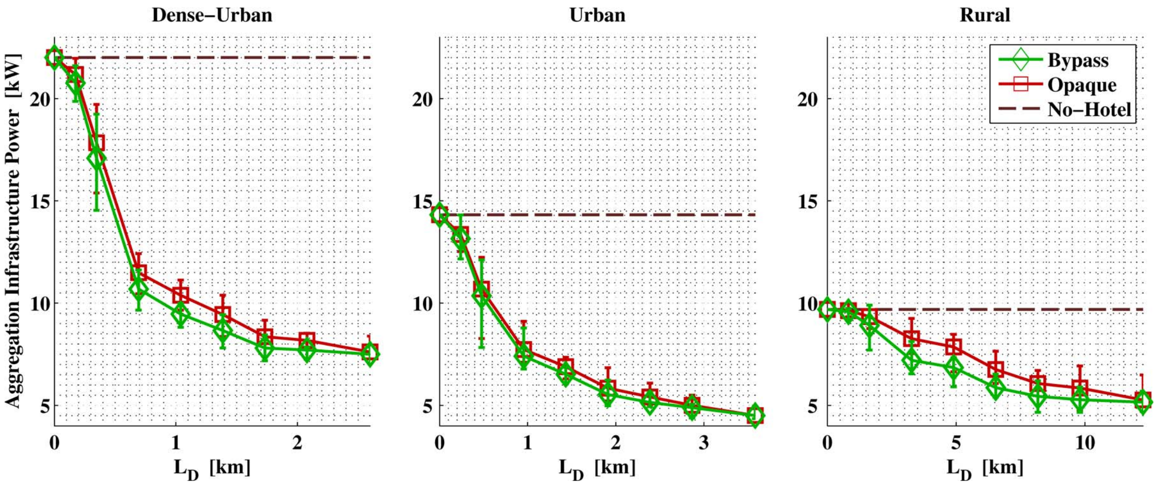

Fig. 4. Aggregation Infrastructure Power (AIP) vs. L_D, for all geotypes.

respectively for the second and third aggregation stage. The procedure allows us to obtain the network instance, i.e., its topology and the lengths of all physical links.

For each network instance, the traffic demands are generated by the following assumptions. Each Mobile End Point collects the traffic of a single macro cell site, providing LTE radio coverage of 3 sectors with 20 MHz bandwidth and 2×2 MIMO configuration. Therefore, the corresponding CPRI demand is computed as 6.29 Gb/s [6], including only the CPRI control overhead and not the 8B/10B line coding, which is not necessary in our CPRI-over-Ethernet transport scenario. The corresponding IP demand is a random value with uniform distribution in the range of 300–750 Mb/s (typical mobile backhaul bitrates for such cell site configuration). The IP demand of each Fixed End Point is a random value with uniform distribution between 10 and 20 Gb/s. Such values are obtained by considering respectively the minimum and maximum density of households for each geotype, an average value of 800 aggregated households per Fixed End Point, a peak access rate equal to 100 Mb/s per household, and a factor 1/5 of statistical multiplexing gain. All traffic demands are generated as integer multiples of a basic granularity, equal to the gross bitrate of the OC-3 signal of the SONET/SDH hierarchy (155.52 Mb/s).

In all cases, the number of wavelengths per link is 40 and each wavelength has capacity equal to 64 OC-3s (about 10 Gb/s). In the following, each value is computed by averaging the results obtained by around 30 independently generated instances, for each geotype and network architecture, and varying the Maximum CPRI Route Length (L_D) and the hotel capacity (B).

Fig. 4 shows the average values of the Aggregation Infrastructure Power (AIP) (i.e., the resulting objective value of Eq. (5)) for the three defined geotypes and network architectures, as a function of L_D. There are also shown the errorbars computed as the distances towards the minimum and maximum values of the data sets. For all geotypes, Bypass and Opaque architectures clearly outperform the No-Hotel. In fact, while in the No-Hotel case the power consumption is independent from L_D, because it is only influenced by the efficiency of routing and aggregation which are performed end-to-end between the CO and the end points, in the two hotelling architectures there is a substantial reduction of power consumption. This means that the energy cost that is paid to make some intermediate nodes active is overcompensated by the gain obtained by consolidating BBUs into a few number of nodes. As intuitively expected, the improvement with respect to the No-Hotel case approaches zero for low values of L_D, because BBUs are pushed towards end points and thus no consolidation can be achieved. By increasing L_D, relevant savings of the AIP are observed, until about 60–65% for Dense-Urban and Urban, and 40% for the Rural case. The smaller relative saving in this last case can be justified by the lower geographical density of mobile and fixed access traffic, with consequently a smaller volume of aggregated traffic and fewer BBUs to consolidate. Nevertheless, in all cases the results confirm the promising energy-reduction opportunity offered by the proposed BBU hotelling FMC architectures.

Focusing on the two hotelling architectures, it can be observed that the Bypass never performs worse than the Opaque, thus confirming the fact that the optical bypassing strategy always leads to the highest energy savings. The difference becomes slightly more relevant for medium values of L_D, because of the higher volume of traffic passing through intermediate nodes, which allows to bypass a higher number of lightpaths. For the highest values of L_D, most of BBUs are consolidated in the CO, therefore the two architectures perform similarly. However, in all cases the difference between Bypass and Opaque is much less relevant than the difference with respect to the No-Hotel. (not greater than approximately 15% of relative difference). This raises the suspect that the tradeoff between optical bypass and active traffic aggregation plays only a marginal role in the energy efficiency, for the analyzed case study.

To further investigate this aspect, we analyze two additional performance indicators. The first one is the BBU Consolidation Factor (BCF), defined as the number of BBU sites (i.e., hotels and cell sites hosting their BBUs), normalized to the number of Mobile End Points. The second indicator is the Average Lightpath Utilization (ALU), which quantifies the efficiency of active traffic aggregation performed by electronic switches. It

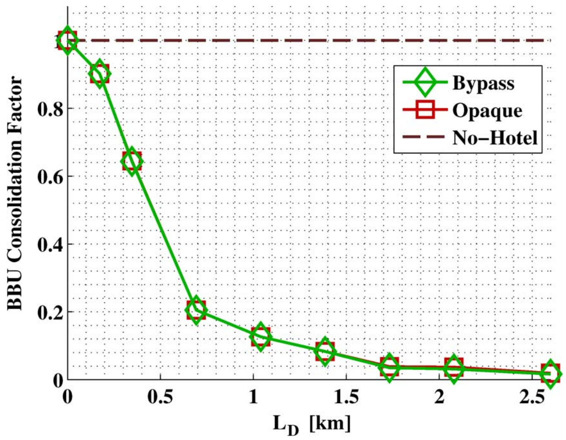

Fig. 5. BBU Consolidation Factor vs. L_D, for Dense-Urban geotype.

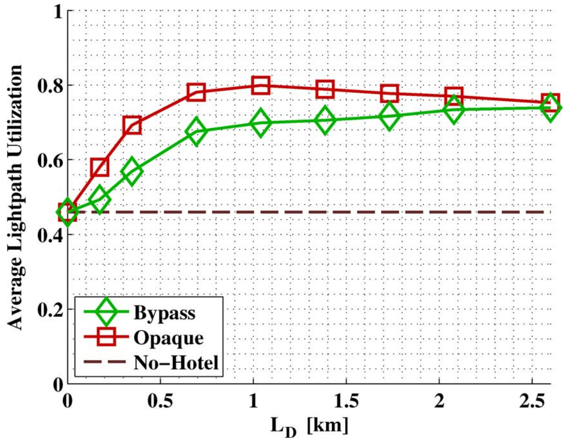

Fig. 6. Average Lightpath Utilization vs. L_D, for Dense-Urban geotype.

is defined as the ratio between the sum of all routed traffic demands and the total lightpath capacity (i.e., the number of established lightpaths multiplied by the wavelength capacity).

Figs. 5 and 6 show the defined quantities, as a function of L_D, for the Dense-Urban geotype and the considered network architectures. For the two hotelling architectures, the BBU Consolidation Factor exhibits large variations, ranging from 1 (lowest L_D) when all BBUs are placed at their cell sites; to $1/|N_M|$, which is the best value, achieved when all BBUs are consolidated into a single site, namely the CO. It can also be observed that the BBU Consolidation Factor is virtually unaffected by the specific hotelling architecture (Bypass or Opaque). Conversely, the Average Lightpath Utilization shows different values. As expected, the addition of intermediate switches in the hotelling architectures enables a more efficient traffic aggregation with respect to the No-Hotel case. Also, the Opaque performs slightly better than the Bypass, but with a relative maximum difference of about 15%. Considering the power amount that can be saved for each less established lightpath ($2 \cdot K_S = 30$ W), it can be inferred that the energy savings due to the more efficient aggregation are not relevant in these cases.

We interpret such results as a strong confirmation that the BBU consolidation is the dominant principle which pushes toward valuable energy savings for the proposed architectures, in the analyzed case study. The possibility of performing optical bypass and active aggregation in intermediate nodes plays only a marginal role in the Aggregation Infrastructure Power. Since the same conclusion can be drawn from the analysis of the Urban and Rural geotypes, we do not report the corresponding figures for sake of space.

TABLE III

MAXIMUM AIP INCREASE WHEN THE HOTEL CAPACITY (B) IS SCALED TO 2/3 AND 1/3 OF THE ORIGINAL VALUE

Geotype	**2/3 capacity scaling**		**1/3 capacity scaling**	
	Bypass	*Opaque*	*Bypass*	*Opaque*
Dense-Urban	3.3%	6.9%	11.1%	26.1%
Urban	11.6%	16.5%	25.4%	40.0%
Rural	4.3%	8.7%	16.7%	28.5%

Finally, to study the effects due capacity limitation of hotels (i.e., when $B < |N_M|$), we consider a sensitivity analysis over different values of B. All simulations have been re-run by scaling them down to approximately 2/3 and 1/3 of their original values, for each geotype. The scaled values are, respectively, 20, 10 for Dense-Urban; 13, 7 for Urban; 7, 4 for Rural. The main effect that can be expected from scaling down the hotel capacities is that the achievable BBU consolidation is also limited by the saturation of the capacity of some hotels. The reduced BBU consolidation causes a slight increase of the AIP with respect to the original capacity, which becomes more and more relevant when BBUs are moved towards the CO (higher L_D). To analyze such effect, in Table III we report the percentage of the maximum increase of the AIP, with respect to the original capacity value, for each hotelling architecture and geotype. As expected, for smaller hotel capacity there is a larger increase of power, because of the lower BBU consolidation. Also, the difference is more evident for the Opaque architecture than for the Bypass one. Anyway, in almost all cases, such increases can be considered as not critical for the analyzed case study, because they could be justified in cases when it is be more cost convenient to have some hotels with reduced capacity (e.g., because of lower lease fees).

VI. CONCLUSION

In this paper, we have presented three different architectures of FMC WDM aggregation networks: Bypass, Opaque and No-Hotel. We have proposed an energy efficient BBU placement optimization problem, whose objective is the minimization of a specific performance indicator, the Aggregation Infrastructure Power (AIP). A fundamental role in the optimization is played by the maximum route length of CPRI flows between Mobile End Points (i.e., cell sites) and the respective hotel nodes. The case study analysis has been carried on randomly generated multi-stage tree topologies, representative of three different geotypes: Dense-Urban, Urban and Rural. The simulation results show that a relevant reduction of the AIP is achieved by both hotelling architectures (Bypass and Opaque), with respect to the No-Hotel. Typical values are around 60–65% of relative saving for Dense-Urban and Urban, and 40% for the Rural geotype. Moreover, it is confirmed that BBU consolidation is the dominant principle which pushes toward valuable energy savings for the proposed architectures, in the analyzed case study, while optical bypass and active aggregation in intermediate nodes play only a marginal role.

This research topic opens the doors to many possible further lines of investigation. We are currently considering some of them for future works. Specifically, we are studying a dynamic traffic scenario, in which the optimization model also embeds the statistical information about daily traffic variation patterns. Another promising investigation in such scenario is about integrating per-node energy-efficiency strategies (e.g., sleep modes) in order to dynamically adapt the network configuration to the varying traffic conditions. A further step is about the study of long-reach networks featuring more complex topologies, which also require a deeper analysis of the wavelength routing capabilities of intermediate optical devices.

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