Placement of Base-Band Units (BBUs) over Fixed/Mobile Converged Multi-Stage WDM-PONs

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Abstract—**The convergence between fixed access networks and mobile backhauling networks is the basis of the evolution towards future Next-Generation Access Networks. Multi-Stage WDM-PONs are the ideal converged infrastructures for carrying both fixed access and mobile backhauling, because they inherit some features of WDM core/metro networks, e.g., large capacity and high transparency. Moreover, they provide support for the "BBU Hotelling" backhauling solution, which consists in separating base stations' Base-Band Units (BBU) from their Remote Radio Heads (RRH), and grouping them into consolidated "Hotels", with reduced costs and energy consumption. In this work, we propose and model by an ILP formulation the novel "BBU Placement" network optimization problem, on a converged Multi-Stage WDM-PON. The aim is to decide in which nodes to place BBUs, together with the routing and wavelength assignment of traffic demands, such that the number of Hotels is minimized. We capture the importance of the maximum latency of Digitized Radio-over-Fiber (D-RoF) flows exchanged between each BBU and its RRH, which becomes a constraint on the maximum propagation delay of corresponding routes. Simulation results are obtained by generating some random multi-stage tree instances and solving them via CPLEX. The analysis of the number of Hotels versus network sizes and maximum D-RoF delay validates the proposed model and highlights the strong impact of such parameters on the achievable BBU consolidation.**

I. INTRODUCTION

The panorama of fixed and mobile access networks is rapidly evolving. In particular, the growth of mobile traffic calls for new radio access network technologies (e.g., HSPA/HSPA+, LTE/LTE-A) that can sustain the increased per-cell capacity. In addition, mobile cells become more pervasive (picocells, femtocells, etc.), in response to the growth of both users' geographical density and per-user capacity. As a result, a widespread, high capacity mobile backhauling infrastructure is required in the metro area. Unfortunately, the current backhauling infrastructure is not evolving at the same rate of radio access technologies and the resulting capacity bottleneck will pose severe limitation to the mobile access performance in next years.

Fixed/Mobile Convergence (FMC) is thought to be the inspiring concept that will guide the development of future Next-Generation Access Networks (NGAN). The basic idea consists in deploying a single network in the metro/access area, for carrying both fixed access traffic and mobile backhauling. This is possible thanks to the mutualization of infrastructure and hardware, like cable plants, cabinets, equipment, sites and buildings. In this way, the FMC infrastructure can be optimized as a whole, opening the doors to an increase of the overall capacity/QoS performance, CapEx/OpEx reduction and even energy consumption saving.

Wavelength Division Multiplexing - Passive Optical Networks (WDM-PON) [1], [2] are the most promising candidate as FMC infrastructures, because of their large capacity and high transparency, which enables a transparent transport of both fixed access traffic and mobile backhauling. Their physical topology will likely evolve towards complex multi-stage and partially-meshed architectures, thus inheriting some powerful features of core/metro WDM networks, like failure resilience, scalability and reconfigurability. These features are enabled by the adoption of optical switching nodes, which transparently switch optical flows in both space (fiber) and wavelength domains, e.g., Passive Splitters, Arrayed Waveguide Gratings (AWG), Reconfigurable Add/Drop Multiplexers (ROADM). All these solutions exhibit different capabilities in terms of routing constraints and degrees of color, direction and contention dependence.

An FMC access infrastructure is expected to support several mobile backhauling solutions. Among those, BBU Hotelling [3] is a promising technique that takes advantage of the functional separation of a generic base station (BS) into two parts, the Base-Band Unit (BBU) and the Remote Radio Head (RRH). The BBU performs layer 1 (L1) digital processing of the baseband signals along with all functions of the upper layers, and interfaces with the backhauling network. The RRH interfaces with antennas' front/back-ends and performs remaining L1 functions, i.e., Digital-to-Analog (DA) / Analog-to-Digital (AD) conversion of the baseband signals, frequency up/down-conversion and power amplification. The BBU Hotelling technique applies to a cluster of BSs and consists in geographically separating each BBU from its RRH, which remains located at the antenna site. All BBUs are consolidated into a common location, called "Hotel". Each BBU/RRH pair exchanges a bunch of Digitized Radio-over-Fiber (D-RoF) baseband signals, one per antenna, per direction (uplink, downlink), for which some open transport interfaces have been already specified (e.g., CPRI [4], OBSAI [5]).

BBU consolidation promises a valuable extent of costs and energy savings, thanks to the sharing of backplanes, power, computational and maintenance resources of BBUs in the same Hotel. Recently, various solutions employing the centralization of multiple BBUs over an FMC infrastructure have been proposed, under the generic name of Cloud Radio Access Networks (C-RAN) [6], [7].

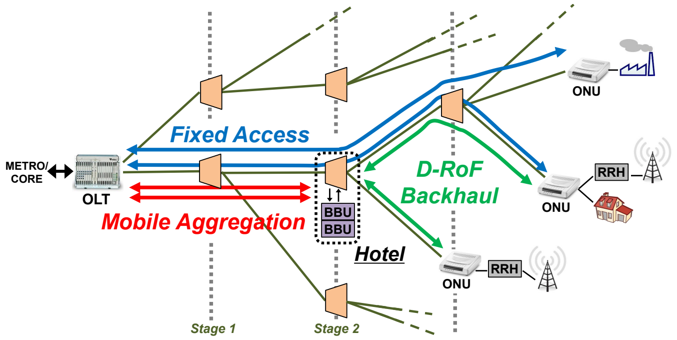

Fig. 1. Example of FMC Multi-Stage WDM-PON architecture; a BBU Hotel with some corresponding traffic flows are highlighted.

In this work, we formalize and solve a novel "BBU Placement" network optimization problem, which will take place over an FMC Multi-Stage WDM-PON. Such model requires the identification of major constraints of the problem and highlights the trade-offs that impact the deployment of BBU Hotels on an FMC access network. We observe that the network's physical size and the signal processing delays into BBU and RRH hardware have a fundamental role in determining the amount of achievable BBU consolidation.

The remainder of this paper is organized as follows. In Section II, the network architecture is introduced and the problem is stated. In Section III, an ILP formulation of the optimization problem is described. In Section IV, some simulation results are shown, by solving the ILP over several randomly generated instances. In Section V, final conclusions are drawn, with possible future lines of investigation.

II. NETWORK ARCHITECTURE AND PROBLEM STATEMENT

In this section, we describe the network architecture, then we introduce and discuss the maximum delay limitation for D-RoF flows. At last, we formalize the BBU Placement problem, identifying the input data, the optimization objective and the main constraints.

A. FMC Multi-Stage WDM-PON Network Architecture

We consider as FMC access infrastructure a generic Multi-Stage WDM-PON, whose terminal nodes are the Optical Line Termination (OLT) and a number of Optical Network Units (ONU) (Fig. 1). The OLT, located at the Central Office (CO), interfaces with the metro/core network. The ONUs, placed at both fixed customers' premises and cellular sites, terminate fixed and/or mobile backhaul traffic. The distribution plant is composed by intermediate nodes interconnected by monodirectional fiber links. The capacity of each link is divided into a given number of WDM channels, or wavelengths, with the same, fixed transmission rate.

The term Multi-Stage indicates that in general more than one intermediate node could be encountered along the paths between the OLT and each ONU. Intermediate nodes are basically non-wavelength-converting optical switches, implemented either as AWGs or OADMs.[1] We model AWGs as direction-constrained switches and OADMs as completely unconstrained switches. More specifically, for a generic AWG, we partition the set of input and output ports into two subset, which defines two sides for the device. The routing is direction-constrained in the sense that each flow incoming from a certain side cannot be routed over any link belonging to the same side, but it must necessarily be forwarded toward the other one. For sake of simplicity, in this paper we do not consider all physical-dependent wavelength routing constraints (as wavelength cyclicity for AWGs [8]).

In our optical access network model, every node represents a site in which several co-located network devices are present, interconnected by dedicated backplanes, and which share energy, computational and maintenance resources. We assume it is possible to place BBUs potentially in any node of the network. This means that, for each RRH, its BBU can be either placed at its ONU (i.e., co-located with it, as a classical BS), or placed at any intermediate node, or even placed at the OLT (i.e., located in the CO). When a node hosts at least one BBU, it becomes Hotel and must be properly adapted in order to partially terminate some traffic. For intermediate nodes, we assume this is feasible by properly adding/dropping corresponding wavelengths, while optical bypassing the others. Realistically, we assume each Hotel is given a certain BBU capacity, which is the maximum number of BBUs it can host.

The FMC infrastructure has to accommodate both fixed and mobile backhaul traffic demands between the OLT and the ONUs. Each fixed demand carries the access IP traffic between the OLT and an ONU. However, for mobile backhaul, each demand gets mapped into two distinct connection requests, whose termination nodes are the Hotels (Fig. 1). The first one, between the OLT and the associated Hotel, is needed to carry the IP mobile traffic between the metro/core network and the BBU. It is worth noting that this is the standard backhaul traffic that the FMC infrastructure would carry in case conventional BSs were employed (no BBU Hotelling). We refer to this as *mobile aggregation* traffic. The second request, between the associated Hotel and the ONU, is needed to carry the bundle of D-RoF signals that are exchanged between the BBU and the RRH. We refer to this as *D-RoF backhaul* traffic (in some literature, it is also called fronthaul). As particular cases: if the OLT is Hotel, it terminates only D-RoF backhaul connections, because it interfaces with the core/metro network; if an ONU is Hotel, it terminates only mobile aggregation connections, because it is co-located with its RRH.

B. Maximum propagation delay for D-RoF backhaul

Fixed access and mobile aggregation traffic (i.e., IP) have very different features with respect to D-RoF backhaul traffic. Because of the transportation of digitized baseband signals, a single D-RoF backhaul flow has a high, constant data rate and is characterized by some synchronization requirements and a maximum end-to-end latency. For our scenario, the latter is a critical issue, because it basically reduces the degrees of freedom in deciding the routes of D-RoF backhaul flows. In general, it comes from the tightest timing constraint on

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[1] Passive Splitters are not accounted here, as a pure WDM-PON is considered in this preliminary analysis.

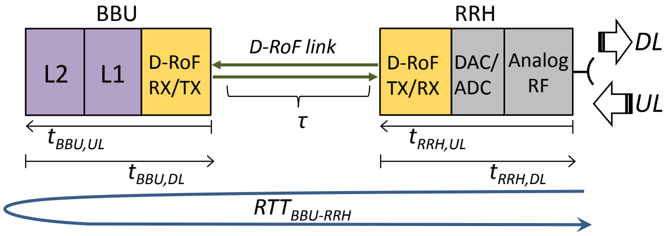

Fig. 2. Delay contributions for the BBU-RRH Round Trip Time

physical layer procedures over the radio interface, and it is mapped in our architecture as indicated in Fig. 2.

Considering the LTE/LTE-A FDD radio interface, there is an upper limit of 3 ms[2] 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 round trip propagation delay (2τ):

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

These processing times include not only the standard BS processing chain delays, but also additional delays due to the transmission/reception of digitized D-RoF signals over/from the optical link.

In this framework, all these processing delays are fixed, because purely technology-dependent. Therefore, the maximum $RTT_{\text{BBU-RRH}}$ directly translates to a maximum admissible one-way propagation delay for every D-RoF backhaul routed flow ($\tau \leq \tau_{\text{MAX}}$), or, equivalently, to a maximum length of its route ($L \leq L_{\text{MAX}}$). In such a way, a *maximum D-RoF delay* constraint can be easily embedded in our formulation, whenever propagation delays for all links and the value of τ_{MAX} are given. For current BBU-RRH technical implementations, which are still not designed to be employed in a Hotelling scenario, $t_{\text{BBU,DL}}$ and $t_{\text{BBU,UL}}$ can be of the order of about 1.2 ms, while $t_{\text{RRH,DL}}$ and $t_{\text{RRH,UL}}$ of about 0.1 ms, which lead to the values: $\tau_{\text{MAX}} \approx 0.2$ ms, $L_{\text{MAX}} \approx 40$ km. Higher values might be obtained by some joint ad-hoc optimization of the processing chain hardware. In general, physical channel impairments introduced by the optical path can pose further severe limitations to D-RoF backhaul in our network architecture. We argue that, since D-RoF is digital data, they basically impacts the BER, so they can be properly compensated by more complex signal processing, leading to increased processing times, and lower values of $\tau_{\text{MAX}}/L_{\text{MAX}}$.

C. The BBU Placement problem

From all previous considerations, given the Multi-Stage WDM-PON with its set of fixed and mobile traffic demands, two decision problems arise: where to place the BBUs and how to route all connection requests. Note that the Hotels, as sources and destinations for some flows, are not a priori given, but they are an outcome of the decision problem, and, for the same reason, it is not possible to know in advance in how many connection requests each mobile traffic demand gets mapped. So we identify a request by: its direction, its type and its associated ONU. The *direction* can be downstream (d) or upstream (u). The *type* refers to: fixed access (f) between the OLT and the ONUs; mobile aggregation (m) between the OLT and the Hotels; D-RoF backhaul (b), between the Hotels and the ONUs. Note that each mobile traffic demand is mapped on a couple of connections requests of type m and b (Fig. 1). For each connection request, the required traffic amount is given, as an integer number of wavelengths (traffic grooming is left as future work).

Under all the above assumptions, we can formally state the optimization problem of BBU Placement over an FMC Multi-Stage WDM-PON as follows:

given: the network topology (including the propagation delays for all links), the location of AWGs and/or OADMs, the set of connection requests with their traffic amounts, the capacity (number of wavelengths) of each link, the BBU capacity of each Hotel (i.e. the maximum number of BBUs it can host) and the maximum D-RoF delay;

decide: in which node to place each BBU, the routing and wavelength assignment for all requests;

so as to minimize: primarily the number of deployed Hotels, pushing for BBU consolidation;[3]

such that: the capacities of links and Hotels are not exceeded, the maximum D-RoF delay constraint (section II-B) is satisfied, the directionality constraints of AWGs are satisfied, exactly one Hotel is assigned to each BBU.

III. ILP FORMULATION OF THE OPTIMIZATION PROBLEM

For the proposed BBU Placement problem, we define an Integer Linear Programming (ILP) formulation, by mathematically modelling the network as a directed graph $\mathcal{G}(N, E)$.

A. Input data (sets and parameters)

- $N = \{OLT\} \cup N_I \cup N_O$: set of nodes;
- N_I : subset of all intermediate nodes;
- $N_I^* \subseteq N_I$: subset of AWGs, i.e., direction-constrained switches (all the others are OADMs, i.e., unconstrained);
- N_O : subset of ONUs;
- E : set of links, i.e. directed arcs (i, j), with $i, j \in N$;
- $H(i) = \{j \in N : (j, i) \in E \vee (i, j) \in E\}$: neighborhood of node $i \in N$;
- $H_1(i), H_2(i)$: disjoint subsets of $H(i)$, with $i \in N_I^*$, induced by the AWG directionality constraint;
- W : set of available wavelengths (λ) for each link, where $|W|$ is the link capacity;
- $\mathcal{F}$: set of all traffic requests;
- $(s, t, k) \in \mathcal{F}$: traffic request of stream $s \in \{d, u\}$ (downstream, upstream), type $t \in \{f, m, b\}$ (fixed access, mobile aggregation, D-RoF backhaul), for ONU $k \in N_O$;

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[2] This value is the Synchronous Uplink HARQ ACK/NACK processing delay. It is defined as the time difference between the complete reception of an uplink data frame by the eNodeB (BS) and the start of transmission of the corresponding ACK/NACK indication to the UE [9].

[3] As secondary objective, we minimize the overall number of wavelengths, pushing for efficient resources utilization. Note that the primary and the secondary function are generally in contrast each other.

- $A_{s,t,k}$: amount of traffic, i.e. number of wavelengths, requested by flow (s,t,k);
- $\tau(i,j)$ or $L(i,j)$: propagation delay of link (i,j), or, alternatively, its length;
- τ_{MAX} or L_{MAX} : maximum D-RoF delay, or, alternatively, maximum lengths of D-RoF routes;
- C : BBU capacity of each Hotel, i.e., maximum number of BBUs it can host;
- sign functions: $\sigma_s = 1$ if $s = d$, -1 if $s = u$;
  $\sigma_t = 1$ if $t = m$, -1 if $t = b$;
- indicator functions: $\mu_m = 1$ if $t = m$, 0 otherwise;
  $\mu_b = 1$ if $t = b$, 0 otherwise;
- M : very big positive number.

B. Decision variables (all binary)

- $x(k,i) = 1$, if node i is Hotel for ONU k;
- $y_{s,t,k}(i,j,\lambda) = 1$, if flow (s,t,k) is routed over link (i,j) and wavelength λ;
- $v_{s,t,k}(\lambda) = 1$, if flow (s,t,k) is routed over wavelength λ (auxiliary);
- $w(i) = 1$, if node i is Hotel, i.e., it hosts at least one BBU (auxiliary);
- $z_{s,t,k}(i,\lambda) = x(k,i) \wedge v_{s,t,k}(\lambda)$ (auxiliary).

C. Objective function

$$\min\Big\{\sum_{i\in N} w(i) + \epsilon \sum_{(s,t,k)\in\mathcal{F}} \sum_{(i,j)\in E} \sum_{\lambda\in W} y_{s,t,k}(i,j,\lambda)\Big\} \quad (2)$$

The first term is the primary objective (BBU consolidation), the second term is the secondary objective (efficient resource utilization). The factor $\epsilon = (|\mathcal{F}||E||W|+1)^{-1}$ ensures that the second term is always < 1, thus giving the first one higher priority than the second one.

D. Constraints

$$\sum_{j\in H(i)} y_{s,t,k}(j,i,\lambda) - \sum_{j\in H(i)} y_{s,t,k}(i,j,\lambda) = \sigma_s \begin{cases} \sigma_t\, z_{s,t,k}(i,\lambda) - \mu_m\, v_{s,t,k}(\lambda) & \text{if } i = OLT \\ \sigma_t\, z_{s,t,k}(i,\lambda) + \mu_b\, v_{s,t,k}(\lambda) & \text{if } i = k \\ [\mu_m - \mu_b]\, z_{s,t,k}(i,\lambda) & \text{otherwise;} \end{cases}$$
$$\forall (s,t,k) \in \mathcal{F},\, i \in N,\, \lambda \in W \quad (3)$$

$$\sum_{\lambda\in W} v_{s,t,k}(\lambda) = A_{s,t,k}\,[1 - \mu_m\, x(k,OLT) - \mu_b\, x(k,k)]; \qquad \forall (s,t,k) \in \mathcal{F} \quad (4)$$

$$w(i) \geq \frac{1}{M} \sum_{k\in N_O} x(k,i); \qquad \forall i \in N \quad (5)$$

$$[\, z_{s,t,k}(i,\lambda) \leq x(k,i)\,] \wedge [\, z_{s,t,k}(i,\lambda) \leq v_{s,t,k}(\lambda)\,] \wedge [\, z_{s,t,k}(i,\lambda) \geq x(k,i) + v_{s,t,k}(\lambda) - 1\,]; \qquad \forall (s,t,k) \in \mathcal{F},\, i \in N,\, \lambda \in W \quad (6)$$

$$\sum_{k\in N_O} x(k,i) \leq C; \qquad \forall i \in N \quad (7)$$

TABLE I

RIGHT-HAND SIDE OF (3), FOR TYPES $t = m$ ($X = OLT$) AND $t = b$ ($X = k$)

	$v_{s,t,k}(\lambda) = 0$	$v_{s,t,k}(\lambda) = 1$	
		$i \neq X$	$i = X$
$x(k,i) = 0$	0	0	$\sigma_s\,\sigma_t$
$x(k,i) = 1$	0	$\sigma_s\,\sigma_t$	0

$$\sum_{(i,j)\in E} \tau(i,j)\; y_{s,b,k}(i,j,\lambda) \leq \tau_{\text{MAX}}; \qquad \forall s \in \{d,u\},\, k \in N_O,\, \lambda \in W \quad (8)$$

$$\sum_{(s,t,k)\in\mathcal{F}} y_{s,t,k}(i,j,\lambda) \leq 1; \qquad \forall (i,j) \in E,\, \lambda \in W \quad (9)$$

$$\sum_{j\in H_\ell(i)} [y_{s,t,k}(j,i,\lambda) + y_{s,t,k}(i,j,\lambda)] \leq 1; \qquad \forall \ell \in \{1,2\},\, (s,t,k) \in \mathcal{F},\, i \in N_I^*,\, \lambda \in W \quad (10)$$

$$\sum_{i\in N} x(k,i) \leq 1; \qquad \forall k \in N_O \quad (11)$$

Eq. (3) is an adaptation of the solenoidality (or flow balancing) constraint. It enforces the routing of traffic demands by imposing the balancing of incoming and outgoing flows, for each source, transit and destination node. The solenoidality constraint is modified since: 1) each wavelength plane is managed separately, because of the absence of wavelength conversion; 2) Hotels, i.e., sources and destinations of mobile flows, are outcomes of the optimization, so not known in advance; 3) in general not all potential type m and b flows are actually routed, because it depends on the location of respective Hotels (section II-C). For type f flows, the equation reduces to the standard solenoidality constraint. For type m and b, the reader can refer to Table I, which clarifies the right-hand side values of (3). When the OLT is Hotel for ONU k, i.e., $x(k,i) = 1$ and $i = OLT$, it is both source and destination for a "degenerated" m flow, which is forced to zero. The same occurs when the ONU k is Hotel for itself, i.e., $x(k,i) = 1$ and $i = k$, for b flows. In conclusion, such degenerated flows are not routed in the network.

Eq. (4) imposes that the number of assigned wavelengths (i.e., the number of established lightpaths) for each flow is equal to its required traffic amount. It is needed because flow balancing constraints (3) are separated into $|W|$ independent wavelength planes. Since degenerated flows are not routed, no wavelength is assigned to them. In these cases (i.e., $x(k,OLT) = 1$ for m flows, $x(k,k) = 1$ for b flows), the right-hand side of (4) is forced to zero.

Eq. (5) defines the auxiliary variables $w(i)$ through a big-M inequality, which ensures that $w(i) = 1$ if node i hosts at least one BBU. Eq. (6) defines corresponding auxiliary variables via linearization of the relation: $z_{s,t,k}(i,\lambda) = x(k,i) \wedge v_{s,t,k}(\lambda)$. Eq. (7) defines the Hotels' BBU capacity constraint, i.e., it imposes that each Hotel can host at most C BBUs. Eq. (8) imposes that the propagation delay (i.e., the sum of propagation delays of all links) for every b flow cannot exceed τ_{MAX} (section II-B). It can alternatively be expressed in terms of lengths ($L(i,j)$ and L_{MAX}). Eq. (9) is the link capacity constraint per wavelength plane, i.e., it imposes that each wavelength of each link is assigned to at most one traffic flow. Eq. (10) applies only to AWG intermediate nodes and enforces the directionality constraint by imposing that at most one lightpath can income/outgo from/to a specific side ℓ of the device. Eq. (11) imposes that each ONU (so its corresponding RRH) must be associated to no more than one Hotel.

IV. RESULTS AND DISCUSSION

The proposed optimization model can be applied to any kind of network topology. In other words, the considered Multi-Stage WDM-PON could be a multi-stage tree (branch-and-tree [10], [11]) or ring (ring-and-spur [12]), as likely as any partially meshed architecture. In this section, we restrict our analysis to multi-stage trees, to validate our model on a common topology for WDM-PONs. To do so, an algorithm for the generation of random multi-stage tree topologies has been developed, whose detailed description is not reported for sake of space limitation. It takes as input three parameters: 1) the number of ONUs ($|N_O|$); 2) the number of stages (n_s), defined as the maximum distance (in terms of number of hops) between the OLT and the ONUs; 3) the network size (S [km]), here defined as the mean physical distance (sum of links' lengths) between the OLT and the ONUs. It gives as outputs the topology ($\mathcal{G}(N, E)$) and the links' propagation delays ($\tau(i, j)$ [s]).

Using this algorithm, several random multi-stage tree topologies have been generated, varying the network size (S) and keeping fixed the number of ONUs ($|N_O| = 32$) and the number of stages ($n_s = 3$), as common basis for comparison.[4] For each generated topology, we consider two extreme cases: 1) *all-AWGs*, i.e., all intermediate nodes perform direction-constrained routing ($N_I^* = N_I$); 2) *all-OADMs*, i.e., all of them perform unconstrained routing ($N_I^* = \emptyset$). The traffic matrix is always uniform and each traffic demand requires only one wavelength ($A_{s,t,k} = 1$). In our analysis, we mainly focus on the impact of the maximum D-RoF delay, expressed in terms of maximum length of D-RoF routes (L_{MAX}), and the network size (S) on the attainable BBU consolidation and resource utilization. Note that results are mostly influenced by the ratio L_{MAX}/S, which can be interpreted as the percentage of the average network size that can be covered by D-RoF routes. We also assume that the link capacity ($|W|$) is never a limiting factorAll the following results have been obtained by solving and averaging over 100 random instances, separately for all-AWGs and all-OADMs cases, and varying the Hotels' BBU capacity (C).

Fig. 3 shows the degree of BBU consolidation, expressed as the number of Hotels (H, first term of objective function (2)), as a function of both L_{MAX} and S, without limitations on Hotels' BBU capacity ($C = \infty$). The results show that higher BBU consolidation is attainable by increasing L_{MAX}, i.e., reducing the signal processing delays of BBU/RRH hardware, or decreasing S, i.e., reducing the network size.

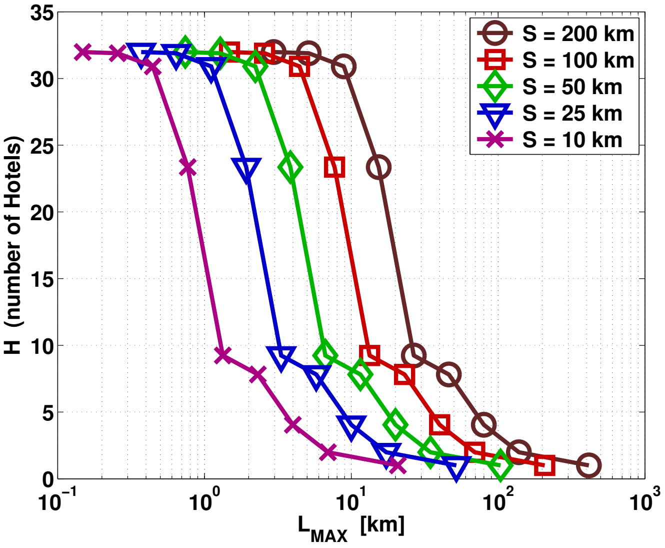

Fig. 3. Number of Hotels (H) for the case $C = \infty$; results are identical for both all-AWGs and all-OADMs cases.

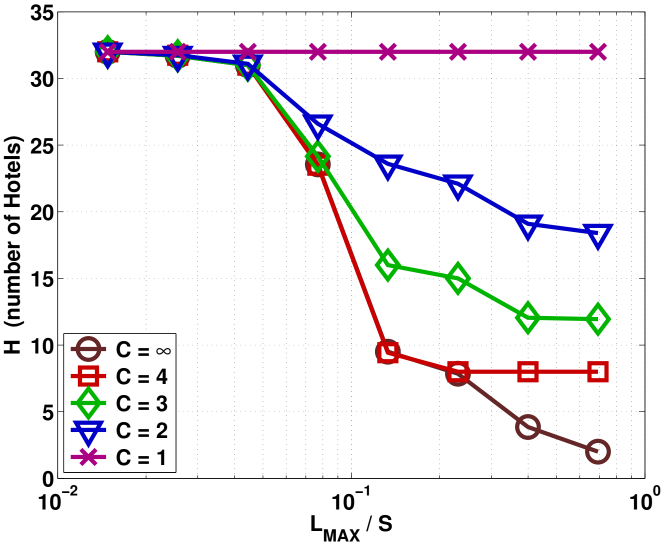

Fig. 4. Number of Hotels (H) for different values of C; results are identical for both all-AWGs and all-OADMs cases.

As expected, for a fixed S, H saturates to the maximum ($|N_O| = 32$) and to 1, respectively for lower and higher L_{MAX}. The first case corresponds to all BBUs placed in their ONUs (all D-RoF backhaul flows are degenerate), the second one corresponds to all BBUs placed in the OLT (all mobile aggregation flows are degenerate). For the considered random network model, the two saturation conditions are obtained by varying L_{MAX} of about two orders of magnitude. Considering the current reference value of $L_{\text{MAX}} \approx 40$ km (as pointed out in Section II-B), a remarkable degree of consolidation ($H < 10$) is achievable for all expected sizes of realistic Multi-Stage WDM-PONs.

In a more practical scenario, the finite value of the Hotels' BBU capacity (C) must be considered. Fig. 4 shows the values of H as function of the ratio L_{MAX}/S, for different values of

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[4] Such values allow to optimally solve all instances using the CPLEX software, within a reasonable amount of computational time (not greater than 30 about minutes, per instance).

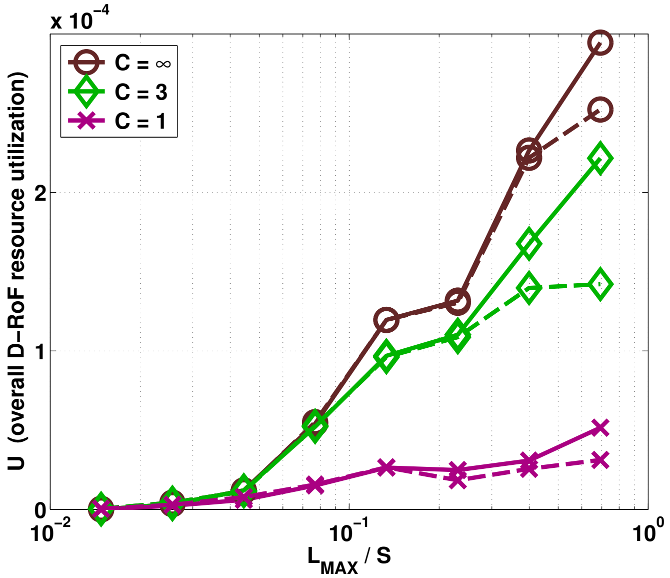

Fig. 5. Overall D-RoF resource utilization (U); *dashed* line for the all-AWGs case, *continue* line for the all-OADMs case.

C. As expected from intuition, for $C = 1$ no consolidation is achievable. For increasing C, H saturates to approximately $\lceil |N_O|/C \rceil$. For lower values of L_{MAX}/S (say, less than 0.1), the Hotel capacity constraint is not more a critical parameter.

The two figures show that H is the same for both all-AWGs and all-OADMs cases. This comes from the fact that, in a pure tree Multi-Stage WDM-PON, the adoption of OADMs instead of AWGs gives no valuable advantage in terms of degree of BBU consolidation. However, this conclusion does not necessarily imply that the routed paths are identical for both cases. To prove this, we propose the investigation of another metric, that quantifies the difference of resource utilization between all-AWGs and all-OADMs cases. Specifically, we define the *overall D-RoF resource utilization* (U), as the normalized sum of occupied wavelengths over all links, for only D-RoF backhaul flows:

$$U = \epsilon' \sum_{s \in \{d,u\}} \sum_{k \in N_O} \sum_{(i,j) \in E} \sum_{\lambda \in W} y_{s,b,k}(i,j,\lambda) \qquad (12)$$

where $\epsilon' = (2|N_O||E||W|)^{-1}$. Note that this is similar to the second term of the objective function (2), except that only type b flows are taken into account. This metric is calculated for each solved instance, then averaged over all instances. The results are shown in Fig. 5, as functions of the ratio L_{MAX}/S, for different values of Hotel capacity (C) and for both all-AWGs and all-OADMs cases. As expected, in all cases U approaches zero for lower L_{MAX}/S, because there are no D-RoF routed flows (no BBU consolidation). For increasing values of L_{MAX}/S, the Hotel BBU capacity (C), and so the BBU consolidation (H), progressively gets saturated. As a consequence, U increases, because of the increased mean length of D-RoF routes. While BBU consolidation is never influenced by the adoption of OADMs or AWGs, here a different trend appears. In fact, for higher L_{MAX}/S, the values of U for the all-OADMs case increase with respect to the all-AWGs case. Hence, we can infer that, thanks to the unconstrained routing, D-RoF flows exhibit longer routes, which allow Hotels to be placed closer to the most RRH-loaded branches of the network. For this reason, we expect to observe a significant gain in terms of BBU consolidation in more meshed network topologies.

V. CONCLUSION

In this paper, we propose and formalize the novel "BBU Placement" network optimization problem, over an FMC Multi-Stage WDM-PON. It consists in deciding where to place each BBU, together with the routing and wavelength assignment for all traffic demands, such as to minimize the number of deployed BBU Hotels. By solving several optimization instances over randomly generated trees, we have shown how the achievable BBU consolidation is strongly dependent on the ratio between the maximum length of D-RoF routes and the network size. We have also shown that OADMs can give some advantages over AWGs, under specific circumstances, which pushes us towards the investigation of partially meshed networks.

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