Optimal BBU Placement for 5G C-RAN Deployment Over WDM Aggregation Networks

Francesco Musumeci, *Member, IEEE*, Camilla Bellanzon, Nicola Carapellese, Massimo Tornatore, *Senior Member, IEEE*, Achille Pattavina, *Senior Member, IEEE*, and Stéphane Gosselin

(Top-Scored)

***Abstract*—5G mobile access targets unprecedented performance, not only in terms of higher data rates per user and lower latency, but also in terms of network intelligence and capillarity. To achieve this, 5G networks will resort to solutions as small cell deployment, multipoint coordination (CoMP, ICIC) and centralized radio access network (C-RAN) with baseband units (BBUs) hotelling. As adopting such techniques requires a high-capacity low-latency access/aggregation network to support backhaul, radio coordination and fronthaul (i.e., digitized baseband signal) traffic, optical access/aggregation networks based on wavelength division multiplexing (WDM) are considered as an outstanding candidate for 5G-transport. By physically separating BBUs from the corresponding cell sites, BBU hotelling promises substantial savings in terms of cost and power consumption. However, this requires to insert additional high bit-rate traffic, i.e., the fronthaul, which also has very strict latency requirements. Therefore, a tradeoff between the number of BBU-hotels (BBU consolidation), the fronthaul latency and network-capacity utilization arises. We introduce the novel BBU-placement optimization problem for C-RAN deployment over a WDM aggregation network and formalize it by integer linear programming. Thus, we evaluate the impact of 1) jointly supporting converged fixed and mobile traffic, 2) different fronthaul-transport options (namely, *OTN* and *Overlay*) and 3) joint optimization of BBU and electronic switches placement, on the amount of BBU consolidation achievable on the aggregation network.**

***Index Terms*—Baseband unit hotelling, centralized radio access network, fronthaul, optical aggregation networks, wavelength division multiplexing, 5G.**

I. Introduction

THE current traffic explosion generated by mobile devices (e.g., smartphones or tablets) requires radical changes to existing radio access networks (RANs). Advanced technologies for mobile-access networks have been developed, based on the utilization of larger frequency bandwidths, mechanisms for increased spectral efficiency (e.g., orthogonal frequency division multiple access), multiple-input-multiple-output (MIMO) transmission/reception and cell densification [1], which form the basis for 4G standards like long term evolution (LTE) and LTE-advanced. Several other improvements are under investigation and will play a key role in future 5G networks. Among them, we focus on two promising principles. The first one is the fixed/mobile convergence (FMC), i.e., the concept of designing and optimizing networks "as a whole" resorting to infrastructure and equipment shared among fixed and mobile networks. The second one, which is the main focus of this study, is the BBU Hotelling [2], i.e., a paradigm exploiting the functional separation of traditional base stations (BSs) into two parts [3]: 1) the base-band unit (BBU), which performs layer 1 digital processing of the baseband signals along with all functions of the upper layers, and interfaces with the backhauling network, and 2) the remote radio head (RRH), which interfaces with antennas front/back-ends and performs remaining layer 1 functions, i.e., digital-to-analog/analog-to-digital conversion (DAC/ADC) of the baseband signals, frequency up/down-conversion, power amplification and signal measurements.

The *BBU hotelling* technique applies to a set of BSs and consists in geographically separating each BBU from its RRH, which remains located at the cell site (CS), where the antennas are located, and consolidating BBUs into a common location, called *BBU hotel*, enabling centralized-RAN (C-RAN) [4]. Thus, cost and energy savings can be achieved by sharing backplanes, power, computational and maintenance resources of BBUs hosted in the same hotel. Moreover, since BBU hotelling can favour advanced techniques for increasing RAN performance via multi-cell processing, such as coordinated multipoint (CoMP) transmission/reception and enhanced inter-cell interference coordination, it is seen as a first step toward the so-called C-RAN [5]–[8].

As BBU hotelling requires a high-capacity and low-latency access/aggregation network to support fronthaul traffic (i.e., the digitized base-band signal exchanged by BBUs and RRHs), optical access/aggregation networks based on wavelength division multiplexing (WDM) are considered as an outstanding candidate for 5G-transport. Since such WDM-based access/aggregation networks are typically hierarchical and multi-stage, the question arising is: at which location of the aggregation network shall the BBU hotels be placed? BBU hotels were originally intended as the centralization of BBUs of different CSs into the first aggregation site (i.e., a central office (CS)). As the main motivations behind hotelling are cost/energy savings and increased radio performance by enabling coordinated processing,

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F. Musumeci, C. Bellanzon, N. Carapellese, M. Tornatore, and A. Pattavina are with the Politecnico di Milano, Milan 20133, Italy (e-mail: francesco.musumeci@polimi.it; camilla.bellanzon@mail.polimi.it; nicola.carapellese@polimi.it; massimo.tornatore@polimi.it; achille.pattavina@polimi.it).

S. Gosselin is with the Orange Labs Networks, Lannion 22300, France (e-mail: stephane.gosselin@orange.com).

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we claim that the possibility of centralizing more BBUs at higher aggregation sites can increase such benefits. This however implies relevant challenges: 1) the high bit-rate fronthaul traffic shall be transported over the existing aggregation network, i.e., it shall be multiplexed and/or routed like conventional backhaul traffic, 2) the strict latency constraints of fronthaul traffic shall be carefully considered. So, a tradeoff between BBU consolidation, fronthaul latency and network capacity utilization arises, and the choice of where to place BBUs is not trivial.

A. *Paper Contribution*

We introduce the novel BBU placement optimization problem for C-RAN deployment. As main contributions we identify the followings: 1) classify different architectural solutions which can be adopted for BBU placement in C-RANs; 2) propose an optimal, i.e., cost-minimized, BBU placement method in WDM aggregation networks, based on integer linear programming (ILP); 3) evolve our proposed model to deal with a scenario featuring the joint optimization of BBU and electronic switches placement; 4) evaluate the impact of two different fronthaul transport options, *OTN* and *Overlay*, on BBU consolidation.

The remainder of this paper is organized as follows. In Section II we describe the BBU Hotelling principle, focusing on the network scenario and the node architecture considered in the paper. In Section III we detail the traffic features for future 5G networks, where both fixed and mobile network users coexist in a common and shared infrastructure. The BBU placement problem is stated in Section IV, where we also show the proposed ILP model. In Section V we extend the problem by considering an independent placement of BBUs and electronic switches. Then, we show numerical results in Section VI and conclude the paper in Section VII.

II. BBU Hotelling

We now describe the BBU hotelling principle and show various architectural solutions which can be implemented.

A. *BBU Hotelling: The Fronthaul Latency Challenge*

Splitting the BSs functionalities between BBUs and RRHs and centralizing BBUs into few hotels brings many benefits, in terms of costs (e.g., reduction of lease fees, energy bills, control and maintenance costs, due to the sharing of facilities) and RAN performance (i.e., enhanced network throughput, due to centralized processing). However, this requires a proper network to transport the new *fronthaul* traffic, i.e., the digitized baseband signals, also known as digital radio-over-fiber (D-RoF), exchanged by BBUs and RRHs [4], in addition to the conventional backhaul traffic. Transporting fronthaul traffic over access networks is critical for two main reasons. First, very high bit-rate, in the order of units to tens of Gb/s for a CS, must be transported, so fronthaul requires much more capacity than backhaul. As an example, an LTE sector configured as 2×2 MIMO with 20 MHz bandwidth requires approximately 2.5 Gb/s for fronthaul [4] [9], which gives 7.5 Gb/s for a typical three-sector CS.[1]

[1]Different functional splits for fronthaul (called "midhaul") are currently being investigated, that could decrease the required capacity of the fronthaul (see [10]). Such analysis is left for future work.

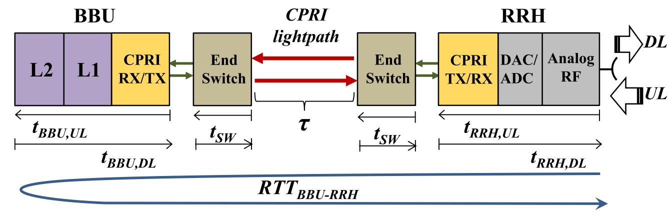

Fig. 1. Delay contributions along the fronthaul processing chain.

Second, strict latency constraints must be met when transporting fronthaul. Thus the physical distance between BBUs and RRHs is limited and a tradeoff between higher BBU consolidation and fronthaul latency requirements arises.

In this scenario, optical fibers are a feasible solution to transport fronthaul, as they provide both high capacity and low latency. As a result, each BBU/RRH pair exchanges D-RoF data, which can be transported over several open interfaces, the most popular being the common public radio interface (CPRI) [11]. As specified in [12], a total round-trip latency budget of $RTT_{\text{BBU-RRH}} = 3\,\text{ms}$ is available between a BBU and its corresponding RRH. Therefore, for the different latency contributions, summarized in Fig. 1, the following condition must hold:

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

Note that, in this study we implicitly assume that fronthaul is transported over the same aggregation network used for data traffic transport, so that all traffic types can be aggregated together (see Section III for details). Here, all the processing delays are considered to be fixed, as they are purely technology-dependent. So, the maximum $RTT_{\text{BBU-RRH}}$ 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 ($L \leq L_D$). Values of L_D which typically range from 20 to 40 km are reported in literature, e.g., in [5]. As a final consideration, much stricter latency constraints might arise if advanced RAN coordination techniques (as CoMP) are considered (see [13]), so a sensitivity analysis on the maximum-allowed latency value will be applied in our numerical examples in Section VI.

B. *Supporting WDM Aggregation Network Architecture*

To support the mobile traffic backhaul (with or without BBU Hotelling), in this study we consider a WDM aggregation network where nodes are assumed as hierarchically organized into a four-stages "ring-and-spur" architecture, as shown in Fig. 2. For sake of generality, we consider a fixed-mobile converged (FMC) network, where several CSs and fixed access sites, inserting mobile and fixed traffic, respectively, are interconnected by optical fiber links. Fixed access sites can be street cabinets or COs, depending on their position in the aggregation hierarchy. Specifically, at the lowest network stage (say stage 0) CSs and street cabinets are present, while stages 1 and 2 are composed by Access COs and Main COs, respectively. In our scenario, a single Core CO, acting as point of presence (PoP), is assumed and represents the interface of the aggregation toward the core

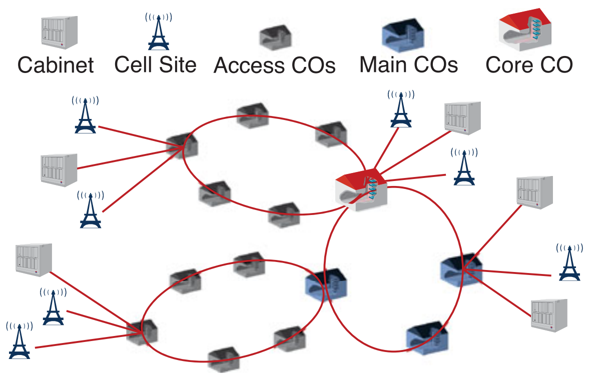

Fig. 2. Aggregation network architecture.

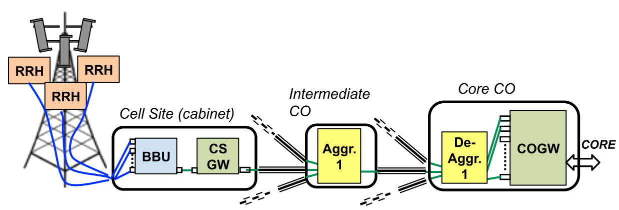

Fig. 3. Distributed BS (No hotelling).

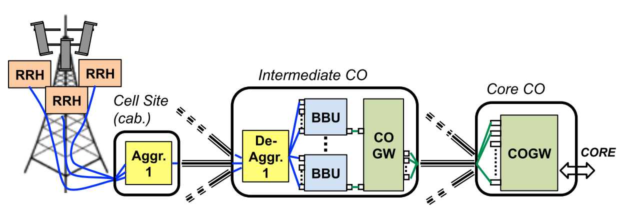

Fig. 4. BBU hotel at first CO.

network segment. The internal architecture of the aggregation nodes of this network will be elaborated in Section II-D.

C. BBU Placement Options

Given the BBU-RRH physical separation, various possible placements are possible across an aggregation network.

1) Distributed BS: A first step toward BBU-RRH splitting is shown in Fig. 3, though it is not, strictly speaking, a hotelling architecture. CSs are generally composed by the antenna site, where antennas are physically mounted, and the cabinet, where the remaining BS equipment is located. Here, BBUs remain in CS cabinets, while RRHs are moved apart from cabinets and directly attached to antennas. To do this, RRHs must be implemented as stand-alone devices, embedding their own power and cooling subsystems and designed for operating in outdoor environmental conditions. The backhaul traffic generated by every BBU is aggregated by a CS GateWay, and sent toward the core, through the remaining aggregation-network portion, made up of several Intermediate and one Core CO.

2) BBU Hotel at First CO: This is the basic BBU hotelling solution, where BBUs of different CSs are placed in their "first" COs, i.e., the CO directly connected to the CSs, which becomes a hotel site (see Fig. 4). On the other hand, RRHs are remotized to antennas. The RAN portion between CSs and first COs is used to transport the fronthaul. An important consequence of this

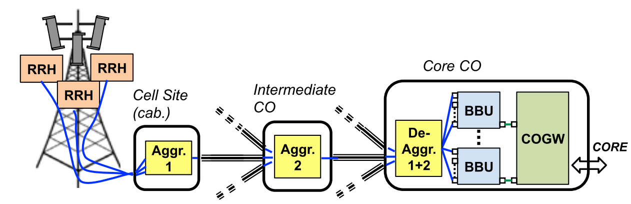

Fig. 5. BBU hotel at higher-level CO.

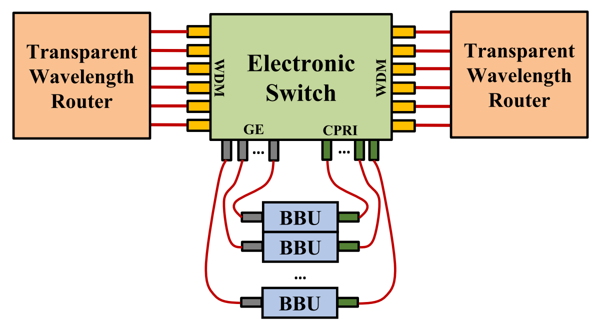

Fig. 6. Implementation detail of a BBU hotel site.

architecture is that the CS cabinet space occupancy is greatly reduced, while the CO can more efficiently manage a large number of hotels, resulting in relevant cost and energy savings.

3) BBU Hotel at Higher-Level CO: BBUs can also be placed at higher-level COs (see Fig. 5), instead of at first COs. With respect to the previous case, the architecture of CSs and hotel sites is unchanged, but there can be different solutions for the fronthaul transport. In fact, first COs become intermediate "transit" nodes for fronthaul, so their implementation is an additional degree of freedom, depending on how the fronthaul is aggregated toward higher-level COs. This architecture allows higher BBUs concentration into single hotels, leading to higher energy and costs savings. However, here the fronthaul latency constraint plays a more critical role, due to the higher distances between CSs and hotels. This could make this solution infeasible in some scenarios featuring spread geographical distribution of COs, e.g., in rural coverage areas.

In our study each of these cases can occur, i.e., BBUs can be placed, in principle, at every level of the hierarchical network, the only constraint being the latency (i.e., distance) between a BBU and its corresponding RRH.

D. BBU Hotel Site Architecture

The internal architecture of a BBU hotel site is depicted in Fig. 6. An electronic switch is equipped with both long-reach WDM transport interfaces, and short-reach tributary interfaces, i.e., gigabit ethernet (GE) for backhaul and CPRI for fronthaul. The incoming wavelength signals (i.e., lightpaths) are mu/demultiplexed by wavelength routers and enter the switch via the WDM interfaces. Backhaul traffic destined to a hosted BBU is extracted and sent over the GE port, while fronthaul is collected by the switch from the CPRI interfaces, to be mapped into one or more output lightpaths. Also transit traffic is electronically switched at the hotel site (i.e., the lightpaths are terminated by using WDM interfaces), where traffic grooming is

TABLE I
DIFFERENT INTERMEDIATE NODE ARCHITECTURES

Option	BBU Hotel	Electronic switch	Transit traffic
1	Yes	Yes	Terminated
2	Yes	Yes	Bypassed
3	Yes	No	Bypassed
4	No	Yes	Terminated
5	No	Yes	Bypassed
6	No	No	Bypassed

also accomplished. Such node architecture is often referred to as *Opaque*.

As a more general remark, different architectures can be considered for the aggregation nodes of the network shown in Fig. 2. Depending on how lightpaths carrying transit traffic are treated and on the possibility of deploying the BBU hotel and the electronic switch independently in the node, different scenarios can be configured, as summarized in Table I. Specifically, whenever a node is not equipped with an electronic switch, transit traffic is always bypassed and no traffic grooming is performed; additionally, if the node hosts a BBU hotel but is not equipped with an electronic switch, an access gateway supporting WDM, GE and CPRI interfaces is still needed to handle both backhaul and fronthaul traffic to be sent/received to/from WDM links, thus acting as mu/demultiplexer.

In our study, we initially consider a joint placement of BBU hotels and electronic switches, i.e., nodes hosting a BBU hotel are also equipped with an electronic switch and all the lightpaths carrying transit traffic are terminated, electronically-switched and re-originated in such nodes (option 1 in Table I). On the other hand, in nodes where no BBU hotel is hosted, all the lightpaths are switched in the optical domain, by directly connecting the two wavelength routers of Fig. 6 (option 6 in Table I).

III. TRAFFIC TYPES AND FRONTHAUL OPTIONS

In the FMC aggregation network here considered, three traffic categories can be identified: 1) *fixed*, between COs/street cabinets and Core CO, 2) *mobile* (*backhaul*), between the Core CO and BBUs, and 3) *fronthaul* (i.e., CPRI), between BBUs and RRHs, for BBUs which are separated from the corresponding CS (RRH).

Mobile (respectively, fixed) traffic is natively packet-based, so we assume that traffic bifurcation over parallel lightpaths, established between BBUs (resp., Cabinets) and the Core CO, is allowed. Conversely, routing constraints for fronthaul are stringent, due to synchronization issues and strict limits on the maximum transport round-trip time, which is constrained by the fact that radio interface physical layer procedures limit the maximum delay between reception of UL frames and transmission of corresponding DL replies [14]. Thus, no bifurcation is allowed for fronthaul traffic.

As for fronthaul, we consider two transport options, on the line of [15]. 1) *OTN*: fronthaul can be multiplexed with backhaul into the same wavelengths, traversing intermediate electronic switches, provided that the node-processing extra latency contribution is subtracted from the BBU-to-RRH latency budget. Note that at least two switches are traversed, one for ingress, the other for egress of fronthaul. As current switching technologies (e.g., Ethernet, or OTN) feature processing delays that are too far from the requirements of fronthaul transport, we assume "low-latency" switches, tailored for fronthaul applications, adding a delay of $t_S = 20\,\mu$s. 2) *Overlay*: fronthaul is transported over dedicated wavelengths, so the only latency contribution is due to fiber propagation.

IV. BBU PLACEMENT PROBLEM

Considering the described FMC aggregation network, we first define a "baseline" BBU placement problem as follows. **Given** the network topology, the number of available fibers per link, the number of wavelengths per fiber and their line-rate capacity, the set of traffic requests, the maximum allowed fronthaul latency, τ; **decide** the placement of BBUs, the grooming, routing and wavelength assignment (GRWA) of traffic requests; **to minimize** the total network cost, intended as either the total number of hotels (*minHotels*) or the total number of fibers (*minFibers*) deployed in the network. We model this optimization problem using the following ILP, which also allows us to compare the aforementioned *OTN* and *Overlay* fronthaul transport strategies.

A. ILP Formulation

We use a two-layer path formulation, where an upper "virtual" layer is made up of virtual links, representing lightpaths originating and terminating in the nodes, and a lower layer consists of multi-fiber links physically connecting the nodes. A set of physical paths is precomputed for each nodes pair in order to reduce problem complexity.

1) *Input Sets and Parameters*

a) N is the set of nodes, partitioned into: one PoP node $\{o\}$ (that receives traffic from the user nodes), and the subset $N_U \in N$ of "user" nodes (i.e., COs and CSs) that can originate traffic. Each user node can be fixed ($\in N_F$), or mobile ($\in N_M$), if it has at least a corresponding request (note that a user node can be both Fixed and Mobile).

b) E is the set of physical links, indexed by e. K is the maximum number of fibers available for each link.

c) P is the set of (precomputed) paths, indexed by p. Moreover, we indicate with P_{i*} (respectively, P_{*j}:) the set of paths starting from node i (resp., ending in node j); $P_{ij} = P_{i*} \cap P_{*j}$ is the set of paths from node i to node j, whereas $P_i = P_{i*} \cup P_{*i}$ is the set of paths starting from or ending in node i; P_v and P^e are the set of paths belonging to virtual link v or passing through physical link e, respectively.

d) V is the set of virtual links, indexed by (i, j), i.e., all pairs of nodes $i, j \in N$, with $i \neq j$, such that the sets V_{i*}, V_{*j}, V_{ij} and V_i are defined similarly as for P.

e) Λ is the set of wavelengths, indexed by λ. Each wavelength has line-rate C [bit/s].

f) R is the set of connection requests, indexed by r. R_F^n, R_M^n and R_C^n represent the set of fixed, mobile and fronthaul request of node n, respectively. $R_{F\cup M}$ is the set of all fixed and mobile requests, whereas R_C includes all fronthaul requests.

g) l_p is the length of path p, or equivalently expressed as (propagation) delay.

h) $l_{\rm EL}$ is the processing delay introduced by each electronic switch, or equivalently expressed as length.

i) L_D is the maximum fronthaul delay, or equivalently expressed as length.

j) c_r is the capacity of request r. Note that, since fronthaul is not splittable among different lightpaths, there must hold: $c_r \leq C, \forall r \in R_C$.

2) *Decision Variables*

a) $y^r_v = 1$, if fixed or mobile request $r \in R_{F\cup M}$ is routed over virtual link v (binary).

b) $\overline{y}^r_p = 1$, if fronthaul request $r \in R_C$ is routed over path p (binary).

c) $u_{p\lambda}$ = number of established lightpaths on path p and wavelength λ (integer).

d) f_e = number of used fibers on link e (integer).

e) $x^n_i = 1$, if the BBU of node n is placed at node i (binary).

f) $w_i = 1$, if a hotel is placed in node i, i.e., with at least one hosted BBU (binary).

3) *Objective Function*

The objective (see eq. (2)) is to minimize the number of hotels and fibers, where the parameters $\alpha, \beta \in [0, 1]$ can be tuned to select the primary objective of the optimization:

$$\text{minimize}\left\{\alpha \sum_{i\in N} w_i + \beta \sum_{e\in E} f_e\right\}. \quad (2)$$

4) *Constraints*

$$\sum_{v\in V_{*i}} y^r_v - \sum_{v\in V_{i*}} y^r_v = \begin{cases} -1 & \text{if } i = n \\ 1 & \text{if } i = o \\ 0 & \text{otherwise} \end{cases}$$
$$\forall n \in N_F,\, i \in N,\, r \in R^n_F \quad (3)$$

$$\sum_{v\in V_{*i}} y^r_v - \sum_{v\in V_{i*}} y^r_v = \begin{cases} -x^n_i & \text{if } i \neq o \\ 1 - x^n_i & \text{if } i = o \end{cases}$$
$$\forall n \in N_M,\, i \in N,\, r \in R^n_M \quad (4)$$

$$\sum_{p\in P_{*i}} \overline{y}^r_p - \sum_{p\in P_{i*}} \overline{y}^r_p = \begin{cases} x^n_i & \text{if } i \neq n \\ x^n_i - 1 & \text{if } i = n \end{cases}$$
$$\forall n \in N_M,\, i \in N,\, r \in R^n_C \quad (5)$$

$$\sum_{r\in R_{F\cup M}} c_r y^r_v + \sum_{\substack{r\in R_C\\ p\in P_v}} c_r \overline{y}^r_p \leq \sum_{\substack{p\in P_v\\ \lambda\in\Lambda}} C u_{p\lambda} \quad \forall v \in V \quad (6)$$

$$\sum_{\lambda\in\Lambda} u_{p\lambda} \geq \sum_{r\in R_C} \overline{y}^r_p \quad \forall p \in P \quad (7)$$

$$\sum_{p\in P} (l_p + l_{\rm EL}) \overline{y}^r_p + l_{\rm EL}(1 - x^n_n) \leq L_D$$
$$\forall n \in N_M,\, r \in R^n_C \quad (8)$$

$$\sum_{i\in N} x^n_i = 1 \quad \forall n \in N_M \quad (9)$$

$$w_i \geq x^n_i \quad \forall n \in N_M,\, i \in N \quad (10)$$

$$\sum_{p\in P^e} u_{p\lambda} \leq f_e \leq K \quad \forall e \in E,\, \lambda \in \Lambda \quad (11)$$

$$y^r_v \leq \sum_{s\in N_M} x^s_i \quad \forall r \in R^n_M, v \in V_i, i \in N_U,$$
$$n \in N_M \quad (12)$$

$$y^r_v \leq \sum_{s\in N_M} x^s_i \quad \forall r \in R^n_F, v \in V_i, i \in N_U - \{n\},$$
$$n \in N_F \quad (13)$$

$$\overline{y}^r_p \leq \sum_{s\in N_M} x^s_i \quad \forall r \in R^n_C, p \in P_i, i \in N - \{n\},$$
$$n \in N_M. \quad (14)$$

Eqns. (3), (4) and (5) enable the routing of fixed and mobile requests over virtual links and of fronthaul over lightpaths, taking into account that the hotels are not only an outcome of the optimization process, but also source/destination nodes for mobile flows. Eq. (6) ensures that the sum of the capacities of requests routed over a virtual link does not exceed its capacity. Eq. (7) avoids multiplexing among fronthaul requests by forcing each of them to be routed in a separate lightpath, so that the total number of fronthaul requests in each path can not be greater than the number of established lightpaths on such path. Eq. (8) enforces the maximum fronthaul delay constraint, by taking into account both the fiber propagation delay (l_p) and the processing delay contributions of traversed electronic switches ($l_{\rm EL}$), whose number is equal to the number of consecutive paths, plus one. The factor $(1 - x^n_n)$ is necessary in order to disable this constraint in case the BBU is located at its CS and fronthaul is not transported. Eq. (9) enforces that each mobile node is associated with exactly one BBU, thus one hotel. Eq. (10) is needed to identify hotels as nodes which host at least one BBU. Eq. (11) establishes the number of fibers used in each link, i.e., $f_e = \max_\lambda \sum_p u_{p\lambda}$, and also limits this number to the upper bound K. Finally, eqns. (12) and (13) impose that lightpaths carrying mobile and fixed requests respectively, are routed over virtual (resp. physical) links initiated or terminated only in nodes hosting a BBU hotel. Similar constraints apply for fronthaul with eq. (14).

5) *Additional Constraints for Overlay transport*

The previous constraints apply to the *OTN* case. When considering the *Overlay* fronthaul transport option, we must ensure that each fronthaul flow is carried over a dedicated wavelength, i.e., we impose:

$$\sum_{p\in P} \overline{y}^r_p \leq 1 \qquad \forall n \in N_M,\, r \in R^n_C. \quad (15)$$

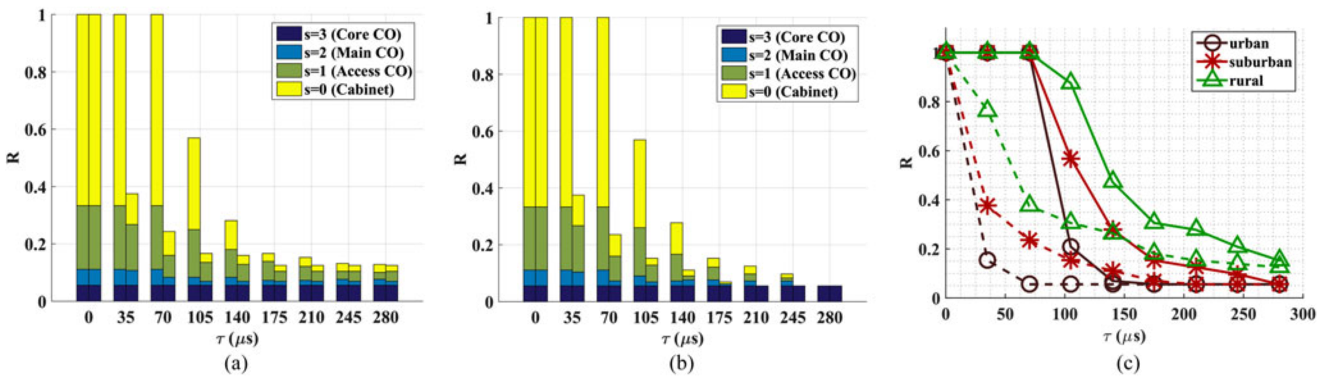

Fig. 7. Consolidation ratio R for increasing τ, different fronthaul transport options (*OTN* versus *Overlay*) and for the two objective functions ("baseline" evaluation with mobile traffic only, $W = 4$, $K = 6$): (a)-(b) "per stage" R in suburban scenario (left bars: *OTN*; right bars: *Overlay*); (c) R values for different geotypes (continuous lines: *OTN*; dashed lines: *Overlay*).

V. Independent BBUs and Electronic Switches Placement Problem

The "baseline" optimization problem described in Section IV can be extended assuming that placement of BBUs and electronic switches is performed independently, to provide more flexibility in aggregating traffic in the electronic domain. Therefore, the output of the new optimization problem is to decide the placement of BBUs and electronic switches *independently*, as well as the GRWA of all traffic requests. Also in this case we distinguish between two fronthaul transport options, i.e., OTN and Overlay. The ILP formulation for this problem can be derived from the one in Section IV by introducing the following changes.

1) *Additional Decision Variable*

In addition to the variables in Section IV, a binary variable is used to capture the placement of electronic switches, i.e.,:

a) $z_i = 1$, if an electronic switch is placed at node i (binary).

2) *Modified Objective Function*

Now the network cost also accounts for the contribution of electronic switches, i.e., the objective function is as follows:

$$\text{minimize}\left\{\alpha\sum_{i\in N} w_i + \beta\sum_{e\in E} f_e + \gamma\sum_{i\in N} z_i\right\} \tag{16}$$

where the parameters $\alpha, \beta, \gamma \in [0,1]$ are used to select the primary objective of the optimization, as for eq. (2).

3) *Additional Constraints*

$$y_v^r \le z_i;\ \forall n \in N_F,\ i \in N - \{o,n\},\ v \in V_i,\ r \in R_F^n \tag{17}$$

$$y_v^r \le z_i + x_i^n;\ \forall n \in N_M,\ i \in N - \{o\},\ v \in V_i,\ r \in R_M^n \tag{18}$$

$$\overline{y}_p^r \le z_i + x_i^n;\ \forall n \in N_M,\ i \in N - \{n\},\ p \in P_i,\ r \in R_C^n. \tag{19}$$

Such constraints substitute eqns. (12)–(14) and are needed to identify nodes equipped with electronic switches. They force to zero all the external traffic routed over virtual links originating from or terminating to any node which is not equipped with an electronic switch.

VI. Case Study and Numerical Results

Numerical results are obtained by averaging over several randomly-generated network and traffic instances. A total of 18 nodes are uniformly scattered over a square region of 15, 142 or 615 km^2, according to the considered geotype, i.e., *urban*, *suburban* and *rural*. Nodes are organized in ring and spur physical topologies and are connected via fiber links (we assume a maximum of $K = 6$ fibers per link, each carrying W wavelengths at 10 Gb/s). Mobile (respectively, fixed) demands are uniformly distributed in the range 300÷750 Mb/s (resp., 10÷20 Gb/s); we assume CSs are configured as LTE macro sites with three sectors, 20 MHz bandwidth and 2×2 MIMO, so the corresponding fronthaul[2] is 6.29 Gb/s. To solve our optimizations we used ILOG CPLEX 12.0 on a workstation equipped with 8×2 GHz processors and 32 GB of RAM.

In the following we show the results for three different scenarios, specifically: 1) a "baseline" case, where we assume that all the 18 nodes are (or have a co-located) LTE CS, so that only mobile traffic and, eventually, the corresponding fronthaul, is carried by the network; 2) the FMC case, where we assume that, among the 18 nodes, 14 are LTE CSs, 2 are COs inserting fixed traffic, and 2 are CSs/COs inserting both fixed and mobile traffic; 3) the FMC case, where we perform an independent placement of BBUs and electronic switches in the nodes.

As performance metric, we consider the ratio R between the number of hotels and the number of CSs, quantifying the degree of BBU consolidation. $R = 1$ indicates no consolidation, i.e., each BBU is located in its CS, whereas $1/n_{CS}$ indicates the highest degree of consolidation, all BBUs in a single hotel (we have indicated with n_{CS} the total number of nodes inserting mobile traffic).

A. Baseline Evaluation: Mobile Traffic

Fig. 7(a) shows the values of *R* as a function of the maximum fronthaul latency τ, for the *OTN* and *Overlay* cases (left and right bars, respectively), when considering the minimization of deployed fibers as objective of the optimization (i.e., *minFibers*).

[2]Note that we only include the CPRI control overhead and not the 8B/10B line coding, which is not necessary in the assumed CPRI-over-Ethernet transport scenario.

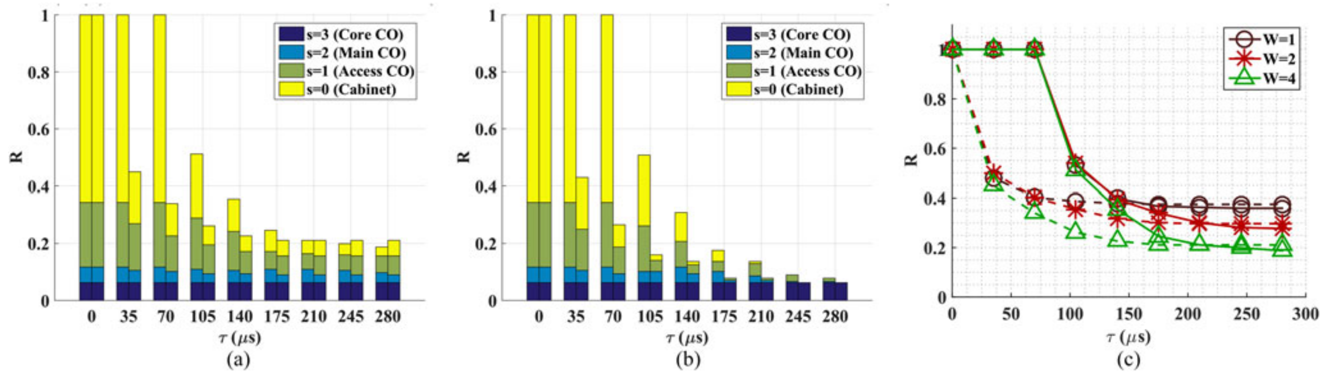

Fig. 8. Consolidation ratio R for increasing τ, different fronthaul transport options (*OTN* versus *Overlay*) and objective functions (FMC, suburban scenario, $K = 6$): (a)-(b) "per stage" R (left bars: *OTN*; right bars: *Overlay*); (c) R values for increasing W (continuous lines: *OTN*; dashed lines: *Overlay*).

The value of R is represented as the sum of four contributions, one for each stage of the network as in Fig. 2, representing the consolidation factor for that stage. The same comparison is shown in Fig. 7(b) for the *minHotel* case. In both figures the results are shown for the suburban geotype case, assuming $W = 4$.

In all cases, when $\tau = 0$ no BBU hotelling is allowed, thus every BBU is placed in its CSs. As τ increases, BBUs can be consolidated in fewer nodes (i.e., R decreases), due to a less-stringent fronthaul latency constraint which allows BBUs to be separated from the corresponding RRHs. Note that higher values of τ ($> 70\,\mu$s) are required to allow BBU hotelling in the *OTN* case, in comparison to the *Overlay* case, where $\tau > 35\,\mu$s is sufficient, due to the penalty introduced by additional electronic switches (20 μs each) in the *OTN* case. When τ increases further, no relevant difference between the two cases is observed. As expected, when latency constraint is not stringent (higher τ), higher consolidation (i.e., lower R) is obtained for both *OTN* and *Overlay* in the *minHotels* case if compared to the *minFibers* case. In particular, in the former case, the highest possible consolidation ($R = 1/n_{CS}$) is obtained, that is, all BBUs are consolidated in the core CO.

Fig. 7(a) shows *R* as a function of τ for the different geotypes and fronthaul transport options, when considering $W = 4$ in the *minHotel* case. High BBU consolidation is obtained already at low τ in urban scenarios, especially for the *Overlay* case. As τ increases, the gap between *OTN* and *Overlay* decreases, until the R values converge to the same value, depending on the considered geotype.

B. *Introducing Fixed Traffic: Evaluation for FMC Network*

We now evaluate the case of an FMC network, i.e., when some nodes also insert fixed traffic. Similarly to the baseline evaluation, *OTN* and *Overlay* are compared in Fig. 8(a) and (b), where we show the values of R for increasing τ in the *minFibers* and *minHotels* cases, respectively, considering the suburban geotype and $W = 4$.

In the *minHotels* case, no relevant difference is observed when introducing fixed traffic into the network, in comparison to the baseline scenario (i.e., comparing Figs. 7(b) and 8(b)). On the other hand, in the *minFibers* case, higher R (i.e., lower consolidation) is obtained when considering FMC [i.e., comparing Fig. 8(a) with Fig. 7(a)], due to the fact that higher capacity is needed to transport the additional fixed traffic, so, to minimize the number of fibers, fronthaul is routed over shorter paths. Thus, the distance between BBUs and their CSs is reduced, and the BBU consolidation becomes lower than in the *minHotels* case. Moreover, in Fig. 8(a) it is also evident that, for higher values of τ ($< 210\,\mu$s), the *OTN* transport solution enables higher consolidation if compared to *Overlay*. This is explained considering that, when higher traffic is transported by the network, mainly due to fronthaul and fixed traffic, if no stringent latency requirements are imposed (i.e., higher τ), lack of capacity is the main constraint for BBU consolidation. In this context *OTN* is beneficial thanks to its efficient capacity utilization provided by grooming fronthaul and backhaul traffic.

This can be also observed in Fig. 8(c), comparing *OTN* (continuous lines) and *Overlay* (dashed lines), in terms of consolidation factor R, for increasing τ and for different values of W, in the *minFibers* case. For all values of W, it is evident that, when τ increases after a certain threshold, *OTN* shows higher consolidation with respect to *Overlay*. Indeed, a breakpoint for τ can be identified, and its value is smaller for lower values of W, that is, when more efficient traffic grooming is needed due to lack of capacity. For further details on this, the reader is referred to [16].

C. *Evaluation for Independent BBUs and Electronic Switches Placement*

To evaluate the benefits obtained by allowing electronic switches placement independently of BBUs placement, we consider the same traffic scenario as in Section VI-B, but we now apply the ILP formulation described in Section V.

In Fig. 9, for the three aforementioned geotypes, we show the comparison, in terms of consolidation ratio R, between the two strategies: 1) the joint BBU-switches placement (*Joint*), where nodes hosting a BBU hotel are also equipped with an electronic switch (continuous lines) and 2) the independent BBUs-switches placement (*Independent*, dashed lines). We consider the *minFiber* scenario with *OTN* fronthaul transport and consider the case of $W = 3$. For strict latency constraints (i.e., if τ is low), the difference between the two strategies is negligible. However, as τ increases, in the *Independent* case higher consolidation (i.e., lower R) is obtained in comparison to the *Joint*

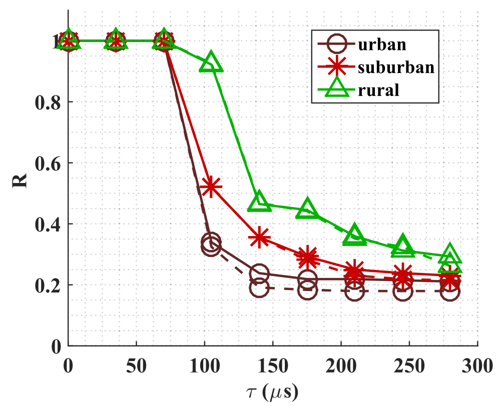

Fig. 9. Consolidation ratio R for increasing τ and different geotypes. Results are shown for *OTN* fronthaul transport, *minFiber* objective function and for the two placement strategies, i.e., *Joint* (continuous line) and *Independent* (dashed lines) BBUs-switches placement.

TABLE II
AVERAGE NUMBER OF ADDITIONAL ELECTRONIC SWITCHES CORRESPONDING TO THE *Independent* BBUS-SWITCHES PLACEMENT CASE OF FIG. 9 FOR THE DIFFERENT GEOTYPES AND INCREASING τ

$\tau\,[\mu s]$	0	35	70	105	140	175	210	245	280
rural	0.3	0.3	0.3	0.3	0.7	0.8	0.7	1.1	1.3
suburban	0.4	0.4	0.4	0.8	0.6	0.8	1.3	1.3	1.2
urban	0.3	0.3	0.3	1.1	1.3	1.3	1.1	1.1	1.1

BBUs-switches placement strategy. This benefit is less evident in the suburban and rural scenarios, where the latency penalty provided by longer links is dominant. In general, a breakpoint between the *Joint* and *Independent* strategies can be identified, representing the minimum tolerated latency (τ) which enables higher consolidation due to electronic switches. This breakpoint for τ is higher for geotypes with larger coverage.

The reduction of R is not a direct consequence of using additional electronic switches, since in Fig. 9 we are considering the *minFiber* objective, which is straightforward when electronic switches are employed. In fact, in both *Joint* and *Independent* BBUs-switches placement cases, the problem solution yields to the same number of deployed fibers. However, when latency requirements become less stringent, the opportunity to use additional electronic switches, besides those already deployed due to BBU hotels placement, further increases the amount of traffic which can be groomed, and also operates over the secondary objective of the minimization (i.e., hotels minimization in eq. (16), i.e., enables additional BBU consolidation. This advantage comes at the cost of deploying only few additional electronic switches. Indeed, in most cases, less than one additional switch is needed, on average. The average number of additional electronic switches corresponding to the *Independent* BBUs-switches placement of Fig. 9 is shown in Table II for the three geotypes and for increasing τ.

VII. CONCLUSION

We have motivated and described a BBU placement optimization problem over a WDM aggregation infrastructure, also comparing two different fronthaul transport cases. Moreover, in vision of fixed/mobile convergent networks, we have analyzed the impact of aggregating mobile backhaul and fronthaul traffic together with fixed traffic over the same WDM infrastructure. Under the considered assumptions, we found that: 1) adopting *Overlay* fronthaul transport, in general, leads to higher BBU consolidation with respect to *OTN* transport, due to the need for electronic switches, in the latter case, which penalize the overall fronthaul latency budget; 2) when non-stringent latency constraints are present and efficient capacity utilization is required (e.g., when high bit-rate fixed traffic is present in the network and/or few wavelengths per fiber are used), *OTN* transport is helpful for BBU consolidation; 3) the opportunity for deploying electronic switches independently from BBU hotels not only helps decreasing the number of deployed fibers, but also enables higher BBU consolidation.

As a future work, we are currently developing heuristic algorithms to deal with problem complexity and solution scalability. Moreover, we target consideration of further aspects of 5G networks, such as comparing different flavors of BBU-RRH functional separation (RAN splits) as well as investigating on the impact of CoMP controller placement over the access/aggregation network performance.

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Authors’ biographies not available at the time of publication.