Design Methodologies and Algorithms for Survivable C-RAN

Bahare M. Khorsandi, Federico Tonini, Carla Raffaelli
DEI, University of Bologna
Viale Risorgimento 2, 40136 Bologna, Italy
email: {bahare.masood, f.tonini, carla.raffaelli}@unibo.it

***Abstract*— In centralized/cloud radio access networks (C-RANs), baseband units (BBUs) are decoupled from remote radio units (RRUs) and placed in BBU hotels. In this way baseband processing resources can be shared among RRUs, providing opportunities for radio coordination and cost/energy savings. However, the failure of a BBU hotel can affect a large number of RRUs creating severe outages in the radio segment. For this reason, the design of a resilient C-RAN is imperative. In this paper, an extension of the facility location problem (FLP) is proposed to find the placement of BBU hotels that guarantees survivability against single hotel failure while the delay is minimized. Different strategies are proposed based on heuristic and integer linear programming (ILP) to solve the survivable BBU location problem and optimizing the sharing of backup resources. The results compare the proposed methodologies in terms of the costs of the BBU placement by referring to different network topologies. The heuristic algorithm is shown to find solutions close to those obtained by the ILP, although evidencing different contributions that are suitably discussed.**

***Index Terms*—C-RAN, Fronthaul, Resiliency, Facility Location, ILP, Heuristics.**

I. INTRODUCTION

Centralized radio access network (C-RAN) was originally introduced to accommodate growth in mobile networking [1]. As opposed to the traditional distributed access networks, where the radio and baseband processing functions are performed at the base station (BS) sites, C-RAN decouples baseband units (BBUs) from BS sites and place them in centralized locations, called BBU hotels. BBUs, that performs baseband processing functions, are connected to remote radio units (RRUs), performing radio processing at BS sites, through the so called fronthaul segment [2], typically based on the common public radio interface (CPRI) [3].

C-RAN introduces considerable benefits compared to the distributed access network, especially when coupled with Network Function Virtualization (NFV) and Sofwtare Defined Networking (SDN), that enable the cloud RAN concept and lead to enhanced flexibility and effectiveness in support of energy and cost reduction, advanced coordination techniques and baseband function virtualization [2]. Despite these advantages, C-RAN introduces many challenges, like the deployment of a reliable C-RAN capable of meeting strict capacity and delay requirements for a large number of cells in wavelength division multiplexing (WDM) optical network. The failure of a BBU hotel can strongly impact the network performance, resulting in service interruption for a potentially large number of mobile users and devices.

Network resiliency against failures is one of the well-established research area for WDM optical networks. The work in [4] presents a routing algorithm for a survivable all-optical mesh topology based on WDM. The authors introduce three primary and backup route computation mechanisms that aim at improving the overall network performance. However, strict latency and capacity requirements, like the one imposed by fronthaul links, are not considered. In [5], authors present a path and link restoration technique for link failures, but protection against node failures is not investigated. The problem of finding optimal location for network functionalities, such as baseband processing functions, is investigated in [6] and [7], while the assignment of BBU functionalities in C-RAN over WDM networks is discussed in [8], but all of the above studies do not consider protection against failures. In [9], the authors deal with protection in traditional distributed radio access networks, but no considerations are made regarding centralized architectures. A previous work proposed a resilient BBU hotel placement against single BBU hotel failure [10]. The approach is based on heuristic with constraints on starting point and maximum distance between each BBU hotel and RRU pair. The results are compared with the case of no protection and show that by adding only 30% more BBU hotels, the resiliency can be guaranteed.

In this work, the classical facility (or node) location problem (FLP) presented in [6] and [7] is extended by introducing the concept of resiliency against single BBU hotel failure. Different design methodologies for survivable C-RAN architectures based on heuristic and an integer linear programming (ILP) are proposed. The main objective of the study is to find the optimal placement for the BBU hotels in order to have protected service for RRUs while minimizing the total distance between RRUs and BBUs. The minimization of backup BBUs and the related deployment are also discussed.

The remainder of this work is organized as follows: in section II, the reference architecture and problem definition are introduced. Section III provides algorithms based on different methodologies to solve the problem. Numerical results obtained for different topologies are described in section IV, while section V concludes the paper.

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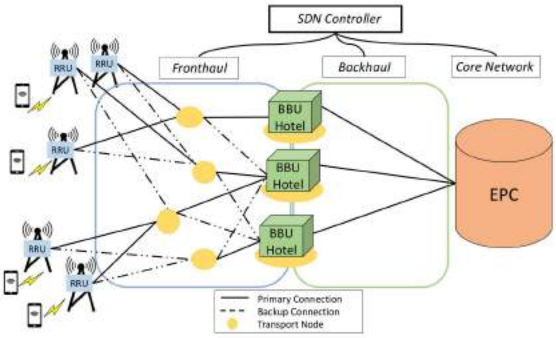

Fig. 1. C-RAN architecture.

II. Reference Architecture and Problem Definition

A C-RAN architecture is shown in figure 1. It is an architecture where a set of RRUs in an area is divided into groups and connected to different nodes of the transport network, called transport nodes. Each transport node represents also a potential BBU hotel site and is connected to one or more transport nodes by means of fiber cables, creating the fronthaul network. A BBU hotel contains several BBUs, each serving a RRU. All RRUs connected to the same transport node have their BBUs hosted in the same BBU hotel for the mitigation of interference in the area. In addition to the fronthaul, another network segment, the backhaul, provides connectivity between BBU hotels and the mobile core network, i.e., the evolved packet core (EPC).

The survivable fronthaul design problem addressed in this paper is defined as follows:

- **Given:** the physical topology of the WDM mesh transport network, the number of RRUs connected to each transport node, the potential location and the cost of activating a new BBU hotel, and the cost of connecting RRUs in transport nodes to BBU hotels.
- **Find:** the minimum cost solution that minimizes the BBU hotel activations and distance between each pair of BBU hotels and RRUs in transport nodes. The solution must ensure that each RRU is always connected to a BBU, also when a single hotel failure occurs.

In the following, some useful parameters and variables are defined, while the notation used throughout the paper is summarized in Table I.

The activation cost of BBU hotels needed to provide full coverage and resiliency of the target area is calculated using the following formula:

$$C_B = \sum_{i=1}^{s} B_i \beta_i \tag{1}$$

where B_i is a boolean variable equal to 1 when the node is set as a BBU hotel, that is when it hosts BBU functionalities related to one or more RRUs. β_i is a parameter associated to the activation cost for a BBU hotel in node i.

TABLE I
Notations used in the different procedures

	Parameters:
S	Set of transport nodes, $\|S\| = s$.
H	$s \times s$ matrix. h_{ij} is the distance in hops between nodes i and j computed with the shortest path.
α	Weight of the hops in the cost function F.
β_i	Weight of the active BBU hotel i in the cost function F.
γ	Weight of the BBU hotel ports in the cost function G.
	Variables:
B_i	1 if node $i \in S$ hosts a BBU hotel, 0 otherwise.
p_{ij}	1 if BBU hotel i is assigned as primary for RRUs at node j $i, j \in S$, 0 otherwise.
b_{ij}	1 if BBU hotel i is assigned as backup for RRUs at node j $i, j \in S$, 0 otherwise.
x_i	Number of BBU ports required at hotel site i for primary purposes.
y_i	Number of BBU ports required at hotel site i for backup purposes.
W	Average number of wavelengths per link.

In order to provide reliability against single BBU hotel failure, it is sufficient to ensure that each RRU is connected to two BBU ports placed in different BBU hotels, one in the primary and one in the backup hotel. The overall distance between BBU hotels and RRUs connecting to the transport nodes in the network, considering both primary and backup hotels, is denoted as D_H:

$$D_H = \sum_{i=1}^{s}\sum_{j=1}^{s} p_{ij} h_{ij} + \sum_{i=1}^{s}\sum_{j=1}^{s} b_{ij} h_{ij} \tag{2}$$

where p_{ij} and b_{ij} are boolean variables that indicates if hotel i is assigned as primary or a backup for the group of RRUs at transport node j. h_{ij} represents the distance, in hops, between transport node i and j computed solving the shortest path problem. By multiplying (2) by the parameter α, the total cost for the distance is achieved:

$$C_H = D_H \alpha \tag{3}$$

Finally, to solve the problem, the proper number of BBU ports must be allocated in each hotel. The total number of primary and backup BBU ports, and the related cost, are calculated according to the following formulas:

$$N = \sum_{i=1}^{s} x_i + \sum_{i=1}^{s} y_i = N_P + N_B \tag{4}$$

$$C_P = N\gamma \tag{5}$$

where N_P and N_B are the total number of primary and backup ports respectively. C_P is the contribution of the total number of ports in each hotel multiplied by the cost parameter γ associated to each port. Since the protection requires that each RRU is connected to two different BBU hotels, the total number of ports should be twice the number of RRUs, and consequently the value for C_P can be fixed. However, only N_P is fixed, while N_B can be reduced. In fact, if exist RRUs which

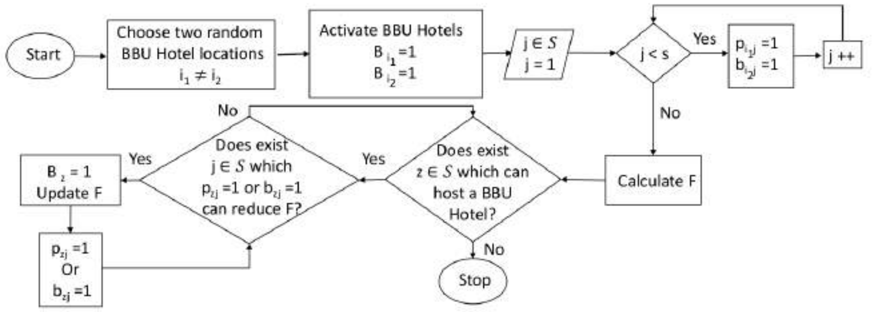

Fig. 2. Flowchart of the BBU hotel placement of heuristic solution.

have separate primary BBU hotels, they can share backup ports due to the single failure assumption done in this work. By sharing the backup ports among RRUs the value for C_P can be reduced, and further cost saving can be achieved.

III. Design Methodologies

In the following, two solutions for survivable fronthaul design are presented. First the problem is solved by the heuristic and in the next subsection an ILP formulation is introduced for comparison.

A. Heuristic

The proposed algorithm is based on the FLP presented in [7], which is applied to networking contexts to find optimal locations for network functions, given a set of possible nodes, under cost constraints. The FLP is extended here by considering also the location of backup functions, in addition to primary functions, while choosing the BBU hotels within the set of transport nodes in the fronthaul network. In the proposed approach, the overall cost of deploying BBU hotels and overall distance, in hops, between BBU hotels and RRUs is minimum, even though it is not guaranteed that a RRU is connected to either a primary or a backup BBU hotel within a given distance.

The heuristic aims at connecting s transport nodes, each containing a given amount of RRUs, through a list of possible BBU hotel locations so that the total cost F is minimum. Let us introduce the total cost F, given by the sum of the cost of activating a new BBU hotel (C_B) and the overall cost of connecting RRUs to BBU hotels (C_H) as follows:

$$Minimize\, F = C_B + C_H \tag{6}$$

The flowchart of the proposed algorithm is reported in figure 2. As an input to the algorithm, it is given an $s \times s$ matrix H which contains the information about the distance computed according to shortest path between each pair of nodes in the network. Also other parameters, α and β_i, are given. These two parameters are related to the cost of distance in hops and activating a new BBU hotel, respectively. The algorithm starts by randomly choosing two candidate nodes for hosting BBU hotels, one for primary $i_1 \in S$ and the other one for backup $i_2 \in S$. In order to provide resiliency, these two locations must be different. After activating new BBU hotels at nodes i_1 and i_2, all RRUs at node $j \in S$ are connected to these two hotels, one as a primary ($p_{i_1 j} = 1$) and the other one as a backup BBU hotel ($b_{i_2 j} = 1$). The total cost F of the initial solution is then computed and used as a reference value. The aim of the rest of the procedure is to reduce the value of F by adding further BBU hotels in order to reduce the contribution of C_H.

The search for a new BBU hotel is performed in the following way. A new location $z \in S$, which is not hosting a BBU hotel, is selected and a new BBU hotel is activated in z. The RRUs involved in the cost reduction, i.e., the ones that can reduce C_H, are then disconnected from their former BBU hotel i_1 or i_2 and connected to the new BBU hotel z. In all steps of the procedure, all RRUs are always connected to two different BBU hotels. The search for a new hotel is repeated until no improvement in F is experienced, and the last solution is considered to be the best solution to the resilient BBU hotel placement, meaning that all RRUs are connected to two different BBU hotels and the obtained cost F is the best combination of the total cost for activating BBU hotels C_B and the cost related to connection C_H.

Once the BBU hotel placement is performed, another procedure is performed to investigate further cost reduction by sharing backup BBU port. BBU hotel port sharing is allowed if and only if two RRUs, namely j_1 and j_2, share the same backup BBU hotel i' and are assigned to different primary BBU hotels. Only in this case, j_1 and j_2 can share the backup ports in BBU hotel i'. This procedure is repeated for all shared backup BBU hotels with the above property.

B. ILP Optimization

The core of our problem is based on the ILP formulation of the FLP introduced in [7]. The formulation in [7] has been modified in order to provide protection, by means of backup hotels, and to include the effects of BBU hotel ports. The problem is here formulated in such a way that, by properly tuning the parameter of the objective function, BBU ports can be minimized while solving the survivable fronthaul design problem.

Additional parameters:

- r_j number of RRUs at site j.
- M a large number.

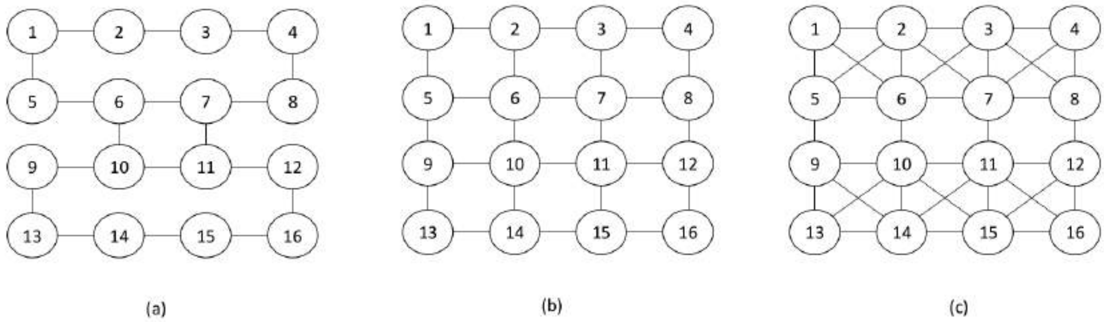

Fig. 3. The reference network topologies, (a) network A with connectivity $N_A = 2.25$, (b) network B with connectivity $N_B = 3$ and (c) network C with connectivity $N_C = 4.5$.

Additional variables:

- $c_{j,i,i'}$ = 1 if source j is using destination i as primary and i' as backup hotel site; 0 otherwise.

Objective function:

$$Minimize\ G = C_B + C_H + C_P \tag{7}$$

The multi-objective function (7) is composed of three members. The first term takes into account the activation cost of each hotel (C_B). The second term accounts for the cost to connect RRUs to BBU hotels, both primary and backup (C_H) while the third term accounts for the cost of BBU ports required in each hotel (C_P).

The problem is subject to the following constraints:

$$\sum_{i \in S} p_{i,j} = 1, \forall j \in S \tag{8}$$

$$\sum_{i \in S} b_{i,j} = 1, \forall j \in S \tag{9}$$

$$p_{i,j} + b_{i,j} \leq 1, \forall i, j \in S \tag{10}$$

$$x_{i,j} \geq \sum_{i \in S} p_{i,j} r_i, \forall i \in S \tag{11}$$

$$c_{j,i,i'} \geq p_{j,i} + b_{j,i'} - 1, \forall i, j \in S, i' \in S - \{i\} \tag{12}$$

$$y_{i'} \geq \sum_{j \in S} c_{j,i,i'} r_j, \forall i \in S, i' \in S - \{i\} \tag{13}$$

$$B_i \cdot M \geq \sum_{j \in S} p_{i,j} + b_{i,j}, \forall i \in S \tag{14}$$

Constraints (8) and (9) ensure that there is one primary and one backup hotel for each RRU. Constraint (10) imposes primary and backup hotels to be disjoint. Constraint (11) counts the number of BBU ports to be installed in each primary hotel. Constraint (12) tells if a primary hotel is in common to a backup hotel for each source and is used in constraint (13) to ensure that there are enough BBU ports in each backup hotel. These two constraints, along with (7), allow to minimize the number of ports in each backup hotel. In fact, the number of BBU ports required at each backup hotel equals the largest number of RRUs that shares the same primary hotel. Finally, constraint (14) activates hotels (i.e., tells if the hotel is a primary and/or backup for RRUs).

IV. Use case Settings and Numerical Results

A. Reference Scenarios

This section presents the analysis of survivable fronthaul in C-RAN to evaluate the strategies proposed in Section III and applied to different scenarios. The reference topologies of the optical transport network used in the performance assessment are presented in figure 3. Three metro/aggregation networks are considered with 16 nodes each but with different levels of connectivity. The connectivity N_i for network i is defined as follows

$$N_i = \frac{\sum_{i=1}^{s} NO_i}{s} \tag{15}$$

where NO_i is the number of optical interfaces in node i and s is the total number of nodes, 16 for all networks in this evaluation.

In all the topologies each node represents a cell site, assumed to serve a value of the upstream traffic equal to 10 RRUs connected to the node, each one requiring two lightpaths, i.e., one connecting the RRU to the primary and one connecting the same RRU to the backup BBU hotel. Each edge in the graph represents a bidirectional fiber connection, all with the same length. The results discussed in this section are obtained using a Java-based simulator and compared with the optimal solution from ILP, obtained using CPLEX commercial tool [11]. The results from the heuristic are averaged over all the possible combinations of BBU hotels pairs that can be used as a starting point. Among the solutions, the maximum observed deviation from the average is 22% which shows the limited impact of the starting point on the results and allows the algorithm to start by random locations. In all the graphs reporting F and G, the results are normalized with respect to α (that was constant) and are reported in each case. All β_i were considered constant and equal to β. The following parameters are used:

$$R = \frac{\beta}{\alpha} \quad , \quad Q = \frac{\gamma}{\alpha} \tag{16}$$

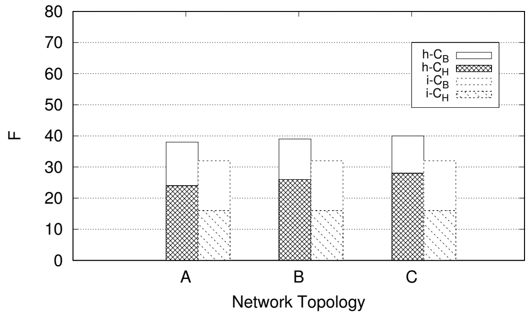

Fig. 4. Total cost F, normalized with respect to α, for ILP (i) and heuristic (h), representing the contributions of the BBU hotel activation cost C_B and the overall distance between each pair of RRUs and BBU hotels C_H, in networks A, B and C when $R = 1$.

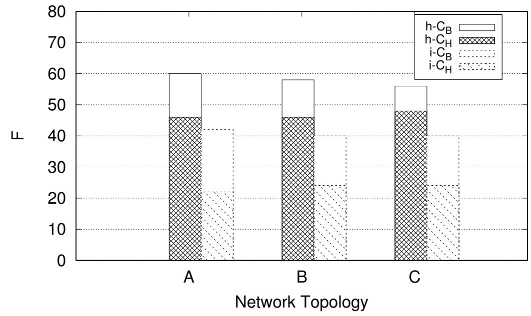

Fig. 5. Total cost F, normalized with respect to α, for ILP (i) and heuristic (h), representing the contributions of the BBU hotel activation cost C_B and the overall distance between each pair of RRUs and BBU hotels C_H, in networks A, B and C when $R = 2$.

B. Numerical Results

Figure 4 reports the total cost of the survivable fronthaul design solution (i.e., the cost function F). In the figure, the two contributions to F are shown for each network when $R = 1$, and the total cost is normalized with respect to α. The cost obtained with the heuristic is compared to the one of the ILP when $\gamma = 0$, so that F has the same meaning as G. The total cost is lower for the ILP, with a different contributions of BBU hotels and distance. While the ILP cost is constant with respect to different network connectivities, the cost of the heuristic is slightly higher when the network connectivity is higher. The reason is that the heuristic is able to activate less BBU hotels than the ILP, which causes the number of hops to grow, and results in an increased overall cost. Similarly to the previous figure, figures 5 and 6 show the total cost function F, normalized respect to α when R equals 2 and 10, respectively. By increasing R, the hotel activation cost becomes more relevant in F, therefore the number of selected hotels decreases when R increases. For $R = 2$ the contribution of the BBU hotels to F is less than in the case $R = 1$. When $R = 10$, the number of active BBU hotels keep decreasing but their contribution to the total cost becomes higher than in the case $R = 2$, due to the large R factor. As a final note, the heuristic provides a good approximation of the ILP when the activation cost and the distance have similar weight in F $(R = 1)$ and when the activation cost is much more relevant than the distance $(R = 10)$. In the case $R = 2$ instead, the heuristic solution is up to 40% more expensive then the ILP.

The number of BBU ports, that is the number of functional interfaces to serve the related RRUs, is calculated based on the number and location of BBU hotels. The previous results, obtained using F or G with $\gamma = 0$, do not include any consideration on the number of ports, not considered so far. In order to compare the results of the heuristic and ILP, the latter has has been run once again to derive the minimum number of BBU hotel ports. α and β were all set to zero, γ was set to 1 and the hotel placement previously obtained was introduced in the ILP model as additional constraint, in order to set the position of the BBU hotels. The overall number of

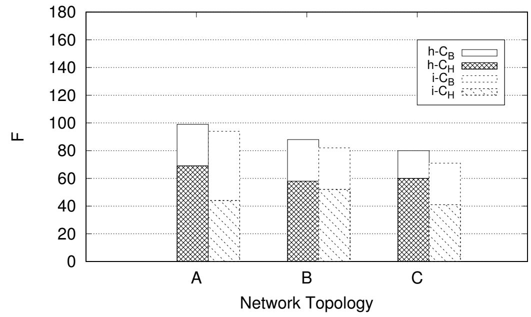

Fig. 6. Total cost F, normalized with respect to α, for ILP (i) and heuristic (h), representing the contributions of the BBU hotel activation cost C_B and the overall distance between each pair of RRUs and BBU hotels C_H, in networks A, B and C when $R = 10$.

backup ports obtained from the modified ILP is compared to the heuristic one, averaged over all the initial cases, and is reported in figures 7 and 8, for the three network topologies when R equal to 1 and 10, respectively. Since the total number of primary BBU hotel ports is fixed and equal to the number of RRUs, it is not included in these figures.

Figure 7 shows that the number of backup BBU hotel ports required by the ILP is lower than the heuristic one. In the case of $R = 1$, both ILP and heuristic have a large number of active BBU hotels, and since this number is higher for the ILP, ILP results more efficient in sharing BBU hotel ports. By increasing the network connectivity, the ILP easily assigns primary and backup BBU hotels such that the sharing of backup ports results higher than with the heuristic that, instead, assigns primary and backup hotels based only on F, and therefore is not aware of their impact on the number of shared backup ports.

Figure 8 shows that the sharing of BBU hotel ports is extremely difficult for the heuristic when R is high and the number of active hotels is very low. The total number of ports is high independently of the connectivity due to the fact that the solution obtained with the heuristic, averaged over all possible starting nodes, requires just two or three hotels to be active. The ILP instead, finds solutions with slightly more

TABLE II
THE EFFECTS OF Q ON THE COST COMPONENTS OF THE OBJECTIVE FUNCTION G FOR THE DIFFERENT NETWORK TOPOLOGIES ($R = 2$).

	Network A							Network B							Network C						
Q	C_B	C_H	F	N_B	C_P	G	W	C_B	C_H	F	N_B	C_P	G	W	C_B	C_H	F	N_B	C_P	G	W
0	20	22	42	100	0	42	12.2	16	24	40	80	0	40	10	16	24	40	60	0	40	6.7
0.001	20	22	42	100	0.1	42.1	12.2	16	24	40	80	0.08	40.08	10	14	26	40	50	0.05	40.05	6.9
0.1	22	21	43	80	8	51	11.7	18	23	41	70	7	48	9.6	14	26	40	50	5	45	6.9

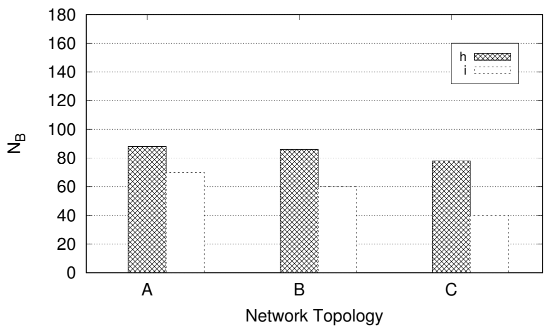

Fig. 7. Total number of backup ports N_B for ILP (i) and heuristic (h) in networks A, B and C with $R = 1$.

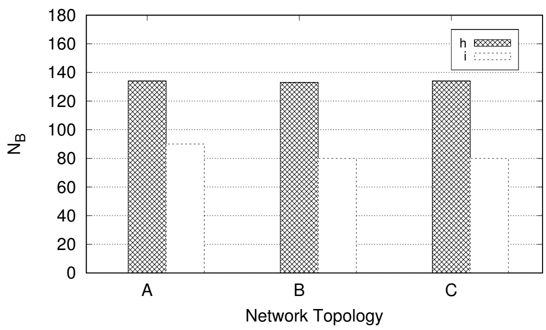

Fig. 8. Total number of backup ports N_B for ILP (i) and heuristic (h) in networks A, B and C with $R = 10$.

active hotels, and therefore can limit the number of BBU hotel ports to lower values.

In order to see the effects of γ on the placement, the value of parameter Q is varied. Table II shows the different values for F and G in the three networks when Q is equal to 0, 0.001 and 0.1, while R is considered constant and equal to 2. As expected, the total cost in each network increases by increasing Q, due to the cost introduced by the ports. For these values of Q, the sum of activation and distance cost are almost the same in the three cases, while their contribution changes. In fact, there may be solutions employing different number of hotels and that leads to have slightly different cost like the case of $Q = 0.1$. The impact of γ on the cost is therefore to select the solution, among solutions with the same cost (measured by F), that minimizes also the total number of ports. Table II also shows the average number of wavelengths per link without considering wavelength continuity. It is possible to notice how the required wavelengths per link decrease when the network connectivity increase, due to the higher number of available links to connect transport nodes. In conclusion, when the contribution of the BBU hotel ports is considerably less relevant with respect to the activation and distance, which well represent a real case scenario, it is safe to neglect the contribution of the BBU hotel ports in a first computational phase. Then, when the hotels to activate are selected and the delay is minimized, a dedicated minimization can be performed to limit the number of BBU hotel ports.

V. CONCLUSION

The paper presents a survivable fronthaul design in C-RAN. Two methodologies have been proposed and compared in terms of relevant cost parameters, namely the number of BBU hotels, overall distance between BBU hotels and RRUs and BBU hotel ports. The different contributions to cost, calculated by heuristics and ILP have been discussed, evidencing the influence of different cost weights on results. The methodologies has been tested against different network topologies of the same size characterized by different connectivity level, showing limited impact on final costs.

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