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BBU Location Algorithms for Survivable 5G C-RAN over WDM

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Abstract

New 5G radio access network is expected to offer competitive advantages in terms of cost, quality of service and mobility, that make it attractive for service providers. The resilience of this part of the network is consequently essential to provide high availability and service continuity in case of failure.

This study focuses on heuristic solutions to design and operate the fronthaul network based on the Centralized Radio Access Network (C-RAN) concept. Facility Location Algorithms (FLA) are proposed to assign primary and backup functionalities to Baseband Unit (BBU) hotels and ensure availability in case of a single BBU hotel or link failure. Sharing techniques are applied to BBU hotel ports and transport wavelengths for hl cost-efficient design. The goal is to minimize the number of active BBU hotels while providing full coverage to all Remote Radio Units (RRU).

Numerical results evaluate cost in relation to main design constraints, namely the number of hops allowed to reach primary and backup BBU hotel. The number of BBU hotels is compared for different location algorithms, showing that a proposed extension of a classical FLA, by including resilience, allows to obtain the best results both in terms of BBU hotels and shared ports. However, the need of suitable trade-off between the number of BBU hotels and the required wavelengths is outlined, depending on relative costs.

Keywords: 5G, C-RAN, Fronthaul, Resilience, Facility Location Algorithm

1. Introduction

The data traffic explosion generated by the increasing number of connected devices, e.g., smartphones and tablets, has produced data traffic demands that exceed the capabilities of current mobile technologies. Next generation mobile and Internet of Things applications will require ubiquitous, Quality of Service guarantees, high capacity, and continuous access to the Internet [1]. As a solution to this supply-demand battle, development of the Fifth Generation (5G) mobile technology is currently underway to enable fully connected and mobile society by the year 2020 [2].

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In the previous generation of mobile networks, e.g. Long Term Evolution, the Radio Access Network (RAN) is the most important asset for mobile operators to provide high data rate, high quality and high availability of services to mobile users. Traditional RAN will become far too expensive for mobile operators to keep themselves competitive in the future mobile internet world. In fact, it lacks the efficiency to support the sophisticated centralized interference management required by future heterogeneous networks [3]. As the first step of the evolution of RAN, the concept of centralized control of radio signals is introduced, which is known as the Centralized Radio Access Network (C-RAN) architecture [4]. This new approach to network architecture has two clear advantages: reduced Capital Expenditure/ Operating Expenses for operators and improved user experience through less interference. By separating the base station into two parts, namely the Baseband Unit (BBU) and the Remote Radio Unit (RRU), connected by the network segment called fronthaul, network operators are allowed to flexibly manage the supported RRUs, while centralizing the baseband processing functions into a BBU hotel. Consequently, the radio resource management is facilitated especially in complex operating environments such as Heterogeneous Network [5] [6]. The most typical interface used on the fronthaul segment is the Common Public Radio Interface (CPRI) [7]. The evolution of C-RAN concept takes advantage of software-based network control and management, like Software Defined Networking (SDN), coupled with Network Function Virtualization (NFV) and cloud networking, leads to the Cloud-RAN [8].

However, as in any other new network technology, the 5G C-RAN architecture also has its own challenges. In particular, the development of a reliable C-RAN to meet capacity and delay requirements for a large number of cells is one of the major ones [9]. In fact, the failure of a BBU hotel can strongly impact on a large number of RRUs, resulting in the interruption of the connectivity for a potentially very large number of mobile users and services.

Network survivability and resilience is a well-established research area for Wavelength Division Multiplexing (WDM) optical networks [10], which are usually adopted to deploy the fronthaul segment and support the high capacities required by CPRI. However, these works mainly focus on path and link protection/restoration in mesh WDM networks [11]. Several protection schemes have been already proposed for the backhaul part of the 5G networks [12] but no in-depth investigation has been done on virtualization aspects of the fronthaul part and related constraints. In the specific, fronthaul has much stricter requirement with respect to backhaul, due to the use of CPRI interface. In addition, since fronthaul allows the use of virtual functionalities for centralized BBU implementation, new protection schemes need to be investigated.

When talking about fronthaul resilience, our main concerns are either BBU hotel or link failure. The target is to maintain a reliable connectivity between BBU functionalities and served RRUs. A solution to this problem is to provide protection for BBU hotel by properly assigning primary and backup BBU functionalities to BBU hotels. The assignment of primary BBU functionalities has been reported in a previous research [13] but with no reference to the protec-

tion. Some investigations on the feasibility and additional costs of resilient BBU hotel placement has been addressed in [20], which represents, at the best of our knowledge, the first work on this topic. Further studies are needed anyway with the purpose of completeness, optimization and scalability of the methodology applied, which are the targets of this research.

In this paper, the key point is to find an optimal placement for BBU hotels in order to have protected coverage through disjoint primary and backup path for the RRUs while meeting the strict requirements of CPRI at minimum cost for highly dense C-RAN. Different algorithms are proposed that can be referred to as the classical Facility Location Problem (FLP) class [14]. They are characterized by different choices on the starting nodes to perform the assignment and on different constraints on the distance between each BBU hotel and RRU pair. Classical FLP theory is also taken as a reference and extended to achieve BBU hotel protection.

The effectiveness of the proposed algorithms is evaluated in terms of the number of BBU hotels needed to support resilience, of the total number of primary and backup ports in BBU hotels and of the number of wavelengths required to connect RRUs to primary and backup BBU hotels. The results, referred to a large network, show that by applying the proposed algorithms, protection can be obtained by a limited amount of additional resources (BBU hotels, ports, and wavelengths) which is evaluated and compared for the proposed approaches. The different algorithms exhibit different backup port sharing capabilities, one of them optimizing both the placement cost and the sharing at the same time. A relationship between the number of BBU hotels and the wavelengths required for resilient fronthaul implementation has been outlined and needs to be suitably considered in the design of the fronthaul network.

The rest of the paper is organized as follows. In Section II, previous studies on WDM resilience and FLP are reviewed. Section III presents the reference network C-RAN scenario and introduces the fronthaul network architecture considered in this paper. Section IV presents the problem definition and methodology. In Section V the different location algorithms proposed. Numerical results are presented in Section VI. Section VII outlines the conclusions of the project.

2. Related Works

Several studies have addressed the concept of resilience in WDM network in the past [15] [16]. These studies looked at different fiber link and optical node failure scenarios. The study in [15] introduces primary and backup route computation mechanisms to improve overall network performance. The key in their design was mainly to reduce the number of required converters per node. When considering a C-RAN architecture resilience provisioning at the transport network level is not enough. An additional problem must be addressed, that is where to locate the BBU functionalities in order to maintain the connectivity even in the presence of BBU hotel failure. A preliminary research was presented in [17] which provides a comprehensive description of the fronthaul segment in C-RAN. The authors in [18] investigate all the characteristics of fronthaul, such

as data rate, delay, etc, and possible implementation of the fronthaul in optical WDM networks. The research done in [19] was one of the first which presented the concept of BBU hoteling and practical use of CPRI in fronthaul part of C-RAN. They were also considering the need of having network protection for optical fiber. Their solution was to introduce a ring between each pair of RRU and BBU hotel and use one trunk cable for primary use and the other just in case of failure.

To achieve C-RAN resilience a placement problem must be solved to find an optimal solution with respect to cost and constraints. In [21] the BBU placement problem has been addressed for 5G C-RAN to find an optimal solution that minimizes the network cost expressed as nodes or optical links. The paper adopts a method based on Integer Linear Programming (ILP) and was not focused on providing protection. The time to compute ILP solutions is often affected by scalability issues that make it not suitable for highly dense aggregation networks with possibly many tens of nodes. So the heuristic approach is adopted here to solve the placement and ensure protection by providing a reliable path for both primary and backup connections. A previous study [20], proposed a resilient BBU hotel placement against single BBU hotel failure. There are some parameters such as maximum allowed distance, limitation on the number of wavelengths and different load per cell, which influence the BBU hotel placement problem. The two-step solution proposed with the first step aims at minimizing the number of BBU hotels by placing them in the highest nodal degree. Step two introduces a sharing technique for backup BBU hotel ports and wavelengths. The results show that by only 30% additional BBU hotels the resilience will be guaranteed and the sharing technique is able to reduce almost 25% of backup BBU hotel ports. In this study, as an extension of what proposed before, the main focus is on defining and comparing strategies in terms of achievable optimization. In fact, this problem can be seen as a classical FLP optimization problem. FLP has been extensively studied over the past several decades [22] [23] and applied to the design of supply and service networks. However, few studies consider facility failure or disruption [24]. The research is done in [25] studied reliable FLP by integer linear model formulation. So existing methodologies for facility location have been suitably investigated and extended to resilient BBU hotel placement thus leading to a completely new proposal. The proposed heuristics are evaluated in terms of their effectiveness in finding a resilient solution in the presence of both BBU hotel and link protection and demonstrated to be useful for dense networks, with a high number of nodes. By providing disjoint primary and backup paths for each RRU service continuity is seamlessly guaranteed in case of failure in any part of the primary path (primary BBU hotel included). Different heuristics are presented and compared with an extension of the approach presented in [26], which fulfills both resilience and specific constraints of the fronthaul networks, as will be described in the following.

In this study, we first propose simple heuristics to obtain optimized solutions to the problem in the presence of single BBU hotel failure varying the assignment strategy. Then an extension of a classical FLP which aims at finding the closest

assignment of RRU to primary and backup BBU hotel is defined and compared with the previous ones, showing improved effectiveness. The description of the different approaches is reported in the following sections after having introduced the reference scenario.

3. Reference C-RAN Architecture

C-RAN is a novel mobile network architecture, which has the potential to help in solving many operator's challenges while introducing centralized processing capabilities [27]. In C-RAN, the co-located functionalities of traditional base stations, namely transmit/receive functions and digital processing, are physically separated and remotized [28]. The segment connecting the two parts is called fronthaul and is shown in Figure 1. The fronthaul traffic exchanged between RRUs and BBU hotels is usually transmitted using Digital Radio-Over-Fiber techniques and standard radio interfaces, e.g., CPRI, which is the most widely used. CPRI is a constant bit rate, bi-directional protocol that requires accurate synchronization and strict latency control. For example, a significantly higher transmission capacity needs to be provided compared to traditional design. In addition, the fronthaul traffic needs to fulfill very tight latency constraints that vary depending on the specific Radio Access Technology used in the mobile network [29].

This solution allows to locate the digital processing related to different cell sites in the same location, namely the BBU hotel. The sharing of the hosting facility is viewed by operators as a potential advantage in reducing costs and power consumption. This solution also enables the implementation of functionalities like the Coordinated Multipoint to achieve radio performance gains and better performance related to mobility. A topic of intensive research is represented by a further evolution of the centralized approach towards the Cloud-RAN [30] which adopts NFV principles to make the BBU hotel flexibly reconfigurable with the possibility of migrating BBU functionalities to different hotels located in different servers. This approach can fully take advantage of the evolution of network control and management towards the SDN principle [31] and open to an extremely wide set of features. In Cloud-RAN new BBU can also be added and upgraded easily, thereby improving scalability and facilitating network maintenance. In the following C-RAN will be used to indicate the cloud-based RAN concept.

To achieve the high capacity requirements of the fronthaul segment, WDM fiber connections are adopted and need to be properly designed and optimized with respect to cost.

In addition to the fronthaul, another network segment, the backhaul, provides connectivity between BBU hotels and the mobile core network. This section of the network is packet-based and has more relaxed characteristics in comparison with the fronthaul.

The potential flexibility and efficiency offered by the C-RAN architecture need properly defined algorithms to assign the required functionalities to network servers in relation to evolving network needs. One aspect that is of primary

importance is represented by BBU hotel reliability and protection. Function centralization represents always a critical aspect in this perspective and, in particular, the failure of a BBU hotel hosting the digital processing units of several cells can cause out of service for very large numbers of users. Protection of BBU hotel functionalities in case of failure needs to be properly designed. Centralization of BBU functionalities, meaning that several BBUs are physically located in the same node, requires, among the main concerns, that the cost of building the suitable structure to provide cooling and energy system for BBU hotels is maintained low. Moreover, to provide resilience, extra ports or BBU hotels need to be added to the total cost of the resilient network increases. One of the challenges for network designers is to ensure enough reliability while maintaining both the cost and the energy consumption as low as possible.

In the solution proposed each RRU is provided with a primary lightpath to the main BBU hotel serving as a digital unit and a backup lightpath to a second backup hotel which is activated in case of failure. The switching operation from the primary to the backup hotel is performed through proper signalling by the SDN controller in case of failure. The selection of the primary and backup BBU hotels to serve the RRU distributed in an area, given the network of interconnected servers (the nodes), is the aim of the algorithms proposed in this paper.

4. Problem Definition and Methodology

This research proposes different cost-efficient strategies for the survivable fronthaul network. All algorithms described here focus on ensuring resilience in case of single BBU hotel or link failure. The procedures are assumed to be revertive, i.e., after a failure is repaired, all settings go back to normal conditions.

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 cost of opening and connecting to a new BBU hotel.

Find: The minimum number of BBU hotels, BBU hotel ports, and wavelengths to have full coverage and resilience for all RRUs.

The proposed methodology is organized into two phases as shown in Figure 2 and described in details in the following:

- **Phase 1** focuses on BBU hotel placement with respect to resilience. The placement requires that each RRU is connected to two separate BBU hotels, one for primary use and the other for backup in case of failure. Since the network has to provide the service for all RRUs at all the times, each RRU will have in this phase a dedicated port both in the primary and in the backup BBU hotels. In addition to resilience for BBU hotel ports, single link failure is also considered in this study. So each RRU

will be provided with two lightpaths toward its primary and backup BBU hotels. In case of failure in any segment of the primary lightpath, then the affected RRU can transmit its data using the backup lightpath under SDN control.

- **Phase 2** has the task of sharing the resources identified in Phase 1 in order to increase the overall utilization and save resources. The basic sharing policy is that two or more RRUs can share the same backup port if and only if they have different primary ports located in two different BBU hotels. The reason is that, if two RRUs have their primary ports in the same BBU hotel and a failure happens in that hotel, then both RRUs will shift their loads to the same backup port. The same policy is adopted for sharing backup wavelengths. Two RRUs can share the same backup wavelength if and only if they are using two different primary lightpaths. So in case of failure in any part of the primary lightpath, RRUs can use the backup one without conflicting with others. In addition to the above procedure, a resilient core network is also required to avoid many BBU hotels to loose their connection in case of failure in this part of the network. However, core network constraints are different from fronthaul ones and for this reason, the problem will be addressed as a further phase in future study.

5. BBU Placement and Sharing Algorithms

Two different sets of algorithms are described in this section to implement Phase 1, namely the Fixed Distance (FD) algorithm and the Variable Distance (VD) algorithm. Then Phase 2, which is common to the two approaches, is also described. To this end, the variables for the mathematical formulation are listed in Table [II](#).

To calculate the cost, the formulas with the different contributions are here introduced. The number of BBU hotels needed to provide both full coverage and resilience is calculated using the following formula:

$$C_B = \sum_{i=1}^n B_i \quad (1)$$

where B_i is a boolean variable equal to 1 when the node is set as a BBU hotel, that is it hosts BBU functionalities related to possible multiple RRUs. A further cost parameter is represented by the number of ports needed to support primary and backup functionalities. A value averaged over the total number of nodes, namely C_P , is calculated by the following formula, which considers the total number of primary ports in addition to shared backup ports resulting after Phase 2:

$$C_P = \frac{\sum_{i=1}^b \sum_{j=1}^n PP_{ij} + \sum_{i=1}^b \sum_{j=1}^n BP_{ij}}{n} \quad (2)$$

N	Set of transport nodes, $ N = n$
L	Set of optical links, $ L = l$
B	Set of transport nodes hosting a BBU hotel, $ B = b$
C_B	Total number of BBU hotels
B_i	1 if node $i \in N$ host a BBU hotel, 0 otherwise
C_P	Average number of BBU ports
PP_{ij}	1 if BBU hotel $i \in B$ is assigned a primary port to the RRUs connected to node $j \in N$, 0 otherwise
BP_{ij}	1 if BBU hotel $i \in B$ is assigned a backup port to the RRUs connected to node $j \in N$, 0 otherwise
C_W	Average number of wavelengths
PW_{ij}	1 if link $i \in L$ contains a primary wavelength assigned to the RRUs connected to node $j \in N$, 0 otherwise
BW_{ij}	1 if link $i \in L$ contains a backup wavelength assigned to the RRUs connected to node $j \in N$, 0 otherwise

Table 1: Notations used in the formulas

Finally, the average number of wavelengths needed to support BBU hotel reliability is calculated as C_W :

$$C_W = \frac{\sum_{i=1}^l \sum_{j=1}^n PW_{ij} + \sum_{i=1}^l \sum_{j=1}^n BW_{ij}}{l} \quad (3)$$

All the above quantities will be shown in graphs and compared for the different algorithms and with the cost of no protection (labelled as WP).

5.1. FD Algorithm

This set of algorithms perform BBU hotel placement under the constraint of a maximum distance between BBU hotels and RRUs. As a consequence, the placement solution performed in Phase 1 will guarantee that each RRU will find both primary and backup BBU hotels within given distance and, consequently, with a possible bounded delay. As a drawback, the solution is expected to be characterized by a quite large number of BBU hotels to ensure protection.

The assignment procedure can start by assigning the Primary BBU Hotel First (P) or the Backup BBU Hotel First (B) first, and then proceeding further. How this choice impacts on resulting costs will be evaluated. In addition, the starting nodes have also an impact on the total number of BBU hotels, depending on network topology. Two extreme different option will be considered, namely Max-D when the algorithm starts from the node with the highest nodal degree, and Min-D when instead it starts from the node with the lowest nodal degree. As a consequence of all possible combinations, we will have for Phase 1 the options indicated as Min-D-P, Max-D-P, Min-D-B, Max-D-B. In the following FD Phase 1 placement algorithms will be described.

Primary BBU Hotel First (P). The objective of this methodology, in addition to minimizing the total number of BBU hotels, is to prioritize the connectivity

between each RRU and its primary BBU hotel. Figure 3 shows the procedure to find the best placement for BBU hotels so that all RRUs have access to their primary ports, and then by applying the resilient placement, either by associating backup functionalities to already connected BBU hotels or by adding extra BBU hotels. A node is first chosen based on Max-D or Min-D policy. Once a new node i is selected to be a candidate host for a BBU hotel, the strategy then checks all nodes j that are within certain distance h from node i and that can be reached using a transparent lightpath.

P or B methodology can be adopted as shown in boxes (a) or (b) in Figure 3 in dashed line. This part is the only difference in the assignment algorithm between P and B algorithms. In case of the P approach, if a primary port (and wavelength) for RRUs connected to node j has not been assigned yet, the BBU hotel i is mapped as node j primary BBU hotel, otherwise, in case of node j has already a primary port, node i is set as its backup BBU hotel and backup port (and wavelength) is assigned according. The opposite happens for the B approach which is explained in the following.

Backup BBU Hotel First (B). This methodology is investigated with the aim of maximizing the sharing of backup BBU hotel ports.

The pseudo-code is shown again in Figure 3 including box (b) instead of (a). Again the starting point impacts on results, so both Max-D-B and Min-D-B will be considered. With B algorithms a transport node i is chosen based on the Max-D or Min-D policy. Then this node is checked as backup BBU hotel first for all nodes j connected within the distance h . If node j has already been assigned a backup BBU hotel then node i will be connected to j as its primary BBU hotel. Once all nodes j within the h hop distance are checked, node i is no longer considered and another node in the set of possible locations for BBU hotels is chosen. These operations are repeated until all RRUs are assigned a backup and a primary BBU hotel.

5.2. VD Algorithm

The Variable Distance algorithm (VD) is based on the FLP [32] which is applied to networking contexts to find the optimal location for network functions, given a set of possible nodes, under cost constraints. The algorithm for node location reported in [32] is extended here to propose the VD algorithm 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. The benefit of this approach is that the overall cost of deploying resilient BBU hotel placement is minimum even though no guarantee is given to RRU to find either a primary or a backup BBU hotel within a given distance. The objective of the VD algorithm is to minimize the total cost F , which is calculated by Equation 4. F consists of the contribution of the cost of activating each new BBU hotel plus the cost of the connection between each pair of BBU and RRU. To minimize the total cost of the network both these two contributions must be minimized. The VD algorithm is able to find the closest BBU hotels (both primary and backup) for each RRU in order not to increase the total cost. Some mathematical formulation regarding the cost optimization

will be presented that will be applied by the proposed heuristics. Then the main aspects of the procedures are explained using pseudocode representation.

All the notations used for the pseudo-codes are summarized in Table 2

F	Total cost
N	Set of transport nodes, $ N = n$
B	Set of transport nodes hosting a BBU hotel, $ B = b$
λ_i	Cost of opening a new BBU hotel in node $i \in N$
μ_{ij}	Cost of connecting the RRU connected to node $j \in N$ to BBU hotel $i \in B$
$Pconn_{ij}$	1 if node $i \in B$ is the primary BBU hotel for the RRUs connected to node $j \in N$, 0 otherwise
$Bconn_{ij}$	1 if node $i \in B$ is the backup BBU hotel for the RRUs connected to node $j \in N$, 0 otherwise
D_i	Nodal degree of node $i \in N$
h	Distance in hops between each pair of BBU hotel and RRU

Table 2: Notations used in the VD procedure

Let us introduce the total cost F , given by the sum of the cost of opening a new BBU hotel (λ_i) and the cost of connecting a RRU and a BBU hotel (μ_{ij}) pair, as follows:

$$\text{minimizing } F = \sum_{i=1}^b \sum_{j=1}^n \lambda_i + \mu_{ij} \quad (4)$$

This equation aims at minimizing F by satisfying the constraints of providing protection for each RRU in the network. This constraint can be explain by Equation 5:

$$\sum_{i=1}^b Pconn_{ij} + Bconn_{ij} = 2, \forall j \in N \quad (5)$$

Equation [5] emphasises on providing protection for all RRUs in the network. In particular, for each node j which has some RRUs to be connected, there must be two separate connections $Pconn_{ij}$ and $Bconn_{ij}$ to two different BBU hotels. This fact is represented by the output of the sum equal to 2.

The BBU hotel location problem with protection aims at connecting $j \in N$ transport nodes, each containing a given amount of RRUs, to possible $i \in B$ BBU hotels so that the total cost F is minimum. As for cost information, μ_{ij} is considered as the distance in hops (h) between each RRU and BBU hotel pairs, while the cost λ_i , being it equal for all new BBU hotels, is not considered in the location procedure.

A pseudocode is presented as Algorithm 1 to explain the VD algorithm. The procedure consists of two main parts: BBU hotel placement and protection procedures which will be explained in details as follows. The procedure starts by randomly choosing a candidate node to host a BBU hotel $i \in N$ in line 5. The reason for choosing randomly is due to the fact that, differently from the FD

approach, the starting point does not impact on the outcome of this procedure. After opening a new BBU hotel in node i (line 6), in lines 7 to 9 all nodes $j \in N$ will be connected to it ($Pconn_{ij} = 1$) and node i will be considered as a primary BBU hotel for all of them (with dedicated primary ports and wavelengths). By having only one BBU hotel in the network and calculating F the worst case cost for node i will be achieved (line 10). The aim of the rest of the procedure is to reduce the cost F by adding further BBU hotels to the network. The 'for' loop started at line 11, is the procedure for finding a new placement, in addition to the BBU hotel i . If a placement with reduced cost exists, namely node $i' \in N$ (line 12), a new BBU hotel will be open in i' and the total cost will be updated accordingly (lines 13 and 14). In addition, those RRUs involved in the cost reduction in lines 15 to 18, will be disconnected from their former BBU hotel i and connected to the new BBU hotel i' .

If no new location exists such that by opening a new BBU hotel the total cost reduced, then the procedure has achieved the lowest cost placement without protection, meaning that each RRU at this point is only connected to its primary BBU hotel.

The second part of the Algorithm 1 is to provide protection for all nodes in the network. This part starts by considering node j with the highest nodal degree in line 22 and will be repeated until all nodes have a backup connection (line 23). To do so, If in a one-hop distance from node j exists a BBU hotel namely node i such that hotel in i is not the primary for node j , then node j can be connected to BBU hotel in node i as its backup BBU (lines 24 and 25). In line 26 the total value for F will be updated. On other hand, if no BBU hotel can be found in one hop distance from node j (line 27), then a BBU hotel will be activated in node j (line 28). Node j can use the local BBU hotel as its backup BBU (line 29) and in line 30 the value for F will be updated.

The estimation of the worst-case complexity of the VD BBU hotel placement procedure is as follows: Algorithm 1 is divided into two main parts. The first part namely BBU hotel placement procedure has two loops starting in lines 7 and 11 respectively. The former executed exactly n times and the later will be executed in the worst case $n - 1$ times. The second part namely BBU hotel protection procedure has one loop starting at line 23 which executes in the worst case n times. Overall the complexity of the Algorithm 1 in the worst case is estimated as $3n - 1$ which can be presented at $\mathcal{O}(n)$.

5.3. Sharing backup ports and wavelengths

This procedure represents Phase 2 described in Figure 2 and is common for both FD and VD algorithms. The aim of this step is to share the backup ports and wavelengths in order to use network resources in an efficient way. As stated before, in this study we consider a single BBU hotel or a single link failure at a time. For backup BBU hotel ports sharing the following rule should be applied: A backup BBU hotel port can be shared among some RRUs if and only if, those RRUs have primary BBU hotel ports in different BBU hotels. When a backup BBU hotel port shared between some RRUs, it will be reserved to be useful in case of failure. When a failure happens in a primary BBU hotel, the RRUs

Algorithm 1 Variable Distance BBU hotel Placement

```
1: Initialization:
2:  $B, F \leftarrow 0$ 
3: Begin:
4: /* BBU Hotel Placement procedure */
5:  $i$  = a random node  $\in N$ 
6:  $B \leftarrow B \cup i$ 
7: for all nodes  $j \in N$ 
8:    $P_{conn_{ij}} = 1$ 
9: end for
10: Calculate  $F$ 
11: for all nodes  $i' \in (N - B)$ 
12:   if exists ( $F_{i'} < F_i$ )
13:      $B \leftarrow B \cup i'$ 
14:     Update  $F$ 
15:     if exists node  $j \in N$  s.t.  $(\mu_{i'j} - \mu_{ij} < 0)$ 
16:        $P_{conn_{ij}} = 0$ 
17:        $P_{conn_{i'j}} = 1$ 
18:     end if
19:   end if
20: end for
21: /* BBU hotel protection procedure */
22:  $j$  = a node with maximum  $D_j$ 
23: while exists a node  $j \in N$  s.t.  $B_{conn_{ij}} = 0$  do
24:   if exists a BBU hotel  $i \in B$  s.t.  $\mu_{ij} = 1$  and  $P_{ij} \neq 1$ 
25:      $B_{conn_{ij}} = 1$ 
26:     Update  $F$ 
27:   else
28:      $B \leftarrow B \cup j$ 
29:      $B_{conn_{jj}} = 1$ 
30:     Update  $F$ 
31:   end if
32: end while
33: Stop
```

connecting to the failed BBU hotel, shifting to their backup BBU hotel. There should be enough BBU hotel ports in backup BBU hotel reserved to serve new RRUs. This is the reason backup BBU hotel ports can be only shared among RRUs from different primary BBU hotels so at each failure only one RRU uses the reserved backup BBU hotel port.

Algorithm 2 explains the procedure of BBU hotel ports sharing. This procedure starts at line 2 by evaluates all the ports in each BBU hotel namely node $i \in B$. In line 3, algorithm checks all nodes j and z which have backup BBU ports in the BBU hotel in node i in order to share their backup ports if they can satisfy the condition for sharing backup BBU port. Line 4 checks this condition. As mentioned before, two RRU can share backup BBU ports if and only if they have different primary BBU hotel. So if exist a BBU hotel namely node $y \in B$ such that it is not the same primary hotel for nodes j and z then in line 5 the BBU hotel ports can be shared. The estimation of the worst-case complexity of the sharing backup BBU hotel ports procedure is as follows: Algorithm 2 has two nested loops starting at lines 2 and 3. The first loop is related to BBU hotels which can be executed b times in the worst case. The second loop is in another hand related to nodes with the total size of n . In conclusion, the worst case complexity of the sharing backup BBU hotel ports procedure is estimated as $\mathcal{O}(b \cdot n)$.

Algorithm 2 Sharing Backup BBU hotel ports

```

1: Begin:
2: for each node  $i \in B$ 
3:   for couple of nodes  $j$  and  $z \in N$  s.t.  $BP_{ij} = 1$  and  $BP_{iz} = 1$ 
4:     if exists node  $y \in B$  s.t.  $P_{conn_{yj}} \neq P_{conn_{yz}}$ 
5:        $BP_{ij} = BP_{iz}$ 
6:     end if
7:   end for
8: end for
9: Stop

```

In order to have resilience against link failure, each RRU needs node and link disjoint lightpaths for its primary and backup BBU hotels. The sharing of backup wavelengths follows the same principle as the sharing of backup BBU hotel ports: a backup wavelength can be shared among some RRUs if and only if those RRUs have node and link disjoint lightpaths to reach their primary BBU hotels. Consequently, in case of single failure, either BBU hotel or link, two or more RRUs can share the same backup wavelength in their backup lightpath, being their primary BBU hotels and primary lightpaths different. If a failure happens in the primary BBU hotel, then the RRU can use the backup lightpath (and reserved backup wavelengths) to reach to the backup BBU hotel. Similarly, if a failure happens in any link of the primary lightpath, the RRU will use the backup lightpath toward its backup BBU hotel.

Algorithm 3 explains the procedure of sharing backup wavelengths. This procedure evaluates all links namely link $l \in L$ in line 2. In line 3, algorithm checks all nodes j and z which have backup wavelengths in link l in order to

share their backup wavelength if they can satisfy the condition for sharing the backup wavelength. Line 4 checks this condition. Same as sharing BBU hotel ports, two RRU can share backup wavelength if and only if they have different primary BBU hotel. So if exist a BBU hotel namely node $y \in B$ such that it is not the same primary hotel for nodes j and z then in line 5 the backup wavelength in link l can be shared. The estimation of the worst-case complexity of the sharing backup wavelength procedure is as follows: Algorithm 3 similar to the previous algorithm, has two nested loops starting at lines 2 and 3. The first one is investigating all links in the network with the size of l and the second one is related to the n nodes. In conclusion, the worst case complexity of the sharing backup wavelengths procedure is estimated as $\mathcal{O}(l \cdot n)$.

Algorithm 3 Sharing Backup Wavelengths

```

1: Begin:
2: for each link  $i \in L$ 
3:   for couple of nodes  $j$  and  $z \in N$  s.t.  $BW_{ij} = 1$  and  $BW_{iz} = 1$ 
4:     if exists node  $y \in B$  s.t.  $P_{conn_{yj}} \neq P_{conn_{yz}}$ 
5:        $BW_{ij} = BW_{iz}$ 
6:     end if
7:   end for
8: end for
9: Stop

```

6. Numerical Result

This section presents the performance analysis of the survivable BBU hotel placement strategies. The results are obtained using an ad-hoc developed Java-based simulator. The reference topology of the optical transport network considered for the performance assessment is presented in Figure 4 taken from [33]. It consists of a metro/aggregation network with 38 nodes and 59 bidirectional fiber links, all with the same length (N1). With the aim to evaluate the effect of network size and topology on the results, different configurations are considered, based on reduced size versions of the original one, with 20 (N2) and 14 (N3) nodes, as indicated in the figure by dashed and dashed/dotted lines, respectively. Each node in the transport network is assumed to serve the same upstream traffic represented by 10 RRUs connected to it, each one requiring two transparent lightpaths, i.e., one connecting the RRU to the primary and one connecting the RRU to the backup BBU hotel.

The results are divided into two main sections: results related to the FD algorithms and results related to the VD algorithms. The aspect of the graphs is influenced by network topology, but they are able anyway to show the main aspects of the algorithms and support comparisons.

6.1. FD results

Figure 5 shows the comparison of the total number of BBU hotels C_B as a function of the distance h in hops for the different approaches applied in FD

algorithms, for N1, N2, and N3 networks. As it can be seen in each set of results, the Min-D approach requires the higher number of BBU hotels in comparison to the Max-D one. All trends are decreasing by relaxing the distance constraint, that is by increasing h . In the case of the N3 network, the behavior for both Min-D and Max-D approaches is the same after 4 hops. The reason is the small size of the topology and the fact that after 4 hops the algorithm can find in any case the best solution which is two BBU hotels with both methods. In the N2 network, small variations between the Min-D and Max-D approaches are present but they are always very close to each other so that these variations can be related to the effect of the topology.

In addition to minimizing the number of BBU hotels in the network, the other goal of the design procedure is to maximize the sharing of the BBU hotel ports among RRUs for the purpose of protection. Figure 6 reports the comparison between the average number of ports per node C_P as a function of the distance h in hops in N1 network topology. The average number of ports per node is calculated by Equation 2, which is the sum of the total number of primary ports plus the total number of shared backup ports, that are assumed to serve multiple RRUs for protection purpose. Figure 6 shows the results for the N1 network, with the best results achieved when B and Max-D approaches are applied. The reason is that, by assigning backup BBU hotel first the possibility of a better sharing is allowed, especially when using Max-D node first which allows covering more RRUs with less number of BBU hotels. Following the same reasoning, the worst result is obtained with combined P and Min-D approaches.

In order to represent the effect of the size of the topology on the FD algorithms, in Figure 7 the best approach in the largest and smallest network topologies are taken into account. The best sharing technique results are obtained with Max-D-B for the largest size of the network, namely the N1 network. This shows that the sharing algorithm is more effective as the size of the network increases.

The further set of results are related to the number of wavelengths needed to support the network configuration with primary and backup BBU hotels, after assignment. The average number of wavelengths per link C_W is reported in Figure 8 as a function of distance h in hops. All the trends are increasing by relaxing the distance constraint. The reason is that, by increasing the distance, the number of BBU hotels decreases and therefore each RRU needs more wavelengths to connect to the primary and backup BBU hotels. In general, all four different approaches show the same behavior with a few hops allowed (one or two hops). Afterwards, the gap between them increases and the best behavior is shown by the Max-D. So another important conclusion is that the Max-D approach provides, at the same time, the least number of BBU hotels and the least amount of wavelengths, compared to other approaches.

As mentioned several times in this paper, minimizing all network resources at the same time is not possible. They result to be in opposite relation with each other meaning optimizing one lead to overusing the other. Figure 9 shows the relation between the total number of BBU hotels C_B needed and the average number of wavelengths C_W in the N1 network. The plot compares the

different methodologies previously explained. In addition, the values regarding the number of needed BBU hotels and the average number of wavelengths in case of no protection are shown under the name of Max-D-WP-BBU and Max-D-WP-Wave. Figure 9 is the clear evidence of the fact that by relaxing the distance constraint, there will be less BBU hotels and more wavelengths are needed to cover all the RRUs in the network. This can be seen also in the case of no protection.

6.2. VD results

The results related to the VD technique and to its comparison with the FD one are reported in the following. As stated before, the VD technique does not relate to starting nodes as the FD approach. On the contrary, it starts by choosing a node in the network and then checks all the placement alternatives. In Figure 10 all starting nodes are considered and the result of the placement in terms of BBU hotels is reported in N1, N2, and N3 networks. For N3 network a minimum of 7 BBU hotels and maximum 9 are found, which shows that the starting node introduces a maximum difference equal to 2 BBU hotels. In the case of N2 and N3 networks, this difference is larger which reflects the effect of topology on results. In the case of the N2 network the difference between the maximum and the minimum is 5 BBU hotels and in the case of the N1 network this difference reaches 6 BBU hotels but these values are due to singularities as a consequence of topology.

The benefit of the VD approach is to find primary and backup hotels at the closest distance as possible. Since our emphasis is on the fronthaul segment based on CPRI, which puts strict requirements on delay, the methodology looks for primary BBU hotels as closest as possible to the RRUs and then proceeds for backup BBU hotels that could be far away. Figure 11 shows the result of the application of this technique. It reports the comparison of average and maximum distance between each pair of RRU and primary or backup BBU hotels, indicated as Ave-P, Ave-B, Max-P and Max-B respectively in the N1, N2, and N3 networks. The interesting fact from this figure is that in all networks the maximum distance between each RRU and primary BBU hotel pair is limited to one hop. This means that each RRU can find a primary BBU hotel either in the same node or at most one hop further. The backup BBU hotel, instead, can reach 5 hops distance with an average below 2 hops to allow service continuity in case of failure.

In order to show the effectiveness of the VD approach in finding optimal solutions, in Figure 12 the total number of BBU hotels C_B as a function of topologies N1, N2 and N3 are shown. In this figure the FD techniques, Max-D and Min-D, combined with P and B, are compared with VD results in the best and worst cases from Figure 11. The best case is referred to the lowest number of BBU hotels needed to have full coverage with protection. The worst case, on the contrary, is the case which requires the highest number of BBU hotels. These two values are the extreme cases for each trend in Figure 11. In all the network topologies the VD approach obtains better results than the FD one, even in the worst case. So it is concluded that VD not only find the closest

distance between RRU and BBU hotels, but it is also able to cover the whole network with resilience by a less amount of BBU hotels.

In the Figure 13, using a similar methodology, the average number of ports per node C_P as a function of the network topology for N1, N2, and N3 networks is reported for FD and VD techniques. The same conclusions can be drawn as for the number of BBU hotels. By using VD a significantly lower number of ports, even in the worst case, is obtained compared to FD algorithms, thus supporting the effectiveness of the method. In relation to best and worst cases for the VD approach, a higher number of ports per node is observed for the best case, in N1 and N2 networks, which is related to the corresponding lower number of BBU hotels which gives less opportunity to share backup ports among BBU hotels. The relationship is different for the N3 network which could be explained as a consequence of specific topology.

Figure 14 shows the comparison of the average number of wavelengths per link C_W as a function of the three network topologies N1, N2, and N3. Since the VD technique can cover the whole network by a lower number of BBU hotels more wavelengths are needed to reach to primary and backup nodes. As long as the network size increases, the wavelength needed to connect each pair of RRU and primary and backup BBU hotel increases accordingly in the variable distance approach. In particular, the difference in the number of wavelengths for the worst and best BBU hotel assignments is particularly evident in limited size networks. This indicates that some trade-offs depending on costs are worth to be investigated.

7. Conclusions

The paper presents a solution based on Facility Location Problem for BBU hotel placement in C-RAN to achieve protection in the fronthaul optical network segment against single BBU hotel failure. Different solutions have been proposed and compared in terms of relevant cost parameters, namely the number of BBU hotels, ports and wavelengths. Additional costs with respect to solutions without protection are evaluated showing the effectiveness of the proposed algorithms to maintain additional costs low. The proposed extension of a classical facility location problem applied to support C-RAN resilience, the VD approach has been shown to achieve the lowest costs for both the BBU hotels and the required number of ports, that are the optical interfaces. In any case, the required amount of wavelengths is against the trend of the number of BBU hotels to support resilience and a trade-off depending on real deployment cost has to be found. Even though the VD algorithm does not put constraint on maximum distance, the primary node location is shown to be less than or equal to 1 hop distance for any topology, while, in case of failure, the backup node is anyway at a limited distance from the served RRU, due to the minimization of the distance cost performed by the VD algorithm.

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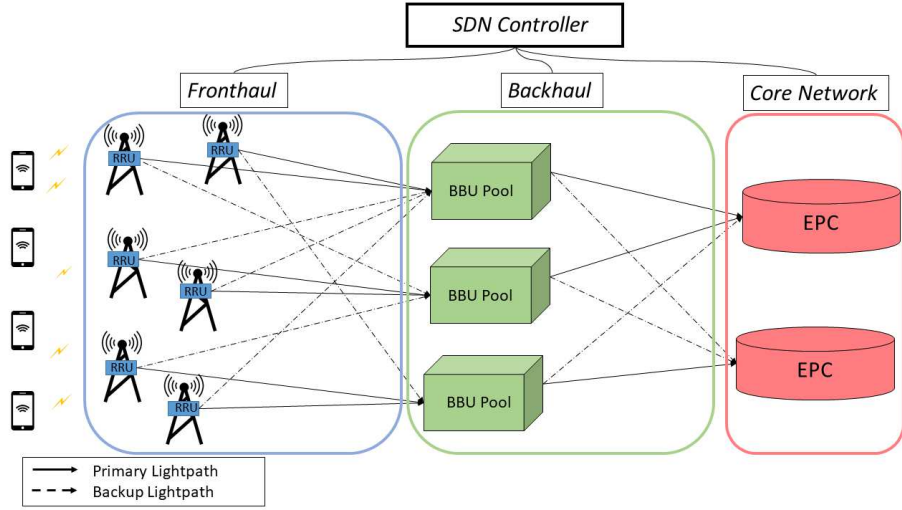


Figure 1: C-RAN architecture.

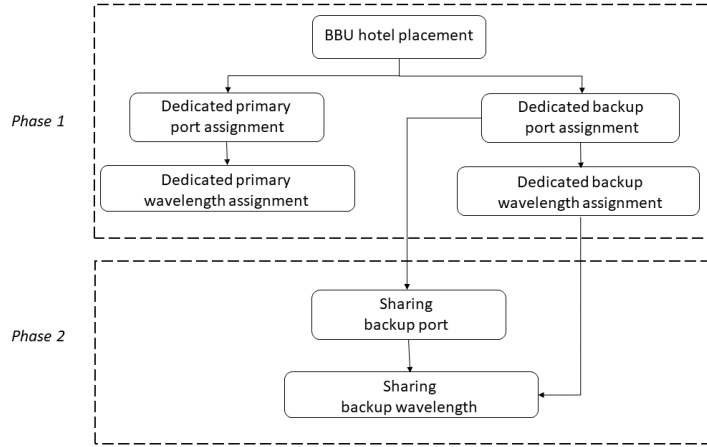


Figure 2: Two-phase organization of the resilient design process.

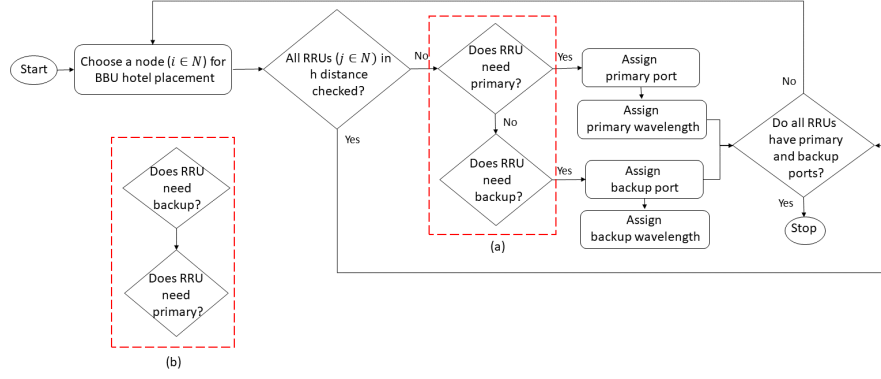


Figure 3: Fixed Distance algorithm [FD], the case of Primary BBU Hotel First (P).

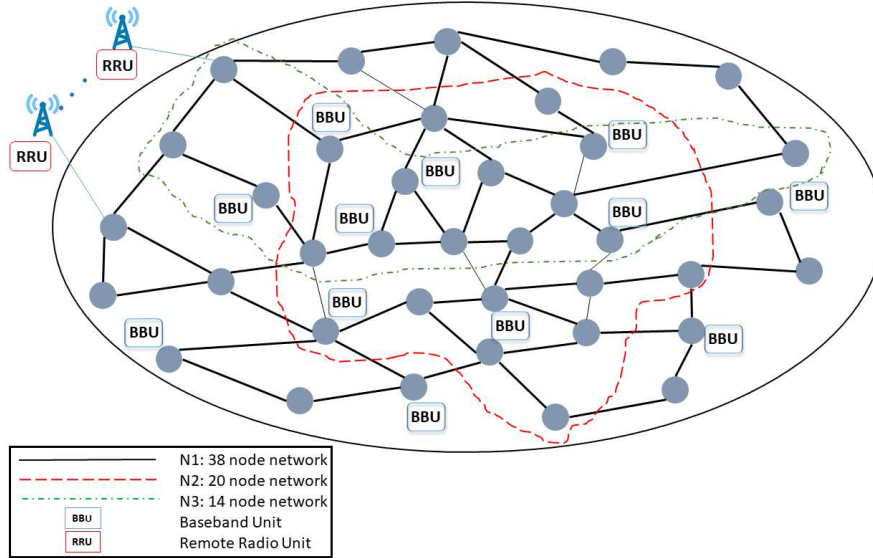


Figure 4: N1, N2 and N3 fronthaul network topologies used in the evaluations.

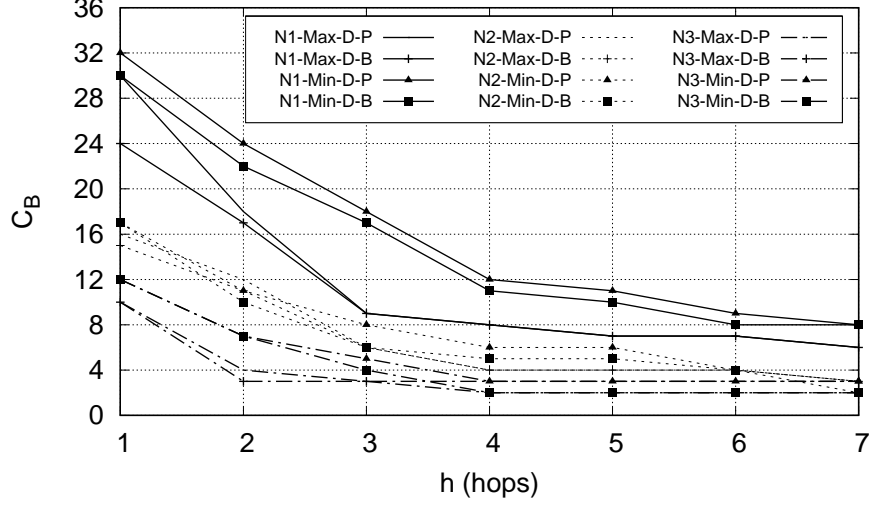


Figure 5: Number of BBU hotels C_B as a function of the maximum distance between a RRU and a BBU hotel h in N1, N2 and N3 network topologies, comparing Min-D and Max-D combined with P and B techniques.

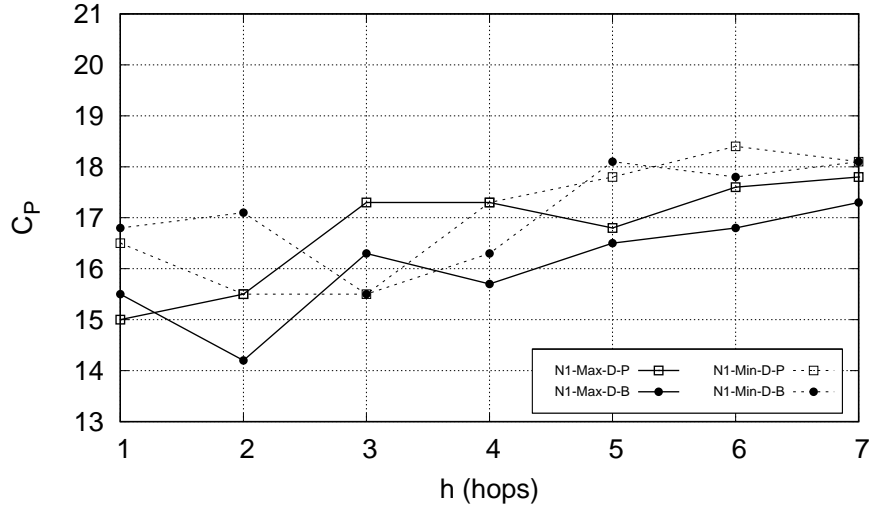


Figure 6: Total number of ports, averaged to the number of nodes C_P , as a function of the maximum distance between a RRU and a BBU hotel h , comparing Min-D and Max-D combined with P and B techniques in N1 network.

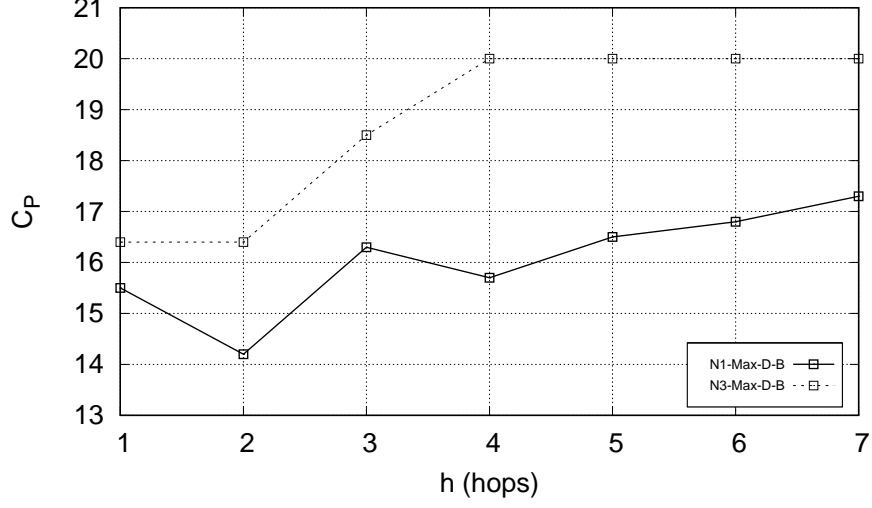


Figure 7: Total number of ports, averaged to the number of nodes C_P , as a function of the maximum distance between a RRU and a BBU hotel h , comparing Max-D-B technique in the largest N1 and the smallest N3 size of the networks.

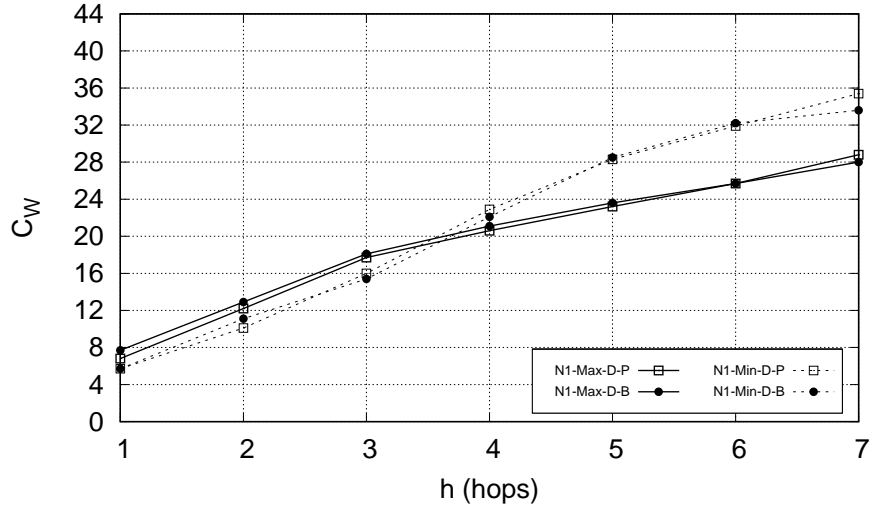


Figure 8: Total number of wavelengths, averaged to the number of links C_W , as a function of the maximum distance between a RRU and a BBU hotel h , comparing Min-D and Max-D combined with P and B techniques in N1 network.

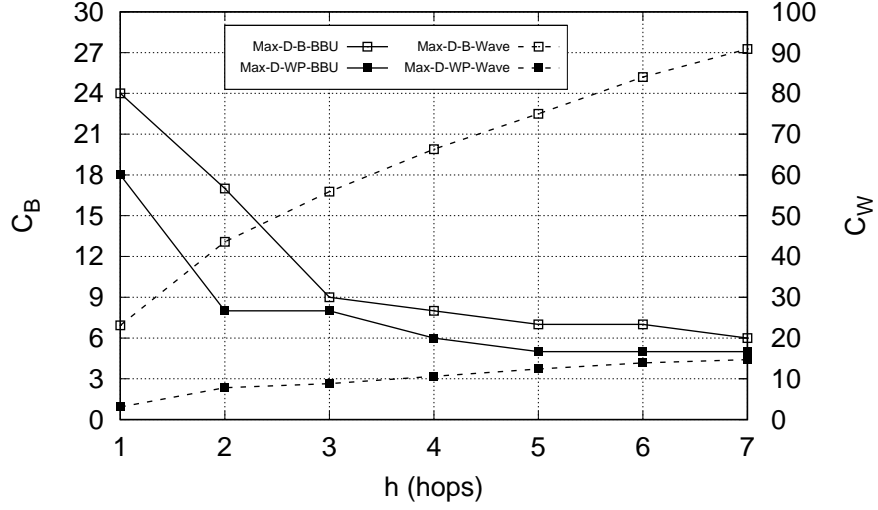


Figure 9: Total number of BBU hotels C_B and average number of wavelengths per link C_W both as functions of the distance constraint h , comparing Max-D technique with respect to the case of without protection WP in the N1 network.

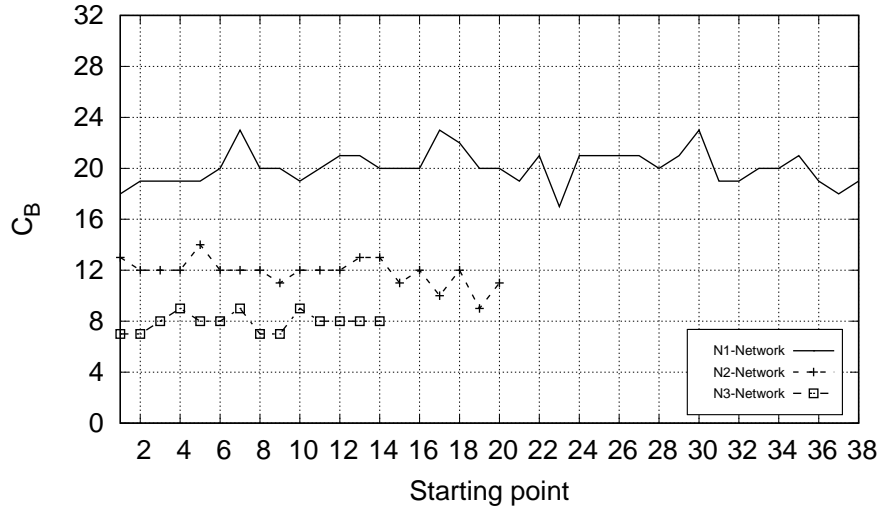


Figure 10: Effect of the starting point as a function of the number of BBU hotels C_B in N1, N2 and N3 networks.

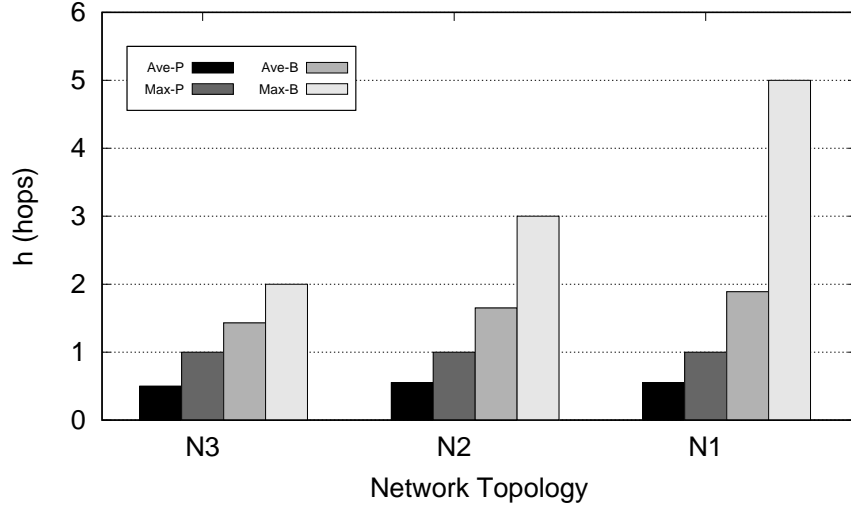


Figure 11: Comparison of average and maximum distance between a RRU and a primary and backup BBU hotels in N1, N2 and N3 networks.

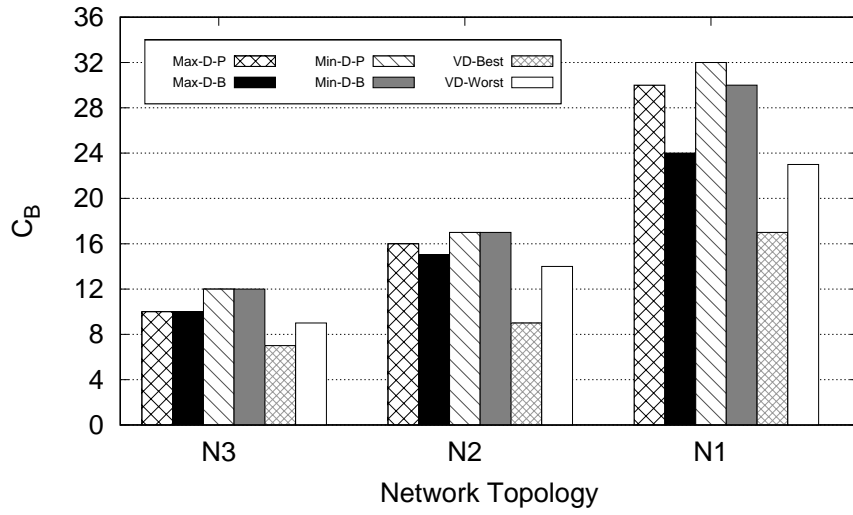


Figure 12: Total number of BBU hotels C_B for network topologies N1, N2 and N3, comparing different FD approaches with VD, by considering the worst and best cases from figure 11

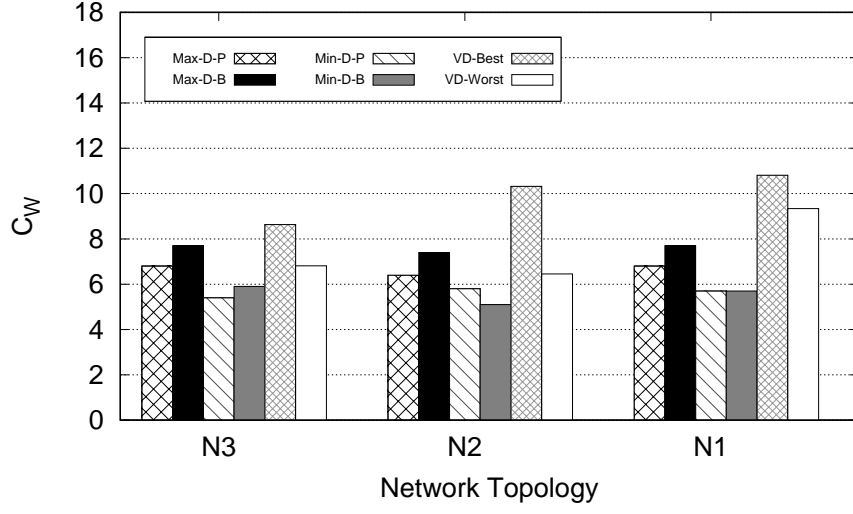


Figure 13: Average number of wavelengths C_W for network topologies N1, N2 and N3, comparing different FD approaches with VD, by considering the worst and best cases from figure 11.

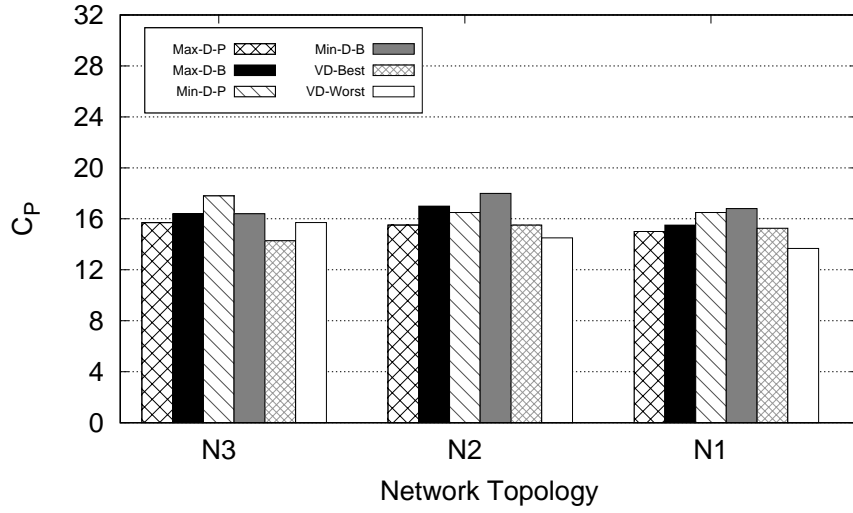


Figure 14: Average number of ports C_P for network topologies N1, N2 and N3, comparing different FD approaches with VD, by considering the worst and best cases from figure 11.