A Novel Optimization Framework for C-RAN BBU Selection based on Resiliency and Price

Mohammed Yazid Lyazidi*, Lorenza Giupponi*, Josep Mangues-Bafalluy*, Nadjib Aitsaadi† and Rami Langar‡

*Sorbonne Universities, UPMC Univ Paris 06, CNRS, LIP6 UMR 7606, 75005 Paris, France.
†Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), 08860 Castelldefels, Barcelona, Spain.
‡University Paris-Est, LIGM-CNRS UMR 8049, ESIEE Paris, 93162 Noisy-le-Grand, France.

Emails: yazid.lyazidi@lip6.fr, [lorenza.giupponi, josep.mangues]@cttc.es, nadjib.aitsaadi@esiee.fr, rami.langar@u-pem.fr

Abstract—As Mobile Network Operators (MNOs) are shifting towards Cloud-Radio Access Network (C-RAN), they have to upgrade their infrastructure to not only support higher processing capacities but also to be more resilient. We consider the problem where a MNO is faced with the choice of selecting virtualized Baseband Units (BBUs) from various cloud service providers, that are each characterized with distinct failure probabilities and prices. We propose to solve the BBU selection problem, formulated as an Integer Linear Program (ILP) subject to the price and resiliency. Simulation results demonstrate the good performance of our algorithm to solve the BBU selection problem for all schemes, while also emphasizing the advantages of a particular one that can realize more than 10% in virtualization cost savings.

Keywords: C-RAN, Optimization, BBU, Resiliency, Virtualization cost, Branch-and-Price

I. INTRODUCTION AND RELATED WORKS

Mobile Network Operators (MNOs) have recently shown keen eagerness to shift to Cloud Radio Access Network (C-RAN) solutions in order to improve their networks migration to LTE-Advanced Pro and meet the advent of the fifth generation (5G) [1][2]. While the premise of C-RAN and the technical feasibility of base station virtualization open up a window of attractive benefits in capital and operational expenses for MNOs, many challenges lie ahead before enabling C-RAN’s full migration towards 5G and its commercial expansion. For instance, the optimization issues of latencies in fronthaul networks includes the study of functional splits and Remote Radio Heads (RRHs) deployment [3]. Other C-RAN related studies encompass end-users admission control regarding fronthaul links capacity and quality-of-service requirements [4]; Baseband Units (BBUs) virtualization [5]; development of dynamic resource sharing mechanisms [6]; and flexible BBU-RRH mappings [7].

However, it is unequivocal that very few research works have addressed the problem of resiliency in C-RAN along with the cost of instantiating the BBU pool. This constitutes a major requirement for MNOs to guarantee less limited disruptions in network availability throughout the day, while respecting the capacity budget and traffic load catering. Some related works have adumbrated this issue, such as [8], which proposed a partial cloud network mapping algorithm to lessen the failure disruptions with a cost on the available bandwidth. In [9], Bouet et al. proposed a placement scheme for virtualized BBUs in a cloud infrastructure to meet the operational cost constraints such as licence fees and/or power consumption. However, these proposals consist only of early work studies, which have not fully exploited the flexibility of centralized C-RAN architecture regarding efficient baseband resource pooling and its ability to benefit from cost-efficient optimization.

In this paper, we consider a C-RAN architecture where the MNO has to select BBU equipments from different Cloud Service Providers (CSPs) to run its virtualized baseband pool. Besides, we assume that each CSP’s BBU is characterized by a failure probability [10] and a capacity cost, that can be equivalent to content delivery network prices [11] for the services required from CSPs. We propose in this context, a novel framework addressing the problem of optimal BBUs selection, from several CSPs, for a BBU-RRH traffic dependent C-RAN. The instantiated BBU pool should meet the MNO’s expectations in terms of reliability, cost efficiency, processing power optimization and traffic load catering. To the best of our knowledge, this paper is the first attempt to present an optimization design for C-RAN BBU selection based on resiliency and virtualization price.

We formulate our selection problem, named Cost-Resilience BBU Selection (CRBS), as an Integer Linear Program (ILP) problem, designed as a weighted objective function with three optimization goals: i) minimizing the BBU pool processing power, ii) maximizing its resiliency and iii) increasing the RRHs traffic load handling, subject to virtualization’s capacity and budget constraints. Additionally, we consider that each RRH is characterized by its hourly traffic, depending on the type of area it covers (e.g., business or residential area). It is worth noting that the third optimization goal focuses on maximizing the overall percentage of traffic that can be handled from the lowest traffic load RRHs at a given hour, subject to ensuring the management of the high-load ones. In fact, we consider that the traffic from the highest traffic load RRHs will not only generate a highest average traffic volume, but also highest peaks. Therefore, since there are more RRHs distributed throughout the radio site, such RRHs
we can write:

\[ \text{that the failure probability of the BBU pool for the latter is in idle mode, and } \]

\[ P \]

\[ i \]

\[ \text{In particular, } P \]

\[ i \]

\[ \text{resiliency, we transform the product of probabilities into linear expressions:} \]

\[ \text{as one of the MNOs intended goals for enhancing the cloud's power consumption in}} \]

\[ \text{is linear with its average utilization. Thus, the processing power consumed at BBU } \]

\[ i \]

\[ \text{is characterized by its per Mbps pricing } m_i \text{ and its failure probability } p_i. \]

\[ i \]

\[ \text{We denote by } r_{ij} \text{ the binary variable, which is equal to 1 if BBU } i \text{ handles RRH } j, \]

\[ j \]

\[ \text{and 0 otherwise. Without loss of generality, we assume that each BBU is limited by a}} \]

\[ \text{fixed capacity } C \text{ in terms of traffic it can handle [5]. We define the average utilization}} \]

\[ y_i = \frac{\sum_{j=1}^{S} r_{ij} l_j}{C} \quad (1) \]

\[ l_j \text{ is the current traffic in RRH } j. \]

\[ P_i \]

\[ \text{P}_0 + \delta P_{\text{max}} y_i \]

\[ P_i \]

\[ \text{In particular, } P_0 \text{ represents the power in the BBU when the latter is in idle mode, and } P_{\text{max}} \text{ when in full usage mode. } \]

\[ \delta \text{ is a constant between 0 and 1, which represents the slope of the equivalent linear power model. On the other hand, we suppose that the failure probability of the BBU pool } p(B) \text{ is equal to 1 if } \]

\[ \text{B} = 0, \text{and } \prod_i p_i, \text{otherwise. In order to optimize this term as one of the MNOs intended goals for enhancing the cloud's resiliency, we transform the product of probabilities into linear summation by defining the following function } I_i, \text{which is equal to the negative value of the logarithmic function on the failure probability of BBU } i, \text{i.e. } I_i = -\log(p_i). \]

\[ I_B = -\log(p(B)) = - \sum_i \log(p_i) = \sum_i I_i \quad (3) \]

\[ \text{Consequently, we can write:} \]

Furthermore, we consider two sets of RRHs in the deployed architecture denoted as \( S_L \) and \( S_C \), which represent the sets of RRHs with high (maximum) traffic load and low (minimum) traffic load, respectively.

We formulate in the following our mathematical CRBS optimization problem \((P)\), expressed as a generic weighted optimization problem with three homogenised objective terms:

\[
\begin{align*}
\text{minimize} & \quad \alpha \sum_{i=1}^{N} x_i P_0 + \delta P_{\text{max}} y_i - \beta \sum_{i=1}^{N} x_i \frac{I_i}{\max(I)} \quad (P) \\
& - \gamma \sum_{i=1}^{N} \sum_{j \in S_C} r_{ij} l_j \quad \sum_{j \in S_C} l_j \\
\text{subject to:} & \quad \sum_{j=1}^{S} r_{ij} l_j \leq C, \forall i \\
& \sum_{i=1}^{N} r_{ij} \leq 1, \forall j \\
& \sum_{i=1}^{N} m_i \sum_{j=1}^{S} r_{ij} l_j \leq B \\
& \sum_{i=1}^{N} \sum_{j \in S_L} r_{ij} l_j = \sum_{j \in S_L} l_j \\
& r_{ij} \in \{0, 1\}, \forall i, j \\
\end{align*}
\]

\( r_{ij} \) is discussed in section IV, followed by Section V, which presents our algorithm design to solve the CRBS problem. Performance evaluation of our proposal is discussed in section IV, followed by Section V, which concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a two-tier C-RAN architecture composed of a macro cell, overlaying a number of \( S \) RRHs [13]. We denote by \( N \) the number of BBU candidates that the MNO is inclined to instantiate in its BBU pool \( B = \{i|1 \leq i \leq N\} \) to handle the traffic load of all \( S \) RRHs. The number \( N \) of needed BBUs can be deduced from the overall existent traffic load on all RRHs and the downlink capacity of the operator, as has been highlighted in [7]. Each CSP’s BBU candidate \( i \) is characterized by its per Mbps pricing \( m_i \) and its failure probability \( p_i \). We denote by \( r_{ij} \) the binary variable, which is equal to 1 if BBU \( i \) handles RRH \( j \), and 0 otherwise. Without loss of generality, we assume that each BBU \( i \) is limited by a fixed capacity \( C \) in terms of traffic it can handle [5]. We define the average utilization of a BBU \( i \) as follows:

\[
y_i = \frac{\sum_{j=1}^{S} r_{ij} l_j}{C} \quad (1)
\]

where \( l_j \) is the current traffic in RRH \( j \). The BBU-RRH dependent traffic is realized by a functional split separating user and cell related functions [3]. Besides, we consider that the baseband processing power consumption in a single BBU is linear with its average utilization. Thus, the processing power \( P_i \) consumed at BBU \( i \) can be expressed as:

\[
P_i = P_0 + \delta P_{\text{max}} y_i \quad (2)
\]

\( P_0 \) represents the power in the BBU when the latter is in idle mode, and \( P_{\text{max}} \) when in full usage mode. \( \delta \) is a constant between 0 and 1, which represents the slope of the equivalent linear power model. On the other hand, we suppose that the failure probability of the BBU pool \( p(B) \) is equal to 1 if \( B = 0 \), and \( \prod_i p_i \), otherwise. In order to optimize this term as one of the MNO’s intended goals for enhancing the cloud’s resiliency, we transform the product of probabilities into linear summation by defining the following function \( I_i \), which is equal to the negative value of the logarithmic function on the failure probability of BBU \( i \), i.e. \( I_i = -\log(p_i) \). Consequently, we can write:

\[
I_B = -\log(p(B)) = - \sum_i \log(p_i) = \sum_i I_i \quad (3)
\]

The proposed objective function consists to minimize the total BBU pool processing power, while maximizing the resiliency (or minimizing the failure probability) of the pool as well as the traffic load that can be handled from the low-traffic RRHs by the instantiated BBUs. \( \max(I) \) represents the maximum value of \( \{I_1, ..., I_N\} \). We define \( \alpha, \beta \) and \( \gamma \) as constant weights between 0 and 1, and whose total sum is equal to 1 (i.e., \( \alpha + \beta + \gamma = 1 \)). We consider that these constants are set in advance by the MNO in order to fix the optimization strategy depending on its prevailing focuses. We define a binary indicator \( x_i \), which represents the state of BBU \( i \), \( x_i = 0 \), if \( \sum_{j=1}^{S} r_{ij} = 0 \), i.e., BBU \( i \) is inactive, and 1 otherwise. \( (C1) \) is the total BBU resource usage limitation constraint, and constraint \( (C2) \) implies that a RRH cannot be shared by more than one BBU. Meanwhile, constraint \( (C3) \) denotes that the capacity costs of all instantiated BBUs should be less than or equal to the MNO’s virtualization budget \( B \). Also, constraint \( (C4) \) ensures that the traffic of high-load RRHs is 100% handled and, finally, \( (C5) \) indicates that variable \( r_{ij} \) is binary.

III. PROPOSED B&P ALGORITHM DESIGN FOR SOLVING THE CRBS PROBLEM

The CRBS problem formalized in \((P)\) is ILP and cannot be solved directly using convex optimization techniques. Besides, problem \((P)\) is NP-hard [5] and can only be solved by exhaustively figuring out all \( N^S \) possible combinations of the BBU-RRH assignment variable, which is impracticable for large-scale networks. To find solutions to our problem, we propose to make use of the B&P framework, which combines the branch-and-bound and column generation approaches to...
compute the optimal solution of ILP problems [12]. The algorithm is based on solving by column generation the linear relaxation in each node of a branch-and-bound tree. In the B&P algorithm, a sets of columns are left out of the LP relaxation in order to handle the problem more efficiently by decreasing the computational difficulty. Columns are then “priced” and added back to the LP relaxation as needed. To decide which column will be added, a sub-problem called the “pricing problem” is created to identify which columns should enter the basis so as to increase the objective function (in case of maximization problem). If such columns are found, the LP is then re-optimized. We detail next, the steps of designing each of the Master and Pricing problems for our B&P algorithm.

The first step consists in reformulating the original problem by applying the well-known Dantzig-Wolfe’s reformulation [12], that sub-divides the problem into a Master and a Pricing Problem. However, before applying the problem reformulation, we found that it is convenient to transform problem (P) by considering two binary variables \(v\) and \(w\) instead of single variable \(r\), which represent low and high-traffic load RRHs assignments to BBU\(\)s, respectively. The new CRBS problem \((P')\) can be expressed as follows:

\[
\begin{align*}
\text{maximize} & \quad \sum_{i=1}^{N} \Phi_i x_i + \Psi \sum_{j \in \mathcal{S}_N} w_{ij} t_j^H \quad (P') \\
\text{subject to:} & \quad \sum_{j \in \mathcal{S}_N} w_{ij} t_j^H + \sum_{j \in \mathcal{S}_L} v_{ij} l_j^L \leq C, \forall i \quad (4) \\
& \quad \sum_{i=1}^{N} w_{ij} \leq 1, \forall j \in \mathcal{S}_L \quad (5) \\
& \quad \sum_{i=1}^{N} w_{ij} \leq 1, \forall j \in \mathcal{S}_N \quad (6) \\
& \quad \sum_{i=1}^{N} m_i (\sum_{j \in \mathcal{S}_N} w_{ij} t_j^H + \sum_{j \in \mathcal{S}_L} v_{ij} l_j^L) \leq B \quad (7) \\
& \quad \sum_{i=1}^{N} \sum_{j \in \mathcal{S}_N} w_{ij} t_j^H = \sum_{j \in \mathcal{S}_N} t_j^H \quad (8) \\
& \quad v_{ij}, w_{ij} \in \{0,1\}, \forall i,j \quad (9)
\end{align*}
\]

where: \(\Phi_i = \beta I_i / \text{max}(I) - \alpha P_{0i} / \text{max}(P)\); \(\Psi = -\alpha \delta / C\); \(\Omega = \gamma / \sum_{j \in \mathcal{S}_L} l_j^L - \alpha \delta / C\). We denote by \(l_j^L\) and \(t_j^H\) the traffic in low and high-traffic load RRH, respectively. Also, \(x_i = 0\), if \(\sum_{j \in \mathcal{S}_L} w_{ij} + \sum_{j \in \mathcal{S}_L} v_{ij} = 0\), and \(1\) otherwise. We apply next Dantzig-Wolfe’s reformulation. Let \(\mathcal{K}_i^L = \{v_1, v_2, \ldots, v_{k_i}\}\) and \(\mathcal{K}_i^H = \{w_1, w_2, \ldots, w_{k_i}\}\) be the sets of possible feasible assignments of low and high-traffic load RRHs to BBU \(i\), respectively. In this case, \(v_i = \{v_{i1}, v_{i2}, \ldots, v_{ik_i}\}\) and \(w_i = \{w_{i1}, w_{i2}, \ldots, w_{ik_i}\}\) constitute a feasible solution to problem \((P')\). Let \(z_{ik} = (\bar{z}_{ik}, \underline{z}_{ik})\) be a new variable, which is equal to \((1,1)\) if feasible solution \((v_i^*, w_i^*)\) is selected, and \((0,0)\) otherwise. We express in the following the Master Problem:

\[
\begin{align*}
\text{maximize} & \quad \sum_{i=1}^{N} \sum_{k=1}^{k_i} (\Phi_i x_i + \Psi \sum_{j \in \mathcal{S}_N} (w_{ij}^H t_j^H) \bar{z}_{ik}^i \quad (MP) \\
& \quad + \Omega \sum_{j \in \mathcal{S}_L} (v_{ij}^L l_j^L) \underline{z}_{ik}^i) \\
\text{subject to:} & \quad \sum_{i=1}^{N} \sum_{k=1}^{k_i} \bar{z}_{ik}^i \leq 1, \forall j \in \mathcal{S}_L \\
& \quad \sum_{i=1}^{N} \sum_{k=1}^{k_i} \underline{z}_{ik}^i \leq 1, \forall j \in \mathcal{S}_H \\
& \quad \sum_{i=1}^{N} m_i (\sum_{j \in \mathcal{S}_N} w_{ij}^H t_j^H + \sum_{j \in \mathcal{S}_L} v_{ij}^L l_j^L) \leq B \quad (13) \\
& \quad \sum_{i=1}^{N} \sum_{j \in \mathcal{S}_N} w_{ij} t_j^H = \sum_{j \in \mathcal{S}_N} t_j^H \quad (14) \quad \bar{z}_{ik}^i, \underline{z}_{ik}^i \in \{0,1\}, \forall i,k
\end{align*}
\]

In the Master Problem \((MP)\), \(z_{ik}^i\) represents a feasible assignment of RRHs to BBU \(j\). Note that \((MP)\) cannot be solved directly due to its exponential number of columns, this is why we consider only a subset of columns that constitutes the Restricted Master Problem (RMP), where the values of the variables that do not appear are padded to zero. The observation is, for large-scale ILPs, most columns will have their associated variables equal to zero in any optimal solution anyway. Let \(z^*\) be the corresponding dual solution of the RMP. The next step consists in adding a number of columns with positive reduced cost that are found by solving the two following sub-problems:

\[
\begin{align*}
\text{maximize} & \quad \{u^i - z^*i\} \quad (16) \\
\text{subject to:} & \quad \sum_{i=1}^{N} (u^i - z^*i) \quad (17) \\
& \quad \Phi_i x_i + \sum_{j \in \mathcal{S}_N} (l_j^H - w_j^*) u_j^i \quad (PP) \\
& \quad + \Omega \sum_{j \in \mathcal{S}_L} (l_j^L - v_j^*) v_j^i \\
& \quad \sum_{j \in \mathcal{S}_N} w_{ij} t_j^H + \sum_{j \in \mathcal{S}_L} v_{ij} l_j^L \leq C \quad (18) \\
& \quad w_{ij}, u_j, v_j \in \{0,1\}, \forall i,j
\end{align*}
\]

where \(w_j^*\) and \(v_j^*\) correspond to the optimal dual price from the solution of the RMP associated with the partitioning constraints of low and high-traffic load RRH \(j\), respectively. In the Pricing Problem \((PP)\), we generate the best feasible low and high-traffic load RRH assignments from all the feasible
ones for each BBU \( i \). After that, we look for the best BBU-RRH assignments over all BBUs, which is precisely done by problem (16). Fig. 1 summarizes the B&P algorithm’s flow-chart. It is worth noting that branching in the B&P occurs when no columns have been “priced out” to enter the basis and the LP solution does not satisfy constraints. Furthermore, it is not required to solve \((PP)\) to optimality; in fact, any column with a positive reduced cost can be accepted. Hence, if the value of the objective function to the column generation sub-problem is less or equal to zero, then the current optimal solution for the RMP is also optimal for \((MP)\).

IV. PERFORMANCE EVALUATION

In this section, we evaluate the benefits of the B&P algorithm to solve the CRBS problem, while comparing the results for different scenarios of the optimization weights \((\alpha, \beta, \gamma)\). We have tested different combinations and outlined in Table I the most representative of the other weights values. The 424-S was chosen in consideration that reliability may be twice less important for a MNO than to serve the whole traffic and minimize the total C-RAN BBU processing power. In all our simulation scenarios, we consider four CSPs, with their corresponding failure probabilities, \(I\)-function values and price per Mbps that are detailed in Table II (data of existent commercial content delivery network that can be closely equivalent to CSPs can be found in [11]). The rest of the default simulation parameters are described in Table III. We consider a total of \( S = 19 \) RRHs, with 15 business and 4 residential RRHs, differentiated by an hourly traffic load given by [1] and illustrated in Fig. 3. The observation is the number of RRHs that can be within the low traffic set \( S_L \) or the highest one \( S_H \) varies depending on the hour. We use the commercial solver IBM ILOG CPLEX [14] to solve both the LP relaxation of the RMP and the Pricing Problem. The average overall computation time of the B&P algorithm is less than 6.5\,ms. For the sake of comparison to a static benchmark, we compare the results to a Static Selection Scheme (SSS) where the MNO targets to satisfy maximum achieved network load at all hours, so as to ensure maximum users quality of service, while contracting with only one CSP (CSP-4) and with no budget constraint. In what follows, we present our performance metrics in terms of: i) BBU pool processing power, ii) resiliency, iii) number of active RRHs, iv) virtualization cost and v) the evolution of the percentage of handled traffic load while varying the number of residential RRHs in the network.

![Fig. 1: B&P algorithm Flow Chart](image)

![Fig. 2: Daily traffic load observed on business and residential area RRHs during a workday [1].](image)

### Table I: Optimization strategies

<table>
<thead>
<tr>
<th>Scheme</th>
<th>((\alpha, \beta, \gamma))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Power Minimization Scheme (TPMiS)</td>
<td>((1;0;0))</td>
</tr>
<tr>
<td>Resilience Maximization Scheme (RMaS)</td>
<td>((0;1;0))</td>
</tr>
<tr>
<td>LP Traffic Maximization Scheme (LTMaS)</td>
<td>((0;0;1))</td>
</tr>
<tr>
<td>Equal-Weighted Optimization Scheme (EWOS)</td>
<td>((1/3;1/3;1/3))</td>
</tr>
<tr>
<td>424-Scheme (424-S)</td>
<td>((0.4;0.2;0.4))</td>
</tr>
</tbody>
</table>

### Table II: CSP inputs from [10][11]

<table>
<thead>
<tr>
<th>CSP</th>
<th>Failure prob. ( p_i )</th>
<th>( l_i )</th>
<th>pricing ( m_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSP-1</td>
<td>0.01</td>
<td>2</td>
<td>0.88/Mbps</td>
</tr>
<tr>
<td>CSP-2</td>
<td>0.05</td>
<td>1.30103</td>
<td>0.98/Mbps</td>
</tr>
<tr>
<td>CSP-3</td>
<td>0.1</td>
<td>1</td>
<td>18/Mbps</td>
</tr>
<tr>
<td>CSP-4</td>
<td>0.01</td>
<td>2</td>
<td>1.13/Mbps</td>
</tr>
</tbody>
</table>

### Table III: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of RRHs ( S )</td>
<td>19</td>
</tr>
<tr>
<td>Number of business RRHs</td>
<td>15</td>
</tr>
<tr>
<td>Number of residential RRHs</td>
<td>( \in [1; 19] ) (\text{default 4})</td>
</tr>
<tr>
<td>( P(W)/I(P_{max})(W) )</td>
<td>1.25/1/3.75</td>
</tr>
<tr>
<td>Number of BBUs ( N)</td>
<td>8 ( \text{2 from each CSP})</td>
</tr>
<tr>
<td>BBU capacity ( C_i(Mbps) )</td>
<td>200</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Physical Resource Blocks</td>
<td>50</td>
</tr>
<tr>
<td>Virtualization budget ( B )</td>
<td>230$/hour (2M$/year)</td>
</tr>
</tbody>
</table>

We consider a total of \( S = 19 \) RRHs, with 15 business and 4 residential RRHs, differentiated by an hourly traffic load given by [1] and illustrated in Fig. 3. The observation is the number of RRHs that can be within the low traffic set \( S_L \) or the highest one \( S_H \) varies depending on the hour. We use the commercial solver IBM ILOG CPLEX [14] to solve both the LP relaxation of the RMP and the Pricing Problem. The average overall computation time of the B&P algorithm is less than 6.5\,ms. For the sake of comparison to a static benchmark, we compare the results to a Static Selection Scheme (SSS) where the MNO targets to satisfy maximum achieved network load at all hours, so as to ensure maximum users quality of service, while contracting with only one CSP (CSP-4) and with no budget constraint. In what follows, we present our performance metrics in terms of: i) BBU pool processing power, ii) resiliency, iii) number of active RRHs, iv) virtualization cost and v) the evolution of the percentage of handled traffic load while varying the number of residential RRHs in the network.
Table IV: Average BBU pool failure probability and number of BBUs

<table>
<thead>
<tr>
<th>Scheme</th>
<th>TPmIS</th>
<th>RMaS</th>
<th>LTMaS</th>
<th>EWOS</th>
<th>424-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>$10^{-5}$</td>
<td>$5 \times 10^{-6}$</td>
<td>$10^{-4}$</td>
<td>$6 \times 10^{-5}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Max.</td>
<td>2</td>
<td>8</td>
<td>5</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>

A. BBU pool processing power

We compare in Fig. 4 the hourly BBU pool processing power returned from the six approaches. We can remark an adaptive behaviour to the fluctuating traffic load for all weights scenarios schemes, with TPmIS having the minimum power consumption. In fact, the latter instantiates the least number of BBUs compared to the others, which lessens the total BBU pool processing power. LTMaS comes second in power minimization, since it has to handle more traffic coming from low traffic load RRHs. Besides, we can remark that 424-S consumes less processing power than LTMaS at certain peak traffic hours, such as at $h = 12:00$, $h = 14:00$ and $h = 15:00$. On the other hand, RMaS has the second highest power consumption, since it tends to maximize the number of invoked BBUs to increase the resiliency. Furthermore, we measured that EWOS and 424-S consume at maximum $30\%$ and $37.5\%$ less processing power than SSS, respectively.

B. Resiliency

Table IV presents the different values of the BBU pool’s highest failure probability $p(B)$ during the day, as well as the minimum and maximum number of instantiated BBUs. Since $p(B)$ is the product of all invoked BBUs failure probabilities, the more BBUs are instantiated, the smaller is the failure probability and the more resilient is the BBU pool. This can be seen in both the RMaS and EWOS schemes as they achieve the maximum resiliency throughout the day by invoking at least more than three BBUs from CSP-2 and CSP-1 and/or CSP-3. On the other hand, TPmIS and LTMaS usually start with few number and BBUs, then instantiates as many as possible to accommodate to peak traffic at high-traffic load hours, and the extra coming from low traffic load RRHs for LTMaS. Regarding 424-S, it invokes fewer number of BBUs than EWOS but, as will be seen next, can handle more RRH traffic.

C. Number of active RRHs

The evolution of the number of active RRHs is depicted in Fig. 5, where it is shown that EWOS, 424-S and LTMaS maximize the total number of handled RRHs. As for TPmIS and RMaS, they cater exclusively to the load of high-traffic cells, since they tend to minimize and maximize, respectively, the number of BBUs ($\gamma = 0$). However, we remark that at peak traffic hours such as at $h = 12:00$, $h = 16:00$, $h = 17:00$, and $h = 19:00$, not all RRHs could be handled by EWOS, 424-S and LTMaS, unlike SSS, due to restricted BBU capacity and budget (as will be detailed in the next figure). Meaning that, all (or a major part) of the traffic from residential areas during office hours will be handled by the macro base station. We can also note how 424-S performs better than EWOS at $h = 16:00$ and $h = 19:00$ as it handles more RRHs traffic.

D. Virtualization cost

Table V: MNO annual expenditure and cost savings

<table>
<thead>
<tr>
<th>Scheme</th>
<th>TPmIS</th>
<th>RMaS</th>
<th>LTMaS</th>
<th>EWOS</th>
<th>424-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cost (K$)</td>
<td>1.681</td>
<td>1.775</td>
<td>1.968</td>
<td>1.843</td>
<td>1.820</td>
</tr>
<tr>
<td>Annual savings</td>
<td>16%</td>
<td>11.3%</td>
<td>1.6%</td>
<td>7.9%</td>
<td>9.8%</td>
</tr>
<tr>
<td>Savings to SSS</td>
<td>64.5%</td>
<td>62.5%</td>
<td>58.5%</td>
<td>62.1%</td>
<td>63%</td>
</tr>
</tbody>
</table>

The study of the virtualization cost is presented in Fig. 6 with the annual expenditure and cost saving to both the annual
This was assessed in the 424-S case which outperformed the resiliency's weight for selecting BBUs in favor of the pro-

F. Final Remarks

From our analysis, we can deduce that decreasing the resiliency's weight for selecting BBUs in favor of the pro-

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