GROVE: A Cost-Efficient Green Radio over Ethernet Architecture for Next Generation Radio Access Networks

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Abstract—Centralized/Cloud Radio Access Network (C-RAN) comes into prominence to reduce the rising energy consumptions and maintenance difficulties of next-generation networks. However, C-RAN has strict delay requirements, and it needs large fronthaul bandwidth. Function splitting and Radio over Ethernet are two promising approaches to reduce these drawbacks of the C-RAN architecture. Meanwhile, the usage of renewable energy sources in a C-RAN boosts the energy-efficiency potential of this network. In this paper, we propose a novel model, which is called Green Radio OVer Ethernet (GROVE), that merges these three approaches to maximize the benefits of C-RAN while maintaining the economic feasibility of this architecture. We briefly explain this model and formulate an operational expenditure minimization problem by considering the several restrictions due to the network design and the service provisioning. Then we linearize this problem to solve it with a mixed-integer linear programming solver. Our experimental results show that our solution surpasses classical disjoint approaches for any diversity in a city population and the geographical location of this city. Besides, our feasibility study guides the mobile network operators to choose the proper size of solar panels and the batteries in this next-generation network.

Index Terms—Cost Optimization in Wireless Networks, Energy Harvesting, Solar Energy, Energy Efficiency, Centralized/Cloud Radio Access Networks, Function Splitting, Radio over Ethernet

I. INTRODUCTION

A Mobile network operator (MNO) requires to serve users with several new small cells to provide larger bit rates in the fifth-generation mobile communication (5G) networks. The current long term evaluation (LTE), where a base station combines baseband (BBU) and radio frequency (RF) processing units together, is not a cost-effective architecture for an ultradense small cell network configuration [1]. As an alternative, Centralized/Cloud Radio Access Network (C-RAN) architecture has several benefits, such as energy-efficiency and ease of maintenance due to the centralization of the BBUs in a central unit (CU). Thus, an MNO reduces its operational expenditure (OpEx), which increases annually as a result of the increasing amount of base stations [2]. The benefits of C-RAN are not limited by its scalability and multiplexing gain capability. This architecture is also a promising approach to increase spectral efficiency by simplifying the coordinated multipoint (CoMP) technique [3].

Despite the advantages of C-RAN, increasing end-to-end delay and high-bandwidth requirement in optical fronthaul links between the CU and radio units (RUs) make this architecture infeasible and uneconomical [4]. Splitting the BBU functions between the CU and RUs is a promising approach to neglect these drawbacks in a C-RAN. Deciding the point where to break the function chain means how many functions are processed at a high powered CU instead of leaving them at a local RU [5]. Besides, these split decisions may be dynamically adjusted by the MNO according to the network variations, such as the daily data demand profile of the users. Therefore, this approach improves not only the overall network performance but also the quality of service (QoS) of the users in the network. Briefly, this method is a trade-off between the energy-efficiency and reducing the delay and bandwidth requirements by choosing the weight of centralization [6].

Another cost of the C-RAN architecture is the capital expenditure (CapEx), which origins from the newly constructed optical fiber links between the CU and RUs [7]. The IEEE 1914 Next Generation Fronthaul Interface (xhaul) (NGFI) Working Group propose Radio over Ethernet (RoE) to reduce these costs [8]. Their standard document details this approach, in which the radio traffic between an RU and the CU is encapsulated in Ethernet frames on a multihop mesh network topology [9]. This approach is more economical than the dedicated links approach by using the advantage of aggregating the traffic of different RUs in the same network lines. Moreover, this network topology may also be integrated with the backhaul network for additional cost-efficiency [10]. On the other hand, the RoE approach complicates the function splitting problem; thus, extra efforts and joint optimization methods are needed to provide cost-efficient solutions.

Using renewable energy sources (RESs) as an alternative to the on-grid energy in a C-RAN architecture is another promising approach to reduce the OpEx of an MNO. Besides, RESs have two critical drawbacks. First, renewable energy should be stored in a storage system such as lithium-ion batteries to use it efficiently. Nevertheless, these systems have limited storing capacity and increasing their capacity impact directly the CapEx. Thus, we need to opt for the solutions which promote the practical usage of the valuable

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storage systems [11]. Second, RESs are sporadic and unstable sources, and they provide highly unpredicted energy across time and space [12]. Therefore, these sources usually need to be supported by a reliable source like on-grid electricity.

In this paper, we aim to reduce the OpEx of an MNO by combining these three new concepts in a C-RAN: splitting the BBU functions between a CU and several RUs, transferring the traffic between them with RoE approach, and using RESs as an alternative energy source in these units. Figure 1 presents this architecture. To the best of our knowledge, there are no studies to model this problem and find a joint solution to reduce the OpEx. Our contributions can be summarized as follows:

1) We model the Green Radio OVer Ethernet (GROVE) concept. This novel concept is a promising approach to make a C-RAN architecture cost-effective for an MNO.

2) We formulate an optimization problem that aims to reduce the OpEx of this new model. We present that in this model, we have to jointly make decisions for the function splitting, dynamic choice of the paths between the CU and RUs, and considering to use the RESs efficiently.

3) We linearize the quadratic constraints in the problem so that it can be solved with a MILP Solver.

4) We experiment with different traffic loads to show the performance of the solution for diverse city populations. Besides, we use real solar data and examine our solution for different seasons to see the impact of seasonal changes in four different geographical areas in the world, which have significantly different solar radiation distributions.

5) We demonstrate a feasibility study which provides the return of capital (RoC) of this RESs system for different size of solar panels and the renewable energy storage units.

The remainder of this paper is organized as follows. The related work is discussed in the second section. Then, we define the GROVE system model and its cost optimization problem in the third and fourth sections, respectively. In the fifth section, we present the results of the computational experiments, followed by the concluding remarks and future works in the last section.

II. RELATED WORK

A. Function Splitting Approaches for C-RAN

One of the key performance metrics of a C-RAN architecture is the multiplexing gain that comes from centralizing the BBU functions in a CU. Thus, we can get rid of the unnecessary energy consumption of underutilized BBUs originate from low traffic loads. Checko et al. advance the multiplexing gain analysis by investigating it for function splitting approaches [13]. They form their proposed architecture in two ways: an N-dimensional Markovian process model and a discrete event simulation model. Then, for each model, they provide the impact of different splitting decisions on the quantitative multiplexing gain results, in terms of energy and cost minimization. Wang et al. introduce a new approach to the function splitting concept, in which some of the functions

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**Fig. 1.** GROVE: Green Radio OVer Ethernet system architecture. Combining the three fundamental decisions of a next-generation wireless network (CU: central unit, RU: radio unit, RRH: remote radio head, PDCP: packet data convergence protocol, RLC: radio link control, MAC: medium access control, FEC: forward error correction, QAM: quadrature amplitude modulation, CRF: cell-related functions).
are processed in an edge cloud (EC) as an alternative to the CU [14]. In this architecture, the ECs may serve more than one RRHs to increase the QoS. They call this architecture "Hybrid C-RAN," and their objective is jointly minimizing the total energy consumption in the network and the bandwidth of the midhaul, which is provided the connections between the CU and ECs. In their next paper, they enhance their study by analyzing the effect of traffic load on their findings [15].

Some studies prefer to model the function splitting problem as a graph, in which the BBU functions are represented as nodes, and the connections between these nodes are shown as weighted edges. Mharsi et al. choose the weight of the edges as the latency requirement [16]. The start nodes of their graph are the antennas, and the end node is the CU. Thus, they perform splitting decisions for all data flows between the antennas and the core node in their studied network. They have a multi-objective function that jointly minimizes the sum of the end-to-end latencies and the total number of CPUs used in their proposed network. Meanwhile, Liu et al. choose more than one metric for the weight of the edges, which are the computational costs and the fronthaul link costs [17]. Then they characterize the tradeoff between these two parameters while choosing the delay as a constraint in their problem formulation.

Shehata et al. focus on static function splitting options, in which they investigate the effect of these options on reducing the energy consumption and the needed giga operations per second (GOPS) in the network [3]. They detail the difference between the local BBU architecture and the BBU pool in C-RAN. Also, they explain the layers that processed in these BBUs and the impact of several split options between these layers. Their analytical model starts with User-Evolved-Node-B (eNB) assignment according to the highest received signal strength indication at the user side. Next, they schedule the physical resource blocks (PRBs) among the users. Then, they provide a detailed energy consumption model of BBUs in a classical distributed-RAN and a C-RAN. Their experiments demonstrate the improvement of the system performance in each split option for different geographical type areas. Harutyunyan et al. suggest a virtual network embedding (VNE) approach in their papers for the purpose of finding the optimum place for splitting the BBU functions [18]. In their first study, they formulate a problem in which they jointly minimize the interference and the fronthaul bandwidth. In their second study, they combine the problem of choosing the optimum places for the BBU functions with minimizing the number of using millimeter-wave wireless fronthaul links in this VNE model [19].

B. Integrating Radio over Ethernet with C-RAN methods

Radio over Ethernet (RoE) approach reduces not only the operating costs but also the planning costs of an MNO. Thus, several recent studies implement this approach to the function splitting problem to improve the feasibility of their proposed models. Garcia-Saavedra et al. present a decision-making engine, called Wizhaul, that jointly choose the flow paths and the weight of the function centralization in a CU [20]. By using this engine, they provide solutions for both network planning and operating phases. In another recent paper, they also implement the multi-access edge computing design in their problem models. These studies are promising guides to integrate the RoE with the function splitting approach to improve the edge computing performance in a C-RAN [2]. Meanwhile, they provide a detailed analysis of the crosshaul approach in a separate study. This approach combines the fronthaul and backhaul networks as a joint packet-based network to reduce the network costs in a further way [10].

Chang et al. focus on three inter-related problems in an RoE network [22]. The first problem aims to packetize the BBU processed data in Ethernet frames according to choosing the function splitting decisions. The second one deals with the scheduling of these frames, and the last one ensures a HARQ-based timing constraint while providing the first and second problems. In their next paper, they specify a detailed key performance analysis of several indicators, such as the network throughput and user satisfaction [23]. Ojaghi et al. highlight the importance of network slicing to improve throughput [24]. They combine it with RoE connections and target to optimize the computational cost and the throughput of the whole network. Diez et al. aim to minimize the total end-to-end latency in their packet-based network by providing a connection for each RRH [25]. They compare their solution with the fixed split and fixed scheduling approaches.

C. Using Renewable Energy Sources in a C-RAN architecture

Alameer et al. provide a solution for a classical C-RAN architecture [26]. They represent a RES system with a queuing model, in which RESs are deployed in each RRHs and BBUs. Their objective is to minimize the overall energy consumption of this model by considering the QoS. Guo et al. focus on a similar problem, in which they represent the system as an MINLP problem [27]. They propose a two-phase heuristic to reduce the brown energy consumption.

Although the function splitting is a new concept, Temesgene et al. integrate the RESs in this concept and provide a detailed energy consumption analysis in this system [28]. They propose a solution for an offline problem to reduce the on-grid energy consumption. Then, in their next study, they enhance this study and provide a solution for an online problem that dynamically change the splitting decisions according to the traffic load and the harvested energy [29]. Meanwhile, Wang et al. propose a novel model to maximize the throughput of the network by solving the function splitting problem with RESs [30]. On the contrary, Ko et al. choose the throughput as a constraint in their problem [31]. Then they target to reduce the overall on-grid energy consumption in the network by using RESs.

III. GROVE System Model

Figure 1 illustrates the overall architecture of the GROVE model. We consider a scenario that a set of RUs, \( \mathcal{R} \), are connected to a CU through a packet-based network \( G = (V, E) \), where \( V \) is the superset of routers, the set of RUs, and the CU; and \( E \) is the set of links between these components. Each...
link $e \in E$ has a limited capacity $\Omega_e \geq 0$ for the downlink transmissions from CU to RUs.

Each RU has a Radio Frequency (RF) equipment with an antenna. Besides, there is a set of RRHs, $C$, that are connected to their corresponding RU with a point-to-point millimeter-wave or dedicated fiber links [32]. While these RRHs do not have any BBUs, this architecture provides throughput enhancement with lower costs. Since the RRHs are geographically close to their corresponding RU, the capital expenditure (CapEx) of the MNO to connect them remains at lower values.

BBU functions are provided by the digital units (DUs) in the RUs and CU, collectively. The chain of these functions is broken in a certain split point. This point is dynamically decided for a set of time intervals in a day period for each user. These users have a different data traffic load on the DUs, $\rho_{it}$, and the maximum delay threshold, $\mu_{it}$, according to their required service.

Cell-related functions (CRFs) and user-related functions (URFs) are the two main divisions of the BBU functions [15]. According to the Small Cell Forum, breaking the chain after CRFs reduces the required bandwidth significantly [6]. While the packet-based network between the CU and RUs should have a limited capacity to achieve a reasonable CapEx of the MNO, we prefer to process all CRFs in the RUs side. Moreover, the processing load and the bandwidth consumption of URFs vary with the user traffic demands; thus, splitting after CRFs also have multiplexing benefits.

We have four splitting options on the CU side which is shown in Figure 2. These options are:

1) CU does not process any URF. This option literally yields a distributed RAN which does not have any C-RAN benefit but very efficient for a user traffic demand which have extremely strict delay requirement.

2) CU processes only packet data convergence protocol (PDCP). The functions in this protocol are not very strict about delay requirements. Besides, centralizing the PDCP functions promotes mobility across the RUs [6].

3) CU processes radio link control (RLC) and medium access control (MAC) in addition to the PDCP. Thus, it processes all URFs in the MAC layer and above.

4) CU processes forward error correction (FEC), quadrature amplitude modulation (QAM), and precoding processes, which means it processes all URFs including the physical layer functions. This split is the most energy-efficient option in this paper, but the delay requirement should be very non-stringent.

In addition to these splitting points, there are also other splitting point options that may be chosen according to MNO’s requirements [6]. Briefly, the more URFs are processed in the CU, and the more energy-saving will be provided by MNOS. However, we increase the required bandwidth and end-to-end latency with the extension in centralization [15].

If we now move to the energy model, Figure 1 illustrates that the CU and the RUs have two different energy sources to facilitate their operations. While the first one, the solar panel, reduces the OpEx of the MNO with renewable energy, the second one, on-grid energy, becomes a reliable source in the case of the lack of insufficient green energy. The other components in the system, RRHs, have only an on-grid energy source. Since most of the 5G RRHs are expected to be indoor, the MNO can easily position them in an indoor area that is not directly exposed to solar radiation. But if needed, RESs can also be used for RRHs.

The energy consumptions in the RUs ($\Psi_{RU}^{rt}$) and the CU ($\Psi_{CU}^{rt}$) are formulated in Equation 1 and Equation 2 respectively. $E_{DU}^{RU}$ is the energy consumption of a DU in an RU, and $a_{dt}$ is the binary decision that identifies the activity of DU $d$ in time interval $t$. Besides, an RU has a static energy consumption ($E_{STAA}^{RU}$) due to the RF equipment, cooling system, and the other idle energy consumptions which do not change by the DU activity. Similarly, a CU also has a static energy consumption ($E_{STAA}^{CU}$), which is similar to the RU side, except it does not include any RF equipment energy consumption.

$$\Psi_{RU}^{rt} = E_{STAA}^{RU} + \sum_{d \in D} a_{dt} E_{DU}^{RU}$$ \hspace{1cm} (1)

$$\Psi_{CU}^{rt} = E_{STAA}^{CU} + \sum_{d \in DCU} a_{dt} E_{DU}^{CU}$$ \hspace{1cm} (2)

The Connections between the CU and RUs also consume

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1 Although we just consider the downlink transmissions for simplicity, the network model can be straightforwardly extended to include uplink transmissions.
IV. MINIMIZING THE OPEx OF GROVE MODEL

A. Problem Formulation

Table I outlines the notations in this section. Over the GROVE system model explained in the previous section, our primary purpose is to reduce the OpEx of this system. This minimization problem can be defined as:

Minimize:

\[
\sum_{t \in T} \left[ \Psi_t^{CU} - s_t^{CU} - \mathbb{P} \cdot p_t^{CU} \right] + \sum_{r \in R} \left( \Psi_r^{RU} - s_r^{RU} - \mathbb{P} \cdot p_r^{RU} \right) \cdot E_t \tag{3}
\]

\[
\sum_{f \in F, i \in I} \rho_{id} m_{idft} < L_{id}^{CU}, \quad \forall d \in D_{id}^{CU} \tag{4}
\]

\[
\sum_{f \in F, c \in C, r \in I} \rho_{id} m_{idfr} < L_{id}^{RU}, \quad \forall d \in D_{id}^{RU}, \forall r \in R \tag{5}
\]

\[
M \cdot a_{dt} - \sum_{f \in F} \sum_{i \in I} m_{idfr} \geq 0, \quad \forall d \in D_{id}^{CU} \tag{6}
\]

\[
M \cdot a_{dt} - \sum_{f \in F} \sum_{c \in C} \sum_{r \in I} m_{idfr} \geq 0, \quad \forall d \in D_{id}^{RU}, \forall r \in R \tag{7}
\]

\[
\sum_{f \in F, d \in D_{id}^{CU}, d \in D_{id}^{RU}} m_{idfr} = |F|, \quad \forall i \in I, c \in C, r \in R \tag{8}
\]

\[
\sum_{f \in F} \sum_{d \in D_{id}^{CU}} m_{idfr} < \mu_{idfr}, \quad \forall i \in I \tag{9}
\]

\[
b_{idfr}^{CU} = b_{idfr}^{CU} - s_{idfr}^{CU} - p_{idfr} + S_{idfr}^{CU} \cdot G_{idfr}^{CU} \tag{10}
\]

\[
b_{idfr}^{RU} = b_{idfr}^{RU} - s_{idfr}^{RU} - p_{idfr} + S_{idfr}^{RU} \cdot G_{idfr}^{RU}, \quad \forall r \in R \tag{11}
\]

\[
b_{idfr}^{CU} \leq B_{idfr}^{CU} \leq B_{idfr}^{RU}, \quad \forall r \in R \tag{12}
\]

\[
s_{idfr}^{CU} \leq \Psi_{idfr}^{CU}, \quad \forall r \in R \tag{13}
\]

\[
s_{idfr}^{RU} \leq \Psi_{idfr}^{RU}, \quad \forall r \in R \tag{14}
\]

\[
\sum_{y \in V} l_{rt(x,y)} - \sum_{y \in V} l_{rt(y,x)} = \begin{cases} 1, & \text{if } x \in V^{RU} \\ -1, & \text{if } x \in V^{CU} \\ 0, & \text{otherwise} \end{cases} \forall x \in V, \forall r \in R \tag{16}
\]

\[
\sum_{r \in R} \sum_{c \in C} \sum_{r \in I} \sum_{d \in D_{id}^{CU}} \sum_{f \in F} \rho_{id} m_{idfr} \leq \Omega_{idfr(x,y)}, \quad \forall (x,y) \in E \tag{17}
\]

The OpEx of the system is the overall on-grid electricity bills of the CU and the RU\(^2\). We have to deal with three fundamental problems to reduce these bills. First, we have to reduce the total energy consumptions in the CU (\(\Psi_{idfr}^{CU}\)) and the RUs (\(\Psi_{idfr}^{RU}\)) by switching off as many DUs in these units. Second, we have to favor the usage of renewable energy (\(s_{idfr}^{CU}\) and \(s_{idfr}^{RU}\)) instead of on-grid energy consumption. This action principally depends on the size of solar panels and the batteries in these units and planning the use of renewable energy in these batteries in an efficient way. Otherwise, the MNO should sell this valuable energy to the grid network at a reduced price (\(\mathbb{P} \cdot p_{idfr}^{CU}\) and \(\mathbb{P} \cdot p_{idfr}^{RU}\)). Lastly, we have to consider the variation of the electricity prices in a day period (\(E_t\)) and try to use renewable energy as much as possible in the time intervals that the price of the electricity is higher than the average price.

The first two constraints (Inequalities \(4\) and \(5\)) model the DUs capacity limitations. \(L_{id}^{CU}\) and \(L_{id}^{RU}\) are the maximum energy. However, most of this energy consumption does not change with the traffic load and remains as a static value. The only way to reduce this energy consumption is by completely switching off these connections \(34\). Despite this, in our system model, the links are always active, and we do not need to optimize this energy consumption; thus, we do not include it in the objective function.

\(2\)Constraints should be satisfied for all time intervals \((\forall t \in T)\).

\(3\)The electricity cost of the RRHs and the maintenance cost of the GROVE system are not included in OpEx calculation. The reason is that these costs do not change by any decision variable given in Table I.
numbers of URFs that can be executed in a DUs of a CU or an RU, respectively. As stated by Mharsi et al., a URF’s processing demand correlates with the traffic load of the corresponding user; thus, the number of executed URFs in a DU \( m_{idf} \) is multiplied with the traffic load in these constraints [16]. Meanwhile, deciding to execute a URFs in a DU leads up to activate that DU \( (a_{dx}) \). Constraints [6] and [7] grant this causality for the CU and the RUs, respectively. Inequality [8] guarantees another critical constraint: processing of all URFs \( f \in \mathcal{F} \) of each user in DUs. Furthermore, choosing of the cloud side for processing a UR depends on the delay threshold of the corresponding user \( (\mu_{it}) \), which is maintained by Inequality [6].

Inequalities [10] to [15] regulate renewable energy usage restrictions. The first two of them calculate the remaining energy in a battery \( (b_i^f) \) according to the remaining energy from the previous time interval \( (b_{i-1}^f) \), consumed green energy \( (s_i^f) \), the sold energy to the grid \( (p_i^f) \), and the generated renewable energy in this time interval \( (S_i^f) \). The capacity of the batteries \( (B_i^f) \) limits the maximum stored renewable energy, and Inequalities [12] and [13] show this limitation for the CU and the RUs. Lastly, it is clear that the consumed green energy \( (s_i^f) \) can be as high as the total energy consumption in the CU and in the RUs \( (\Psi_i^f) \), which are granted by Inequalities [14] and [15].

Equation [16] ensures exactly one connection from each RU to the CU. \( (x, y) \in E \) represents an edge that connects the nodes \( x \in \mathcal{V} \) and \( y \in \mathcal{V} \). If the node is an RU node \( x \in \mathcal{V}_{RU} \), there should be an edge that connects this node to another node in the network. On the other hand, if the node is a CU node \( x \in \mathcal{V}_{CU} \), there should be an edge that connects another node in the network to this node. For the nodes between the RUs and CU, the summation of the number of incoming and outgoing edges should be equal to zero, which means that the path could not be disconnected at a switch node. Although this equation does not restrict a cycle in the path, a cycle does not have any beneficial effect on the objective function and the constraints. Moreover, it increases the bandwidth usage, and by adding the bandwidth constraint (Inequality [17]) to each edge, we eliminate a cycle in the network.

The edges in this model have a limited bandwidth capacity \( \Omega_{x,y} \) which depends on two values: the number of URFs that execute in the DUs of the CU \( (d \in D_{CU}) \), and the traffic loads of each user \( (p_i^f) \). This relation is provided by Inequality [17]. However, this inequality is a quadratic constraint as a result of the multiplication of the path existence decision variable \( I_{rt(x,y)} \), and the URF usage decision variable \( m_{idf} \). Thus, we need to linearize this constraint to solve this mathematical model with a MILP solver, as shown in the next subsection.

### B. Problem Linearization

**Proposition 1.** Let \( z_{rt(x,y)} \) is a continuous decision variable and can take on any value between \( [0, \Omega_{x,y}] \). If \( m_{idf}, I_{rt(x,y)}, \text{and } z_{rt(x,y)} \) decision variables satisfy Inequalities [18].

\[
\sum_{c \in \mathcal{C}} \sum_{r \in \mathcal{R}} \sum_{d \in D_{CU}} \sum_{f \in \mathcal{F}} \rho_{it} m_{idf} \leq M \times (1 - I_{rt(x,y)}) + z_{rt(x,y)}, \forall r \in \mathcal{R}, \forall (x, y) \in E 
\]

**Proof.** (Sketch) For the static routing case, we can remove Inequalities [16] and [17]. Further, if we choose the size of solar panels and the batteries as zero, Inequalities [10] to [15] can be eliminated. Alabbasi et al. emphasize that this new reduced problem involves the bin packing problem [15]; thus, it is an NP-Hard problem.

### C. Complexity Analysis

**Proposition 2.** Minimizing the OpEx of GROVE model is an NP-Hard problem.

**Proof.** (Sketch) For the static routing case, we can remove Inequalities [16] and [17]. Further, if we choose the size of solar panels and the batteries as zero, Inequalities [10] to [15] can be eliminated. Alabbasi et al. emphasize that this new reduced problem involves the bin packing problem [15]; thus, it is an NP-Hard problem.
A. Evaluation Settings

The network topology of our primary use case is shown in Figure 5. It contains 12 nodes (one CU, six RUs, and five switch nodes) and 29 edges \(|(|\mathcal{V}|,|\mathcal{E}|) = (12, 29)\). First, user downlink data traffic flows from the CU to any of the two routers in the first tier. Then, the data flow to any of the three routers in the second tier, which are also connected by each other. In the next step, the data flows to the RU, which serves to the corresponding user. Finally, the data reaches the user either directly from the RU in an umbrella cell or from the RRH in a small cell.

The number of RRHs connected to a RU equals five \(|(|\mathcal{C}_c| = 5)\), and there are ten users in each RRH small cell \(|(|\mathcal{I}_c| = 10)\). The delay threshold of the required service from each user \((\mu_{it})\) is randomly generated in \([0, |\mathcal{F}|]\). These users have a daily sinusoidal shape traffic load created by Equation (20) in which \(\varphi\) is a random value between the \(3\pi/4\) and \(7\pi/4\) which defines the peak hour of the traffic profile, \(\nu = 3\) determines the slope of the traffic profile and \(n(t)\) is a random value which produces a fluctuation in this traffic profile. In addition, we generate different peak hours for each RU to affect distinctive zones in a city such as residential, industrial, or shopping areas \([1]\). Thus, we simulate both temporal and spatial variations of a traffic load in the region of a city. Lastly, we multiply the calculated traffic load by \([0.5, 1, 1.5]\) to analyze the model for three traffic densities, which are called Low, Medium, and High.

\[
\lambda_{it} = \frac{1}{2\nu}[1 + \sin(\pi t/12 + \varphi)]^\nu + n(t), i \in \mathcal{I}
\tag{20}
\]

Generated green energy from a solar panel \((G_{pri})\) is calculated by the pvWatts application \([35]\). We use the solar radiation data of four different cities (Stockholm, Istanbul, Cairo, Jakarta) that have a distinct distribution in a year period. Thus, we can investigate the effect of seasonal change in our model. Besides, energy prediction models may also be included easily in our system model \([36]\). The rest of the parameters used in our simulations are given in Table II. The electricity price values are from Republic of Turkey Energy Market Regulatory Authorities (EPDK) variable electricity tariff regulation that has different price policies according to the time of the day \([37]\). The exchange rate is chosen as 1 USD = 7 TRY.

B. Performance of OpEx Minimization

As mentioned in the introduction section, one of the contributions of this paper is to show that we have to jointly consider the function splitting, renewable energy usage, and routing decisions. Thus, we compare the results of our proposed solution with the results of two models: a model that jointly consider the function splitting and renewable energy but does not take into account the routing decisions, called "Static Routing," and a model that take into account the function splitting and the routing decisions together but ignore the renewable energy usage decisions, called "Traffic-Aware." We used Gurobi \([38]\) as a MILP solver, and computational experiments were run on an Nvidia DGX-1 Station \([39]\) with a Dual 20-Core Intel Xeon E5-2698 v4 2.2 GHz. The termination time was chosen as 4 hours.

Figure 4 shows the one year period OpEx results for different traffic loads and solar radiation distributions. The results confirm that our proposed solution has lower OpEx for any traffic load and solar radiation distribution. Thus, we can use this model for any city or urban region around the world.

| Instance | Unit | CU Side | RU Side |
|----------|------|---------|---------|
| $E_{STA}$ | Wh   | 1000    | 500     |
| $E_{DU}$ | Wh   | 400     | 400     |
| $S$      | kWh  | 80      | 20      |
| $B$      | kWh  | 50      | 20      |
| $E_t$    | TRY  | [0.29, 0.46, 0.70] | [0.29, 0.46, 0.70] |
| $P$      |      | 0.5     | 0.5     |

TABLE II

| EXPERIMENT PARAMETERS |
|------------------------|
| Instance | Unit | CU Side | RU Side |
|----------|------|---------|---------|
| $E_{STA}$ | Wh   | 1000    | 500     |
| $E_{DU}$ | Wh   | 400     | 400     |
| $S$      | kWh  | 80      | 20      |
| $B$      | kWh  | 50      | 20      |
| $E_t$    | TRY  | [0.29, 0.46, 0.70] | [0.29, 0.46, 0.70] |
| $P$      |      | 0.5     | 0.5     |
Meanwhile, Figure 4 also shows that with higher traffic loads, the OpEx increases due to the boosting of the number of active DUs. Also, the cities that have higher solar radiation rates have lower OpEx owing to the increase in renewable energy availability. Moreover, these cities can earn higher profits by selling it to the grid, which is shown in Figure 5.

If we now turn to analyze why our proposed solution provides better results than the static routing, we have to focus on the number of active DUs in the RUs and CU. As we can see in Figure 6, our proposed solution decreases the number of active DUs in the RUs by choosing the flow paths efficiently. Thus we can reduce the overall energy consumption by centralizing the functions in the CU. In the meantime, our proposed solutions also beat the “Traffic-Aware” algorithm by activating the DUs of RUs which have renewable energy in their batteries. Thus we can use this valuable renewable energy efficiently and prevent the unstored energy, which is shown in Figure 7. Moreover, our solution reserves the renewable energy of the RUs for more profitable hours (Figure 8). Therefore, we can reduce the OpEx further by considering the renewable energy in the batteries of the RUs and the CU.

C. Network Scalability Analysis

The standard network configuration we studied is explained in Section V-A, and its results are represented in the previous subsection. Now, we will analyze the outcomes of larger topologies. Figure 9 shows three network topologies that have different sizes. Figure 9a is our standard topology, which has six RUs and five switch nodes connect them to the CU. In Figure 9b, we doubled the number of RUs (12 RUs), and then we need eight switches to connect them to the center. Lastly, Figure 9c shows an architecture that has 24 RUs and 14 switches.

Due to the non-polynomial difficulty of the optimization problem, as the network size gets larger, the required memory (As indicated in Figure 10) and computational power are increasing very rapidly. Thus, the size of the third topology is a boundary for the GROVE Model by using the DGX-1 Station. Moreover, the increase in the network size reduces the performance of our proposed solution. The main reason for this outcome is related to the size of the solution space of the compared solutions. Our proposed solution has a more extensive solution space; thus, a MILP solver needs more processing time to approximate the lower bound. Besides, an MNO gets better results with our proposed solution for larger network sizes, according to the results shown in Figure 10.

D. Economic Feasibility Analysis

Reducing the OpEx of an MNO does not entirely satisfy the economic feasibility of the proposed network model. We
also need to investigate the CapEx of this novel RESs system, which is the summation of the solar panel and battery deployment costs. In Equation (21), which represents this calculation, $S$ and $B$ stand for the size of solar panels and the batteries, respectively. The unit prices of these components are presented with $c^S$, and $c^B$. Energysage informs that the price of a solar panel is $c^S = 2$ per Watt in 2019 [40], and Goldie-Scott notifies the battery prices to be around $c^B = 0.15$ per Watt in 2019 [41]. Calculating the other deployment costs (such as leasing cost) is out of scope in this paper, but they can easily be added in this equation.

$$\text{CapEx} = \sum_{r \in R} \left[ S_{RU}^r \cdot c^S + B_{RU}^r \cdot c^B \right] + S_{CU}^r \cdot c^S + B_{CU}^r \cdot c^B$$

Next, we model a new pure grid system for the MILP solver. The network model in this system is the same as our proposed C-RAN, but this new system does not have any renewable components. Thus, this system does not have any CapEx but has higher operating expenses as a result of higher grid energy consumption. Then, we calculate the return of capital (RoC) of an MNO that prefers a RESs system in their network. Equation (22) shows this calculation, in which $\text{OpEx}_{\text{GRID}}$, $\text{OpEx}_{\text{RES}}$ are the electricity costs of a pure grid and a RESs systems in a year, respectively. They are calculated using Equation (3) by considering the constraints in their corresponding network. Also, a RESs system has another operational cost, which is the maintenance cost ($MC$) of their renewable systems in a year period. This value does not change by the capacity of the renewable system components, and Fixr determines this value as $MC = 300$ per year for a single renewable system [42].

$$\text{ROC} = \left[ \frac{\text{CapEx} + \text{OpEx}_{\text{RES}} + \text{MC}}{\text{OpEx}_{\text{GRID}}} \right]$$

Figure 11 presents the change of total cost of ownership (TCO) of pure grid and RESs networks in low traffic rates. The subfigures from up to down represent the diversity between the cities, and from left to right illustrate the impact of increasing the size of the RESs system. The solar panel and...
battery size values in Table [I] are multiplicated with the vector \([0.25, 5, 1, 2, 4]\), and the problem is solved again for each city to perform this variation. For example, the sizes of the RES components in \((d), (j), (p), (v)\) are the double size of the standard values.

The arrow markers show the RoC point of an MNO. This value is around eight years for any city except Stockholm, which has limited solar irradiation average in a year period. Besides, the proper system sizes that provide the minimum RoC value should be chosen when \(\text{OpEx}^{\text{RES}} + \text{MC}\) value is near to zero; what is more, this significant finding can be applied for any city. One of the reasons is that selling the unused renewable energy to the grid is not profitable for an MNO. On the other hand, an insufficient amount of harvesting energy prevents the MNO to get the maximum profit from the GROVE model.

Lastly, the results of the other traffic rates are similar to their corresponding instances in Figure [I]. There are two significant facts that yield this similarity. First, the OpEx gap between the two systems does not change with the traffic rates. Second, MNO has the same capital expenditure for all traffic rates. We omit to show the results of these traffic rates in this paper due to the lack of space.

VI. CONCLUSION

We propose a novel network model named GROVE as a cost-efficient solution for using RESs in a C-RAN network. Then, we formulate an OpEx minimization problem which jointly takes into account the function splitting, RoE, and renewable energy usage in this model. We linearize the quadratic constraints in the formulation to solve this problem with a MILP Solver. The results show that our model improves the performance of the disjoint approaches, and it is more feasible for different solar radiation distributions and various traffic densities. The proposed solution outperforms the static routing by multiplexing gain. Also, it performs better than the traffic-aware method by optimizing the usage of profitable renewable energy in the batteries of the CU and RU.

The network scalability analysis shows that a MILP solver can maintain a network model with 40 nodes with reasonable RAM consumption. Besides, our proposed solution performs better results even with larger networks, and we may increase the termination time to reduce the gap between the lower bound of the MILP solver to improve this performance. Lastly, our economic feasibility analysis addresses the RES sizing problem in the proposed network, and the findings are highly valuable to support MNOs to choose the proper size of solar panels and the batteries for their potential green C-RAN network.

For the cases studied, the proposed solution surpasses the disjoint models with a MILP Solver, and it may maintain its performance with a longer termination time for slightly larger problems. For even larger problems, we plan to develop a heuristic using lower CPU processing and memory resources. We will investigate the economic benefits of constructing an RoE network as an alternative to a standard network with dedicated links. Hence, we are planning to encourage MNOs to implement the proposed RESs system to their next-generation networks to improve their cost and energy efficiency.

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