Towards Energy Efficient Functional Split and Baseband Function Placement for 5G RAN

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***Abstract*—The energy efficiency of 5G and beyond 5G (B5G) networks is critical for reducing the high operational expenditure (OPEX) of mobile network operators. In 5G RAN, functional split enables the disaggregation of baseband functions, which significantly increases energy efficiency but induces various challenges in the placement of baseband functions. Various recent works have focused on addressing these challenges; however, most of the solutions do not consider the delay and data rate requirements of different slices as well as different functional splits. In this work, we aim to develop an energy-efficient baseband function placement strategy that jointly considers different functional splits and network slice-specific requirements. We formulate an Integer Linear Program (ILP) based optimization model to minimize the energy consumption in the network by selecting appropriate functional split and baseband function placement options for RAN slices. We show that our proposed model outperforms the baseline strategies in providing energy efficient baseband function placement solution. To tackle the computational complexity of ILP, we also design a polynomial time heuristic algorithm that can be applied in large-scale scenarios.**

***Index Terms*—Energy Efficiency, Functional Split, Network Slice, Radio Access Network**

I. Introduction

With the growing surge in mobile data traffic, a massive increase in energy consumption is expected in 5G and Beyond 5G (B5G) networks [1]. It is well known that the primary source of energy consumption in a mobile network is Radio Access Network (RAN). Hence, developing an energy-efficient RAN solution is crucial for reducing the OPEX of network operators. The introduction of functional splits [2] in 5G RAN enables the disaggregation of baseband functions which can bring higher flexibility and efficiency in RAN. However, leveraging these concepts is not straightforward as it makes the placement of baseband functions challenging due to several factors described as follows:

1) Different functional splits have different delay and data rate requirements [2]. Hence, functional split should be selected based on the underlying network characteristics.
2) 5G and B5G must support services such as enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC), and massive Machine Type Communications (mMTC). These services have different delay and data rate requirements [3] that must be considered during the placement of baseband functions.
3) The capacity of processing nodes and links is limited. Thus, all deployment options may not be feasible.

Although many works have been conducted on baseband function placement, only a few consider all the above-mentioned factors together. Most of the previous works do not consider delay requirements of the slices [1], [4]. In [5], slice-specific requirements are taken into account with a fixed functional split option between the Centralized Unit (CU) and Distributed Unit (DU). Some works select functional split for base stations [6] or slices [7]–[9] by considering a single CU in the network; hence, different placement options and consolidation of baseband functions are not considered. In [10], multiple factors are considered together; however, it does not focus on the overall energy efficiency of 5G RAN. Moreover, most of the works on the energy-efficient functional split selection are based on optimization models or exact solutions, whereas very few propose a heuristic solution for the same [11], [12]. In this work, we address these issues by jointly considering the requirements of functional splits and network slices, and different placement options for baseband functions to achieve better energy efficiency in 5G RAN. The main contributions of this work are as follows:

- We design an optimization model based on ILP for placing the baseband functions of slices with the objective of minimizing the energy consumption in 5G RAN. We consider requirements of functional splits and network slices, and available capacity in the network while placing the functions.
- We show that the proposed solution outperforms various baselines in providing energy-efficient placement of baseband functions.
- To deal with the high computational complexity of the ILP, we propose a polynomial time heuristic solution and analyze its performance.

II. System Model

A base station performs a series of functions known as baseband functions. These functions include Radio Resource Control (RRC), Physical Data Convergence Protocol (PDCP), Radio Link Control (RLC), Medium Access Control (MAC), and Physical layer (High-PHY and Low-PHY). Leveraging different functional splits [2], a 5G base station is disaggregated into Radio Unit (RU), Distributed Unit (DU), and

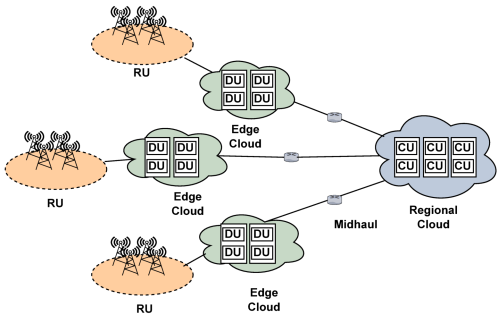

Fig. 1: RAN system model.

Centralized Unit (CU). The RU performs Low-PHY functionalities, whereas the DU and CU perform the remaining layers based on the functional split. We consider a hybrid cloud architecture (shown in Fig. 1) as our system model. Multiple RUs are connected to their edge clouds which are further connected to the regional cloud. The edge and regional cloud consist of multiple processing nodes where the baseband functions can be placed. To route the traffic between different components, various transport links are used - fronthaul (RU and edge cloud), midhaul (edge cloud and regional cloud), and backhaul (regional cloud and core network). Different slices belonging to the same RU can use different functional splits [7] according to their requirements. In this work, we assign split numbers 0-3 with 0 being the lowest split and 3 being the highest. In the lowest split (Split-0), all these layers are placed in the DU at the edge cloud. All the layers except the High-PHY layer are placed in the CU at the regional cloud for the highest split (Split-3).

III. Problem Formulation

A. Objective Function

We formulate our objective function to minimize the total energy consumption in processing nodes and midhaul links while selecting functional split and baseband function placement of RAN slices. The total energy consumption for processing nodes (E_p) is composed of energy consumption in edge and regional cloud, which is defined as,

$$\begin{aligned} E_p = \sum_{n\in \mathrm{ES}} (u_n c_n + \sum_{s\in S}\sum_{f\in F} x^n_{s,f} d_{s,f} c'_n) + \\ \sum_{m\in \mathrm{RS}} (v_m c_m + \sum_{s\in S}\sum_{f\in F} y^m_{s,f} d_{s,f} c'_m) \end{aligned} \tag{1}$$

where c_n and c'_n are the idle and active state energy consumption [13] in processing node n respectively.

Energy consumption of the activated midhaul links (E_m) is defined as,

$$E_m = \sum_{e\in \mathrm{EC}} \mu_e \beta_e \tag{2}$$

where β_e is the energy consumption for activating midhaul link corresponding to edge cloud $e \in \mathrm{EC}$.

The final objective of the optimization model is defined as,

$$Minimize : E_p + E_m \tag{3}$$

B. Constraints

i) The total processing placed in any node in the edge or regional cloud should not exceed the capacity of that node.

$$\sum_{s\in S}\sum_{f\in F} x^n_{s,f} d_{s,f} \leq \mathrm{CE}_n, \forall n \in \mathrm{ES} \tag{4}$$

$$\sum_{s\in S}\sum_{f\in F} y^m_{s,f} d_{s,f} \leq \mathrm{CR}_m, \forall m \in \mathrm{RS} \tag{5}$$

ii) Total traffic routed through a midhaul link should not exceed the capacity of that link.

$$\sum_{n\in \mathrm{ES}_e}\sum_{m\in \mathrm{RS}}\sum_{s\in S}\sum_{f\in F-\{f_s\}} x^n_{s,f} y^m_{s,f+1} t^s_{f,f+1} \leq \kappa_e, \forall e \in \mathrm{EC} \tag{6}$$

iii) If any function of a slice is placed on a node in edge or regional cloud, that node is considered to be active.

$$u_n \geq x^n_{s,f}, \forall n \in \mathrm{ES}, \forall s \in S, \forall f \in F \tag{7}$$

$$v_m \geq y^m_{s,f}, \forall m \in \mathrm{RS}, \forall s \in S, \forall f \in F \tag{8}$$

iv) If any function belonging to a slice in edge cloud e is placed in regional cloud, then that midhaul link is activated.

$$\mu_{e'_s} \geq y^m_{s,f}, \forall s \in S, \forall f \in F, \forall m \in \mathrm{RS} \tag{9}$$

v) Each function of a slice can be placed on only one processing node in either edge cloud or regional cloud.

$$\sum_{n\in \mathrm{ES}} \eta_{s,n} x^n_{s,f} + \sum_{m\in \mathrm{RS}} y^m_{s,f} = 1, \forall s \in S, \forall f \in F \tag{10}$$

vi) During the selection of functional split, the sequence of baseband functions must be maintained. Let f_0 and f_s denote the first and last function of the baseband processing chain. If a function is placed in the DU, its previous functions are also

Notation	**Description**
$x^n_{s,f}$	Function f of slice s is placed in edge node n or not
$y^m_{s,f}$	Function f of slice s is placed in regional node m or not
u_n	Server n in edge cloud is active or not
v_m	Server m in regional cloud is active or not
μ_e	Midhaul corresponding to edge cloud e is activated or not
ES	Set of servers in edge clouds
RS	Set of servers in regional cloud
EC	Set of edge clouds
RU	Set of Radio Units
F	Set of baseband functions
S	Set of all slices
CE_n	Capacity of edge server n
CR_m	Capacity of regional server m
$\eta_{s,n}$	Slice s belongs to the same edge cloud as node n or not
$d_{s,f}$	Processing requirement of function f of slice s
δ_e	Latency of a midhaul corresponding to edge cloud e
dreq_s	Delay budget of slice s
$t^s_{f,f+1}$	Bandwidth requirement between f and $f+1$ for slice s
t^s_{fs}	Bandwidth requirement of slice s for functional split fs
$l_{f,f+1}$	Latency requirement of consecutive functions f and $f+1$
κ_e	Capacity of midhaul link corresponding to edge e
e_n	Edge cloud that node n belongs to
e'_s	Edge cloud that slice s belongs to

TABLE I: Notation and Description

placed in the DU. Similarly, if a function is placed in the CU, its successive functions are also placed in the CU.

$$x_{s,f}^{n} \leq x_{s,f-1}^{n}, \forall f \in F-\{f_0\}, \forall s \in S, \forall n \in \mathrm{ES} \quad (11)$$

$$y_{s,f}^{m} \leq y_{s,f+1}^{m}, \forall f \in F-\{f_s\}, \forall s \in S, \forall m \in \mathrm{RS} \quad (12)$$

vii) The High-PHY layer must be placed in the edge cloud.

$$\sum_{n \in \mathrm{ES}} x_{s,f_0}^{n} \eta_{s,n} = 1, \forall s \in S \quad (13)$$

viii) The delay of each split should be supported by the midhaul link. Also, the delay requirement of a slice must not be exceeded by the midhaul link.

$$\begin{gathered} x_{s,f}^{n} y_{s,f+1}^{m} \delta_{e_n} \leq l_{f,f+1}, \\ \forall m \in \mathrm{RS}, \forall n \in \mathrm{ES}, \forall s \in S, \forall f \in F-\{f_s\} \end{gathered} \quad (14)$$

$$\begin{gathered} \sum_{s \in S} \sum_{f \in F} x_{s,f}^{n} y_{s,f+1}^{m} \delta_{e_n} \leq dreq_s, \\ \forall m \in \mathrm{RS}, \forall n \in \mathrm{ES}, \forall s \in S, \forall f \in F-\{f_s\} \end{gathered} \quad (15)$$

C. Linearization of the optimization model

There quadratic term $x_{s,f}^{n} y_{s,f+1}^{m}$ is linearized by introducing a new variable $\mathrm{xy}_{s,f,f+1}^{m,n}$ and its constraints.

$$\mathrm{xy}_{s,f,f+1}^{m,n} \leq x_{s,f}^{n} \quad (16)$$

$$\mathrm{xy}_{s,f,f+1}^{m,n} \leq y_{s,f+1}^{m} \quad (17)$$

$$\mathrm{xy}_{s,f,f+1}^{m,n} \geq x_{s,f}^{n} + y_{s,f+1}^{m} - 1 \quad (18)$$

IV. Heuristic Solution

The baseband function placement problem is a bin-packing problem, which is known to be NP-Hard. Hence, we provide a polynomial time heuristic of our proposed solution that can be used in large-scale scenarios. Our proposed heuristic (ESP-Heu) is based on the following assumptions. Due to the higher level of connectivity, placing the baseband functions in the regional cloud is advantageous as it will enable more consolidation. Moreover, some edge nodes must be switched ON to support delay-sensitive functions and slices. The central idea of this heuristic is to utilize these activated edge servers as much as possible so that no server in the regional cloud are activated unnecessarily. The heuristic is shown in Algo 1. We consider that the edge and regional cloud have sufficient capacity to support the baseband functions of all slices.

The algorithm consists of three steps. In the first step (lines 2-12), we find the set of edge servers that must be activated to support the low latency functions. We sort the slices based on their data rate requirements. Since slices with higher data rate requirements need more processing resources, considering the slices in decreasing order of their data rate requirement can help to save more energy. For each slice in the sorted list, we select the highest possible functional split and place its corresponding DU in an edge server. The motivation behind selecting the highest possible split is that, in this way, only the necessary functions are placed in the edge cloud, which helps to minimize the overall number of active servers. To select an edge server, we first consider the activated ones and sort them on the basis of remaining capacity in decreasing order (first-fit strategy). Considering an already active server helps to minimize unnecessarily switching on servers, whereas sorting the activated servers based on remaining capacity helps to reserve capacity for slices with high data rate requirements. If no active edge server can accommodate the DU, a new server is activated. Finally, we find the set of edge servers (ES') that need to be activated. In the second step (lines 13-22), we select the regional cloud servers to place the CU of the slices. Here, we consider only the edge servers (ES') chosen in the first step. We start the procedure from the lowest functional split as this helps to estimate the minimum number of regional cloud servers due to more functions being placed in the switched-on edge servers. Note that the placement of other slices is kept fixed while updating the functional split of a slice. For selecting a server in the regional cloud, we follow the similar

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Algorithm 1: ESP-Heu: Proposed Heuristic Solution

Data: Slice load, type, origin and network capacity.
Result: Functional split and baseband function placement decision for RAN slices

1 $S' \leftarrow Sort(S)$ `// Sort slices based on data rate requirements in decreasing order`
2 $\mathrm{ES}' = \phi$ `// Set of edge cloud servers to be activated`
3 **foreach** *slice s in* S' **do**
4     $\mathrm{fs} \leftarrow 3$ `// Start from the highest split`
5   **while** $\mathrm{fs} \geq 0$ **do**
6   **if** $\mathrm{fs} > 0$ *and* $\delta_{e'_s} \leq \mathrm{dreq}_s$ *and* $\delta_{e'_s} \leq l_{\mathrm{fs}}$ *and* $\kappa_{e'_s} \leq t_{\mathrm{fs}}^{s}$ **then**
7   a. Find edge server $e \in \mathrm{ES}$ and regional server $r \in \mathrm{RS}$ in first fit manner for DU and CU.
8   b. If server r is found, add e to ES', update residual capacity and break.
9   **else**
10   a. Find edge server e in first fit manner for DU.
11   b. Add e to ES', update residual capacity, break.
12        $\mathrm{fs} \leftarrow \mathrm{fs} - 1$
13 $\mathrm{RS}' = \phi$ `// Set of regional cloud servers to be activated`
14 **foreach** *slice s in* S' **do**
15     $\mathrm{fs} \leftarrow 0$ `// Start from the lowest split`
16   **while** $\mathrm{fs} \leq 3$ **do**
17   **if** $\mathrm{fs} > 0$ *and* $\delta_{e'_s} \leq \mathrm{dreq}_s$ *and* $\delta_{e'_s} \leq l_{\mathrm{fs}}$ *and* $\kappa_{e'_s} \leq t_{\mathrm{fs}}^{s}$ **then**
18   a. Find edge server $e \in \mathrm{ES}'$ and regional server $r \in \mathrm{RS}$ in first fit manner for DU and CU.
19   b. If server e is found, add r to RS', update residual capacity and break.
20   **else**
21   a. Find edge server e in first fit manner for DU, update residual capacity, break.
22        $\mathrm{fs} \leftarrow \mathrm{fs} + 1$
23 **foreach** *slice s in* S' **do**
24     $\mathrm{fs} \leftarrow 0$
25   **while** $\mathrm{fs} \leq 3$ **do**
26   Check if fs can further minimize load-dependent energy consumption and update the functional split
27         $\mathrm{fs} \leftarrow \mathrm{fs} + 1$

steps described in the first step along with evaluating midhaul and find the set of regional cloud servers (RS') that will be activated. After the two steps, we get ES' and RS' that help to minimize the energy consumption of the idle servers, which is the dominant part of the total energy consumption. In the final step (lines 23-27), we further try to minimize the load-dependent energy consumption by selecting the best possible functional split for slices using only the selected edge and regional cloud servers. If any functional split is found that can further minimize the energy consumption, we update the functional split and baseband function placement for that slice.

V. Simulation and Results

The simulation parameters are mentioned in Table II. The network consists of three edge clouds and a regional cloud with a total of 36 servers having a processing capacity of 1000-1100 Giga Operations Per Second (GOPS) and 30 RUs having 20MHz bandwidth with single antenna. We consider two types of slices - eMBB and URLLC. The processing and bandwidth requirements are calculated using [8], [14], [15]. The results are obtained with 95% confidence interval for 50 randomly generated inputs in each case. We implemented the optimization model using Gurobi solver [16] in Python 3.8. We compare the performance of our proposed optimization model (ESP-Opt) with the following baselines.

1) No-HC: This is similar to the model proposed in [17] where functions in CU and DU are fixed according to NG-RAN standards. Moreover, different energy consumption in different processing nodes is not considered.
2) All-Edge: In this strategy, all the baseband functions are placed at the edge cloud (only Split-0 is considered).
3) ESP-NC: In this strategy, the proposed optimization model is solved without consolidating the processing nodes (in Eqn. 1), i.e., it only minimizes the load-dependent energy consumption as done in [8].

A. Performance of the Optimization Model

In this subsection, we analyze the energy efficiency of our proposed optimization model (ESP-Opt). We consider 20% of the total slices to be of URLLC and the others as eMBB slices. Due to the power usage effectiveness (PUE), the regional cloud is considered to be more energy efficient than edge clouds [19].

Simulation Parameters	Description
Number of edge and regional cloud	3 and 1
Total number of servers	36 servers
Number of server in regional cloud	12
Number of servers in edge cloud	8 in each cloud
Slice types	eMBB and URLLC
URLLC and eMBB Data-rate	25 & 50 Mbps
URLLC and eMBB Delay	1 & 10 ms [18]
Number of slices	10-50 slices
Server capacity in Regional and edge cloud	1100 and 1000 GOPS
Each midhaul link capacity and delay	4 Gbps & 2 ms
Idle energy consumption of servers	50% of peak energy
PUE of edge and regional clouds	1-1.5
Power consumption of using a midhaul link	0.5 W

TABLE II: Simulation Parameters

We consider this energy efficiency factor of edge and regional cloud are 1 and 1.25 respectively.

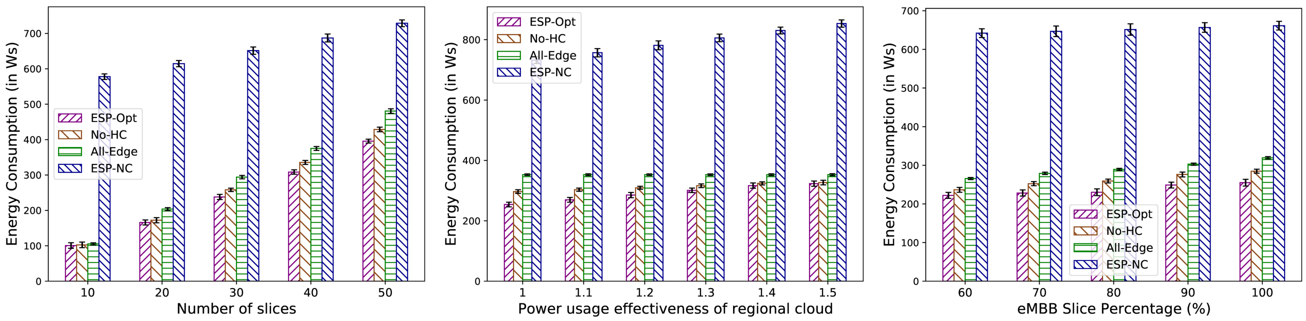
Fig. 2a shows the energy consumption for different strategies by varying the number of RAN slices. We observe that ESP-Opt consumes the lowest energy. ESP-NC tries to minimize only load-dependent energy consumption. As a result, it tries to place more functions in the regional cloud. However, it unnecessarily activates more nodes due to not consolidating the baseband functions, resulting in the highest energy consumption. All-Edge places all baseband functions in the edge clouds, thereby cannot consolidate the functions efficiently. Moreover, the energy consumption per unit processing is more in edge clouds due to their PUE. Because of these reasons, All-Edge consumes higher energy than ESP-Opt. No-HC has fixed functions in CU and DU. Also, it does not consider the dynamic energy consumption of different nodes. Hence, it cannot place the baseband functions flexibly, resulting in higher energy consumption than ESP-Opt. ESP-Opt consumes around 7% less energy than No-HC.

The regional clouds are considered more energy efficient than the edge clouds due to the lower PUE of large data centers [14], [19]. In Fig. 2b, we vary this energy efficiency factor in the regional cloud and analyze its impact on overall energy consumption. The PUE of the edge cloud is fixed at 1.5, whereas in the regional cloud, it is varied from 1 to 1.5. When the difference in this value in different clouds is higher (1-1.2), the performance gap between ESP-Opt and No-HC increases. No-HC incurs more energy than ESP-Opt due to having fixed functions in the DU. As the value increases in the regional cloud, the difference between No-HC and ESP-Opt becomes less. This is because placing the functions in the edge or regional cloud does not make much difference in such cases. As the PUE in the edge cloud is fixed, we see no effect of varying the regional cloud energy consumption in All-Edge. ESP-NC has the highest energy consumption as it does not consider the consolidation of processing nodes.

In Fig. 2c, we vary the number of eMBB slices and observe its impact on energy consumption. We consider a network with 30 slices and vary the percentage of eMBB slice requests from 60-100% of total slice requests, while the rest are considered URLLC slices. We observe that the energy consumption increases with the number of eMBB slices due to their high datarate requirements. URLLC slices have low delay requirements, due to which their baseband functions are mostly processed in the edge clouds. This makes the selection of functional split less flexible for URLLC slices. As a result, we can observe the performance gap between the All-Edge and the rest of the strategies increases with the increase in the eMBB slice percentage. The performance gap between No-HC and ESP-Opt also increases with the number of eMBB slices as ESP-Opt gets more flexibility for placing the baseband functions.

B. Performance of the Heuristic Solution

In Fig. 3, we compare the performance of the proposed optimization model (ESP-Opt) and the proposed heuristic



(a) Energy consumption vs. Number of slices.

(b) Total Energy consumption vs power usage effectiveness in regional cloud.

(c) Total Energy consumption vs. eMBB slice percentage.

Fig. 2: Comparison of different strategies.

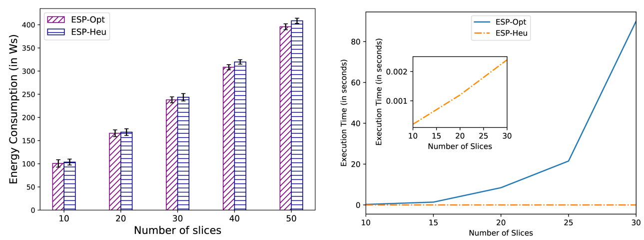


Fig. 3: Perfromance of the heuristic solution

(ESP-Heu) by varying the number of slice requests. We can observe that when the number of slices is less, the heuristic achieves a similar performance compared to the optimization model. As the number of slices increases, the energy consumption of ESP-Heu becomes more than ESP-Opt. On average ESP-Opt consumes around 2.7% less energy than ESP-Heu. However, due to carefully considering different functional split and baseband function placement options through the three different stages of the algorithm, ESP-Heu is able to achieve comparable performance to ESP-Opt. In contrast to ESP-Opt, the execution time of ESP-Heu grows linearly, which enables its application in real-time scenarios.

VI. Conclusion

With technological advances such as functional split, network slicing, and virtualization, higher energy efficiency can be realized in 5G RAN. However, this flexibility in 5G RAN increases the complexity of baseband function placement. In this work, we address this issue by jointly considering different functional splits and slice-specific requirements to provide an energy-efficient solution for placing baseband functions. We propose an ILP based optimization model to minimize the energy consumption of processing nodes and transport links. We also provide a polynomial time heuristic to deal with the complexity of the optimization model. We show that our proposed optimization model achieves better energy efficiency while placing the baseband function placement in various scenarios compared to the baselines. We also show that the proposed heuristic can minimize energy consumption in the network within a reasonable amount of time.

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