Profit Maximization under Investment Budget and Optical Link Constraints in Open RAN

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***Abstract*—The rapid evolution of wireless communication systems has led to the development of 5G networks, which offer several advantages such as higher throughput, lower latency, and higher reliability compared to the previous generation. However, the deployment of 5G networks in developing countries is significantly slowed down due to high deployment costs. In this paper, we propose a framework formulated as a Mixed Integer Linear Program (MILP) that considers a green-field scenario, assuming no pre-existing network infrastructure, and provides a minimum-cost solution for deploying Open Radio Access Network (RAN) components, including Distributed Unit (DU) logical functions, Central Units (CUs), and capacity-constrained optical transport links. The proposed model enables operators to gradually deploy their network according to their available budget. Depending on the allocated budget, operators can obtain the resulting network infrastructure and the corresponding estimated profit. In addition, the framework allows the analysis of user admission as a function of both the investment budget and the available capacity of the optical transport links.**

The proposed framework is designed as a network planning tool that supports operators in the design and techno-analysis of 5G networks. This approach is particularly beneficial for operators with limited financial resources.

***Index Terms*—5G networks, Logical Functions, Optical Links.**

I. Introduction

The growing complexity of Beyond 5G (B5G) and future wireless networks calls for innovative approaches to network design and optimization. These networks are expected to provide ultra-low latency, high-capacity connectivity, and flexible as well as scalable deployments in order to support emerging technologies such as autonomous systems, immersive applications, and real-time interactive services [1]. These advancements pose critical challenges related to the architectural disaggregation of the RAN into three fundamental components: Radio Units (RUs), Distributed Units (DUs), and Centralized Units (CUs). This segmentation directly impacts deployment cost, power consumption, and end-to-end latency, all of which must be carefully addressed to meet the stringent performance requirements of 5G networks. These requirements can be summarized by three key service categories: ultra-reliable low-latency communications (uRLLC), massive machine-type communications (mMTC), and enhanced mobile broadband (eMBB) [2]. The Open Radio Access Network (Open RAN) architecture further refines this segmentation by introducing three transport components: fronthaul (FH), midhaul (MH), and backhaul (BH) [3], [4]. Specifically, the FH connects RUs to DUs, the MH links DUs to CUs, and the BH provides connectivity between CUs and the data center (DC). Although 5G networks are widely deployed in most countries, their deployment remains very limited in developing regions, mainly due to the high associated infrastructure costs, particularly those related to the provisioning of high-capacity optical backhaul and fronthaul links. In this paper, we propose a framework that provides the following contributions:

- The proposed framework enables cost-efficient Open RAN deployment by determining suitable locations for DU and CU functions, identifying which RUs should be activated, and performing optical link placement, while accounting for fronthaul, midhaul, and backhaul latency constraints, optical link capacities, and computational resource limitations.
- After estimating the minimum deployment cost, the framework evaluates network deployment under the operator's available budget. It defines feasible deployment configurations according to the invested budget and simultaneously estimates the operator's profit based on service monetization.
- Given a fixed budget, the framework further analyzes user admission using Jain's fairness index. This analysis allows operators to identify which investment yields are favorable budget-profit trade-offs.
- Using the same framework, operators can also study user admission by varying optical link capacity in order to determine the fiber capacity required to achieve an acceptable level of service admission.

We assess our model by solving practical deployment scenarios. The framework accounts for real-world constraints, including user distribution, coverage requirements, and capacity constraints, thereby enabling practical and cost-effective network designs.

II. Related Works

In the literature, several authors have proposed models aiming to reduce deployment costs or maximize user's quality

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TABLE I: Comparison of selected related works

Paper ID	Objectives	Latency	Profit Maximization.	User or request admittance.	Deployment under Budget Constraint.	UE-RU allocation	Network Deployment from green-field	Optical Transport Cost
[1]	Minimizing Deployment cost	–	–	–	–	✓	–	✓
[2]	Minimizing Deployment Cost.	✓	–	–	–	–	✓	✓
[5]	Maximize Users Admittance	✓	–	✓	–	✓	–	–
[6]	Maximize the InP profit	✓	✓	✓	–	–	–	✓
Our Work	Profit Maximization and User admittance.	✓	✓	✓	✓	✓	✓	✓

of service. Among them, Hojeij et al. [5] developed an optimal Open Distributed Units (O-DU) and Open Centralized Units (O-CU) placement model in the O-Cloud nodes (i.e., edge and regional clouds) by considering MH delay and server capacity. In this work, the authors aimed at maximizing user admission in the network while considering the deployment cost as a performance metric. Njanda et al. [2] proposed a planning model for Open RAN DU and CU function placement with the objective of minimizing deployment costs. In this work, the Users equipment (UE)–RU association is assumed to be predefined; consequently, the model starts from a fixed set of RUs and focuses on determining the optimal locations for deploying DU and CU logical functions in order to connect them to the data center (DC). Mushtaq et al. [6] proposed a profit maximization model for the Infrastructure Provider (InP) in Next Generation Radio Access Network (NG-RAN). They introduced the JointFSAPR model, which focuses on the joint optimization of functional split selection, slice request admission, CU/DU placement, and traffic routing. Their work aimed at maximizing the InP profit by increasing the revenue generated from admitted requests while minimizing the operational costs associated with these decisions. In [1], the authors propose an optimization framework for designing a 5G network that optimizes the placement of O-RAN and optical transport components using a MILP. Our work is inspired by [5]. However, unlike existing approaches in the literature, our study is primarily designed to reduce deployment costs. In addition, we propose a model that evaluates user profit as a function of the investment budget allocated by the operator. This enables us to analyze user admissibility in the network with respect to the available budget and Optical link Capacity. A comparison of the key features among our work and the selected literature is illustrated in Table I.

III. Problem Statement

An operator aims to deploy an Open RAN 5G network in green field. From a network planning perspective, the operator requires a decision support tool capable of maximizing profit while accounting for a progressive investment strategy. Figure 1 illustrates the green field scenario. A set of candidate sites is defined, representing potential locations for deploying DU and CU functions, while D_C is considered the destination. The operator seeks to determine the optimal placement of logical functions as well as the deployment of optical links required to interconnect the different network entities. The main challenges can be summarized as follows:

- How should users be associated with RUs, and which RUs should be activated or left inactive?
- Which candidate sites should host the logical network functions?

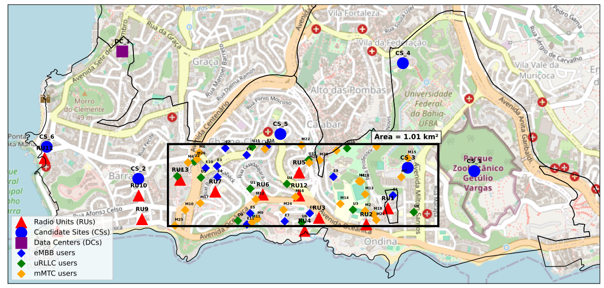


Fig. 1: Network Example - (Salvador-Bahia, Brazil)

- Between which sites should optical links be deployed to ensure connectivity between entities?
- Given a progressive investment strategy, what infrastructure can be deployed at each stage?
- How does the level of investment affect network admission for different users?
- How does the investment strategy impact the operator's estimated profit?

To address these planning and investment-related challenges, this paper proposes an effective and rigorous modeling framework.

IV. Mathematical Formulation

A. Parameters and Variables

Tables II and III list the notation symbols of the parameters and variables, respectively, along with their definitions used in the formulation.

B. Delay Model

The delay requirements associated with the fronthaul and midhaul are formulated in Equation (1a). In equation (1b) $(\Delta^{BH}_{(j,k)})$ ensures backhaul delays requirements and $(\Delta^{c}_{(u,r)})$ ensures radio coverage for users served by an RU.

$$\Delta^{FH}_{(r,j)} = \begin{cases} 1 & \text{if} \quad \underbrace{\delta^{FH}_{(r,j)}}_{=\frac{n\,d_{(r,j)}}{c}} \leq \Lambda^{FH}, \\ 0 & \text{otherwise,} \end{cases} \qquad \Delta^{MH}_{(j,\ell)} = \begin{cases} 1 & \text{if} \quad \underbrace{\delta^{MH}_{(j,\ell)}}_{=\frac{n\,d_{(j,\ell)}}{c}} \leq \Lambda^{MH}, \\ 0 & \text{otherwise,} \end{cases} \tag{1a}$$

$$\Delta^{BH}_{(j,k)} = \begin{cases} 1 & \text{if} \quad \underbrace{\delta^{BH}_{(j,k)}}_{=\frac{n\,d_{(j,k)}}{c}} \leq \Lambda^{BH}, \\ 0 & \text{otherwise,} \end{cases} \qquad \Delta^{c}_{(u,r)} = \begin{cases} 1 & \text{if } d_{(u,r)} \leq R, \\ 0 & \text{otherwise,} \end{cases} \tag{1b}$$

C. Traffic Model

The maximum achievable traffic for a user is given by Equation (2), as defined in [5].

$$W_u \text{ [Mbps]} = \frac{N_{\text{sym}} \cdot N_{SC} \cdot M \cdot C \cdot L \cdot (1 - OH) \cdot Rb_u}{1000}, \quad \forall u \in UE \tag{2}$$

TABLE II: List of parameters and their definitions

Symbol	Definition	Symbol	Definition
CS	Set of Candidate Sites	UE	Set of Users
UE^{eMBB}	Set of Users eMBB	UE^{uRLLC}	Set of Users URLLC
UE^{mMTC}	Set of Users mMTC	D_C	Set of Data centers
RB^m	Maximum available number of resource blocks (RBs) in RUs	RB^{eMBB}	Maximum available number of RB for eMBB service
RB^{uRLLC}	Maximum available number of RBs for uRLLC service	RB^{mMTC}	Maximum available number of RBs for mMTC service
α^{DU}	Computational complexity of DU	α^{CU}	Computational complexity of CU
Rb_u	RBs allocated to user u	W_u	The maximum achievable throughput of a given user u
RU	Set of RUs	N_{sym}	Number of Symbol
N_{SC}	Number of Subcarrier per RB	L	MIMO Layers
C_u	Coding rate of user u	OH	overhead
M	Modulation Order	C^{DU}	Cost of DU deployment
C^{CU}	Cost of CU deployment	C^{RU}	Cost of RU deployment (activation)
C^L	Cost related to optical link connection per km	c	light speed
n	optical fiber indice	$d_{(j,\ell)}$	distance between CS j and CS ℓ
$d_{(u,r)}$	distance between Users u and RU r	$d_{(r,j)}$	distance between RU r and CS j
$d_{(j,k)}$	distance between CS j and DC k	R	Radius coverage of RU
Λ^{FH}	Fronthaul(FH) delay define	Λ^{MH}	Midhaul (MH) delay define
Λ^{BH}	Backhaul (BH) delay define	$\Delta^{FH}_{(r,j)}$	Binary parameter indicate 1 if RU r and CS j respect FH delay, 0 otherwise.
$\Delta^{MH}_{j\ell}$	Binary parameter indicate 1 if CS j and CS ℓ respect MH delay, 0 otherwise.	$\Delta^{BH}_{(j,k)}$	Binary parameter indicate 1 if CS j and DC k respect BH delay, 0 otherwise.
$U_{(j,\ell)}$	Midhaul link capacity between CS j and CS ℓ	$H_{(j,k)}$	Backhaul link capacity between CS j and DC k
R^{DU}	Computational resource capacity of DU	R^{CU}	Computational resource capacity of CU
A	Number of Antenna	g_u^{slice}	Monetary gain associated with user u accessing slice. slice $\in$ {eMBB, uRLLC, mMTC}.
B	Budget available	Φ^c	Total deployment Cost
M^B	Big Number	$\delta^{FH}_{(r,j)}$	Fronthaul delay compute
$\delta^{MH}_{(j,\ell)}$	Mildhaul delay compute	$\delta^{BH}_{(j,k)}$	Backhaul delay compute
C^{oper}	Cost related to Giga Operational per second(GOPS)	$\Delta^c_{(u,r)}$	=1 if user u is in the radio coverage of RU r, 0 otherwise
M^{RU}	Maximum number of RU supported by a single DU	M^{DU}	Maximum number of DU supported by a single CU
$\epsilon^{\text{services}}$	Priority according to user services, with services $\in$ {eMBB, uRLLC, mMTC}		

TABLE III: List of variables and their definitions

Symbol	Definition	Symbol	Definition
$t_{(r,k)}$	Traffic of RU r to DC k	$x_{(u,r)}$	Binary variable indiquate 1 if user u is connected to RU r
Z_r^{RU}	=1 if RU r is activated; 0 otherwise	$Y_{(r,j)}$	=1 if RU r is connected to CS j; 0 otherwise
Z_j^{DU}	=1 if DU function is deploy at CS j; 0 otherwise	Z_j^{CU}	=1 if CU function is deploy at CS j; 0 otherwise
$\theta_{(r,j)}$	=1 if there is a optical link between RU r activated and CS j processing DU functions	$\zeta_{(j,\ell)}$	=1 if there is a optical link between CS j processing DU functions and CS ℓ processing CU functions
$y_{(j,k)}$	Flow variable moving from CS j to DC k	$w_{(j,k)}$	= 1 if there is a optical link between CS j processing CU functions and DC k
$f^k_{(j,\ell)}$	Flow variable from CS j passing through CS ℓ to DC k	$\lambda^j_{(r,k)}$	Auxiliary variable representing : Traffic from RU r to DC k passing through CS j
$\beta_{(r,j)}$	Auxiliary variable : indicate the RU r traffic is processing on DU function at CS j	$\eta_{(j,\ell)}$	Auxiliary variable: represents the traffic from the DU at CS j processed by the CU at CS ℓ.
Rb_r	intermediate continuous variable uses to get Total coding rate times RBs received from users by RU r.	ρ_j^{DU}	Auxiliary variable used to aggregate the traffic from RUs directed to a computing site where the DU is located.

D. Cost Minimization Model

1) Objective Function:

$$\text{Minimize} \quad \Phi^c = \underbrace{\sum_{r\in RU} C^{RU} Z_r^{RU}}_{\text{RU deployment}} + \underbrace{\sum_{j\in CS} C^{DU} Z_j^{DU}}_{\text{DU deployment}} + \underbrace{\sum_{j\in CS} C^{CU} Z_j^{CU}}_{\text{CU deployment}}$$
$$+ \underbrace{\sum_{j\in CS}\sum_{\ell\in CS} C^L d_{(j,\ell)}\zeta_{(j,\ell)}}_{\text{Midhaul links cost}} + \underbrace{\sum_{r\in RU}\sum_{j\in CS} C^L d_{(r,j)} Y_{(r,j)}}_{\text{Fronthaul links cost}}$$
$$+ \underbrace{\sum_{j\in CS}\sum_{k\in D_C} C^L d_{(j,k)} w_{(j,k)}}_{\text{Backhaul links cost}} + \underbrace{\sum_{r\in RU}\sum_{j\in CS} C^{oper}\alpha^{DU}\beta_{(r,j)}}_{\text{DU operational cost}}$$
$$+ \underbrace{\sum_{j\in CS}\sum_{\ell\in CS} C^{oper}\alpha^{CU}\eta_{(j,\ell)}}_{\text{CU operational cost}}. \tag{3}$$

The objective function illustrated by Equation (3) minimizes the total deployment cost, including the costs associated with RU, DU, and CU installation; the installation costs of fronthaul, midhaul, and backhaul optical links; and the operational costs of the DU and CU.

2) Constraints:

$$\sum_{r\in RU} x_{(u,r)} = 1, \quad \forall u \in UE \tag{4}$$

Equation (4) requires each user to connect to a single RU; in addition, all users must have access to the network.

$$x_{(u,r)} \leq \Delta^c_{(u,r)}.Z_r^{RU}, \quad \forall u \in UE, \quad \forall r \in RU \tag{5}$$

Equation (5) requires that a user connect only to an RU within their coverage area; moreover, if a user is connected to an RU, that RU must be activated.

$$\begin{aligned} &\sum_{u\in UE^{eMBB}} x_{(u,r)}\, Rb_u \leq RB^{eMBB}, \quad \forall r \in RU,\\ &\sum_{u\in UE^{uRLLC}} x_{(u,r)}\, Rb_u \leq RB^{uRLLC}, \quad \forall r \in RU,\\ &\sum_{u\in UE^{mMTC}} x_{(u,r)}\, Rb_u \leq RB^{mMTC}, \quad \forall r \in RU. \end{aligned} \tag{6}$$

Equations (6) ensure that user resource allocations do not exceed the maximum planned resources for each service on the RU.

$$\sum_{j\in CS} Y_{(r,j)} <= 1, \quad \forall r \in RU \tag{7}$$

$$\sum_{r\in RU} Y_{(r,j)} \leq M^{RU}, \quad \forall j \in CS \tag{8}$$

Equation (7) requires each RU to connect to a single DU, and Equation (8) imposes the maximum number of RU connections that a DU can support, given the number of available ports.

$$Y_{(r,j)} \leq \Delta^{FH}_{(r,j)} \underbrace{Z_j^{DU}\cdot Z_r^{RU}}_{\theta_{(r,j)}}, \quad \forall r \in RU, \quad \forall j \in CS \tag{9}$$

$$\begin{aligned} &\theta_{(r,j)} \leq Z_r^{RU}, && \forall r \in RU,\ j \in CS,\\ &\theta_{(r,j)} \leq Z_j^{DU}, && \forall r \in RU,\ j \in CS,\\ &\theta_{(r,j)} \geq Z_r^{RU} + Z_j^{DU} - 1, && \forall r \in RU,\ j \in CS. \end{aligned} \tag{10}$$

Equation (9) ensures that a connection exists between an RU and a CS. If the fronthaul delay constraint is satisfied, the DU function is placed at this CS, and the RU is activated. This results in a quadratic product, which is linearized in Equation (10).

$$y_{(j,k)} \ \leq \ H_{(j,k)}\, w_{(j,k)}, \quad \forall j \in CS,\ k \in D_C \tag{11}$$

$$w_{(j,k)} \;\leq\; \Delta^{BH}_{(j,k)}\, Z^{CU}_j, \quad \forall j \in CS,\; k \in D_C \tag{12}$$

Equation (11) ensures that the traffic arriving at the DC does not exceed the backhaul optical link capacity. Equation (12) ensures that a D_C can be connected to a CS where the CU function is deployed, while respecting the backhaul delay constraint.

$$\sum_{k \in D_C} f^k_{(j,\ell)} \;\leq\; U_{(j,\ell)}\, \Delta^{MH}_{(j,\ell)}\, \underbrace{Z^{DU}_j\, Z^{CU}_\ell}_{\zeta_{(j,\ell)}}, \quad \forall j,\ell \in CS,\; j \neq \ell \tag{13}$$

$$\begin{aligned} &\zeta_{(j,\ell)} \leq Z^{DU}_j, && \forall j,\ell \in CS,\; j \neq \ell,\\ &\zeta_{(j,\ell)} \leq Z^{CU}_\ell, && \forall j,\ell \in CS,\; j \neq \ell,\\ &\zeta_{(j,\ell)} \geq Z^{DU}_j + Z^{CU}_\ell - 1, && \forall j,\ell \in CS,\; j \neq \ell. \end{aligned} \tag{14}$$

Equation (13) ensures that traffic between CSs occurs only between those where the DU and CU functions are deployed, in accordance with the midhaul delay constraint and the capacity of the midhaul optical link. This results in a quadratic product, which is linearized in Equation (14).

$$\sum_{j \in CS} \zeta_{(j,\ell)} \;\leq\; M^{DU}, \quad \forall \ell \in CS, \quad j \neq \ell \tag{15}$$

Equation (15) limits the maximum number of DU connections that can be supported by a CU.

$$t_{(r,k)} = \sum_{u \in UE} W_u.x_{(u,r)}, \quad \forall r \in RU, \quad \forall k \in D_C \tag{16}$$

$$\sum_{r \in RU} \underbrace{t_{(r,k)}\, Y_{(r,j)}}_{\lambda^j_{(r,k)}} \;+\; \sum_{\substack{\ell \in CS\\ j \neq \ell}} (f^k_{(\ell,j)} - f^k_{(j,\ell)}) \;=\; y_{(j,k)}, \quad \forall j \in CS,\; k \in D_C \tag{17}$$

$$\begin{aligned} &\lambda^j_{(r,k)} \leq t_{(r,k)}, && \forall r \in RU,\; \forall k \in D_C,\; \forall j \in CS,\\ &\lambda^j_{(r,k)} \leq Y_{(r,j)}\, M^B, && \forall r \in RU,\; \forall k \in D_C,\; \forall j \in CS,\\ &\lambda^j_{(r,k)} \geq t_{(r,k)} - (1 - Y_{(r,j)})\, M^B, && \forall r \in RU,\; \forall k \in D_C,\; \forall j \in CS. \end{aligned} \tag{18}$$

Equation (16) defines the user traffic for D_C, as we have only one DC, he allows us to track the traffic accurately, while Equation (17) enforces flow conservation between entities. The associated quadratic term is linearized in Equation (18). The computational server capacity required by each user u is modeled based on an estimation of the processing complexity in terms of Giga Operations Per Second (GOPS). The total computational capacity is distributed among the RU, DU, and CU according to the PHY split and the RLC–PDCP split. Specifically, the considered splits are split-7.2x (between RU and DU) and split-2 (between DU and CU). Accordingly, 40% of the processing is performed at the RU, 50% at the DU, and 10% at the CU, as reported in [5]. The computational model of the functional unit (FU) is given in Equation (19).

$$r^{FU}_u[\text{GOPS}] = \alpha^{FU}\, \frac{(3A + A^2 + \frac{M \cdot C \cdot L}{3})}{10} Rb_u, \quad \forall u \in UE \tag{19}$$

The DU function processes the traffic from the RU, while the CU function processes the traffic coming from the DU. To achieve this, Equation (20) represents the DU computational complexity constraint, while Equation (22) represents the CU computational complexity constraint.

$$\begin{aligned} &Rb_r = \sum_{u \in UE} \frac{\left(3A + A^2 + \frac{M\, C_u\, L}{3}\right)}{10} RB_u\, x_{(u,r)}, \forall r \in RU\\ &\sum_{r \in RU} \alpha^{DU}\, \underbrace{Rb_r\, Y_{(r,j)}}_{\beta_{(r,j)}} \leq R^{DU}, \quad \forall j \in CS. \end{aligned} \tag{20}$$

$$\begin{aligned} &\beta_{(r,j)} \leq Rb_r, && \forall r \in RU,\; j \in CS,\\ &\beta_{(r,j)} \leq M^B\, Y_{(r,j)}, && \forall r \in RU,\; j \in CS,\\ &\beta_{(r,j)} \geq Rb_r - (1 - Y_{(r,j)})\, M^B, && \forall r \in RU,\; j \in CS. \end{aligned} \tag{21}$$

Equation (20) ensures that the DU server computational capacity is respected. The quadratic form arises from tracking RU traffic until the DU server processing it is identified. This quadratic product is linearized in Equation (21).

$$\begin{aligned} &\rho^{DU}_j = \sum_{r \in RU} \underbrace{Rb_r\, Y_{(r,j)}}_{\beta_{(r,j)}}, && \forall j \in CS,\\ &\sum_{j \in CS} \alpha^{CU}\, \underbrace{\zeta_{(j,\ell)}\, \rho^{DU}_j}_{\eta_{(j,\ell)}} \leq R^{CU}, && \forall \ell \in CS,\; j \neq \ell. \end{aligned} \tag{22}$$

$$\begin{aligned} &\eta_{(j,\ell)} \leq M^B\, \zeta_{(j,\ell)}, && \forall j,\ell \in CS,\; j \neq \ell\\ &\eta_{(j,\ell)} \leq \rho^{DU}_j, && \forall j,\ell \in CS,\; j \neq \ell\\ &\eta_{(j,\ell)} \geq \rho^{DU}_j - (1 - \zeta_{(j,\ell)})\, M^B, && \forall j,\ell \in CS,\; j \neq \ell \end{aligned} \tag{23}$$

Equation (22) ensures that the CU server computational capacity is respected. The quadratic form arises from tracking DU traffic until the CU server processing it is identified. This quadratic product is linearized in Equation (23).

$$Z^{DU}_j + Z^{CU}_j \leq 1, \quad \forall j \in CS \tag{24}$$

The equation (24) imposes that the DU and CU should not be placed in the same CS. This constraint comes from the fact that we use split-2, which implies that the DU and CU are very far apart. In our small-dimension simulation framework, we impose this constraint in order to place the DU and CU on different location.

E. Profit Maximization Model

1) Objective Function:

$$\begin{aligned} \text{Maximize} \quad \text{Profit} = \Bigg(&\underbrace{\sum_{u \in UE^{eMBB}} \sum_{r \in RU} g^{eMBB}_u\, x_{(u,r)}\, W_u}_{\text{eMBB users revenue}}\\ &+ \underbrace{\sum_{u \in UE^{uRLLC}} \sum_{r \in RU} g^{uRLLC}_u\, x_{(u,r)}\, W_u}_{\text{uRLLC users revenue}}\\ &+ \underbrace{\sum_{u \in UE^{mMTC}} \sum_{r \in RU} g^{mMTC}_u\, x_{(u,r)}\, W_u}_{\text{mMTC users revenue}} \Bigg)\\ &- \underbrace{\Phi^c}_{\text{Deployment cost}}. \end{aligned} \tag{25}$$

Equation (25) illustrates the gain for operators in terms of the number of users with access to the network, as we have only one DC.

TABLE IV: List of parameters and their adopted values

Symbol	Values	Symbol	Values
RB^m	100 [5]	RB^{eMBB}	50% RB^m [5]
RB^{uRLLC}	25% RB^m [5]	RB^{mMTC}	25% RB^m [5]
α^{DU}	0.5 [5]	α^{CU}	0.1 [5]
RB_u	[10,20] (eMBB), [1,5] (uRLLC, mMTC) [5]	N_{sym}	14 symbols per sub-frame [5]
N_{SC}	12 [5]	L	2 [5]
n	1.5 [5]	OH	0.14 [5]
M	$\log_2(64)$ [5]	C^{DU}	3800 $
C^{CU}	4800 $	C^{RU}	1800 $
C^L	1600 $/km	c	3×10^5 km/s
R	0.45 km	$U_{(j,\ell)}$	2 Gbps
$H_{(j,k)}$	5 Gbps	M^B	10^6
R^{DU}	1000 GOPS	R^{CU}	2000 GOPS
A	4 antennas [5]	C^{oper}	1.59 $/GOPS
M^{RU}	12	M^{DU}	6
g_u^{eMBB}	250$/Mbps	g_u^{uRLLC}	250$/Mbps
g_u^{mMTC}	250$/Mbps		

2) Constraints:

$$\sum_{r \in RU} x_{(u,r)} \leq 1, \quad \forall u \in UE \tag{26}$$

Equation (26) represents the constraint defined in Equation (4), but here user access to the network is optional.

$$\Phi^c \leq B \tag{27}$$

Equation (27) restricts the operator's profit to the invested budget. The remaining constraints of the cost minimization model are applied identically.

F. Maximization User admittance under Optical Midhaul Link Constraint Model

1) Objective Function:

$$\text{Maximize} \quad \text{Admittance} = \Bigg(\underbrace{\sum_{u \in UE^{eMBB}} \sum_{r \in RU} \epsilon^{eMBB} x_{(u,r)}}_{\text{eMBB users admittance}} + \underbrace{\sum_{u \in UE^{uRLLC}} \sum_{r \in RU} \epsilon^{uRLLC} x_{(u,r)}}_{\text{uRLLC users admittance}} + \underbrace{\sum_{u \in UE^{mMTC}} \sum_{r \in RU} \epsilon^{mMTC} x_{(u,r)}}_{\text{mMTC users admittance}} \Bigg) \tag{28}$$

Equation (28) maximizes user admissibility in the network by the priority levels assigned to the service. The constraints are the same as those in the profit maximization model; the difference here is that the budget is fixed and defined to be equal to the cost required for deployment obtained from the cost minimization model. In this case, we vary the capacity of the midhaul optical link to observe how it impacts users admissions to the network and the revenue earns.

V. Results and Discussion

The simulations of the previously presented model are performed using the CBC solver implemented in PuLP [7] on a computer equipped with an Intel Core i7 CPU running at 2.7 GHz and 16 GB of RAM. The simulation parameters of the model are summarized in Table IV.

We consider the network topology illustrated in Figure 1, which depicts the considered deployment scenario. We assume an industrial area of $1\,\text{km}^2$, with users distributed over the green field (Salvador, Bahia, Brazil), with a total of 50 users, and we assume the presence of an industrial area in accordance with [5], the distribution of users across services is as follows: 25% eMBB users, 25% uRLLC users, and 50% mMTC users. The level of admission is evaluated using Jain's fairness index, which measures how fairly users are admitted across the three service types (eMBB, uRLLC, and mMTC) [5], as formulated in equation (29).

$$\sigma = \frac{(\sum_{j=1}^{N} AAR_j)^2}{N \sum_{j=1}^{N} AAR_j^2} \tag{29}$$

Where $N = 3$ refers to the number of heterogeneous service types,AAR_j is the average admittance ratio of users of service type j. In our simulations, the fronthaul (FH), midhaul (MH), and backhaul (BH) delays are set to $\Lambda^{FH} = 6\ \mu s$, $\Lambda^{MH} = 10\ \mu s$, and $\Lambda^{BH} = 15\ \mu s$, respectively. Figure 2 illustrates the deployment solution proposed by the model. It can be observed that, out of the 13 available RUs, only 5 are activated. Moreover, among the six candidate sites (CSs), two are selected: CS5 for the deployment of the DU function and CS2 for the deployment of the CU function. We also note that all users are successfully admitted to the network as equation (4) imposes, and the placement of optical links is clearly illustrated as follows: the red link represents the fronthaul connection, the green link between CS5 and CS2 corresponds to the midhaul connection, and the purple link between CS2 and the data center (DC) represents the backhaul link. Figure 3a illustrates the profit earned by the operator as a function of the invested budget, which strongly depends on the operator's service monetization strategy. Figures 3b and 3c illustrate the level of user admission with respect to the available budget and the capacity of the midhaul optical link, respectively. Figure 3b shows that for a budget of $17.5k\$$, which represents 68.3% of the required cost, the operator cannot guarantee network access for all users, as imposed by the constraint in equation (26). In addition, we observe that a lower budget leads to a lower level of user admission. It can also be seen that uRLLC users are admitted in significantly higher proportions compared to users of other services. To analyze Jain's fairness index as a function of the link capacity, three prioritization schemes are defined as follows:

- **Priority 1**: $\epsilon^{eMBB} = \epsilon^{uRLLC} = \epsilon^{mMTC} = \frac{1}{3}$, where all users have the same priority.
- **Priority 2**: $\epsilon^{eMBB} = 0.2$, $\epsilon^{uRLLC} = \epsilon^{mMTC} = 0.4$, where uRLLC and mMTC users are prioritized over eMBB users.
- **Priority 3**: $\epsilon^{eMBB} = 0.8$, $\epsilon^{uRLLC} = \epsilon^{mMTC} = 0.1$, where eMBB users are prioritized over uRLLC and mMTC users.

Figure 3c shows how the choice of optical link capacity affects user admission to the network, while Figure 3d illustrates the revenue generated based on the optical link capacity. These figures also show the impact of the defined priority level on user admission (Figure 3c) and the estimated revenue (Figure 3d) earned by the operator. Our framework enables the model to advise operators on which user services to prioritize, given the available optical capacity, to improve revenue margins.

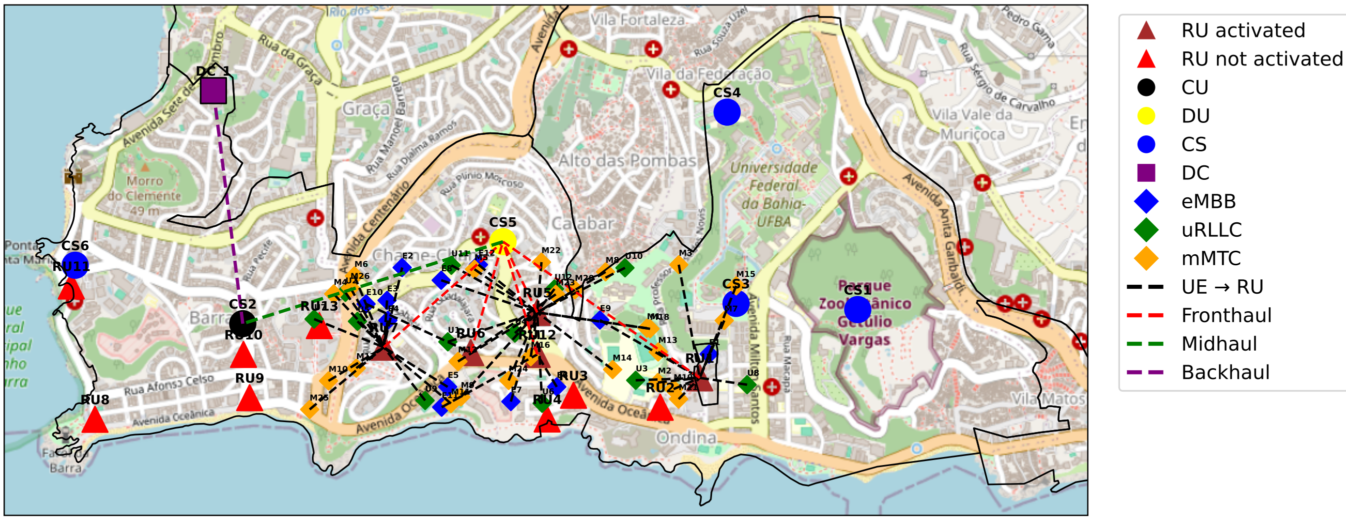
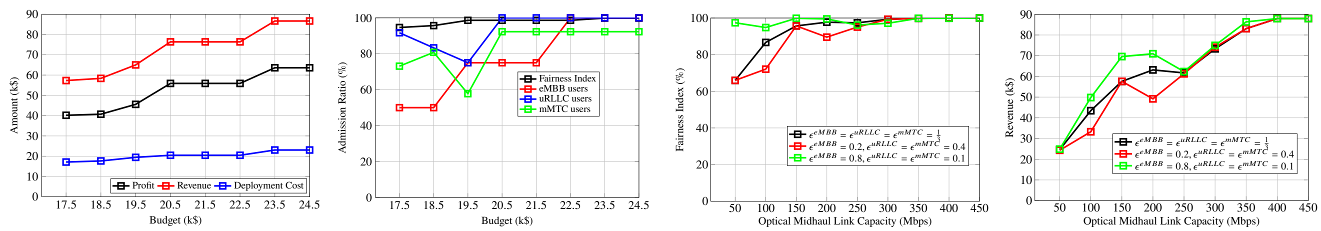


Fig. 2: Deployment Solution, Cost =25630.17\$, Simulation Time ($< 15s$)



(a) (b) (c) (d)

Fig. 3: a): Operator: Profit vs Revenue vs Deployment Cost, b): Fairness Index-based on Budget Investment, c): Fairness Index-Based optical link capacity, d): Revenue Based on Service Priority

VI. Conclusion

In this work, we propose a planning tool that enables operators to design a 5G Open RAN network considering a green-field scenario. The tool allows operators to determine the placement of RAN components while minimizing deployment cost. It further supports gradual network deployment based on the available budget and simultaneously evaluates the resulting operator profit. In addition, the tool enables operators to analyze user admission as a function of budget constraints or optical link capacity, thereby helping them decide which users or services should be prioritized. As future work, we plan to solve larger-scale scenarios with a higher number of users, and to extend the framework to incorporate heuristic approaches to handle increased problem dimensions. Furthermore, we aim to investigate service monetization strategies in order to achieve a balance between affordable services for users and sustainable profits for operators.

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