Automatic Backhaul Planning for 5G Open RAN Networks based on MNO Data

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***Abstract*—The Quality of Service (QoS) requirements for the 5^{th} Generation (5G) services are ambitious and broad, particularly for the latency targets. To cover those, a flexible and cost-efficient Radio Access Network (RAN) is essential as proposed by the Open-RAN (O-RAN) concept. In addition, the deployment of O-RAN 5G networks can be expedited by considering network access, aggregation, and core locations of legacy technologies, where physical requisites as power supply, fiber optic links, and others are already met. With this in mind, this paper extends previous simulation work that proposed a radio network planning algorithm for 5G Millimeter Wave (mmWave) small cells to O-RAN-based networks. The backhaul planning algorithm considers both the 5G/O-RAN QoS constraints, a real 4^{th} Generation (4G) network topology, and the respective Key Performance Indicators (KPIs) from a Mobile Network Operator (MNO) as the foundation to plan an O-RAN compliant backhaul network. Our findings identified that the latency of current networks is greatly determined by the network load. In the utmost case, comparing the network baseline and busy hour KPIs, the baseline planned O-RAN network requires 7%of the equivalent busy hour network nodes. This approach has the potential to help MNOs to outline an enlightened strategy, minimizing Capital Expenditure (CAPEX) and augmenting QoS towards upgrading legacy networks to O-RAN 5G networks.**

***Index Terms*—5G, Open RAN, Cloud Network, Network Planning, KPIs.**

I. Introduction

The 5G of mobile wireless communications has been developed towards accommodating three main service categories: Enhanced Mobile Broadband (eMBB), Massive Machine Type Communications (mMTC), and Ultra-Reliable Low Latency Communications (URLLC) [1]. Consequently, a comprehensive range of QoS requirements has arisen, demanding a flexible, intelligent, and cost-efficient network architecture [2].

In the 5G RAN, also named Next Generation - RAN (NG-RAN), the concept of Cloud Radio Access Network (C-RAN) was soon identified as one of the key 5G enablers, as it provides some of the foundations to improve network efficiency [3]. By considering other technological trends as Software Defined Network (SDN) and Network Function Virtualization (NFV), a new concept, the Virtual Radio Access Network (V-RAN), emerged. It increases the scalability and flexibility of RANs due to being programmable, adaptable, and centrally managed, allowing the network to deliver higher QoS in a cost-effective architecture [4]. Then, forwarding the V-RAN concept, the O-RAN embodies two more fundamental pillars for RANs: openness and intelligence [5].

This work exploits a front and backhauling planning algorithm for 5G networks under an O-RAN architecture. It further exploits network access, aggregation, and core locations from real MNOs (*e.g.,* from a Long Term Evolution (LTE) network) as candidate locations to deploy a 5G O-RAN network considering its constituting elements: O-RAN Radio Unit (O-RU), O-RAN Distributed Unit (O-DU), and O-RAN Central Unit (O-CU). From the candidate locations, the methodology strives to identify the minimum set of locations to implement an O-RAN architecture, constrained to the 5G QoS requirements. This work extends previous simulation work, developed for planning 5G mmWave small cell networks [6].

For 5G RAN planning, some work has been proposed as in [7], where the authors focus on a Serving Gateway (S-GW) Controller Placement Problem (CPP) with latency constraints and balancing controller load and handover frequency in a 5G V-RAN; the CPP was formulated using Mixed Integer Linear Programming (MILP). In [8], the authors proposed a new optimization approach for the deployment of distributed controllers in V-RAN architectures taking into account bandwidth and delay bounds. A Simulated Annealing (SA) algorithm was used to identify candidate controller locations before evaluating if the respective QoS constraints were complied. Also, in [9], the authors studied the CPP considering response time constraints with MILP and Integer Linear Programming (ILP) formulations in wired link architectures. For architectures with wireless links between the controllers and their controlled elements, the authors resorted to Chance Constrained Stochastic Programming (CCSP).

This paper focus on applying a backhauling planning algorithm to solve the CPP of the O-RAN elements for an O-RAN based 5G network. The CPP is limited to the existing infrastructure of a live LTE network; therefore, a simulation of the transition from a legacy network to a O-RAN 5G network is obtained and discussed.

The paper is organized as follows: in Section II, an overview of the O-RAN concept is presented; Section III highlights the O-RAN planning methodology; Section IV presents a real scenario where the proposed methodology is applied. Finally, conclusions are drawn in Section V.

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II. Open RAN

The main goal of the O-RAN concept is to evolve RANs by introducing open interfaces and more intelligence than in previous generations. Real-time analytics that drives embedded Machine Learning (ML) systems and Artificial Intelligence (AI) backend modules will empower network intelligence [10]. Additional virtualized network elements with open and standardized interfaces overcome the limitations imposed by proprietary radio systems. Moreover, the RAN infrastructure, which accounts for the highest share of an operator's CAPEX, remains locked into proprietary hardware and software, limiting the MNOs flexibility in network deployments.

A. Overview

The O-RAN architecture provides an open standard interface that ensures operators can deploy Base Band Units (BBUs) and Remote Radio Units (RRUs) hardware from different vendors to build a best-of-breed multi-vendor network. Technologies as V-RAN and C-RAN are helping to implement more cost-effective options but do not eliminate the vendor lock-in. The proprietary nature of the Common Public Radio Interface (CPRI) interface is among the factors that continue to keep the virtualization of RAN relatively slow compared to other mobile network domains (*e.g.,* core network). The lack of an alternative to the proprietary CPRI is a significant roadblock to C-RAN adoption. As a result, establishing open Radio Frequency (RF) interfaces were identified as a critical requirement by MNOs to maximize the benefits of virtualization and cloud deployments.

Another major problem about the typical RAN, C-RAN, or V-RAN is that all hardware and software are proprietary, and MNOs can not use RRUs and BBUs from different vendors. The CPRI, for instance, is a vendor-specific protocol, reserving time slots for the transmission of vendor-specific data, which allows manufacturers to customize their solutions but hinders interoperability. Moreover, new features developed in the proprietary RAN world are slow and time-consuming [11].

Creating an open and standardized interface and decoupling RAN hardware from software allows scalability, cost-effective and flexible deployments, and choice for MNOs by decoupling selection and deployment of hardware infrastructure from software selection, regardless of the vendor. With open architectures, MNOs can open their RAN to collaborate with independent software developers to build new RAN features that augment RAN capabilities or enable the deployment of new services and applications [12].

B. Cloud Architecture

The NG-RAN introduces new terminology, new interfaces, and new functional modules consisting of a set of Base Stations (BSs) (known as Next Generation NodeBs (gNBs)) connected to the 5G Core (5GC) network and each other. The gNB incorporates three main functional modules: the Central Unit (CU), the Distributed Unit (DU), and the Remote Unit (RU), which can be deployed in multiple combinations. Similarly, O-RAN has an identical architecture, as can be seen in Fig. 1.

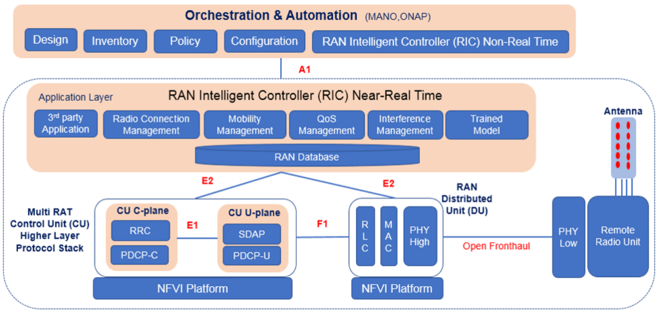

Fig. 1. O-RAN architecture.

The CU has Multi-Radio Access Technology (RAT) and higher layer protocol stack functionalities, along with non and near real-time functions with user and control planes splitting. The DU has lower-layer protocol stack functionalities and can have non and near real-time functions to reduce services latency. The RU has the lower layer protocol stack functionalities in the absence of a DU, or just physical layer and radio functionalities. In cloud architectures, O-RAN defines three locations, Edge Cloud (EC), Regional Cloud (RC) and Core Cloud (CC), where the processing power needed in each cloud type is what distinguishes them [13]:

- **Edge Cloud (EC)** - location supporting virtualized RAN functions or Multi-Access Edge Computing (MEC) and providing centralization of functions for multiple cell sites.
- **Regional Cloud (RC)** - location that supports virtualized RAN functions for many cell sites in multiple ECs, and provides high centralization of functionality.
- **Core Cloud (CC)** - location that supports virtualized RAN functions for many ECs in multiple RCs, and provides functionalities with low latency requirements to the end-user.

The three O-RAN locations can be associated with the three 5G use cases. The mMTC services, with the lowest capacity and latency requirements (15 ms), can be deployed in CCs sites. The eMBB services with a higher capacity requirement can be located in RCs sites (with a maximum latency of 4 ms), and the URLLC services with the highest latency requirements (1 ms) can be located in the ECs sites, near the end-users [13].

Considering the main gNB modules and the O-RAN cloud architecture, the RU is designated, under the O-RAN terminology, by O-RU being located at the cell site. The DU is designated by O-DU and located at the EC. Finally, the CU is designated as O-CU and located in the CC, RC, and EC for the 5G services mMTC, eMBB, and URLLC, respectively.

In such an architecture, an MNO is faced with the challenge to identify optimal locations to deploy the CCs, RCs, and ECs, according to the associated 5G service requirements and existing legacy network. By reusing existent network locations, an MNO can initiate a network upgrade in a fast and cost-effective process.

III. O-RAN Backhaul Planning

In this section, the main aspects of the backhaul planning algorithm (initially proposed in [6]) are presented within the scope of the O-RAN network planning.

The backhaul planning algorithm was used to define the placement of CCs, RCs, and ECs, considering a tree-like topology. As seen, these relate to the appropriate O-CUs locations for the respective services. In [6], the tree, star, and mesh topologies were compared, in simulation scenarios, considering the minimum number of gateways to satisfy a given set of QoS constraints. The mesh topology attained the best performance, followed by the tree topology with similar performance. Considering that the tree topology has a higher ability to scale for networks with a higher number of nodes, as a real MNO network, it was chosen for the O-RAN CPP. The tree topology allows dividing (logically) the network into clusters where each cluster has a gateway (O-CU) serving multiple nodes (O-RUs).

A. Problem Definition

The backhaul planning algorithm, extended to O-RAN architectures proposed in this work, has two essential inputs. The first input is a digraph that represents the entire network. The nodes of the digraph constitute all the O-RUs, and possible O-CU locations, while the edges account for the links between them. Using real data from a legacy network, each node and each link are further characterized by a maximum traffic capacity. Then, the actual network traffic volumes and respective latency are derived from the network KPIs (detailed in Section IV-A). The second input is the minimum service requirements; these serve as QoS constraints, which translate into capacity and latency targets that must be met for each O-RU. The backhaul planning algorithm will solve the O-CU placement problem, which essentially consists of choosing optimal O-CU nodes and splitting the network into a minimum number of disjoint clusters that include all O-RUs and satisfy their requirements.

Resorting to an example presented in Fig. 2, the capacity and latency restrictions imposed on the network planning are explained. In Fig. 2, the O-CU nodes are colored blue, and the O-RU nodes are colored white. Table I shows the QoS requirements for each of the O-RU nodes portrayed in the example.

For the sake of simplicity, within this example, the maximum achievable throughput of all the links is 1000 Mbps, and the latency considers only the delay introduced by each hop (0.4 seconds).

Fig. 2 (a) depicts a network where the O-CU supports only node A. Node A has a capacity requirement of 388 Mbps, which means that, from the 1000 Mbps available throughput of the link, node A will consume 388 Mbps, thus ensuring its capacity requirement. This results in a cluster with 612 Mbps (1000 Mbps - 388 Mbps) available capacity for any O-RU node that later wants to connect to node A. The latency

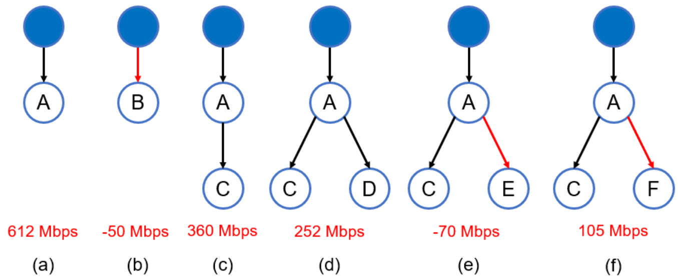

Fig. 2. Example of the constraints for tree topologies.

TABLE I
QoS NODES REQUIREMENTS.

Node	Capacity Req. [Mbps]	Latency Req. [s]
A	388	0.5
B	1050	0.6
C	252	0.9
D	108	1.5
E	430	2.4
F	255	0.7

requirement is also met. There is only one hop between the O-CU and node A, introducing a delay lower than 0.5 s. Fig. 2 (b) depicts a network with the same features as the previous case, apart from the capacity requirement of the O-RU node, node B. Since this value exceeds the available link throughput, node B is unable to connect to the O-CU, even though its delay requirement is met.

Fig. 2 (c) depicts a network where the O-CU supports two nodes. Since node C requires 252 Mbps, which is lower than 612 Mbps, its capacity requirement is met if it connects to node A. Furthermore, there are two hops between the O-CU and node B, which results in a delay of 0.8 s. Since this is lower than the latency requirement of node C, it can be added to the cluster. With two nodes being served by the O-CU, the newly available capacity decreases to 360 Mbps (1000 Mbps - 388 Mbps - 252 Mbps).

Fig. 2 (d), Fig. 2 (e), and Fig. 2 (f) depict networks where the O-CU supports a third node, in addition to nodes A and C. To be added to the cluster, the new node must have a capacity requirement lower than 360 Mbps and allow a delay of at least 0.8 s. Seeing as node D is at two hops distance from the O-CU, it satisfies both these criteria, as shown in Fig. 2 (d). Fig. 2 (f) depicts a scenario where the cluster's overall available capacity cannot support the capacity requirement of node E due to the bottleneck of the first connection. The opposite occurs in Fig. 2 (g). Given that node F requires 255 Mbps, it meets the capacity criteria but fails the latency. Node F only allows latency values up to 0.7 s, which is not possible to guarantee at two hops distance from the O-CU. Consequently, neither can be added to the cluster, as shown in Fig. 2 (e) and Fig. 2 (f).

B. Algorithm Description

The algorithm performs recursive calls with the allowed number of hops, increasing with each iteration. The first iteration consists of placing O-CUs to support the network allowing only one hop. A greedy approach was used, where the nodes with the most connections are prioritized to become O-CUs, as they are likely to cover more O-RUs. The O-CU node and its direct neighbors become a cluster. This process is repeated until all nodes are included in a cluster. The pseudocode of the O-RAN backhaul planning is presented in Algorithm 1, where D is the network digraph representing all the nodes and connections, V is the set of nodes, i is the iteration index, and $\max_{hops}$ is the allowed number of hops.

Algorithm 1 Recursive_Clusters $(D, V, i, \max_{hops})$

```
U ← V
C ← []
if first iteration then
    D = Remove_Unfeasible_Edges(D)
end if
while U ≠ [] do
    v = Greedy_Selection(D)
    C ← C ∪ v
    U ← U − v
    for each N ∈ Neighbors(v) do
        if first iteration then
            S′ = v ∪ N
            cluster_temp = Build_Cluster(v, S′, D)
            if Satisfy_Requirements (cluster_temp) then
                U ← U − N
            end if
        else
            S′ = Cluster_v ∪ Cluster_N
            cluster_temp = Build_Cluster(v, S′, D)
            if Satisfy_Requirements (cluster_temp) then
                U ← U − N
            end if
        end if
    end for
end while
D = Create_Digraph(C)
if i + 1 > max_hops then return D
else return Recursive_Clusters (D, V, i + 1, max_hops)
end if
```

The following iterations consist of merging the existing clusters to reduce the number of gateways (O-CUs) if possible. With each iteration, the allowed number of hops increases by 1. For a merge between two clusters to occur, the O-CU of the cluster with the most served nodes must support the nodes of the second cluster and his own. Thus, the nodes of both clusters must have their QoS requirements ensured, and the distance to the gateway cannot exceed the maximum hop distance for that iteration for any of the nodes. A validation procedure, according to the rules described in Fig. 2, is performed on each node (of both clusters) to determine if a merge is possible. The backhaul planning algorithm will have as many iterations as the maximum number of hops allowed. The result of one iteration will serve as input for the next.

To better comprehend the algorithm, Fig. 3 and Fig. 4 will be used to illustrate the algorithm. Considering a random layout of 93 nodes, the goal is to split the network into a minimum number of disjoint clusters subject to the QoS constraints discussed above and an upper bound of 5 on the allowed number of hops. Fig. 3 shows the initial digraph, D, with all connections.

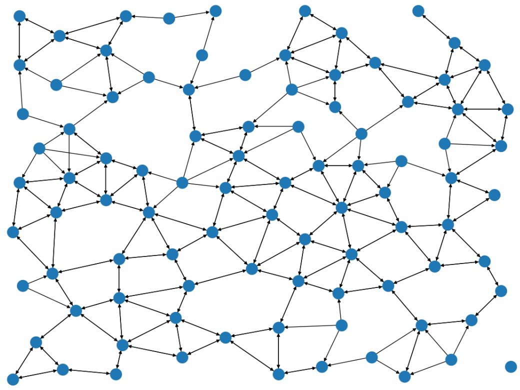

Fig. 3. Initial digraph with feasible connections.

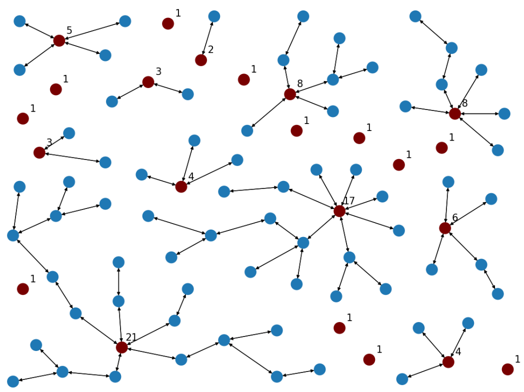

Fig. 4. Resulting clusters of the last iteration. 23 Clusters, Number of hops = 5.

Having D as an input, the recursive portion of the algorithm begins with the first iteration. In this example, the algorithm terminates at the fifth iteration, as it is the maximum number of allowed hops. Fig. 4 shows the final result, depicting a total of 23 clusters.

The index at each O-CU node, which are colored in red, represents the degree of each node, and the O-RUs are colored in blue.

IV. Network O-RAN Backhaul Planning

In this section, data from a live LTE network was considered, including data from the network sites (access, aggregation, and core) and from the transmission network. The goal is to apply the O-RAN backhaul planning algorithm from a digraph based on the existing network, planning a 5G O-RAN network; the digraph nodes represents the whole network sites and the edges represent the respective transmission network. Furthermore, KPIs from a set of network access sites are used to measure network traffic loads and latency. With this data, the O-RAN backhaul planning algorithm evaluates if the O-RAN CCs, RCs, and the ECs can meet the associated latency requirements. More than 4000 network sites were considered, and a sample of traffic KPIs from 103 access sites was used.

A. Network Traffic

The traffic KPIs were measured only on a subset of the network nodes. However, the backhaul planning algorithm requires a complete description of the nodes' traffic. Thus, for the unmeasured nodes, a traffic generator algorithm was used to extrapolate the traffic values from the nodes with traffic KPIs [14]. The traffic generator considers the cell density, the cell environment type (*e.g.,* urban), the transmission type (*e.g.,* microwave or fiber optic), and the RAT to extrapolate the traffic volume of each missing node.

Having all access nodes with real and extrapolated KPIs, the respective traffic is flooded to the higher tier nodes until the traffic is propagated through all network nodes. With the data volume and connections bandwidths, the latency is estimated in each connection, which will be compared with the required latency for each O-RAN cloud type. The network traffic is evaluated both at baseline (late-night period) and busy hour. The results are summarized in Table II.

TABLE II
NETWORK VOLUME AND LATENCY VALUES.

	Mean	Median	Max
Baseline Hour			
Volume [Mbps]	0.38	0.07	58.07
Latency [ms]	0.24	0.06	16.60
Busy hour			
Volume [Mbps]	5.12	1.26	874.31
Latency [ms]	4.45	0.89	218.28

As expected, the busy hour has much more data volume and consequently higher latency than the baseline hour. These two load levels will be used in the next section to evaluate how the O-RAN backhaul planning is conditioned by the latency associated with different network load levels.

B. O-RAN Backhaul Planning

Initially, the O-RAN backhaul network planning algorithm was applied to an urban area before being applied to the complete network. The tested area for the network busy hour load is presented in Fig. 5, alongside the planned CCs, RCs, and ECs pictured as purple, red, and dark green circles after applying the O-RAN backhaul network planning algorithm.

The two blue symbols, with a marker, are the live core nodes containing data centers that provide service to the nodes in this urban area. As latency requirements were not so tight in (legacy) generations before 5G, the need for processing capacity close to the access nodes was less, and consequently, it was possible to centralize it in fewer locations.

The algorithm's results provide a complete picture of the cloud node density required to fulfill the high latency requirements in 5G and O-RAN networks. With that, MNOs can evaluate which nodes should be prioritized for being updated/upgraded towards a cost-effective network investment strategy. Moreover, connections and congestion zones can be identified where an upgrade may be required to meet latency requirements. An example, considering an aggregation node that connects five access nodes, and one of them is set both as RC and EC, it is concluded that from that access node to its aggregation node, the latency is higher than 1 and 4 ms but lower than 15 ms. With a connection upgrade, the latency requirements can be fulfilled, and that access node will no longer be set as both RC and EC.

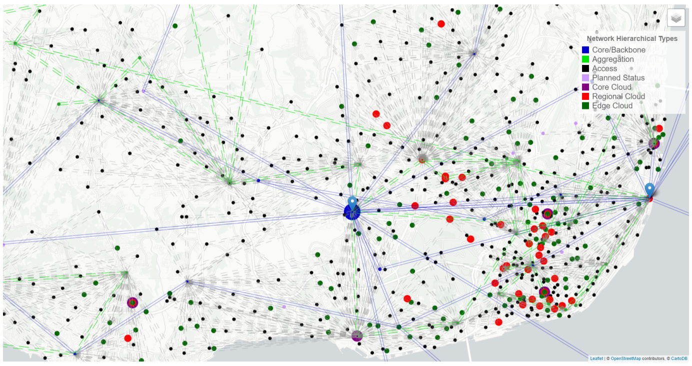

Fig. 5. O-RAN network planning in an urban area for busy hour traffic load.

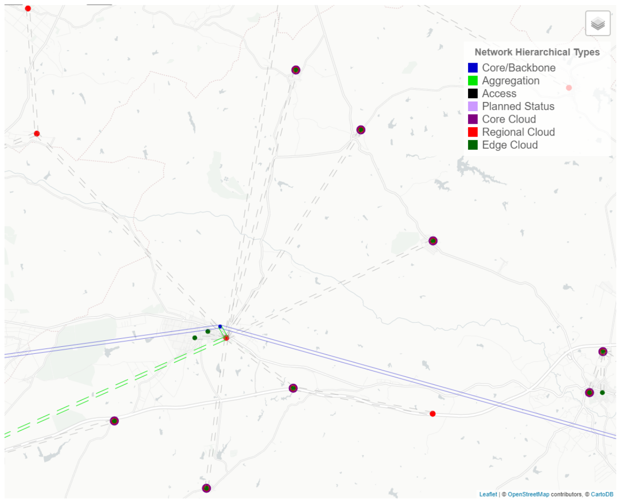

Fig. 6. O-RAN network planning in a rural area for busy hour traffic load.

After using the O-RAN backhaul planning algorithm with the complete network, the previous example is verified when comparing the required nodes of the same rural area between the busy hour and the baseline hour traffic loads, Fig. 6 and Fig. 7, respectively.

In Fig. 6, the access nodes that connect to the aggregation node (centralized one with a green connection), on the one hand, are often jointly set as CCs, RCs and ECs as they do not meet the latency requirements, so the observed latency is higher than 15 ms. On the other hand, in Fig. 7, the same nodes are not set as any type of cloud as in the baseline hour the latencies meet the requirements (due to lower traffic). The analysis of the planned nodes with the busy hour traffic load allows identifying connections that need to be upgraded so that the network can embrace 5G.

The overall results of the O-RAN backhaul planning algorithm for the whole network are presented in Table III.

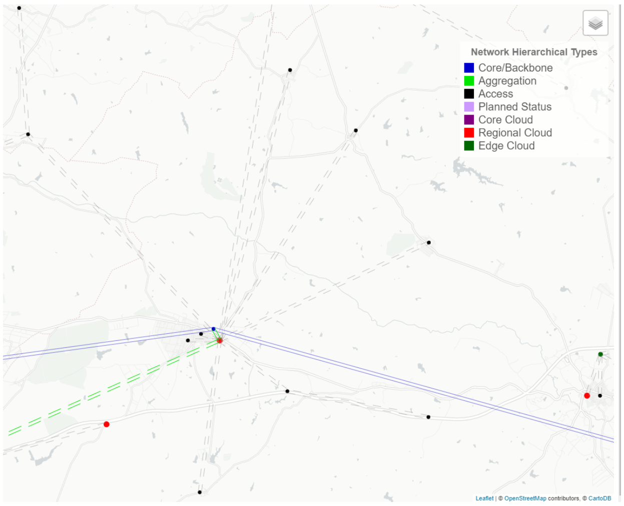

Fig. 7. O-RAN network planning in a rural area for baseline hour traffic load.

TABLE III
NODES NUMBER PER CLOUD TYPE IN BASELINE AND BUSY HOURS.

	Nodes Number	Max Hops
Baseline Hour		
Core Cloud	38	9
Regional Cloud	81	10
Edge Cloud	237	8
Busy Hour		
Core Cloud	699	8
Regional Cloud	1562	6
Edge Cloud	2313	5

In fact, for the baseline hour, the number of planned clouds is much lower than in busy hours. Hence, MNOs can save investment in processing capacity when upgrading the transport connections accordingly.

V. CONCLUSIONS

This paper presents an O-RAN backhaul planning algorithm applied to a live LTE network. The impact of the network load on the network latency significantly affects the number of planned clouds for an O-RAN network. The network conditions in the baseline hour would require, on average, 7% of total planned nodes for the busy hour conditions to satisfy the 5G latency requirements. Additionally, the busy hour traffic load ensures the network planning for the more stringent requirements, while the algorithm can also be used to identify bottlenecks in the transmission network by evaluating the locations density/overlap proposed for CCs, RCs, and ECs, respectively.

This study was focused on the latency requirements for the 5G services using network KPIs from a live LTE network. Despite that, two valuable conclusions are obtained: on the one side, a lower bound on the number of clouds nodes for a 5G O-RAN network upgrade is set; on the other side, the current transmission/node latency bottlenecks will be even harsh considering the anticipated 5G load. Hence, these locations are crucial to achieving the required 5G network QoS.

Overall, this work supports MNOs to anticipate an optimized and gradual deployment strategy for an O-RAN 5G network, considering the current legacy network performance and topology.

Research is underway to adjust the generated traffic by legacy networks to the expect load and distribution of 5G services in order to plan the O-RAN network accordingly to the future networks requirements and expected demand.

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