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Minimum Cost Deployment of Radio and Transport Resources in Centralized Radio Architectures

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***Abstract*—The traffic in mobile access networks is increasing at an exponential rate, with the majority of this traffic being generated indoor. To cope with this trend, heterogeneous network (HetNet) architectures based on the centralized radio architecture (CRA) concept have been recently proposed. A CRA network is able to reach high wireless network performance by centralizing the radio physical layer functions of macro and small cells. On the other hand, a CRA network puts strict latency and capacity requirements on the transport segment, which usually comprises a mixture of fiber- and copper- based infrastructure. These strict constraints may translate into high deployment costs if not carefully addressed. This paper proposes an optimized deployment strategy for CRA networks in residential areas. The objective of the proposed strategy is to contain the total deployment cost by minimizing the number of wireless and transport resources required. We demonstrate that our deployment strategy allows for a significant reduction of the required amount of network components and the overall network cost compared to the existing deployment solutions.**

I. Introduction

The growing demand for broadband connectivity together with an ever increasing number of new services is triggering an exponential growth of traffic in mobile networks. Data traffic is expected to reach 24.3 Exabytes/month by 2019, i.e., an almost tenfold increase with respect to 2014 [1], with 70% of this traffic originating from indoor users [2], [3]. To keep up with this trend mobile networks need to evolve to support higher capacities. Macro densification, i.e., increasing the number of macro base station (BS) sites and reducing the inter-site distances, is one of the possible ways to provide more capacity. However, this approach is expensive due to the high cost of purchasing and installing new macro sites. In addition, it is power-inefficient in serving indoor users because of the high attenuation experienced by the radio signal when penetrating walls [4].

Heterogeneous network (HetNet) deployments represent an alternative to macro densification. HetNets are based on the roll out of a low-cost and low-power layer of small cells in addition to the macro BS layer. More specifically, indoor small cells can be used to create hot-spots that provide indoor users with high capacity in a cost- and energy-efficient way, while the macro BS layer guarantees the required coverage. Conventional indoor small cells are user-deployed and are connected to the operator core network through a fixed broadband infrastructure [4]. However, small cells have no ability to coordinate amongst themselves or with the macro BSs. As a result, the overall mobile network performance is degraded because of the high interference levels among neighboring cells and between small cells and other macro BSs.

One way to improve the performance of HetNets is to use a centralized radio architecture (CRA) [2]. According to the CRA concept some of the BS physical layer radio functionalities (e.g., baseband processing) can be decoupled from the BS site and aggregated in selected locations interconnected by the transport network infrastructure, i.e., using radio over fiber/copper transmission techniques. This architecture allows for better coordination among the BSs and leads to an overall improved wireless network performance. On the other hand, the centralization of the radio physical layer functions introduces strict latency and capacity requirements on the transport network. Thus, efficient CRA deployment strategies become extremely important for minimizing the overall network cost and making the CRA concept attractive for mobile operators.

Several works have been published on the CRA topic recently, primarily focusing on proving the feasibility of the CRA concept and on evaluating the transmission performance of radio over fiber/copper techniques. The work in [2] presents a proof of concept of a new indoor coverage solution based on CRA. Studies in [5], [6] show the radio performance benefits of enabling small cell coordination. However, to the best of our knowledge, optimized deployment strategies for a CRA network that consider both placement of radio and transport resources have never been investigated before.

In this paper, we address the deployment cost minimization for CRA networks in a residential scenario. We formulate the problem of placing the minimum number of radio and transport network resources required to cover a dense residential area as an integer linear program (ILP) and compare the obtained number of network components as well as the network cost with the theoretical lower bound and a non-optimized deployment strategy taken from the literature [2]. Our results show that our strategy significantly reduces the number of components and the operational cost of the network compared to [2].

II. Centralized Radio Architecture

A Centralized Radio Architecture (CRA) is composed of three main blocks: the *indoor antennas*, the *remote radio units (RRUs)*, and the *baseband units (BBUs)*. An example of a CRA architecture is depicted in Fig. 1.

Antennas are ultra compact, equipped with a small power amplifier, and they provide high-capacity wireless access to a relatively large indoor area (i.e., 500 to 800 m^2). The antennas are connected to RRUs, which perform analog signal processing of the radio signal. One RRU can be connected to at most k antennas. RRU communicates with the antennas via analog transmission over a standard copper cable (e.g., Ethernet cable Cat 5/6/7). This enables to reuse the existing copper infrastructure inside a building. However, copper cables are subject to high attenuation imposing a limitation on the maximum length of the links between the antennas and the RRU (i.e., a few tens of meters depending on the category of the copper cable).

RRUs are connected to BBUs in charge of performing the digital baseband processing, which includes interference management and cells coordination. The transport segment connecting a RRU and a BBU is called *fronthaul*. The fronthaul data are transmitted using either analogue or digital radio over fiber technology (i.e., A-RoF, or D-RoF, respectively). The latter is the most popular choice and is based on a standard radio interface referred to as common public radio interface (CPRI). A D-RoF transmission with CPRI poses strict latency and capacity constraints on the fronthaul segment. In terms of capacity, CPRI requires a constant bit-rate of several Gb/s on the fronthaul link [9], so that usually a dedicated fiber connection is required between the RRU and the BBU. The latency requirement, on the other hand, comes from the radio physical layer functions. More specifically, the hybrid automatic repeat request (HARQ) mechanism in long term evolution (LTE) networks has a constraint on the maximum round trip time that in turn can be translated into a maximum signal propagation delay over a RRU-BBU link [7], [8]. Considering the speed of light in an optical fiber, this round trip constraint can be transformed into a maximum length of around 20 km [8].

Multiple BBUs can be aggregated in a single BBU Hotel, usually located in a central office (CO). A BBU Hotel normally serves a large number of RRUs and macro BSs by exploiting the pooled baseband resources, so that a single BBU Hotel may cover an entire residential area, i.e., a concept referred to as centralized radio access network (C-RAN). In a BBU Hotel, it is possible to share BBU resources among RRUs and macro BSs in order to achieve better radio performance and to reduce the number of sites that an operator needs. In addition, having all BBUs in the same site allows for sharing power supply, cooling, and interconnection network equipment. For this reason

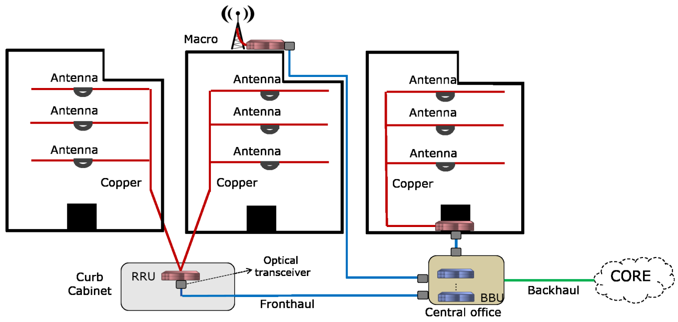

Fig. 1. The Centralized Radio Architecture (CRA) concept.

the CRA concept is a feasible way to reduce both capital and operational expenditure of mobile operators. However, increasing the distance between BBUs and RRUs leads to a higher amount of fiber cables required in the fronthaul network, which may translate into higher deployment costs for the transport network.

Finally, we consider that the last segment of the network that connects BBU with the core network is a packet-based traditional backhaul.

III. RRU Placement for Minimum-Cost Network Deployment

A crucial step towards deploying a cost-efficient CRA network is finding an RRU placement which provides the coverage at the minimum cost. In this section we describe and mathematically formulate the RRU placement problem as an ILP.

A. Problem Description

In this paper, we study the optimal CRA deployment in a residential area where we assume a greenfield scenario with no existing network infrastructure other than the copper inside the buildings. Fig. 2 presents a view from the top of the residential area under consideration. The grey squares represent the buildings. We assume that one or more indoor antennas are placed in each floor of every building to provide broadband wireless access to the indoor users. Depending on the distance limitations of the copper links between antennas and RRUs, the RRUs can be placed either inside buildings or in curb cabinets located nearby. The green squares in Fig. 2 represent all the possible RRU locations. When inside a building, RRUs are placed at the entrance, where they can be connected to the in-building copper infrastructure. In this case an RRU can be connected only with antennas located in the same building. On the other hand, the squares outside the buildings represent the curb cabinet locations. An RRU placed in a curb cabinet can be connected to antennas in different buildings (provided that their distance is within the maximum length allowed for the copper link). We assume that macro BSs are placed on the top of some of the buildings to provide coverage to the residential area and serve the outdoor users. Moreover, a CO owned by the mobile operator is present in the area. We assume that all BBUs are placed in the CO and serve the whole residential area (i.e., all RRUs and macro BSs). This is possible by assuming that the

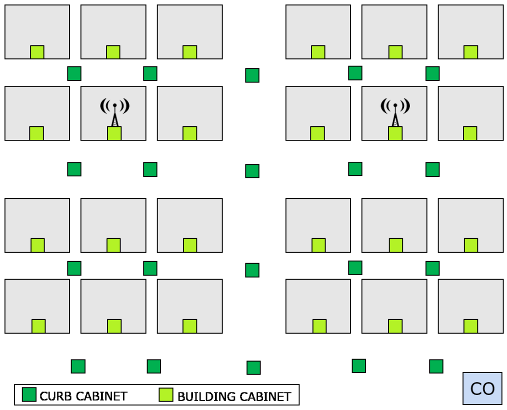

Fig. 2. Example of an urban scenario considered in the study.

maximum distance between RRUs, macro BSs, and the CO is lower than the maximum reach of a fronthaul link (i.e., 20 km), which is the typical case in an urban scenario.

In order to calculate the length of fiber/copper, we consider the distance between two points as the sum of the distances in each of the three spatial dimensions. For example, given a 3D space and two points (x_1, y_1, z_1) and (x_2, y_2, z_2), the length of fiber/copper d needed to connect these two points is computed as follows:

$$d = |x_1 - x_2| + |y_1 - y_2| + |z_1 - z_2| \tag{1}$$

The distance between an antenna and a RRU located inside a building, matching the length of the link between them, is obtained using (1). The distance between an antenna and an RRU located in a curb cabinet is computed as the sum of the distance between the antenna and the entrance of the building and the distance between the entrance of the building and the curb cabinet, both computed using (1).

In the scenario described above it becomes clear how different RRUs placements translate into *(i)* different total length of copper and fiber cables to be deployed, *(ii)* different amount of network equipment to buy/operate (i.e., total number of RRU and BBU units in the network), and *(iii)* different number of locations to activate and manage (i.e., the total number of RRU sites). In other words, the RRU placement directly impacts the overall network cost. In this paper, we propose a RRU placement strategy with the objective of minimizing both the number of locations to activate and the amount of equipment required to operate the network. To solve this deployment problem, an integer linear programming (ILP) formulation is derived, whose details are described in the next section.

B. ILP Formulation for the Optimal RRU Placement

The RRU placement problem consists in placing the minimum number of RRUs in the network in the fewest possible distinct locations. The solution must guarantee that each antenna is connected to one RRU, while making sure that the distance between the RRU and the antenna it is covering does not exceed the maximum reach of the analog transmission over copper. The mathematical formulation of the RRU placement problem is given below.

<u>*Notation:*</u>

- R: set of possible RRU locations; each location can host 1 or more RRUs.
- A: set of antenna locations.
- D: maximum allowable distance between an RRU and an antenna.
- d_{ij} : distance between a candidate RRU location $i \in R$ and an antenna location $j \in A$.

<u>*Input parameters:*</u>

- $C[i \times j]$: coverage matrix, where $C[i, j] = 1$ if an RRU placed at location $i \in R$ can cover an antenna at location $j \in A$, i.e., if $d_{ij} \leq D$, 0 otherwise.
- $M \in \mathbb{N}$: a large number.
- $\alpha, \beta \in \mathbb{N}$: tuning parameters.
- $k \in \mathbb{N}$: maximum number of antennas that can be connected to an RRU.

<u>*Decision variables:*</u>

- $m_{ij} \in \{0, 1\}$ = 1 if an RRU placed at location $i \in R$ is covering the antenna at location $j \in A$; 0 otherwise.
- $r_i \in \mathbb{N}$ = the number of RRUs placed at location $i \in R$.
- $z_i \in \{0, 1\}$ = 1 if at least one RRU is placed at location $i \in R$; 0 otherwise.

The RRU placement problem is formulated as follows:

$$Minimize \quad \alpha \cdot \sum_{i \in R} r_i + \beta \cdot \sum_{i \in R} z_i \tag{2}$$

Under the following constraints:

$$\sum_{i \in R} C_{ij} m_{ij} = 1, \forall j \in A \tag{3}$$

$$k \cdot r_i \geq \sum_{j \in A} C_{ij} m_{ij}, \forall i \in R \tag{4}$$

$$M \cdot z_i \geq r_i, \forall i \in R \tag{5}$$

The goal of the objective function (2) is to minimize the total number of RRUs and the total number of RRU locations. By tuning the values of α, β it is possible to assign different weights to the two members of the objective function. Constraint (3) ensures that each antenna in the network is covered by a RRU within its reach, while constraint (4) ensures that the RRUs placed at location i cover all antennas which are assigned to that location. Finally, constraint (5) models the deployment of RRUs at location i.

IV. CASE STUDY

In this Section, we first describe in detail the scenario that we analyzed in our simulations and then we present the obtained numerical results.

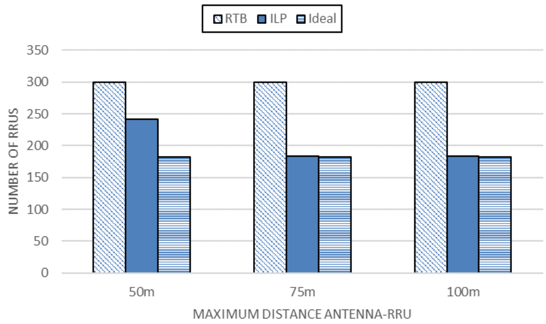

Fig. 3. Number of RRUs as a function of the maximum distance between antenna and RRU.

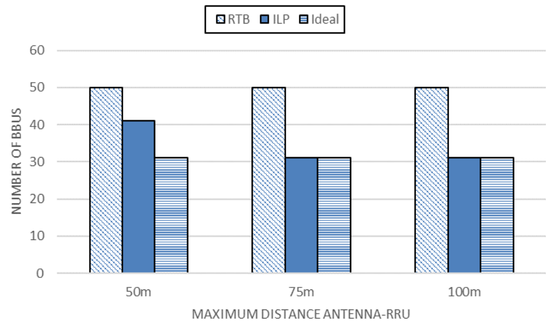

Fig. 4. Number of BBUs as a function of the maximum distance between antenna and RRU.

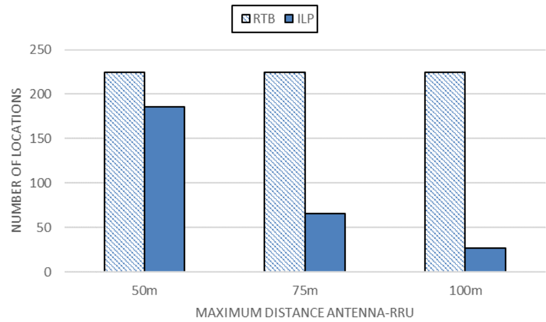

Fig. 5. Number of locations that needs to be activated as a function of the maximum distance between antenna and RRU.

A. Simulation Scenario

The considered scenario is based on a Manhattan street model with buildings arranged in blocks. More specifically, the map is composed of 25 blocks organized in a 5×5 matrix. The horizontal and vertical streets between two blocks are 15 meters wide. A single block is composed of 9 buildings organized in a 3×3 matrix. Between two buildings in a block, there is a 10 meters wide horizontal street and a 5 meters wide vertical street. The total size of the map is 410×475 m^2. Each building is represented by a square with 20 m sides, while the height of each floor is 3 m. The number of floors in each building is a random variable following a discrete uniform distribution over the interval [1,12]. In our case study, we assume that one omnidirectional indoor antenna is sufficient to cover an entire floor and each antenna is placed in the center of the ceiling. Each antenna is connected to a RRU through a Category 6 copper cable and each RRU is connected to a BBU port through a dedicated fiber. Each point-to-point fiber link between a RRU and a BBU requires two small form pluggable optical transceivers plus (SFP+) modules. We assume that two macro BSs are deployed on the top of two buildings in different blocks and are used to serve the outdoor users. All BBUs are placed in the CO that is located in the building in the right bottom corner of the map.

A set of simulations has been performed varying the maximum length of the link that connects RRUs and antennas D. Since the maximum distance over a twisted pair cable in the 1000 BASE-T standard is 100 meters, values for D were set to 50 m, 75 m and 100 m. The values of α and β have been set to 1 and 2, respectively, in order to prioritize minimization of the total number of distinct RRU locations. In all scenarios, k has been considered equal to 8 [2] while the maximum number of RRUs that can be connected to a single BBU has been set to 6 [2].

B. Numerical Results

For each of the scenarios described above, the input data is preprocessed in order to generate the matrix C used in the ILP formulation. The RRU placement problem formulation is then solved using CPLEX v12.4 [10], run on an HP workstation with 8 2.67 GHZ processors and 16 GB RAM. The obtained results are compared with a reference deployment approach referred to as RoF to the building (RTB) [13]. This approach places RRUs at the entrance of the buildings and connects them to the CO directly with a dedicated fiber. In the RTB approach the RRUs are not located in curb cabinets and therefore each RRU covers only the antennas inside the building in which it is located. In addition to the RTB approach, the results of the ILP are also compared to an ideal theoretical value which represents the absolute minimal number of RRUs and BBUs that would be required to cover the area without any limitation on the length of the copper links (i.e., D=∞). For each simulation setting, 10 different configurations of the residential area are considered, with varying number of floors in each building, and the results are averaged over these configurations.

In Figs. 3 and 4 the number of RRUs and BBUs required to serve the area are reported as a function of D. From the figures, it is possible to observe that the number of RRUs and BBUs required to cover the area using our ILP is always lower than that required by the RTB approach. The number of RRUs and BBUs required by the RTB strategy is constant with respect to D, because it depends only on the number of antennas in the building. However, in the case of our ILP approach, the equipment needed decreases with D and reaches the ideal case when D = 75 m. This is due to the fact that higher values of D increase the number of antennas that can be connected to an RRU located in a curb cabinet, which leads to a higher sharing factor and a reduced total number of required RRUs and BBUs. It can also be observed

TABLE I
NORMALIZED COST OF THE NETWORK COMPONENTS [11] [12].

Component	Normalized cost (CU)
SFP+	1
RRU	3.75
BBU	15
Cabinet	2.75
Copper cable (Cat. 6) (km)	1
Fiber cable (MMF) (km)	1

TABLE II
TOTAL LENGTH OF COPPER AND FIBER LINKS.

Algorithm	Copper cable (km)	Fiber cable (km)
ILP 50m	45.1	106.4
ILP 75m	82.0	79.9
ILP 100m	102.3	80.3
RTB	34.9	132.0

from Fig. 3 and 4 that with D = 75 m the proposed ILP approach reduces the required amount of required mobile network equipment by almost 50% compared to RTB.

Fig. 5 shows the number of distinct RRU locations that an operator has to activate to cover the area. Similarly to the previous figures, the number of locations needed in the RTB strategy is constant with respect to D. Conversely, the number of locations needed in the proposed ILP approach decreases significantly with an increasing value of D, and is almost 10 times lower than the RTB result for D = 100 m. As a final note, in the ideal case the number of location is always equal to 1 (not reported in Fig. 5).

To understand how the savings in terms of the number of RRUs, BBUs and curb cabinets translate into cost savings, we assessed the total network equipment cost for each strategy analyzed so far. The cost of each network component is reported in Table I. These costs are normalized with respect to the cost of a SFP+ module, which corresponds to 1 cost unit (CU). The total cost of the fiber and copper cables is obtained by multiplying the per-kilometer cost value reported in Table I with the total length of the fiber and copper links required to serve the area. These latter values have been obtained via simulation and are reported in Table II. Figure 6 presents the total cost for the network equipment obtained with the ILP-based and the RTB deployment approaches. From the figure, it is possible to observe that our proposed approach significantly reduces the cost with respect to the RTB strategy (almost by a factor of 2 for D = 100 m). This is mainly due to reduction in the number of expensive RRU and BBU components needed in the area. On the other hand, the RTB approach is based on a higher use of fiber technology (see Table II), which may ultimately lead to a slightly higher network scalability in case of a significant increase of network traffic over the years.

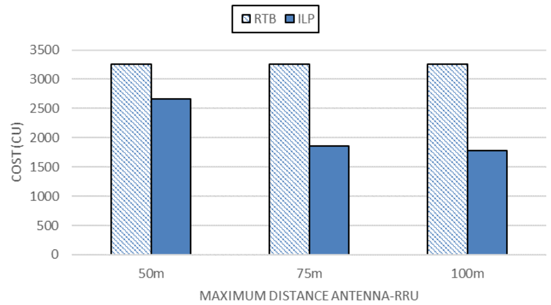

Fig. 6. Total cost of the network as a function of the maximum distance between antenna and RRU.

V. CONCLUSION

We propose a deployment strategy for the mobile networks based on the CRA concept with the aim of the deployment cost minimization. We provide an ILP formulation aimed at minimizing both the number of RRUs and the number of active sites in which RRUs are placed in a residential area. As a result, the overall mobile network deployment cost, which also includes the transport network equipment, is minimized. The proposed strategy is capable of significantly reducing the total network cost with respect to a conventional deployment approach based on RoF to the building. In our future work, we will develop a heuristic algorithm in order to obtain a scalable method to solve the RRU placement problem with the objective of deployment cost minimization in larger deployment scenarios.

VI. ACKNOWLEDGMENTS

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