

Research Article

Optimization Methods for Feasible Deployment Planning of Future Mobile Networks

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Received 28 March 2020; Revised 8 February 2022; Accepted 6 September 2022; Published 26 September 2022

Academic Editor: Laurie Cuthbert

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The exponential growth of mobile traffic requires mobile operators to update their network infrastructure to provide greater capacity and better connections for end-users. A promising alternative is to deploy heterogeneous networks (HetNets) that combine macrocells and small cells; however, this alternative increases the complexity and cost of transport (connections between the small cells and the operator's control center). Most planning strategies outlined in the literature are aimed at reducing the number of small cells without considering important aspects involving transport (access backbone). With the advent of centralized architectures, this point becomes essential, since it is necessary to consider the potential impact of the transport segment on the deployment cost of the network (with the advent of the fronthaul). In this sense, this work proposes an optimal multiobjective model of radio and transport allocation based on linear programming to minimize the total cost of the network and two efficient heuristics to obtain a near-optimal solution. Considering a real case study of the literature, we show the cost (financial and computational) of the optimal placement of radio and transport infrastructure and the limitations of the solution. We also compare the proposed function placement heuristic with the optimal solution in terms of cost efficiency and execution time and demonstrate that it can provide a good estimation of the deployment cost in a much shorter time, with an approximation of up to 10% in relation to the optimal model.

1. Introduction

The growth of data traffic on mobile networks draws attention, mainly because the infrastructure cannot yet adapt to new demands. The increase in the number of connected devices and users and the need to elevate the throughput, to decrease the latency to meet new applications and to improve the quality of service (QoS), are examples of emerging needs.

In its annual review, Cisco [1] reports several points of increased demand for mobile networks; its main indicator is the compound annual growth rate (CAGR), which indicates the annual growth of data traffic, and its value is currently 46%. Following the future projection, in 2022, Cisco

is expected to have 77 exabytes of data per month being transmitted on mobile networks.

With the introduction of increasingly rigorous demands, an evolution in the infrastructure is necessary to supply them. Thus, several emergent solutions/technologies are notable: the increase in the frequency spectrum, carrier aggregation, the use of small cells, multiple input multiple output (MIMO), and the change in the architecture of the network infrastructure.

The use of very high frequencies, expanding the usable spectrum to 100 GHz facilitates the provision of a greater amount of resources for data transmission, ensuring greater data throughput. In [2], the expansion of the frequency spectrum combined with the use of millimeter wave (mmWave)

technology has the potential to generate data transmission rates of up to hundreds of Gbps. However, very specific conditions, such as a small distance between the transmitter and the receiver, in addition to no obstacles between them, are necessary.

Another technology that is aimed at offering a greater amount of bandwidth resources to the end user is carrier aggregation, which can provide more bandwidth for transmission. In [3], the author explains the various modes of carrier aggregation, their specificities and prerequisites for correct operation, such as the reservation of bandwidth to avoid overlap between two aggregated carriers.

The use of small cells to increase the capacity of mobile networks is another alternative that is widely reported in the literature. This alternative presents a cheaper solution (concerning the implantation of macrocells) that can increase the capacity of frequency reuse and bring users closer to their receiving source, resulting in an improvement in the signal, consequently improving the quality of the connection. The joint use of large and small base stations is referred to as heterogeneous networks (HetNets), and the massive densification of small cells is referred to as ultra-dense networks (UDNs): a solution that has not only great gains but also great challenges, mainly related to the management and mitigation of interference [4, 5].

The use of multiple transmit/receive antennas is a technology that is capable of improving the quality of a connection. In long-term evolution (LTE), MIMO is already in use, and certain smartphones, such as Samsung Galaxy S8, Apple iPhone 7, Sony XZ, LG G6, Motorola Moto Z2 Force, and their successors, support 4×4 MIMO and, consequently, obtain a better connection, with higher data transfer rates and quality of the received signal. In [6], a study of MIMO technology (focusing on the 4×4 configuration) was conducted, demonstrating that reaching a rate of 1 Gbps is possible, approaching the target established for 5G networks.

Another widely disseminated proposal is the change in infrastructure architecture. The centralized radio access network (C-RAN) is appointed as the main option for change due to its advantages: centralized management, savings in operation and energy costs, resource sharing, greater control of interference mitigation, and ease of use of technologies that require coordination between two base stations [7]. While in the distributed architecture each base station has its radio and baseband processing equipment, in C-RAN, they are divided into remote radio heads (RRHs) that perform the radio functions and communicate with user equipment (UE) and baseband units (BBUs) with the baseband processing function. These devices are connected by fronthaul, which requires great robustness [8] to guarantee high transmission capacity and low latency even over long distances. For this reason, a high-capacity wired connection such as optical fibers is essential.

In the work carried out in [9], the differences between centralized networks and distributed networks are noted. The use of C-RAN facilitates the management of a network, causing a decrease in operational costs (OPEX). The deployment cost (CAPEX) of these networks intrigues the scientific community, with the cost of the fronthaul

being the main factor of the high cost of the infrastructure [10]. In this sense, some authors work with the hypothesis of using wireless fronthaul [11, 12]; however, its use has several peculiarities that limit its application.

Thus, the implantation planning of C-RAN networks is considered an open problem and difficult to solve, involving several minor factors that, if separately treated, can render its implementation unfeasible. Among these challenges, the densification in HetNets (UDNs), positioning of RRHs dependent on demand, and the location of users are notable, among others. These elements have high dynamics behavior, making the problem of implementing RRHs difficult to computationally (NP-hard) solve, as demonstrated in [13].

This work is aimed at proposing techniques that assist in the process of planning and deploying mobile C-RAN networks, minimizing the deployment cost and maximizing the QoS of users. An optimization model will be presented through mixed integer linear programming (MILP) and two heuristics based on the positioning of users and the cost of transport deployment. MILP will serve as an optimal model for comparing and validating the performance of heuristics. The major contribution of this study is summarized below.

- (i) This paper proposes an optimal multiobjective model of radio and transport allocation based on linear programming to minimize the total cost of a network. In particular, by introducing the cost of a transport network (fiber and trenching cost), the proposed model became a more realistic and practical solution
- (ii) This paper also proposes two efficient heuristics to obtain a near-optimal solution, which is an option that has a lower computational cost
- (iii) The algorithm was compared with other similar approaches from the literature for the sake of comparison and evaluation

The remainder of this document is organized as follows: Section 2 presents some related works concerning the deployment of mobile networks; Section 3 details the applied scenario and the propagation model, as well the parameters used to measure the users' QoS; in Section 4, the optimization models will be presented; in Section 5, the results of the modeling will be discussed; and the results are presented Section 6.

2. Related Works

Several works in the scientific community seek solutions to minimize the cost of implementation generated by the centralized architecture. Some of these solutions will be presented with their gaps, for which this work intends to present a solution.

Due to the assignments of RRHs and BBUs, high-capacity and low-latency links are necessary for the communication of this equipment. In [14], a study is conducted to try to balance the tasks that RRH and BBU perform. Some

services that were originally granted to BBUs can be moved to the RRHs, and in this way, the amount of traffic needed via the fronthaul is reduced; consequently, it becomes less expensive due to the lower need for robustness. These changes help decrease the fronthaul infrastructure cost but do not have a great impact on the final cost because the entire preparation process for fiber passage is still necessary.

In [15], the author uses Voronoi's algorithms and diagrams in his work in an attempt to map and indicate possible cell implantation sites to serve users in a given region. Regarding planning, the algorithm seeks, as much as possible, to ensure that the quality of service is optimized for most users, trying to minimize the number of resources (number of cells implanted) necessary to reach the demands. The main gaps in the proposal are attributed to not using the cost of implementation for decision-making, including disregarding the fronthaul (or backhaul) technology used.

Another work that uses the demand and positioning of users for the composition of possible RRH deployment locations is presented in [16]. In this work, demand requests were collected during three months in a certain area, and according to the observed behavior, the points for implanting RRHs were determined. The main idea is to cover an area that is served only by a macrocell: the map is divided into smaller sectors, creating traffic demand points (TDPs), in which the demands of users close to that location are allocated. After characterization, an RRH is deployed to guarantee the connection. Despite commenting on the importance of using the C-RAN architecture, the paper does not mention the type of fronthaul used in the formulations of the presented technique. The focus is dimensioning of the RRHs needed to cover the encountered demands rather than on more effective planning of the network.

Considering that it is essential to use wired solutions to create a fronthaul with the ideal capacity and that the transport cost holds the highest percentage of the total cost as indicated [17], the positioning planning of RRHs should be concomitantly performed with the cost of fiber passage/trenching, which is referred to as the transport cost. The author in [17, 18] creates an optimization model for the implementation of C-RAN networks, optimizing both the positioning of RRHs and the transport cost. The author's most recent work discusses possible protocols for the fronthaul, showing its advantages/disadvantages and costs, and judiciously models the planning and optimization of the deployment of C-RAN mobile networks. However, the work does not consider any type of propagation and interference model (between two cells) to perform the calculation of the channel capacity, which falls slightly short of reality.

In [8], an optimization model that minimizes the deployment cost of centralized networks, ensuring transmission capacity for certain areas, is created. The modeling is quite complete and considers radio, fiber, and excavation equipment. At work, street orientation is respected so that fronthaul cabling occurs. The work is very interesting, as it considers several elements that bring it closer to reality, including the interference between radio equipment to calculate the quality of a channel. However, there is no individ-

ual modeling about users, and each region has its minimum transmission capacity. Thus, if user is far from the regions served, they will be without communication.

Numerous studies address the deployment of HetNets in C-RAN; however, there are still gaps that this work aims to address: the nonuse of the interference factor that RRHs cause among themselves; the nonindividualization of the QoS calculation for users; the lack of full coverage for users, rendering the 5G's objective of having an omnipresent network uncharacteristic; the nonuse of heuristics that are capable of presenting results near the optimum but that use much less computational resources; and the nonuse of transmission techniques, such as MIMO, showing the impact on the cost of implantation.

3. Scenario Description and Propagation Model

3.1. Possible RRH Locations and Fiber Implantation. The scenario was modeled taking into account the street orientation of Manhattan city, and square blocks were created with side sizes of approximately 416 meters based on [8]. Taking into account that the MILP optimization technique requires a very high computational cost, a square map with a side equal to 2.5 km was defined, in which the possible locations for RRH deployment were positioned on the corners of the blocks. Thus, 49 points of possible RRH implantation were defined, as shown in Figure 1.

The black "X" represents the points of possible RRH implantation, while the red "X" represents the neighbors considered for fiber passage and trenching. Note that the cabling follows the orientation of the streets, which in this case is only vertical and horizontal (dashed line). The green squares are the places where the implanted RRHs need to be connected (BBU pools) through the wired fronthaul.

An important factor that influences capital expenditure is represented by the cost related to the deployment of a BBU and the number of RRHs to be served by the BBU pool: the larger the distance between the RRHs and the BBU pool is, the larger the cost of fiber and trenching.

3.2. User Distribution. Users are randomly and uniformly distributed, with the minimum and maximum intervals being the coordinates of the ends of each quadrant. Four user concentration sectors were created to model malls, stadiums, large shopping centers, etc. [19]. A total of 12.5% of the total number of users are distributed in each of these locations with the highest densification. The remainder (50%) is distributed over the entire map, and some of these users may fall into areas of high concentration. Figure 2 illustrates the distribution of users and their densified areas.

In the above image, users are represented by red asterisks, while possible locations for RRH implantation are denoted by a black "X," as shown in Figure 1. Notably, the areas of concentration have a square shape with a side length of 625 m.

3.3. Propagation Model and QoS Assessment. The selected propagation model is the modified version of the Stanford University Uterim (SUI) [20], which was chosen because it

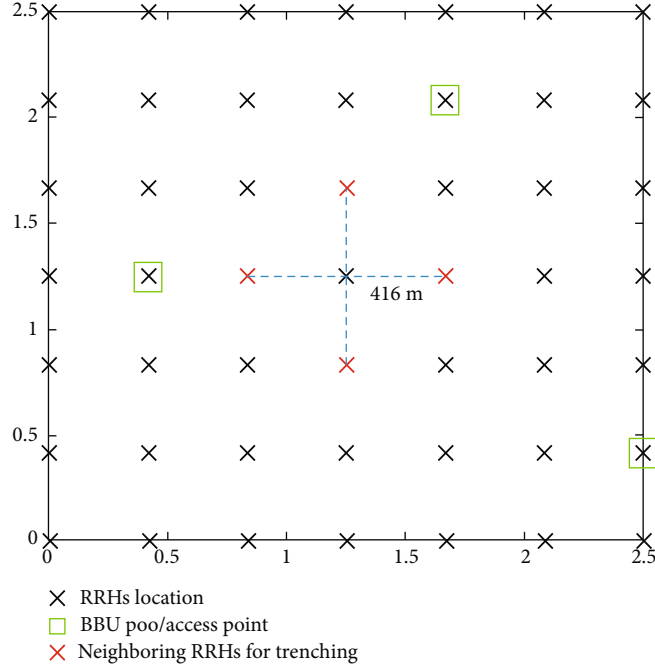


FIGURE 1: Representation of the scenario used in modeling.

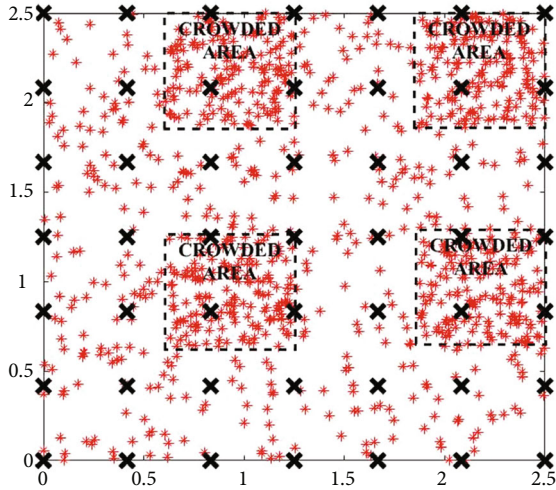


FIGURE 2: Exemplification of the distribution of users.

is possible to model urban environments with shading if the correct parameters are utilized [21]. The signal strength received by the user is calculated using Equation (1), which assumes that all small cells transmit at maximum power PM with gain G , a signal that suffers from the fading (L_{SUI}) caused by the environment and obstacles.

$$P_{k,b(k)} = \frac{10^{(PM+G-L_{SUI})/10}}{1000}. \quad (1)$$

To calculate the quality of the transmission channel, the signal-to-noise plus interference ratio (SINR) metric presented in Equation (2) is applied, and the variable

$P_{k,b(k)}$ is the power received by user k from base station $b(k)$, which is the signal used for data transmission. σ_k^2 is the white noise value of the channel for user k , and I_k is the interference between two cells caused by neighboring base stations. The results will be presented using the signal-to-noise ratio (SNR) metric that can be obtained by removing the variable I_k from the following equation.

$$SINR_k = \frac{P_{k,b(k)}}{\sigma_k^2 + I_k}. \quad (2)$$

Note that the extended version of the SUI model was selected due to the limiting factor that the reference distance brings in its basic version. Thus, a new reference distance is calculated according to the correction coefficients related to the propagation frequency and height of the receiver, with the addition of being able to model cases in which the distance is less than the reference distance. The equations below show the fading calculation, new reference distance, and correction parameters.

$$L_{SUI} = \begin{cases} 20 \log \left(\frac{4\pi d}{d_0} \right), & \text{se } d \leq d'_0 \\ A + 10\gamma \log \left(\frac{d}{d_0} \right) + \Delta_{bf} + \Delta_{bh} + S, & \text{se } d > d'_0, \end{cases} \quad (3)$$

$$A = 20 \log \frac{4\pi d'_0}{\lambda}, \quad (4)$$

$$d'_0 = d_0 10^{-((\Delta_{bf} + \Delta_{bh})/10\gamma)}, \quad (5)$$

$$\gamma = a - bh_b + \frac{C}{h_b}, \quad (6)$$

$$\Delta_{bf} = 6 \log \frac{f}{2000}, \quad (7)$$

$$\Delta_{bh} = \begin{cases} -10 \log \left(\frac{h_r}{3} \right), & \text{se } h \leq 3 \\ -20 \log \left(\frac{h_r}{3} \right), & \text{se } h > 3. \end{cases} \quad (8)$$

Some variables of the presented equations are detailed below:

- (i) d : distance between the signal source and the user, in meters
- (ii) d_0 : standard reference distance of the SUI model, which is equal to 100 meters
- (iii) d'_0 : new reference distance, in meters
- (iv) λ : wavelength, in meters
- (v) γ : path loss exponent
- (vi) h_b : transmitter height, which ranges between 10 and 80 meters
- (vii) h_r : receiver height, in meters
- (viii) a , b , and c : constants that depend on the type of terrain used
- (ix) S : shadowing effect
- (x) Δ_{bf} : correction factor related to the frequency of transmission
- (xi) Δ_{bh} : correction factor related to the reception height

The shadowing effect is calculated as a random variable with a Gaussian probability density function, in which its average is equal to 9.4 dB and the variance is 1.2 dB, following the guidelines of the SUI model, which indicates that S must fall between 8.2 dB and 10.6 dB.

After obtaining the SINR values for each user, it is possible to calculate the Shannon capacity parameter, which was chosen to validate users' QoS. Thus, the maximum data transmission rate that each user k can obtain is determined according to Equation (9), where B is the bandwidth available to the user in Hz.

$$CA_k = B \log_2(1 + \text{SINR}_k). \quad (9)$$

Although Equation (9) indicates the theoretical maximum, in LTE, these values are never reached due to the losses of the physical link (which differ according to the applied transmission technique) and band reserve to avoid overlapping carriers, which are necessary for smooth transmissions. In this sense, Equation (9) undergoes several mod-

ifications, and the effective transmission capacity of LTE (CE_k) follows Equation (10) [22]:

$$CE_k = t_{\text{mimo}} \times \eta_{\text{mimo}} \times B \times \text{ef}i_{\text{mod}}. \quad (10)$$

The t_{mimo} value is the type of MIMO used, and in this work, only types with the same number of transmitters/receivers are considered. For MIMO 2×2 , the value of t_{mimo} is equal to 2; for 4×4 , the value is 4, which returns us to the increase in the transmission capacity with the use of multiple antennas.

The η_{mimo} coefficient is the efficiency value of the physical link and varies according to the type of MIMO used. The use of more antennas in transmission/reception generates less efficiency because of the greater losses due to increased interference and more signaling messages that are necessary to correct transmission errors. The efficiency values are presented in [22].

The value of B remains the maximum bandwidth (measured in Hz), while the value of $\text{ef}i_{\text{mod}}$ is the modulation efficiency used (measured in bps/Hz). The technique selected to define the modulation and its efficiency is adaptive modulation and coding (AMC), in which the choice is made through values, in dB, of SINR or SNR. In [22], it is possible to identify the mapping of the modulation and efficiency rate with the SINR/SNR necessary for its use.

4. Optimization Models

In this section, the proposed optimization models used to reduce the deployment cost of the above scenarios will be presented. First, the modeling of the optimal model will be shown through MILP, and second, the heuristics, which use the cost of transport in the decision process, will be presented.

4.1. Optimal Model (MILP). The MILP was created using the IBM ILOG CPLEX tool. In CPLEX, the default model is the simplex, and the encoding did not contain parallelism because it was run on a personal computer with a core i5-5200U processor clocked at 2.20 GHz and 8 GB RAM.

MILP was created to validate the results of the heuristics that will be presented because it presents the optimal model (OM) for the purpose that was programmed. Its main disadvantage is the high computational cost, forcing the modeling of smaller scenarios to solve any problem, serving much more as a basis for comparison than the final optimization method.

In this work, the main objective is to reduce the deployment cost of a centralized network that can meet all users who request a certain demand. However, before showing the equations and explaining how the modeling of this problem works, some input parameters and variables need to be explained.

Input parameters are as follows:

- (i) P : possible equipment deployment locations

- (ii) $RRHs$: maximum number of RRHs that can be implanted
- (iii) $Users$: total number of users
- (iv) QoS_{\min} : minimum transmission capacity, measured in Kbps
- (v) $PRBs$: number of physical resource blocks (PRBs) that each RRH has
- (vi) D : distance between neighboring points of P
- (vii) C_{RRH} : unit cost of RRH
- (viii) C_{Trn} : cost of 1 meter of trenching
- (ix) C_{Fib} : cost of 1 meter of fiber
- (x) RRH_p : 1 if it is a possible RRH deployment site and 0 otherwise, with $p \in P$
- (xi) BBU_p : 1 if there is a BBU pool in that location and 0 otherwise, with $p \in P$
- (xii) $W_{p,p}$: 1 if the path between two nodes is capable of building trenching and fiber passage and 0 otherwise, with $p \in P$
- (xiii) $CE_{k,i}$: capacity that user k receives from RRH i when using a PRB

Decision variables are as follows:

- (i) Y_i : 1 if RRH i is chosen to be implanted, 0 otherwise
- (ii) $U_{k,i}$: 1 if user k is served by RRH i , 0 otherwise
- (iii) $UPRB_{k,i}$: number of PRBs that user k receives from RRH i
- (iv) $POOL_{i,z}$: 1 if BBU pool z is the destination of RRH i
- (v) $R_{p,p}^i$: route of RRH i to its destination

The objective function is shown in Equation (11); the part that is not in brackets is related to the radio part, which is represented by the number of implanted RRHs. The part inside the brackets represents the transport cost (fiber and trenching).

$$\begin{aligned} \text{Minimize } & \sum_{i \in RRHs} Y_i \times C_{RRH} + \left[\left(\sum_{p1, p2 \in P} \min \left(1, \sum_{i \in RRHs} R_{p1, p2}^i \right) \right) \times C_{Trn} \right] \\ & + \left(\sum_{i \in RRHs} \sum_{p1, p2 \in P} R_{p1, p2}^i \times C_{Fib} \right) \times D. \end{aligned} \quad (11)$$

Radio restrictions are described below:

$$U_{k,i} \leq Y_i, \forall k \in Users, i \in RRHs, \quad (12)$$

$$\sum_{i \in RRHs} U_{k,i} = 1, \forall k \in Users, \quad (13)$$

$$UPRB_{k,i} \times CE_{k,i} \geq QoS_{\min} \times U_{k,i}, \forall k \in Users, i \in RRHs, \quad (14)$$

$$\sum_{k \in Users} UPRB_{k,i} \leq PRBs_i, \forall k \in Users, i \in RRHs, \quad (15)$$

Equation (12) defines that the user can only connect to an RRH that is deployed; Equation (13) restricts the user to connect to only one RRH; Equation (14) establishes that the transmission capacity received by the user must be greater than or equal to the established value (QoS_{\min}); and Equation (14) defines that the amount of PRBs provided by an RRH to its users cannot exceeds the maximum PRBs that it has.

Transport restrictions are described below:

$$\sum_{z \in P} POOL_{i,z} \leq Y_i, \forall i \in RRHs, \quad (16)$$

$$\sum_{p2 \in P} R_{p1, p2}^i + POOL_{i, p1} - \sum_{p2 \in P} R_{p2, p1}^i = Y_i, \forall p1 \in P, i \in RRHs | p1 = i, \quad (17)$$

$$\sum_{p2 \in P} R_{p1, p2}^i + POOL_{i, p1} - \sum_{p2 \in P} R_{p2, p1}^i = 0, \forall p1 \in P, i \in RRHs | p1 \neq i, \quad (18)$$

$$\sum_{i \in RRH} R_{p1, p2}^i = 0, \forall p1, p2 \in P, | W_{p1, p2} = 0, \quad (19)$$

$$R_{p1, p2}^i + R_{p2, p1}^i \leq 1, \forall p1, p2 \in P, i \in RRHs. \quad (20)$$

Equation (16) ensures that each RRH connects to only one BBU pool; Equations (17) and (18) guarantee the passage of trenching and fiber from the origin (implanted RRH) to the destination (BBU pool). Thus, there are two situations: the first situation is at the beginning of the fiber/trenching passage (origin node) represented by Equation (17). Equation (18) represents the implementation of the fiber/trenching set in several other nodes up to the BBU pool; Equation (19) guarantees that there will be no trenching or fiber passage at points that are not neighbors; and Equation (20) ensures that the paths for creating trenching are considered only once.

4.2. Heuristic for the Deployment of C-RAN Networks. To indicate that the transport cost has a great influence and should be considered in the implantation planning of C-RAN networks, a heuristic (named H1) was proposed based on work performed in [19]. This approach is generally used in telephone companies that prioritize places with a very high density of users (or potential users). This approach gives preference to deploy RRHs that can serve the largest number of users, without considering the cost necessary for its construction. Using the transport cost as the main factor and giving preference to implanting RRHs that generate fewer costs, and consequently, lowering the total cost of the infrastructure as a whole, a new heuristic (H2) is proposed.

Each RRH is individually tested, and the selection procedure is similar for the two heuristics. This testing is conducted as follows: a stack of tests is created with all the candidates' RRHs; the RRH at the top of the stack is removed; and the attribution process between users and the remaining RRHs is remade. With all users covered and satisfied, RRH can be discarded; otherwise, it will have to be implanted.

The ordering of the test stack will always be performed in decreasing order of the total RRH cost (value of C_{RRHi}), which is calculated according to

$$C_{RRHi} = \frac{C_{RRH}}{\sum_{k \in U_{Users}} U_{k,i}} + \left(R_{pt,pt}^i \times C_{Trm} + R_{pf,pf}^i \times C_{Fib} \right) \times Z. \quad (21)$$

The left side of the first sum indicates the deployment cost of an RRH being attenuated by the number of users that it serves; only this characteristic is used in H1, so the value of Z is equal to 0.

The second part of Equation (21) shows the use of the transport cost (trenching and fiber) to calculate the cost that serves as the basis for the creation of the test stack, which is an attribute used in H2; for this reason, the value of Z is equal to 1. Algorithms 1 and 2 detail the network planning procedure, the set of RRHs is represented by the St matrix, and the users are denoted by the UEs matrix.

Lines 1 to 3 of Algorithm 1 perform the assignment of each user in the RRH, in which the power of the received signal is greater but which has available PRBs, creating a prior admission control. In Lines 4 to 6, the deployment cost of each RRH is calculated, in which the value of the variable Z will define the use of the fronthaul cost. For the calculation of the transport cost, the Djisktra algorithm of the shortest path was employed, with weights updated where trenching was built. Line 7 orders the RRH matrix according to the cost in decreasing order. Between Lines 8 and 11, the SINR and the transmission capacity of all UEs are calculated, thus obtaining the QoS metric required to perform the tests in Algorithm 2.

Algorithm 2 starts (Line 1) by calling the procedure `allocate_UEs()` because it is necessary to preallocate users in their respective RRHs, according to the rules presented in Algorithm 1. Between Lines 2 and 11, there is a loop that will go through all RRHs. A copy of the RRH matrix is made (Line 3), and the RRH at the top of the stack is removed (Line 4). Subsequently (Line 5), the procedure `allocate_UEs()` is called again to reallocate users in the remaining RRHs to perform new cost and QoS calculations. Between Lines 6 and 10, tests are performed with users: the minimum quantity of covered users needs to be met and everyone covered by an RRH needs to reach at least the minimum QoS measure (Line 6). When testing positive for the two presented conditions, the applied matrix will be the matrix in which the RRH was removed (Line 7); otherwise, the RRH is considered indispensable, and the copy made, in Line 3, is utilized (Line 9).

After checking all RRHs, the St matrix will have those that will be implanted. Thus, Algorithm 1 is called again (Line 12) to calculate the deployment cost of all RRHs (and consequently the total cost) and the transmission capacity of each user.

5. Results

This section shows the performance evaluation results of the proposed optimal model (OM) with two other heuristics: the heuristics proposed in [19] and the transport cost heuristic (H2). For each scenario, 30 runs of experiments were carried out. To minimize the effect of the outliers and to draw the common behavior on each scenario, the average of the results from multiple experiments was obtained. The averaged results are then used for performance comparison and analysis. The input parameters used in the modeling are shown in Table 1.

Note that the presented costs are characterized by the values of acquisition and installation and are normalized concerning 1 meter of optical fiber.

Four scenarios were created with different numbers of users (400, 600, 800, and 1000). The objective is to measure the impact of the demand growth on the final cost and the performance of the optimization methods. In addition to the change in the number of users, four transmission modes were utilized (SISO, 2×2 MIMO, 3×3 MIMO, and 4×4 MIMO) to present the impact on cost when using transmission technologies with greater capacities. The results will be divided between the use of SNR and SINR; for the former, the two heuristics will be compared with an optimal model, and only the two techniques will be compared.

5.1. Results Using SNR. In Figures 3–6, the results are presented using the technologies SISO, 2×2 MIMO, 3×3 MIMO, and 4×4 MIMO, respectively. Figure 3 illustrates the averages of the total cost that the three methods (H1, H2, and OM) obtained in the 30 iterations for each number of users. It is essential to analyze that the total cost of all techniques increases with the increase in the number of users, showing that the increased demand creates the need for a more robust, and consequently, more expensive network.

OM obtained the lowest costs in all cases, which was expected because it is the reference model. Regarding H1, in the worst case, an increase of 16% was obtained with the optimized model; its characteristic of considering only the dimensioning of RRHs and not considering the transport cost substantially increases the total cost. This finding demonstrates that inadequate planning generates more costly networks, which becomes financially unfeasible.

H2 achieves very promising results, with a total cost in relation to the optimum model remaining at a threshold below 14.4%, considering the SISO transmission technology. This result proves that considering the costs of cabling when planning centralized networks generates more reliable results. The good results are supported by the better reuse of trenching (tunneling), an element with the greatest impact on the total cost.

Entry: RRHs (St), Z , and UEs
Result: List St of RRHs organized in decreasing order of cost

1. **For all** $i \in St$
2. Allocate the UE to RRH_i with the best signal and available PRB;
3. **End for**
4. **For all** $i \in St$
5. Calculate the deployment cost of RRH_i (using variable Z and Equation (21));
6. **End for**
7. St = matrix St ordered by cost in **descending** order;
8. **For all** $k \in UE$
9. Update the SINR of k using Equation (2);
10. Calculate the transmission capacity of k using Equation (10);
11. **End for**

ALGORITHM 1: allocate_UEs.

Entry: St , Z , UEs , QoS_{min} , and $coverage_{min}$
Result: St

1. allocate_UEs (St , Z , and UEs)
2. **For all** $i \in St$
3. $St' = St$;
4. St = remove RRH_i from the vector St ;
5. aloca_UEs (St , Z , and UEs)
6. **If** (UEs coverage $\geq coverage_{min}$) && (UE capacity $\geq QoS_{min}$)
7. $St = St$;
8. **Else**
9. $St = St'$;
10. **End if**
11. **End for**
12. allocate_UEs (St , 1, UEs)

ALGORITHM 2: Network deployment based on the predefined position of RRHs.

TABLE 1: Network parameters.

Parameter	Value
Frequency	3.5 GHz
Receiver height	1.5 meters
Transmitter height	10 meters
Bandwidth	100 MHz, 500 PRBs by RRH
Maximum power	30 dBm, with a gain of 7 dbi
Modulation used	AMC, up to 64 QAM (LTE release 10)
Minimal QoS (QoS_{min})	1000 Kbps
Fiber cost (m) (C_{Fib}) [29]	1
Trenching cost (m) (C_{Trn}) [29]	$4 \times C_{Fib}$
RRH cost (C_{rrh}) [29]	$375 \times C_{Fib}$
Block size	416 m \times 416 m
Total map size	2.5 km \times 2.5 km
Minimal user coverage	100%

Figure 4 shows that the total costs of all techniques decrease (Y axis); this notion can be explained by the greater capacity of data transmission that MIMO generates, causing

the need for a lower number of RRHs and, consequently, fewer resources for construction fronthaul. Another factor that deserves attention is the difference between the H1 technique and the H2 technique for the optimal model, which also decreases, realizing again the positive influence caused by the MIMO technology. In some cases, the cost difference between H2 and OM is approximately 10%, which is considered quite favorable considering the use of a heuristic.

Comparing H1 and H2, the technique based on the transport cost is always more financially viable. This difference is minimal in certain scenarios, such as modeling with 800 users and using 4×4 MIMO technology, because the H1 technique favors the high concentration of users on the map and the high transmission capacity of the RRHs when using better transmission technologies.

It is essential to analyze the influence of each resource on the total cost. The cost of RRH has minimal influence, between 12.9% and 14.3%, while the cost of fiber and trenching varies from 23.5% to 26% and from 63.6% and 59.7%, respectively, considering the scenarios with different numbers of users. As the cost of RRH is the least influence on the total cost, it is concluded that planning a centralized network only by dimensioning the RRHs as H1 does will not yield the best results in terms of reducing the total cost of the

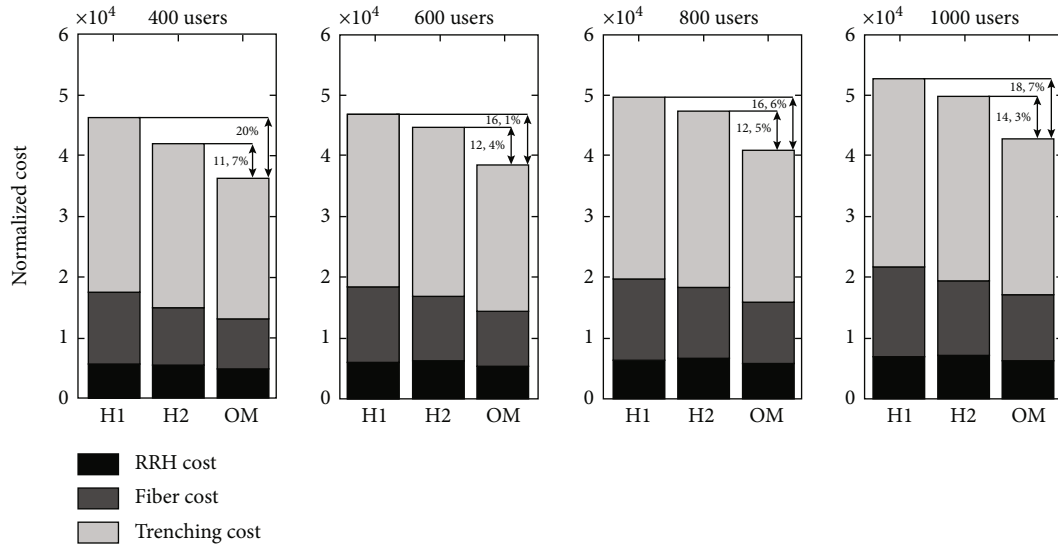


FIGURE 3: Results of the three optimization techniques using SISO transmission technology.

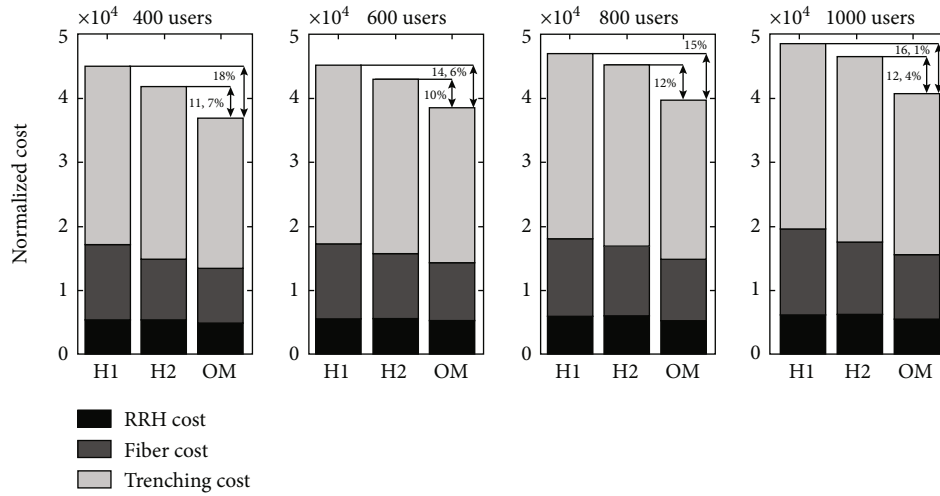


FIGURE 4: Results of the three optimization techniques using 2×2 MIMO transmission technology.

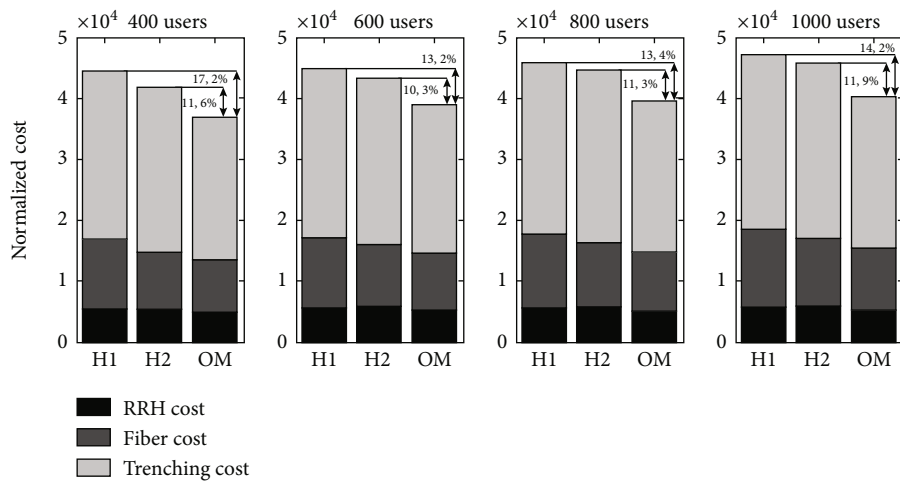


FIGURE 5: Results of the three optimization techniques using 3×3 MIMO transmission technology.

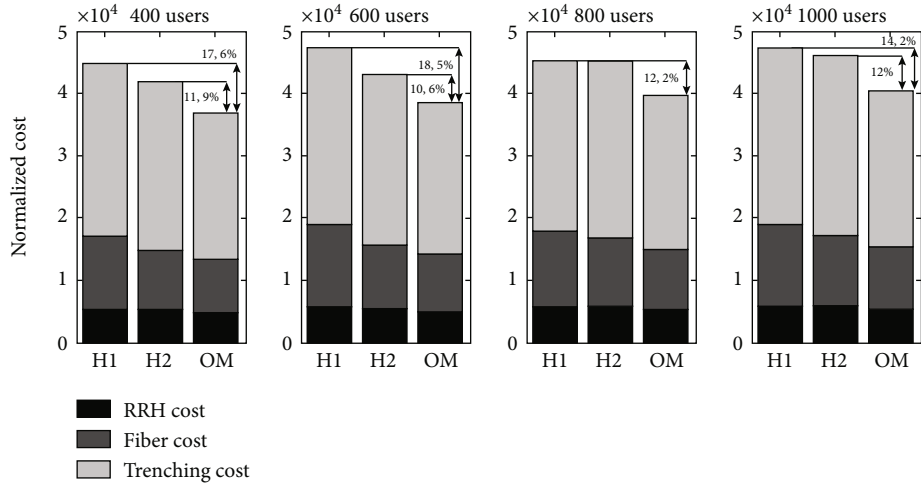


FIGURE 6: Results of the three optimization techniques using 4×4 MIMO transmission technology.

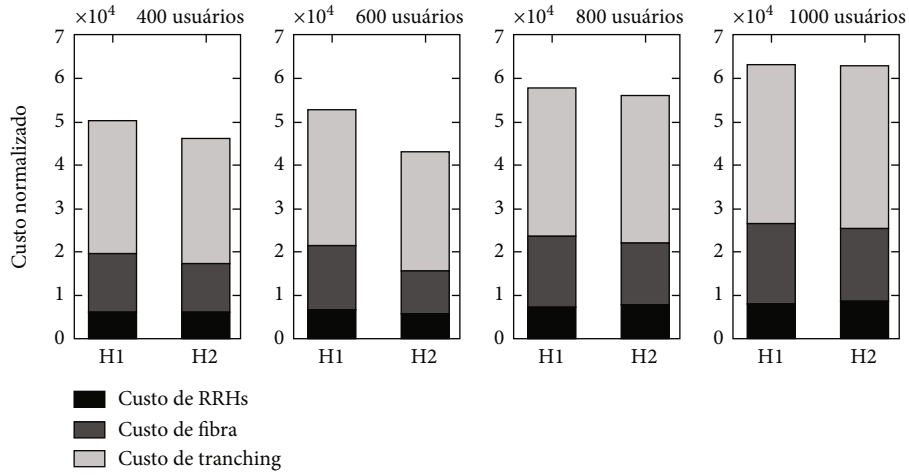


FIGURE 7: Results using SINR and SISO.

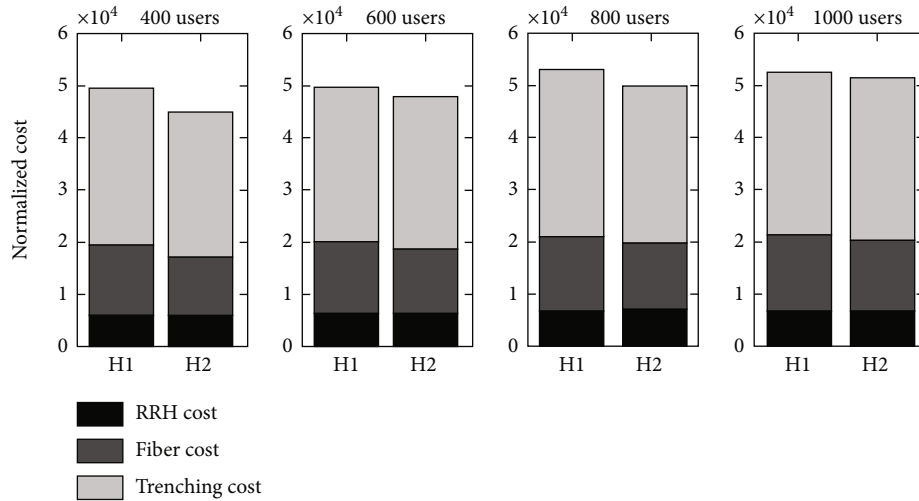


FIGURE 8: Results using SINR and 4×4 MIMO.

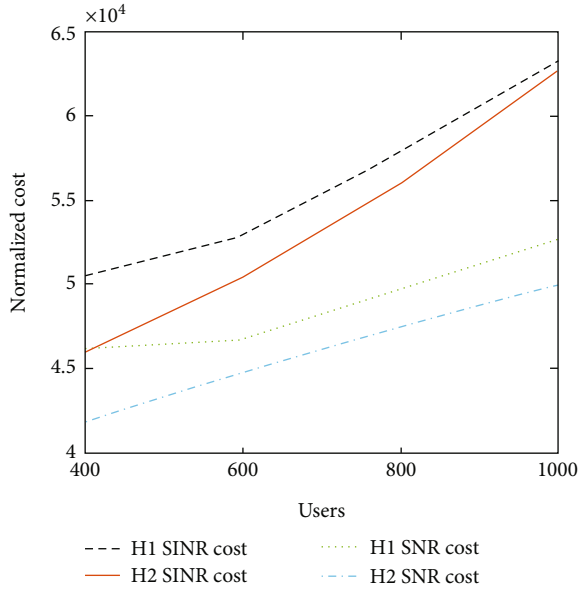


FIGURE 9: Comparison of the results between SNR and SINR using the H1 and H2 techniques.

network. It is known that the costs of RRHs that use more advanced technologies may be higher, but the same C_a value, which is shown in Table 1, was employed for all transmission technologies due to their small impact on the total cost.

The trenching cost, despite being the element with the greatest influence on the total cost, is the only element in which there is a drop in the amount of investment necessary for the creation of its infrastructure due to the previously mentioned reuse mentioned. On the other hand, the fiber is not reused, being an exclusive connection of each RRH to its respective BBU; taking this finding into account, it is possible that in very large networks, the weight of the optical fiber cost is greater than that of trenching.

Through Figures 3–6, it is possible to verify the impact of the use of MIMO on the total cost of deployment, not only in radio access technology (RAT) but also in the infrastructure necessary to offer the service (fiber and tunneling). Additionally, the cost does not substantially increase among the MIMO approaches, since there is only a change in the quantity of radio and fiber. However, the availability of radio resources, which makes the network more apt to serve more users, considerably increases.

5.2. Results Using the SINR. The results using the SINR are aimed at demonstrating the impact on the total cost when considering the interference between two RRHs to calculate the quality of the channel. In heuristics, the 49 candidate RRHs are considered linked at the beginning of the tests as part of the interference calculation. When discarded, their interference is disregarded. Due to the high computational cost necessary to calculate the interference among all RRHs, it was not possible to use the optimized scenario; this limitation has already been discussed in [17, 18]. This finding cor-

roborates the need for less computationally costly solutions, such as heuristics and metaheuristics.

Analysis of the results obtained with the use of the SINR (Figures 7 and 8) reveals that the total cost increases in all occasions compared with the results obtained using the SNR. This finding confirms the importance of considering interference between two RRHs, as it is presented in real systems. The use of MIMO technology once again caused a substantial decrease in cost and generated a cost difference between two networks with both higher demands (1000 users) and smaller demands (400 users) to achieve a decrease from approximately 26% (using SISO) to 12% (using 4×4 MIMO).

Another relevant point to analyze is the performance of H2 compared with H1, which achieved better results in all scenarios. However, for denser scenarios and with the use of RRHs with greater transmission capacity (MIMO technique), their values are closer. A similar behavior is explained in the results using the SNR.

Figure 9 provides a new perspective on the comparison between H1 and H2. The curves of H1 (using the same interference model) are higher than those of H2, confirming the higher cost of deployment (Y axis). In contrast to the use of the interference model, the model closer to reality (SINR) generates a need for a greater number of resources and, consequently, a higher cost of deployment.

6. Conclusion

The increased demand forces operators to invest in infrastructure to meet this new need. Among the existing alternatives, the use of heterogeneous networks (HetNets), small cells, centralized architectures, and MIMO are essential elements. This work presented optimization models for planning the deployment of centralized mobile networks, intending to minimize its total implementation cost. The results show that the MILP technique obtains the best results regardless of the configuration of the scenario, ratifying it as an optimal model. Heuristics were presented to have an option that needed a lower computational cost but that achieved acceptable results, with the case of H2 always being at a threshold between 10% higher and 15% higher than the optimal cost.

In addition to the presented techniques, other contributions are notable: the use of a specific propagation model for urban environments; the individualization of users with 100% coverage of users, characterizing the ubiquitous network; the use of different transmission modes (SISO and MIMO), presenting the impact generated on the cost of implementation; discussion about which of the resources has the greatest influence on the total cost; and the comparison between the use of SNR and that of SINR to calculate the quality of the channel.

Data Availability

All codes used to generate the results can be found in 10.6084/m9.figshare.12003795.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors declare that they received support from PRO-PESP/UFPA through the PAPQ program.

References

- [1] Cisco, *Virtual Networking Index: Forecast and Methodology, 2017-2022*, White Paper, 2019.
- [2] S. Parkvall, E. Dahlman, A. Furuskar, and M. Frenne, "NR: the new 5G radio access technology," *IEEE Communications Standards Magazine*, vol. 1, no. 4, pp. 24–30, 2017.
- [3] J. Wannstrom, *Carrier Aggregation Explained*, 3rd Generation Partnership Project, 2013.
- [4] M. Kamel, W. Hamouda, and A. Youssef, "Ultra-dense networks: a survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 4, pp. 2522–2545, 2016.
- [5] H. Peng, Y. Xiao, Y.-N. Ruyue, and Y. Yifei, "Ultra-dense network: challenges, enabling technologies and new trends," *IEEE China Communications*, vol. 13, pp. 67–79, 2016.
- [6] C. Yang and C. Taylor, *4x4 MIMO boosts 4G and gives consumers a taste of the gigabit experience*, Networks & Service Platforms, Strategy Analytics, 2017.
- [7] A. Checko, H. L. Christiansen, Y. Yan et al., "Cloud RAN for mobile networks—a technology overview," *IEEE Communication Surveys and Tutorials*, vol. 17, no. 1, pp. 405–426, 2015.
- [8] F. Tonini, C. Raffaelli, L. Wosinska, and P. Monti, "Cost-optimal deployment of a C-RAN with hybrid fiber/FSO fronthaul," *Journal of Optical Communications and Networking*, vol. 11, no. 7, pp. 397–408, 2019.
- [9] M. Jaber, D. Owens, M. AliImran, R. Tafazolli, and A. Tukmanov, "A joint backhaul and RAN perspective on the benefits of centralised RAN functions," in *2016 IEEE International Conference on Communications Workshops*, pp. 226–231, Kuala Lumpur, Malaysia, 2016.
- [10] M. N. Islam, A. Sampath, A. Maharshi, O. Koymen, and N. B. Mandayam, "Wireless backhaul node placement for smallcell networks," in *2014 48th Annual Conference on Information Sciences and Systems*, pp. 1–6, Princeton, NJ, USA, 2014.
- [11] M. Jaber, F. J. Lopez-Martinez, M. A. Imran, A. Sutton, A. Tukmanov, and R. Tafazolli, "Wireless backhaul: performance modeling and impact on user association for 5G," *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, pp. 3095–3110, 2018.
- [12] X. Xu, W. Saad, X. Zhang, X. Xu, and S. Zhou, "Joint deployment of small cells and wireless backhaul links in next-generation networks," *IEEE Communications Letters*, vol. 19, no. 12, pp. 2250–2253, 2015.
- [13] S.-F. Chou, Y.-J. Yu, and A.-C. Pang, *Mobile small cell deployment for service time maximization over next generation cellular networks*, IEEE Globecom, 2014.
- [14] A. Checko, A. P. Avramova, M. S. Berger, and H. L. Christiansen, "Evaluating C-RAN fronthaul functional splits in terms of network level energy and cost savings," *Journal of Communications and Networks*, vol. 18, no. 2, pp. 162–172, 2016.
- [15] D. G. González, H. Hakula, A. Rasila, and J. Hämäläinen, "Spatial mappings for planning and optimization of cellular networks," *IEEE/ACM Transactions on Networking*, vol. 26, no. 1, pp. 175–188, 2018.
- [16] Q. Shen, Z. Ma, and S. Wang, "Deploying C-RAN in cellular radio networks: an efficient way to meet future traffic demands," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 8, pp. 7887–7891, 2018.
- [17] C. Ranaweera, C. Lim, A. Nirmalathas, C. Jayasundara, and E. Wong, "Cost-optimal placement and backhauling of small-cell networks," *Journal of Lightwave Technology*, vol. 33, no. 18, pp. 3850–3857, 2015.
- [18] C. Ranaweera, E. Wong, A. Nirmalathas, C. Jayasundara, and C. Lim, "5G C-RAN with optical fronthaul: an analysis from a deployment perspective," *Journal of Lightwave Technology*, vol. 36, 2018.
- [19] W. El-Beaino, A. M. El-Hajj, and Z. Dawy, "On radio network planning for next generation 5G networks: a case study," in *2015 International Conference on Communications, Signal Processing, and their Applications*, pp. 1–6, Sharjah, United Arab Emirates, 2015.
- [20] G. Senarath and IEEE 802, *Multi-hop relay system evaluation methodology (channel model and performance metric)*, IEEE, 2007.
- [21] P. K. Sharma, D. Sharma, P. C. Sau, and A. Gupta, "Comparative analysis of propagation models in LTE networks with spline interpolation," in *2016 2nd International Conference on Communication Control and Intelligent Systems*, Mathura, India, 2016.
- [22] N. T. Rodvalho, *Experimental Performance Analysis of LTE-Advanced Networks Based on MIMO and Carrier Aggregation*, Instituto Nacional de Telecomunicações, 2017.