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5G DIMENSIONING AND OPTIMIZATION THROUGH USE ANALYSIS OF A REAL SCENARIO

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Advisor: José Antonio Lázaro, Anna Umbert Juliana

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Title of the thesis: 5G DIMENSIONING AND OPTIMIZATION THROUGH USE ANALYSIS OF A REAL SCENARIO

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Abstract

Mobile networks have become essential to our daily communications. The growth of mobile traffic and users has increased exponentially in recent years, with increasing demands on throughput and latency. To handle this growing traffic, a scaling strategy that guarantees quality of service over time is essential. This thesis proposes the dimensioning of a mobile network based on a real 4G scenario, using techniques such as the implementation of new carriers and 5G technology. It also proposes the dynamic implementation of Cloud RAN, assigning the location of BBU pools according to network characteristics.

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1. Introduction

Mobile communications have transformed the way we communicate and connect with each other. With the arrival of wireless technology, we are no longer tied to a physical location to make a call or send a message. Mobile communications have become an integral part of our daily lives, allowing us to stay in touch with friends, family and colleagues wherever we are. From the early days of analogue cellular systems to the latest 5G networks, mobile communications have come a long way. Today we have access to a wide range of mobile services, including voice, messaging, video, and data.

The 5G networks need to be able to handle different multimedia applications that require faster data transfer speeds, lower delay times, better indoor connectivity, and improved energy efficiency [1]. To achieve all these expected requirements, the design of the Radio Access Network (RAN) becomes a challenge. Cloud RAN (C-RAN) is a proposed network architecture in 5G wireless networks to address challenges such as faster user data transfer speeds and lower latency. In this architecture, the RAN functions are virtualised and provided by cloud-based data centers, instead of traditional hardware-based network elements.

On the other hand, it is important to optimise the placement of BBU pools in the network to ensure that the chosen location meets the necessary bandwidth and latency requirements, while maximising the benefits of centralisation. The objective is to find the most appropriate location for BBU pools to achieve optimal network performance in terms of performance and energy efficiency [1].

The growth of mobile traffic and users has increased exponentially in recent years [2], with increasing demands on throughput and latency. To handle this growing traffic, a scaling strategy that guarantees quality of service over time is essential. Dimensioning the network is a crucial aspect of mobile communications engineering. It involves designing and optimizing the network to ensure that it can handle the expected traffic and provide the required quality of service. This process includes determining the number and location of base stations, selecting the appropriate frequency bands, and configuring the network parameters. Proper dimensioning of the network is essential to ensure that the network can meet the demand for mobile services and provide reliable and high-quality connectivity to users. It also helps to minimize the cost of network deployment and operation while maximizing the network's performance and efficiency.

This thesis is divided into two parts. In the first, a realistic cloud RAN scenario is defined using Integer Linear Programming (ILP) to determine the optimal location and number of BBU pools. The scenario is based on information from a real 4G network (cell location, traffic, bandwidth, etc.). The second part plans to use different techniques to deal with network congestion and increasing network traffic over a 5-year forecast, such as the implementation of new 4G carriers and 5G deployment. This research also aims to analyze the feasibility of 5G deployment in Colombia and its potential impact on the telecommunications industry.

Objectives:

- Use realistic mobile network data to dynamically distribute BBU Pools and assign resources to cells.
- Detect congested cells and deploy new carriers if they are available.
- Managing growing traffic with 5-year forecasting.
- Propose a 5G network deployment to support growing traffic.

This thesis is organised as follows. Section 2 presents the design specifications and requirements based on a real scenario. This section outlines the necessary details and criteria used to develop the design. Section 3 describes the state of the art, presenting information on C-RAN and other approaches to BBU pool placement and mobile traffic prediction. Section 4 presents the project methodology, defining the proposed solution and the details of each block of the model. Section 5 then presents the results of the implemented model. Finally, Section 6 presents the main conclusions and ideas for future developments.

2. Scenario of studio

2.1. Network Area

For this work, the real 4G network of one of the main mobile operators in the city of Cartagena, Colombia, was selected.

Cartagena is the fifth most populated city in Colombia with 1.055.035 inhabitants [3] and an extension of 623 km^2, with an urban area of 76 km^2 [4]. Cartagena is the most important touristic city of the country, being the second city of Colombia with most visitors, after the capital Bogotá. Its historical downtown was awarded as National Heritage of Colombia in 1959 and UNESCO World Heritage in 1984 [5].

The importance of the city, the mobile traffic it handles and the author's access to real traffic information were essential in choosing Cartagena as the site for the study. Figure 1 shows a satellite view of the city.

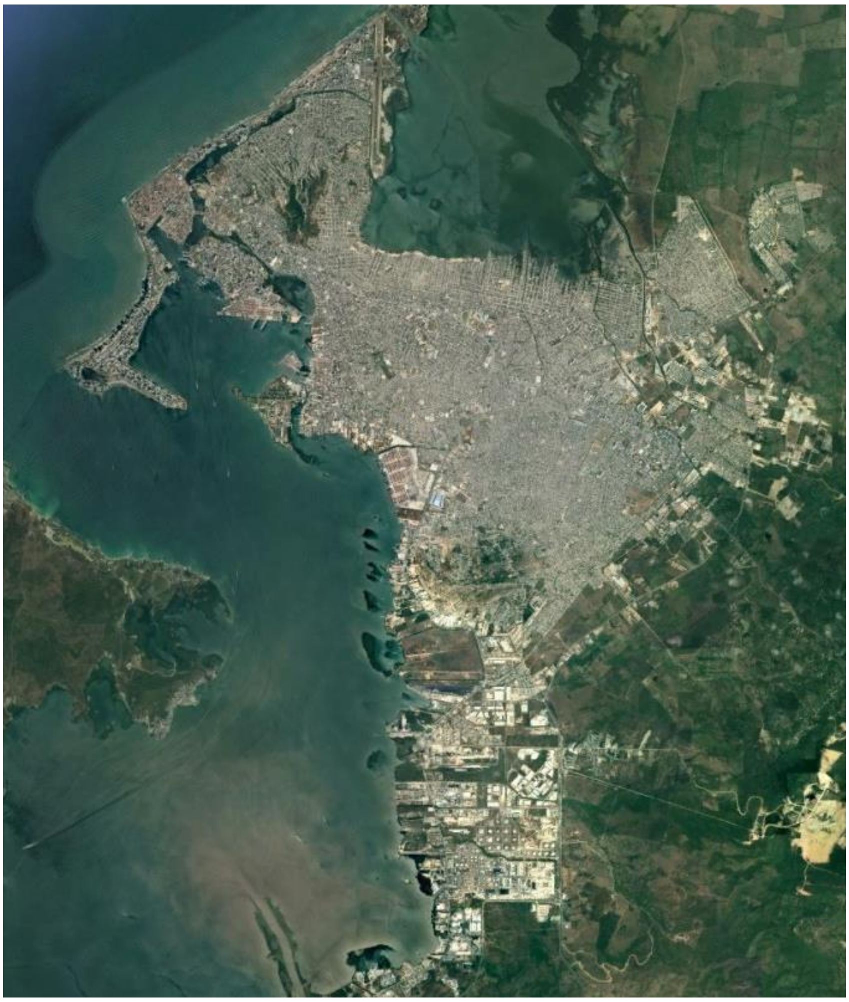


Figure 1. Satellite view of Cartagena, Colombia.

2.2. Real network

The studied network consists of 168 nodes and 578 4G cells. Of these 578 cells, 264 cells operate in the 850 MHz frequency (Band 5) and 314 cells operate in the 1700-2100 MHz frequency (Band 4 AWS), as shown in Table 1.

Number of nodes	Number of cells	Frequency (MHz)	Band	Bandwidth (MHz)
168	264	850	5	10
	314	1700-2100	4	15
Total	**578**			

Table 1. Number of nodes and cells in the network.

Figure 2 shows the distribution of the cells in the city, with the 850 MHz cells in purple and 1700 MHz cells in orange.

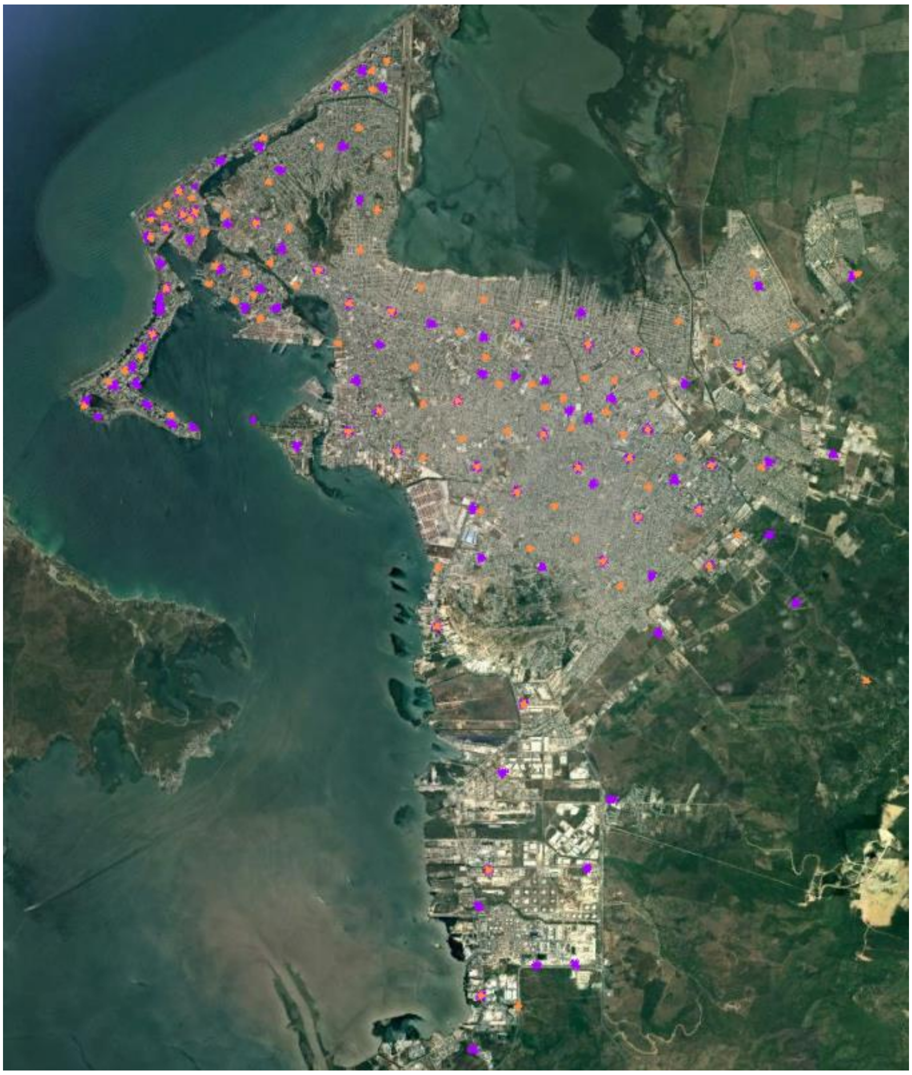


Figure 2. Real Distribution of cells in the network.

3. State of the art of the technology used or applied in this thesis

3.1. Cloud RAN Networks

Cloud Radio Access Network (C-RAN) in 5G networks refers to a network architecture that uses cloud computing technologies to deliver 5G network services and applications. In a traditional cellular network, the Radio Access Network (RAN) consists of physical network elements such as base stations, controllers, and other hardware-based components that are responsible for managing the communication between mobile devices and the core network. In the C-RAN architecture, the RAN functions are virtualised and provided by cloud-based data centers, instead of traditional hardware-based network elements. The traditional hardware element is the Base-Band Unit (BBU). These data centers operate as a group of BBUs (BBU Pool) that provide connectivity to a group of Remote Radio Head (RRH), as shown in Figure 3. Resource allocation takes place at the BBU Pools and the RRHs are only used to transmit and receive the signal [6]. The BBU pool is located at a central location where multiple BBUs are placed, and it is connected to the RRHs via a high capacity fronthaul network.

C-RAN offers several benefits, such as increased network capacity, improved network efficiency, and reduced costs. In addition, C-RAN in 5G networks enables network operators to manage more easily and efficiently network upgrades, add new services, and deploy new technologies. This leads to a faster time-to-market for new services and helps operators stay ahead of the competition [7].

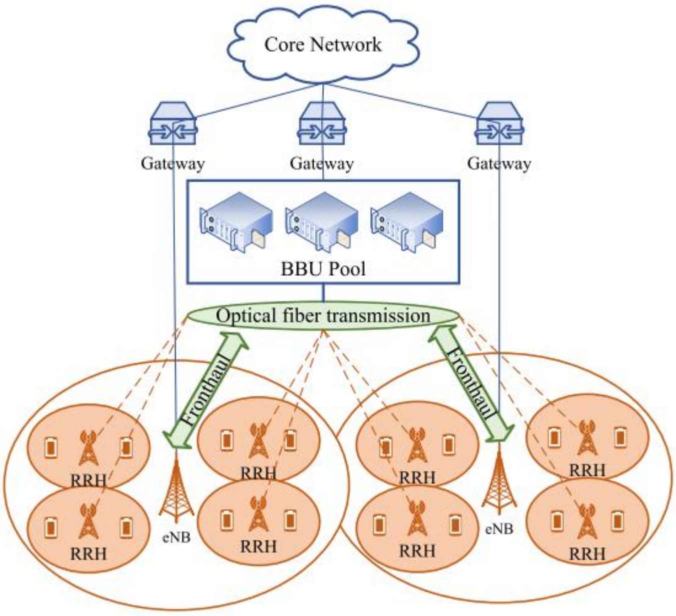


Figure 3. Cloud RAN architecture for 5G [6].

Although C-RAN is in the standard for 5G, it is possible to implement it in 4G networks [8], with the mentioned advantages, such as improve efficiency and reduce costs in the network.

Overall, C-RAN in mobile networks represents a significant step forward in the evolution of wireless networks, providing enhanced network capabilities and enabling new, innovative use cases for mobile technology.

3.2. BBU Pool Placement

The location of the BBU Pools in a network is key to providing a good service that meets requirements such as low latency, but without oversizing the number of BBU Pools, which results in higher costs.

BBU pool location is an important aspect of C-RAN architecture. BBU pooling has a significant impact on reducing power consumption and computing resources due to the possibility of having data centers sharing BBU resources to a cluster of cells, rather than having a local BBU for each node. However, the optimal placement of BBU pools in the network is critical to meet latency and data rate requirements while effectively supporting the challenging requirements of 5G mobile networks. Several previous research works have been conducted to propose robust BBU placement schemes using machine learning-based heuristic BBU-RRH switching algorithms [9] and dynamic load consolidation algorithms [10] to optimise BBU pooling in C-RAN and improve network performance, reliability and efficiency. Rafaelli et al [11] proposed a distributed algorithm for BBU placement in C-RAN.

Shehata et al [12] formulate an optimisation problem for three protection approaches to the C-RAN deployment problem over an optical aggregation network. The approaches include dedicated path protection, dedicated BBU protection, and dedicated BBU and path protection. The authors used Integer Linear Programming (ILP) to solve the optimisation problem, minimising the number of BBU pools, the number of wavelengths per link and the overall computational complexity. The authors show that minimising the computational effort leads to additional savings compared to the traditional minimisation of the number of BBU pools. ILP has also been used in other areas to find the optimal location among a set of possibilities, as in the work of Peng [13], who used ILP to find the optimal location and number of data centers among a set of potential data centers, assigning one data center to each train station.

ILP has been proven to be a powerful, flexible and simple optimization technique that can be applied to many real-world problems. Its easy implementation and good results make it suitable as a tool to optimize the network studied in this thesis.

3.3. Network traffic forecast

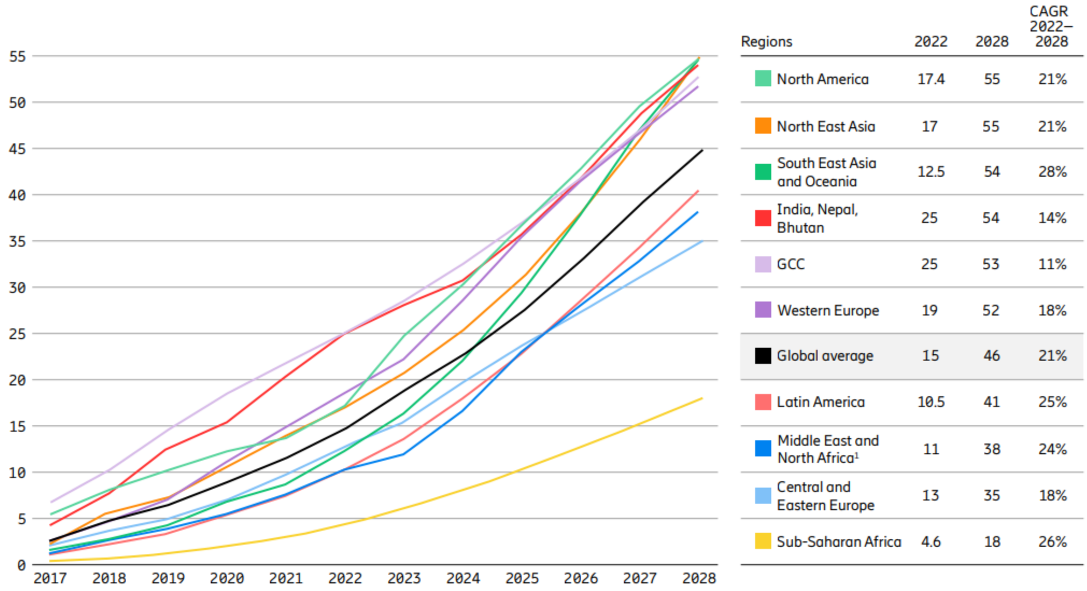
The growth in mobile data traffic can be attributed to a variety of factors, such as the increasing popularity of smartphones and the rise of mobile-based applications and services. The COVID-19 pandemic has also contributed to the growth, as more people have been working remotely and relying on mobile devices for communication and entertainment.

Some models have been developed to predict mobile traffic, such as the model of Bastos [14], which uses an Autoregressive integrated moving average (ARIMA) model to predict the traffic of a 3G network in a 28-day horizon. Zhang and Patras [15] used Deep Spatio-Temporal Neural Networks to predict mobile traffic in horizons of less than 24 hours. These models have proven useful for forecasting traffic in small horizons such as hours or days, but are not suitable for long forecasts in years, such as a 5-year forecast, which is one of the objectives of this thesis.

The growth of mobile data traffic can be unstable and unpredictable from year to year, being influenced by a multitude of factors that are difficult to model. For example, changes in consumer behaviour, advancements in technology, shifts in market competition, and even unexpected events such as natural disasters or pandemics can all have a significant impact on mobile data traffic growth. Furthermore, accurately modelling mobile data traffic requires not only understanding the complex interplay of these factors, but also considering the unique characteristics of different mobile networks and their user bases. This can be a challenging task, as different networks may have varying levels of infrastructure, user demand, and other factors that affect their data traffic growth patterns.

According to Ericsson [2], the total global mobile data traffic is projected to grow by a factor of nearly 4, reaching 325 Exabytes per month in 2028, from around 90 Exabytes per month by the end of 2022. The adoption of Extended Reality (XR) services such as Augmented Reality (AR), Virtual Reality (VR) and Mixed Reality (MR), is expected to increase data traffic significantly, especially in the uplink. Mobile network operators may need to upgrade their infrastructure to support higher bandwidth and lower latency.

Traffic growth can differ greatly between countries depending on local market conditions. In Latin America, the expansion of coverage areas and the acceptance of 4G networks (and subsequently, 5G networks) have been the primary drivers of traffic growth. This is strongly associated with the escalation in smartphone subscriptions and an amplified consumption of data per device. It is projected that the average data traffic per smartphone will escalate to 41 GB per month by the year 2028, with a compound annual growth rate (CAGR) of 25%, as it shown in Figure 4.



Regions	2022	2028	CAGR 2022–2028
🟩 North America	17.4	55	21%
🟧 North East Asia	17	55	21%
🟩 South East Asia and Oceania	12.5	54	28%
🟥 India, Nepal, Bhutan	25	54	14%
🟪 GCC	25	53	11%
🟪 Western Europe	19	52	18%
⬛ Global average	15	46	21%
🟥 Latin America	10.5	41	25%
🟦 Middle East and North Africa[1]	11	38	24%
🟦 Central and Eastern Europe	13	35	18%
🟨 Sub-Saharan Africa	4.6	18	26%

Figure 4. Mobile data traffic per smartphone (GB per month) [2]

4. Methodology / project development

4.1. BBU Pools placement and assignment

The initial problem to be solved focuses on finding the location and number of BBU pools required to serve the considered network in Cartagena, and the assignment of each cell to a BBU pool. To determine the potential locations of the BBU pools, all antenna locations were considered in order to take advantage of these locations and not have to rent in new locations, minimizing costs. In total, 168 possible BBU pool locations were considered.

To determine the number of BBU pools and their locations, an Integer Linear Programming (ILP) model was developed. As mentioned in Section 3.2, ILP is a technique suitable for solving this problem. This method requires some inputs and objectives to find the optimal solution. In this case, the objective is to determine a set of BBU Pools that minimises latency and cost by assigning each cell to a BBU Pool. Table 2 and Table 3 show the inputs and outputs of the ILP model.

Input parameter	Description
$N: \{N_1, N_2, \dots, N_n\}$	Set of all cells
$C: \{C_1, C_2, \dots, C_m\}$	Set of all potential BBU Pools
$B: \{B_1, B_2, \dots, B_n\}$	Bandwidth demand of cells
V_c	Bandwidth capacity of potential BBU Pool c
D	Max distance between cells and BBU Pools
p_e	Cost of Optical Fiber (€/km)
p_c	Cost of BBU Pool (€/year)
$d(n, c) \to n \in N,\, c \in C$	Distance from a cell to a potential BBU Pool

Table 2. Input parameters of the ILP Model.

The following equation is used to calculate the maximum distance between the RRHs and the BBU pools (fronthaul distance):

$$\boldsymbol{D_{FH(km)} = V \cdot {}^{\delta_{RTT}}/_{2}} \tag{1}$$

where:

$$\boldsymbol{V = 200\ {}^{km}/_{ms}} \tag{2}$$

is the light speed in optical-fiber and δ_{RTT} is the two-way delay (Round-Trip Time: RTT) in Fronthaul connection. The acceptable two-way delay for fronthaul links in 5G networks depends on the specific requirements of the application or service being provided. Typically, a two-way delay of $200\ \mu s$ is considered [16]. However, as 5G networks aim to provide low latency and high reliability, the acceptable two-way delay is typically kept to a minimum. For this model, a two-way delay of $50\ \mu s$ (3) was considered, resulting in a maximum distance *D* of $10\ km$.

$$\boldsymbol{\delta_{RTT} = 0.05\ ms} \tag{3}$$

Output parameter	Description
x	Binary variable equal to 1 if a cell is assigned to a BBU Pool
δ	Binary variable equal to 1 if a BBU Pool is selected by at least one cell
$BBUP'$	Set of BBU Pools used in the network

Table 3. Output parameters of the ILP Model.

Constraints:

- Distance constraint: Distance in connection between a cell and its BBU Pool must be equal or lower than maximum distance D (1).

$$\sum_{c \in C} (\boldsymbol{x}(\boldsymbol{n},\boldsymbol{c}) \cdot \boldsymbol{d}(\boldsymbol{n},\boldsymbol{c}) \leq \boldsymbol{D}) \tag{4}$$

- BBU Pool capacity constraint: Aggregated BW assigned to BBU Pool must be equal or lower than its processing capacity, V_c.

$$\sum_{n \in N} (\boldsymbol{x}(\boldsymbol{n},\boldsymbol{c}) \cdot \boldsymbol{B}_{\boldsymbol{n}}) \leq \boldsymbol{V}_{\boldsymbol{c}} \tag{5}$$

- Single assignment constraint: Each cell is assigned to exactly one BBU Pool.

$$\sum_{c \in C} \boldsymbol{x}(\boldsymbol{n},\boldsymbol{c}) = \boldsymbol{1} \tag{6}$$

- Active BBU Pool constraint.

$$\boldsymbol{x}(\boldsymbol{n},\boldsymbol{c}) = \leq \boldsymbol{\delta}_{\boldsymbol{c}} \tag{7}$$

Objectives:

- Distance minimization: Minimizes the distance for connections between a cell and its assigned BBU Pool.

$$\boldsymbol{min}\, \boldsymbol{z}_{\boldsymbol{d}} = \sum_{n \in N} \sum_{c \in C} (\boldsymbol{x}(\boldsymbol{n},\boldsymbol{c}) \cdot \boldsymbol{d}(\boldsymbol{n},\boldsymbol{c})) \tag{8}$$

- Cost minimization objective: Minimizes the OPEX.

$$\boldsymbol{min\, z_c = \sum_{c\in C}(\delta_c \cdot p_c) + \sum_{e\in E}\sum_{n\in N}\sum_{c\in C}(dist(n,c)\cdot p_e)} \tag{9}$$

- The complete optimization is the minimization of the sum of:

$$\boldsymbol{min\ (z_c + z_d)} \tag{10}$$

The order of the two minimization objectives is quite different (km vs €), so it is necessary to implement weights *alpha* and *beta* for each objective and normalization, in order to avoid giving more importance to the objective of higher order magnitude, in this case the cost. In this case, since the magnitude of the cost is much greater than that of the distance, one way to take this into account is to assign a higher value to beta than to alpha. Each objective is divided by the optimal value, with the new objective being the sum of both.

$$\boldsymbol{min\ (\alpha * (z_d/optimal\ z_d) + \beta * (z_c/optimal\ z_c))} \tag{11}$$

This model was implemented in MATLAB, which has ILP capabilities. ILP is a type of optimization problem where the goal is to find the best solution among a set of feasible solutions, where some or all the variables must take on integer values. In other words, it is like solving a math problem, but with the added requirement that the variables must be integers. This type of problem is often used in operations research, supply chain management, and other areas where decisions must be made about how to allocate resources.

4.2. Network growth implemented model

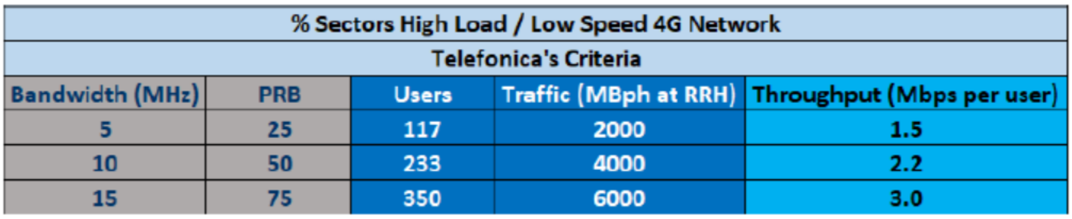
As mentioned in the State of the Art, the growth of mobile networks is difficult to model because there are a variety of factors that can influence its evolution, making it difficult to predict its trajectory accurately. In [17], Castro Gonçalves used a fixed growth factor per year to predict traffic in his model. For this project, a growth factor of 1.25 per year is used to forecast network growth, considering the growth forecast of Ericsson [2] for Latin America, as shown in Figure 4. A 5-year forecast was also considered, taking into account the above forecast and the time between the introduction of mobile technologies.

4.3. Solutions for traffic growth forecasting

4.3.1. Assignment of new carriers

In mobile networks, congestion is a frequent problem that can slow down data transmission. Detecting and dealing with congestion is essential to ensure efficient data flow and prevent service interruptions. A common way to improve congestion is to deploy new carriers in the congested node sectors, providing more traffic capacity.

Figure 5 illustrates Telefonica's criteria for determining whether a sector is congested based on bandwidth and Physical Resource Blocks (PRBs). The PRB is the basic unit of frequency and time resources in 4G and 5G networks. PRBs are used to allocate radio resources to users on the network. The number of available PRBs is directly proportional to the available bandwidth. Each PRB has a bandwidth of 180 KHz. For instance, taking into account that 10% of the bandwidth is for guard band (narrow frequency that separates two ranges of wider frequency, to avoid interference), 25 PRBs are available for a 5 MHz carrier, as shown in equation (12).



% Sectors High Load / Low Speed 4G Network				
Telefonica's Criteria				
Bandwidth (MHz)	PRB	Users	Traffic (MBph at RRH)	Throughput (Mbps per user)
5	25	117	2000	1.5
10	50	233	4000	2.2
15	75	350	6000	3.0

Figure 5. Criteria of high load in Telefonica Colombia.

Telefonica Colombia has limits based on number of users, traffic or throughput where they consider a sector to have high load, not just in percentage of PRB usage. According to these limits, they have determined that there is poor performance in the network for users.

$$PRBs = {}^{4.5\ MHz}\!/_{180\ KHz} = 25 \tag{12}$$

The operator has available a 10 MHz carrier in the 850 MHz band and a 15 MHz carrier in the 2100 MHz band, as shown in Table 1. For this project, the cells with high load based on traffic were detected and a new carrier was assigned in the sector. If the cell is of 10 MHz, a new carrier of 15 MHz was assigned, and if the cell is of 15 MHz, a new carrier of 10 MHz was assigned. Then, the traffic of the two carriers of a sector was distributed with a 60% for the 15 MHz carrier and 40% for the 10 MHz carrier. Figure 6 shows a diagram of this process.

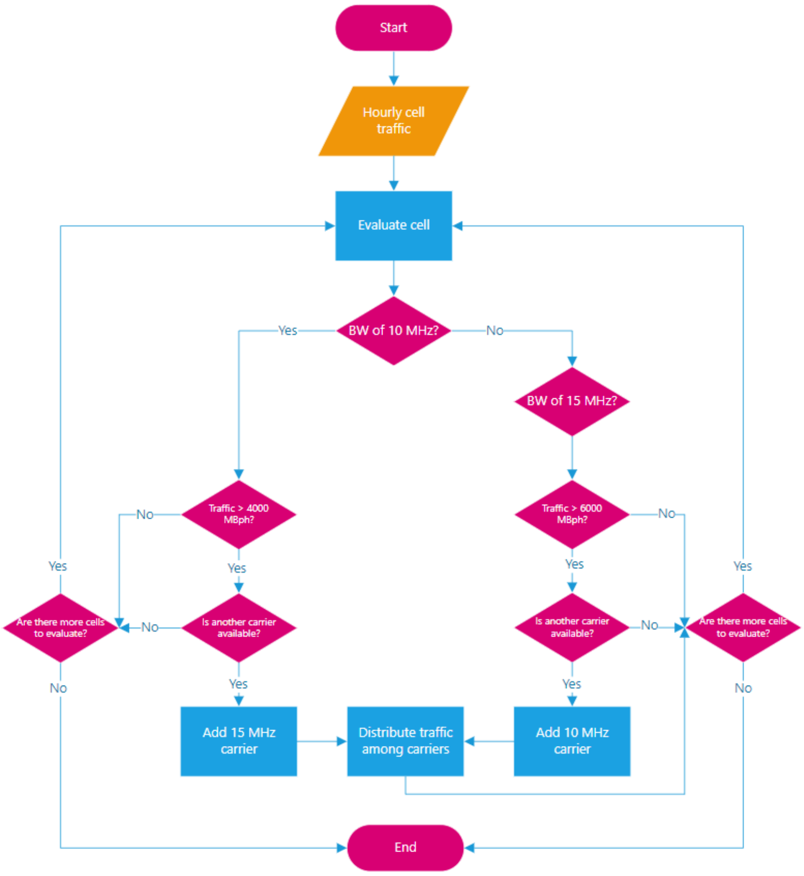


Figure 6. Assignment of new carriers Diagram.

4.3.2. Implementation of new 5G cells

To support the current congestion in the 4G network and the growing traffic, the 5G network deployment was proposed for this thesis, considering the current antenna locations. Currently, the 5G network is not commercially implemented in Colombia, but one of the frequencies reserved for 5G is 3500 MHz, which corresponds to band n78 for 5G using Time Division Duplex (TDD), and it is the one that will be used in this scenario [18]. TDD is a method of wireless communication in which a single frequency band is shared between the uplink and downlink transmissions by dividing the time into alternating uplink and downlink slots. Table 4 shows the characteristics of the 5G technology to be implemented. This research aims to analyze the feasibility of 5G deployment in Colombia and its potential impact on the telecommunications industry.

Frequency	3500 MHz
Band	n78
Band type	TDD
Bandwidth	100 MHz

Table 4. Characteristics of the 5G technology to be implemented.

For this thesis, a 5G mobile penetration rate of 20% in Colombia is considered [19]. This means that 20% of mobile devices would support 5G technology when it would be available. A growth factor of 1.25 per year is also assumed, as for 4G.

5. Results

5.1. BBU Pools placement and assignment optimization

First, the developed MATLAB program was used to find an optimal number of BBU pools in the initial network, with real data traffic. Since the potential locations of the BBU pools are also the locations of the nodes, the optimal solution in terms of latency would be one BBU Pool in each location, but this would be much more expensive, and it would be the same as the traditional RAN. The objective is to find an optimal solution in terms of latency and cost.

The model produced a result of 17 BBU pools out of 168 possible locations, as shown in Figure 7. The distribution of cells per BBU pool is shown in Figure 8. In addition, Figure 9 shows the maximum traffic handled by each BBU pool. It is possible to observe the difference in traffic and cells handled by each BBU pool, but the goal of the distribution is to optimize the latency/cost trade-off, not to balance the BBU pools traffic. For example, BBU Pool 1 has more cells and traffic because it is located in the downtown area where cell density is higher. On the other hand, BBU Pool 10 has less traffic and cells because it is located on the northern edge of the network.

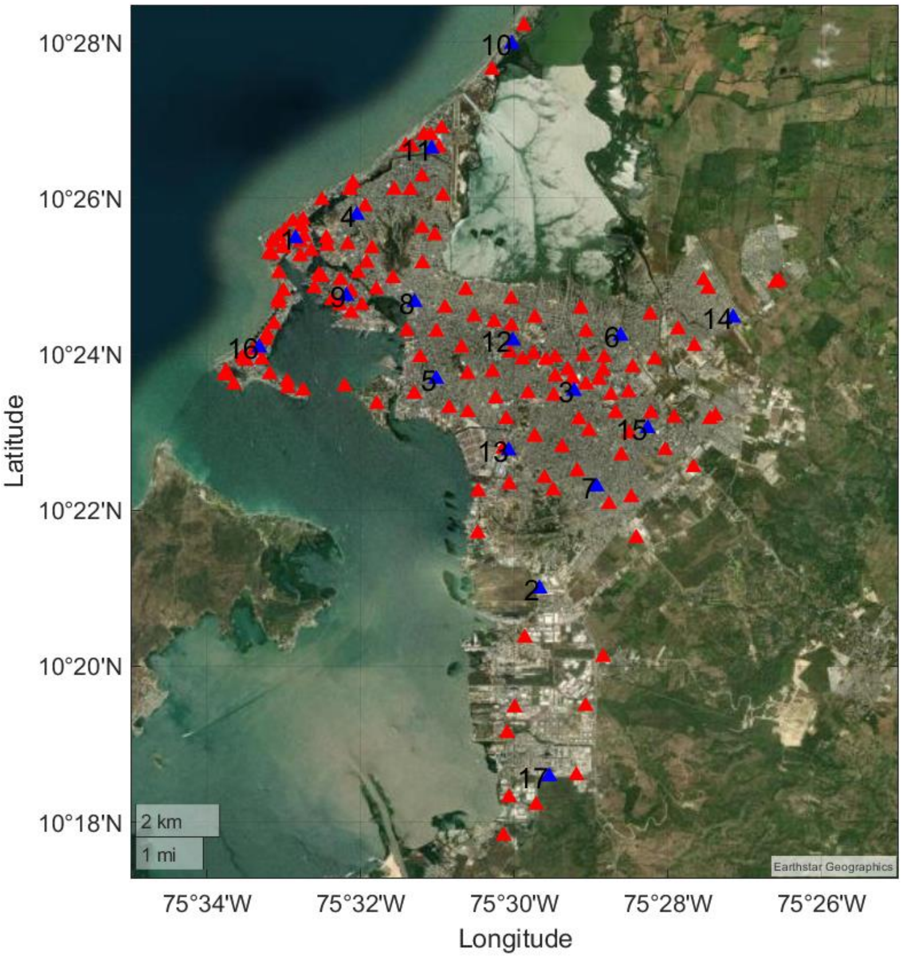


Figure 7. Obtained location of BBU Pools (in blue). RRHs in red.

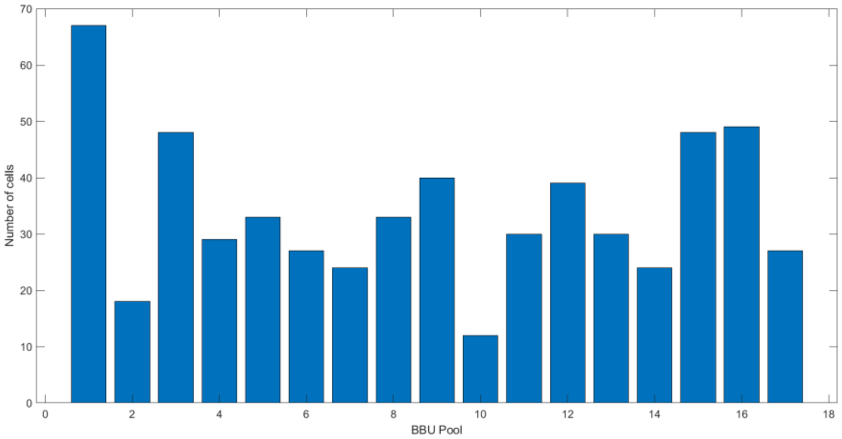


Figure 8. Number of cells per BBU pool.

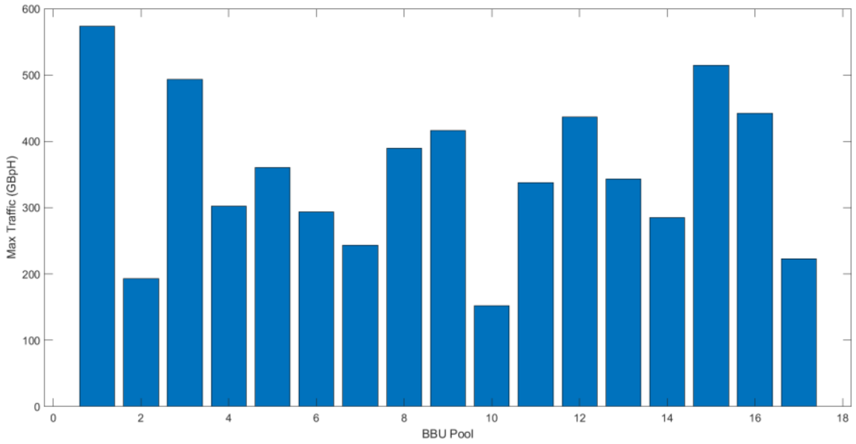
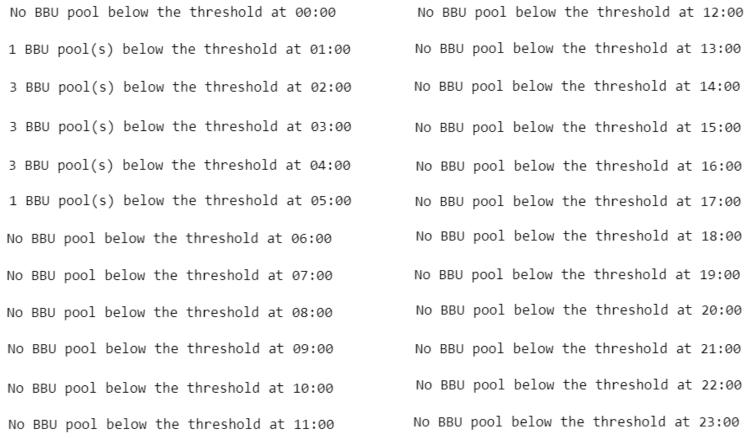


Figure 9. Maximum traffic carried per BBU pool.

The next step is to analyse the traffic of the BBU pools every hour and determine which ones have traffic below a given threshold. These BBU pools will be shut down during that hour to optimize resources and save energy. Figure 10 and Figure 11 show the results of the initial scenario.



```
No BBU pool below the threshold at 00:00      No BBU pool below the threshold at 12:00
1 BBU pool(s) below the threshold at 01:00    No BBU pool below the threshold at 13:00
3 BBU pool(s) below the threshold at 02:00    No BBU pool below the threshold at 14:00
3 BBU pool(s) below the threshold at 03:00    No BBU pool below the threshold at 15:00
3 BBU pool(s) below the threshold at 04:00    No BBU pool below the threshold at 16:00
1 BBU pool(s) below the threshold at 05:00    No BBU pool below the threshold at 17:00
No BBU pool below the threshold at 06:00      No BBU pool below the threshold at 18:00
No BBU pool below the threshold at 07:00      No BBU pool below the threshold at 19:00
No BBU pool below the threshold at 08:00      No BBU pool below the threshold at 20:00
No BBU pool below the threshold at 09:00      No BBU pool below the threshold at 21:00
No BBU pool below the threshold at 10:00      No BBU pool below the threshold at 22:00
No BBU pool below the threshold at 11:00      No BBU pool below the threshold at 23:00
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Figure 10. Number of BBU Pools with traffic below the threshold.

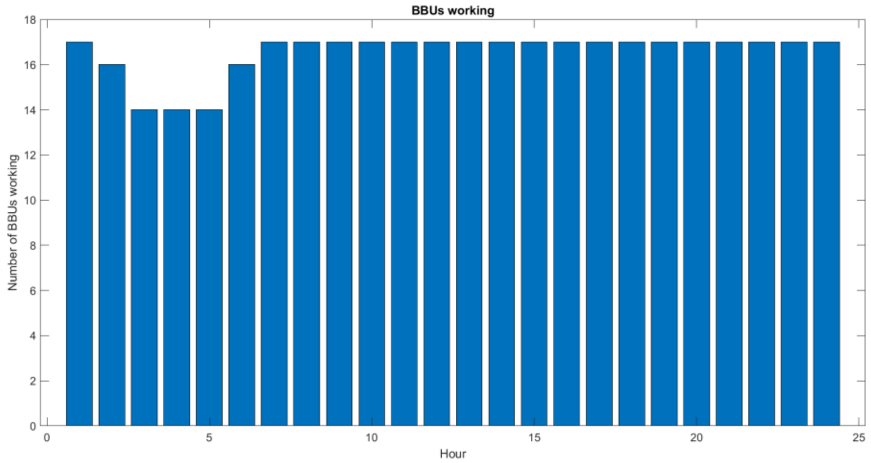

Figure 11. Number of BBUs activated per hour.

Figure 12 shows the location of the BBU pools and cells at 1:00. The BBU pool at the top center is now turned off, with 16 BBU pools working instead of 17. The assignment of cells to the remaining 16 BBU pools is done by running the ILP Model again, which gives the best result in terms of delay. Figure 13 shows the location of the BBU pools and cells at 2:00. In this case we have 3 BBU pools off, the BBU Pools further south are also off.

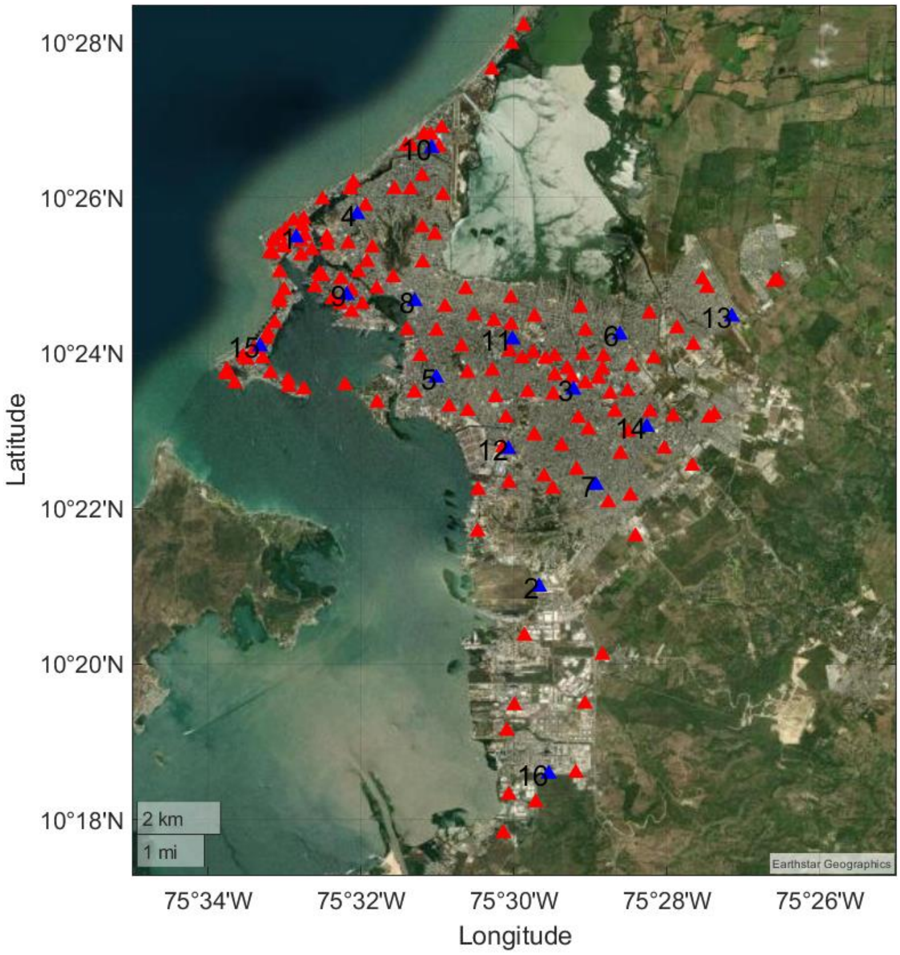

Figure 12. Location of BBU Pools (in blue) at 01:00.

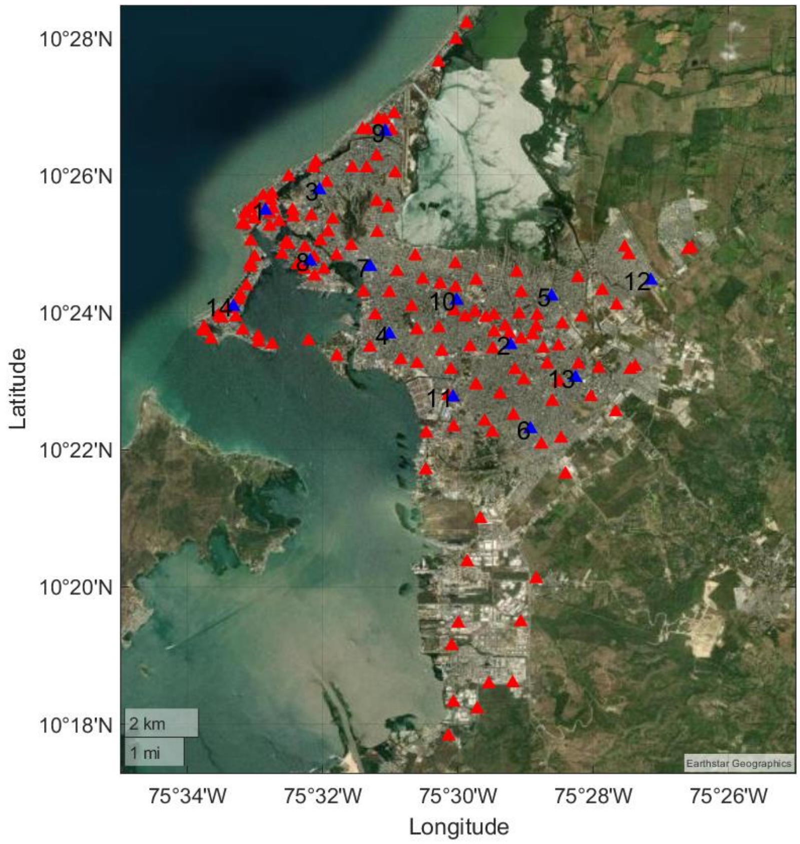

Figure 13. Location of BBU Pools (in blue) at 02:00.

Thus, it is possible to save energy and resources during these hours, without affecting the performance of the network. Figure 14 and Figure 15 show the average and total delay of each RRH of the network. This is calculated with the Round-Trip Time (RTT), as shown in equation (1). As expected, the average delay increases during the hours when some BBU pools are turned off.

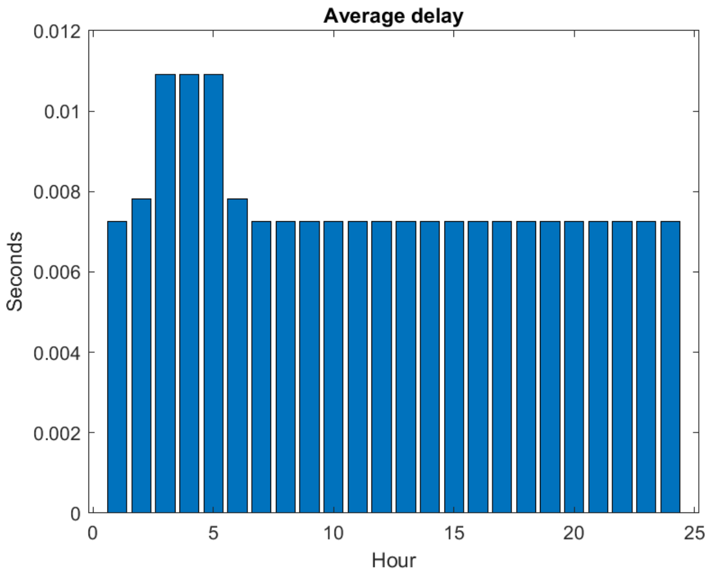

Figure 14. Average delay per hour.

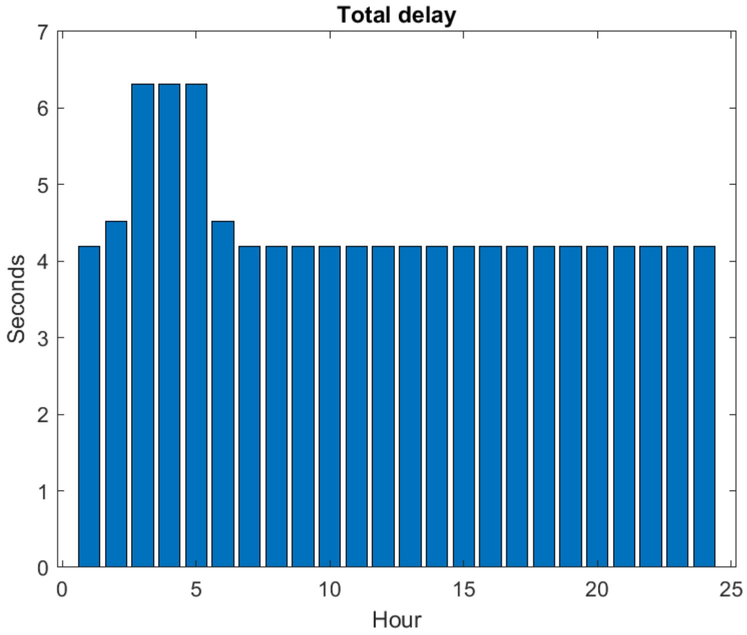

Figure 15. Total delay per hour.

On the other hand, there is a gain in energy and money savings as some BBU pools are turned off. Figure 16 and Figure 17 show the difference in Capital Expenditure (Capex) and Operational Expenditure (Opex) for the initial network, the C-RAN deployment and the implementation of the hourly BBU pool shutdown. Significant savings in both Opex and Capex can be seen with the implementation of C-RAN. Savings of approximately 71% in Capex and 56% in Opex are observed. With the implementation of the hourly shutdown, the OPEX savings is approximately 1627 Euro per year. Capex and Opex are calculated as show in equations (13) to (16).

$$\boldsymbol{CAPEX_{without\ C-RAN} = p_{inst} * c} \tag{13}$$

being p_{inst} the installation price of a BBU and c the number of BBUs.

$$\boldsymbol{CAPEX_{with\ C-RAN} = p_{inst} * c + d * pe} \tag{14}$$

being p_{inst} the installation price of a BBU pool, c the number of BBU pools, d the km of optical fiber installed and pe the installation price of optical fiber per km.

$$\boldsymbol{OPEX_{without\ C-RAN} = (p_{ls} + p_{en}) * 12 * c + (p_{main} * c)} \tag{15}$$

Being p_{ls} the cost of one month of BBU space rental, $\boldsymbol{p_{en}}$ the cost of energy per month, $\boldsymbol{c}$ the number of BBUs and $\boldsymbol{p_{main}}$ the cost of maintenance per year.

$$\boldsymbol{OPEX_{with\ C-RAN} = (p_{ls} + p_{en}) * 12 * c + (p_{main} * c) + \left(p_{ls_{RRH}} * c_{RRH}\right) * 12} \tag{16}$$

Being $\boldsymbol{p_{ls}}$ the cost of one month of BBU pool space rental, $\boldsymbol{p_{en}}$ the cost of energy per month, $\boldsymbol{c}$ the number of BBU pools, $\boldsymbol{p_{main}}$ the cost of maintenance per year, $\boldsymbol{p_{ls_{RRH}}}$ the cost of rental space of locations with RRH without BBU pool and c_{RRH} the number of locations with RRH without BBU pool.

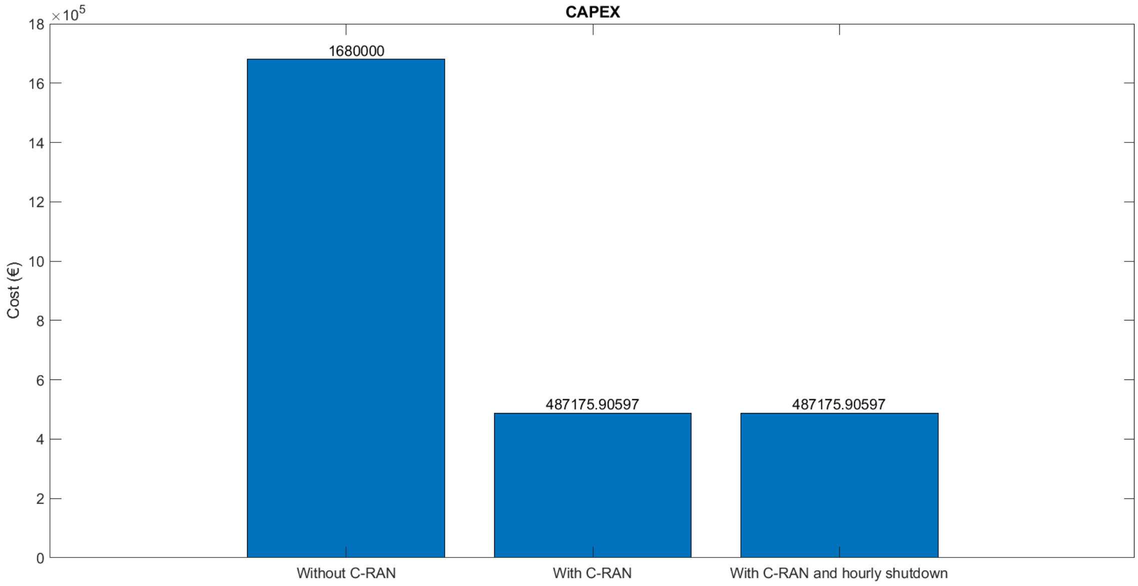

Figure 16. Difference in CAPEX for the initial network, the C-RAN deployment and hourly BBU pool shutdown.

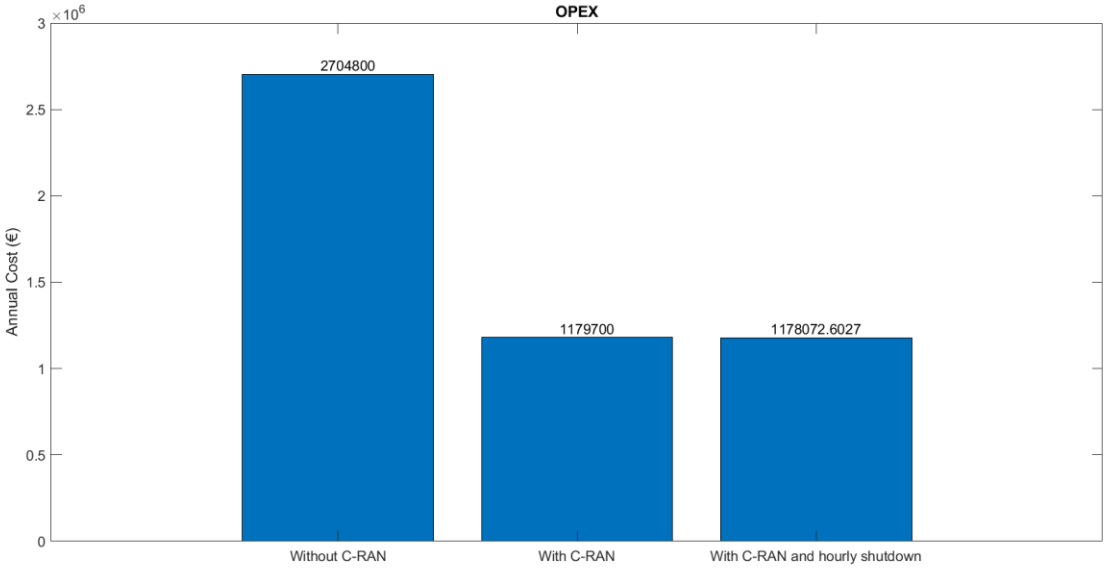

Figure 17. Difference in OPEX for the initial network, the C-RAN deployment and hourly BBU pool shutdown.

5.2. Solutions for traffic growth forecasting

5.2.1. Assignment of new carriers

According to the methodology explained in Section 4.3.1, the following results were obtained. For the original network of 578 cells, 353 were found to show a 61.1% of congestion and need a new 4G carrier to solve it. After assigning the new carriers, the network has 931 cells with 138 new cells of 15 MHz and 215 new cells of 10 MHz.

With this new distribution, it is necessary to recalculate the number of BBU pools and their optimal location. After calculation of BBU Pools with ILP, 21 BBU pools are required instead of the original 16. Their locations are shown in the Figure 18.

After additional carrier implementation, there are still 192 congested cells. For this scenario, only two 4G carriers are available. It is necessary to consider other solutions. Section 5.2.2 discusses this scenario after the deployment of 5G.

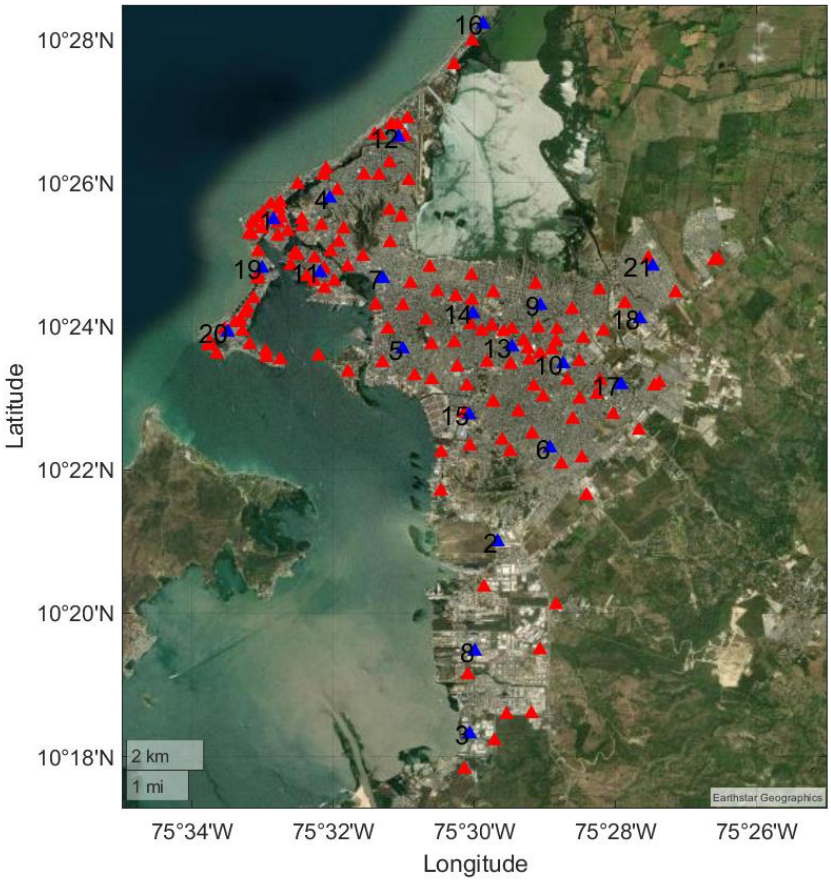

Figure 18. Obtained location of BBU Pools (in blue), after assignment of new carriers.

As mentioned in Section 4.2, a network growth factor of 1.25 per year is considered.

For the next year (year 1), 401 cells will need more capacity, but it is only possible to deploy new carriers in 61 of them. Finally, the network would be 992 cells after the expansion. This scenario requires 22 BBU pools, one more than the previous one. Their locations are shown in Figure 19.

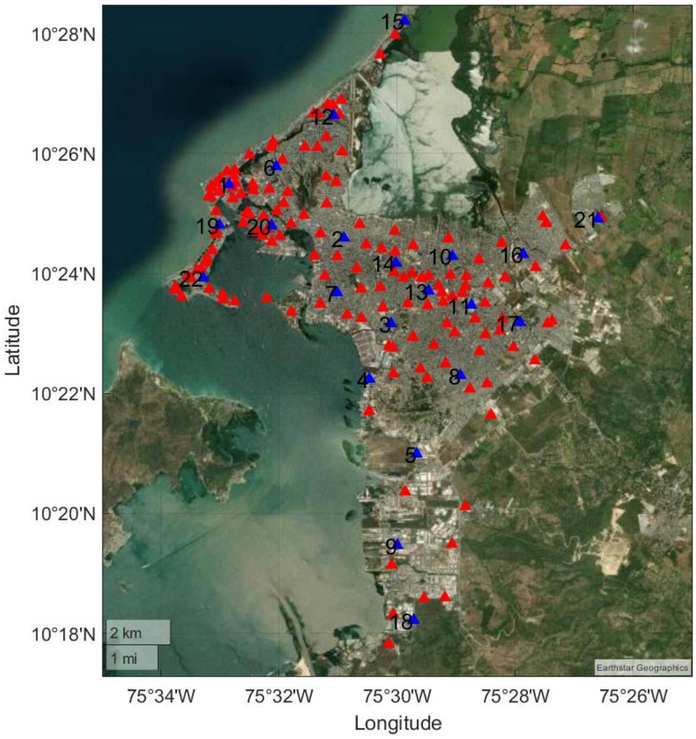

Figure 19. Obtained location of BBU Pools (in blue), after assignment of new carriers forecast year 1.

For the next year (year 2), 545 cells will need more capacity, but it is only possible to deploy new carriers in 45 of them. Finally, the network would be 1037 cells after the expansion. This scenario requires 23 BBU pools, one more than the previous one. Their locations are shown in Figure 20.

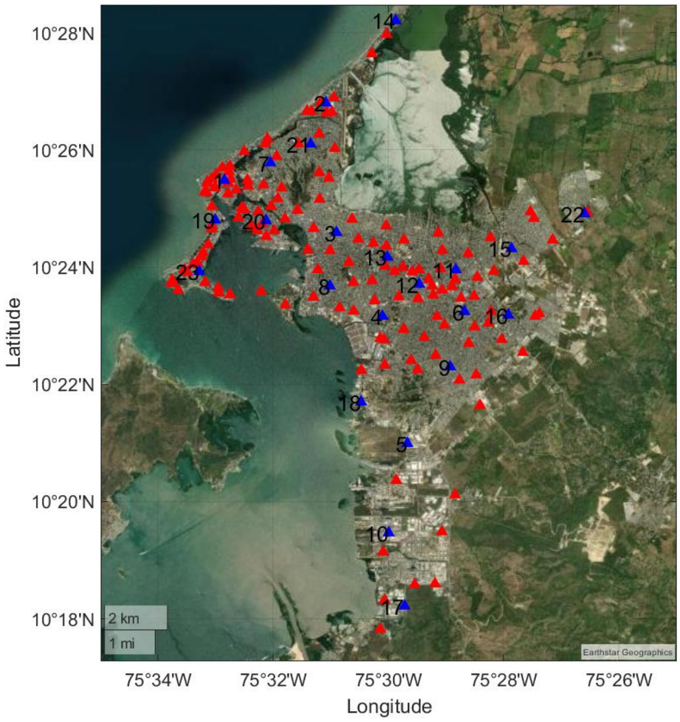

Figure 20. Obtained location of BBU Pools (in blue), after assignment of new carriers forecast years 2, 3 4 and 5.

For the next year (year 3), 670 cells will need more capacity, but it is only possible to deploy new carriers in 37 of them. Finally, the network would be 1074 cells after the expansion. This scenario requires 23 BBU pools, the same than the previous one.

For the next year (year 4), 789 cells will need more capacity, but it is only possible to deploy new carriers in 23 of them. Finally, the network would be 1097 cells after the expansion. This scenario requires 23 BBU pools, the same than the previous one.

For the next year (year 5), 849 cells will need more capacity, but it is only possible to deploy new carriers in 11 of them. Finally, the network would be 1108 cells after the expansion. This scenario requires 23 BBU pools, the same than the previous one.

Figure 21 shows the network forecast with the annual growth scenario and the possibility of implementing a 15 MHz carrier and a 10 MHz carrier. It is possible to observe that although more carriers are required every year, it is possible to implement fewer and fewer carriers. This is a major constraint and increases network congestion every year. Therefore, the next chapter discusses solutions based on 5G implementation to address this issue.

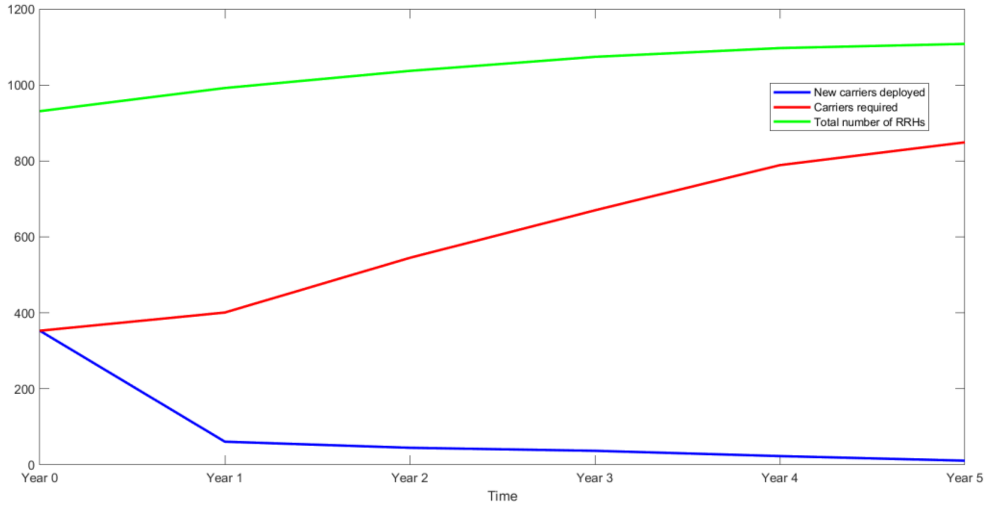

Figure 21. 4G Network forecast with additional 4G carrier implementation.

5.2.2. Implementation of new 5G cells

As mentioned in the previous chapter, a solution to combat 4G network congestion is to deploy 5G cells. After the implementation of 5G cells in the network, the following results were obtained.

For the original network of 578 4G cells, 259 were found to need a new carrier, showing a 44.8% of congestion. Although this is still a high percentage, it is lower than the 61.1% shown in the scenario without 5G. After assigning the new 4G carriers, the network has 837 cells with 95 new cells of 15 MHz and 164 new cells of 10 MHz.

After 4G carrier amplification, there are still 66 congested cells since for this scenario, only two 4G carriers are available. In this scenario, 5G is already deployed, but there is still high congestion in the 4G network. This is due to limitations such as the low penetration rate of 5G mobile devices in the market, leaving 4G traffic high and growing over time.

For the next year (year 1), 286 cells will need more capacity, but it is only possible to deploy new carriers in 94 of them. Finally, the network would be 931 cells after the expansion.

For the next year (year 2), 401 cells will need more capacity, but it is only possible to deploy new carriers in 61 of them. Finally, the network would be 992 cells after the expansion.

For the next year (year 3), 505 cells will need more capacity, but it is only possible to deploy new carriers in 45 of them. Finally, the network would be 1037 cells after the expansion.

For the next year (year 4), 659 cells will need more capacity, but it is only possible to deploy new carriers in 37 of them. Finally, the network would be 1074 cells after the expansion.

For the next year (year 5), 747 cells will need more capacity, but it is only possible to deploy new carriers in 23 of them. Finally, the network would be 1097 cells after the expansion.

Figure 22 shows the comparison in the 4G network forecast with or without 5G deployment, and the possibility of implementing a 15 MHz carrier and a 10 MHz carrier. It is possible to observe that the behaviour is similar, but less carriers required in the 5G scenario. It can be seen that the deployment of 5G was not enough to handle the growth of 4G traffic and that in this scenario other solutions would have to be analysed, such as new 4G nodes in new locations, increasing carrier bandwidth or deploying new 4G carriers.

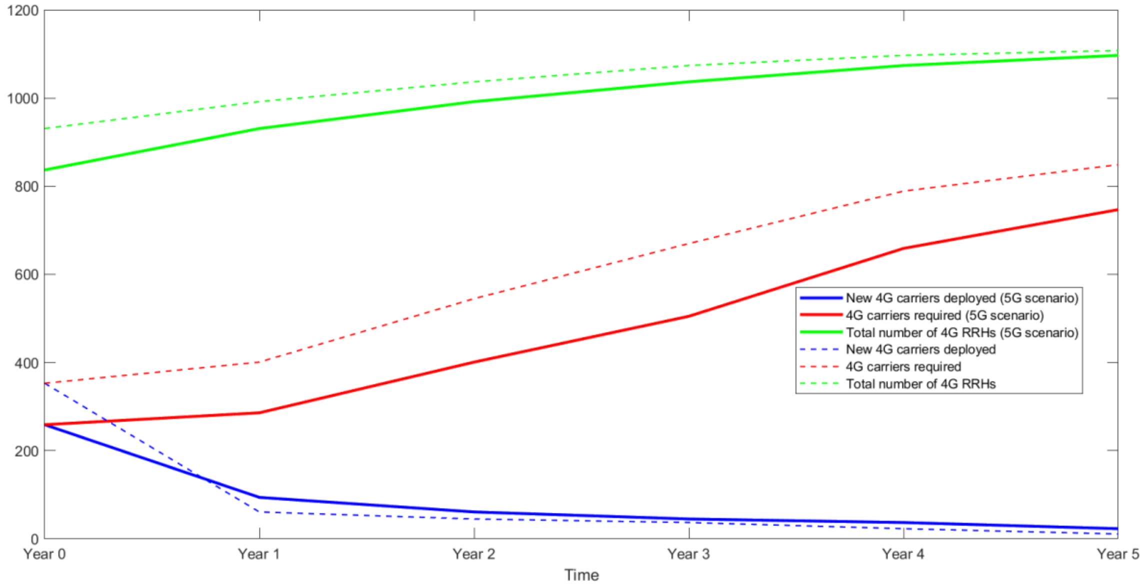

Figure 22. 4G Network forecast with additional 4G carrier implementation and 5G deployment.

6. <u>Conclusions and future development</u>

The proposed methodology for the placement and assignment of BBU pools in mobile networks using Integer Linear Programming (ILP) has been successfully implemented. The ILP model was able to determine the optimal location and number of BBU pools required for the network, as well as the assignment of each cell to a BBU pool, with the objective of minimizing latency and cost.

The results of the ILP model show that the proposed methodology is effective in reducing the cost of deploying BBU pools while maintaining the required level of latency. The model was able to find a solution that uses fewer BBU pools than the traditional method of deploying one BBU pool per cell site, resulting in significant cost savings of up to 71% in CAPEX and 56% in OPEX.

The implementation of the ILP model in MATLAB demonstrated the effectiveness of using ILP for optimization problems in mobile network design. The model can be applied to future network planning scenarios, providing a more efficient and cost-effective approach to network design.

On the other hand, the study found that the traffic load on the 4G network in urban areas of Colombia is growing fast and the existing network infrastructure is struggling to handle this growth. While the implementation of 5G technology offers a potential solution to this problem, the low penetration of 5G devices, especially in developing countries like Colombia, means that it is not yet a viable option for most users. In addition, the capacity of the 4G network still has room for improvement, which could be a reason for mobile operators to delay the deployment of 5G in these countries.

Therefore, it is recommended that further research be conducted to explore alternative solutions to handle the increasing traffic load, such as deploying new nodes in new locations to reduce the load on neighbouring cells, while continuing to improve the capacity of the existing 4G network. Further research can also extend the model to include additional factors such as energy consumption and environmental impact, to provide a more comprehensive approach to network design.

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