A Fuzzy Strategy for Planning Centralized Access Networks in the Installation of Hybrid Fiber Radio Systems

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ABSTRACT 5G networks have arrived and are able to shift paradigms within the areas of connectivity, maintainability, scalability and availability. Their aim is to ensure that users can remain online with their devices at any time and in any place. In light of this, solutions for centralized networks are becoming attractive since they are manageable and low-cost. In these conditions, the use of computing techniques such as fuzzy logic benefits the supervision and planning of networks by optimizing and controlling resources as well as managing the system. However, planning a centralized network tends to raise challenges in the optical sectors that are located between the telecommunications center and the base station. Technologies such as radio over fiber are being examined to meet the demands in the fronthaul market, although they raise many other challenges. For this reason, in this study, we have adopted an intelligent strategy to determine in a balanced way which radio over fiber signals should be allocated in the optical sector. This strategy is implemented using fuzzy logic and may be used in decision making to plan the future of centralized networks. The results show that it is possible to make tradeoffs between the capital expenditure and performance of the system.

INDEX TERMS Radio over fiber, fronthaul, planning, C-RAN, fuzzy logic.

I. INTRODUCTION

The introduction of data services that have increased data network traffic has made operators adjust and optimize a large number of parameters at the base station during the planning stage so that they can understand their full capacity [1].

Thus, recent modifications in the architecture of telecommunications networks tend to reap benefits that allow the expansion of services that seek a greater bandwidth capacity to meet the needs of the growing number of users and emerging services, such as the IoT (Internet of Things).

The first stage of this evolutionary trend was the implementation of a centralized radio architecture in 5G networks, known as C-RAN (Centralized Radio Access Network).

In this architecture, fronthaul is based on the concept of optical wireless communications in which optical fibers are used between the central telecommunications system that hosts the BBU (Base Band Unit) and BS (Base Station), and this architecture also contains the RRH (Radio Remote Unit); this concept is addressed in [2].

The required conditions of 5G are related to latency, capacity, low costs, communication and profitability and can allow a network to be inspected from point to point. However, from the standpoint of practical application, there is a precondition that the solutions must reduce the implementation and maintenance costs without impairing high-capacity connectivity for the end user and thus making scalability in the system possible.

The concern about ensuring that efficient concepts are implemented for optimization and resource scheduling is discussed in [3] through the use of a new architecture called C-RoFN (cloud-based radio over optical fiber network). This architecture optimizes resources in various strata and adds new users by means of software-defined networking. This
tendency stimulates the services of operators, as it is a means of reducing OPEX and CAPEX. Thus, it is of crucial importance to design 5G transport networks and the corresponding NGFIs (Next-Generation Fronthaul Interfaces) to address the essential requirements of these technologies [4].

One of the alternative ways of supporting advanced wireless technologies that should be considered is RoF (radio over fiber), which can achieve transmission efficiency either in the analog format (A-RoF) or in the digital format (D-RoF). In addition, there is the IF-RoF that uses radio signals with a lower frequency for modulating light before being transported over the optical link. The performance in the link depends on the spectrum allocation for a particular BS, which can vary in terms of distance, bandwidth, number of antennas, etc. Hence, adopting a strategy for suitably allocating the signal in the fronthaul depends on planning the network and deciding how efficiency can be ensured in a holistic way.

In this context, the aim of 5G is to revolutionize the planning of high-performance networks. This entails the use of computational intelligence to act as a driving force for flexibility both in SE (spectral efficiency) and EE (energy efficiency) and in arranging the allocation of architectures that meet the required conditions. Additionally, these networks offer alternative choices for RRM (Radio Resource Management), MM (Mobility Management) and orchestration based on a C-RAN [4], [5]. In the domain where 5G networks seek to meet the required conditions for scalability, methodologies such as elastic optical networks are becoming more autonomous and intelligent. These employ computational intelligence algorithms as dynamic fuzzy clustering methods for the allocation of resources based on the requirements of users in future network services [6].

Thus, although traditional strategic planning for networks generally structures wireless networks separately from transport networks (owing to questions related to scalability, better cost-effectiveness, maintenance and performance), this is becoming an inefficient method for the future planning of wireless networks. In light of this, planning mobile and transport networks at the same time, while taking the requirements and possible drawbacks into account, makes it possible to conduct a better analysis of installation costs, scalability, and performance, especially with regard to the selection of suitable technologies and architectures.

With this purpose in mind, in this paper, we investigate the applicability of RoF architectures to the fronthaul, with the aim of putting forward a cost-benefit relationship for the C-RAN architecture. This entails making use of fuzzy logic for decision making with regard to one of the RoF variations and conducting a critical analysis of its criteria, its installation costs, its linkage range, the simplification of the base station and the performance of the 5G link.

The fuzzy model applied in this paper establishes a set of rules of inference for the range of inputs to ensure that the process can carry out planning for 5G fronthaul. The results provide the basis for a configuration of the BBUs and RRHs through the specification of schematic diagrams of the RoF system, given the strategies for installing the network with regard to scalability, availability and interoperability of a future 5G network. Employing the recommended methodology results in the RoF architecture with the best system in terms of the performance of the link, installation costs and configuration of the RRH. Thus, the results provide the basis for the strategies required for installing the optical fronthaul, which include cost benefits for the technologies and are essential for the implementation of 5G networks in the future. This is due to the fact that network scenarios generally consist of a set of systems that must coexist when faced with several possible kinds of installations. Thus, in the context of installing and planning both new and pre-existing infrastructures based on RoF and C-RAN, together with the use of fuzzy logic, the planned methodology is becoming attractive. This is particularly due to its possible use in large urban areas as well as its features and degrees of pertinence, which make it a novel feature in terms of its coverage.

This paper is structured in the following way: In Section II, there is a survey of the challenges raised by the 5G C-RAN project, and its subtopics include studies that examine the feasibility of RoF and its technical limitations caused by the requirements of the network. Section III sets out the methodology used for designing the model based on fuzzy logic, and the subtopics feature the routes, the list of rules of inference and finally, the outputs. There is a case study in Section IV in an urban setting, with a wide range of opportunities for configuring possible architectures that can be analyzed. An analysis of the results is conducted in Section V by applying the scenario of the case study to the planned fuzzy model, and finally, the study is concluded in Section VI with a summary of the findings.

II. CONTEXTUALIZATION OF THE PROBLEM
Before the aims of this study can be fully understood, a sequential view of the strategies that have to be analyzed is needed. These kinds of paradigms are currently being studied as a means of ensuring that the conditions required by 5G network are met.

A. 5G AND ACCESS TO CENTRALIZED NETWORKS
Distributed systems must have a capacity for high availability, connectivity, maintainability, scalability and interoperability for a wide range of networks and applications. In the environment in which 5G seeks to operate, a number of challenges arise, particularly those concerning the objectives with regard to the bandwidth requirements for supporting a high data rate and low latency for the applications of the end user. There are other key issues concerning the infrastructure, energy efficiency, spectrum efficiency and low costs that are the objects of studies and include C-RANs. In view of this, fiber-optic links between the BBUs and RRHs are generally used to deal with these requirements.

In the C-RAN architecture, the complex functionalities that require more processing are carried out in the BBUs located in the central office, while the RRH, which is located in
the antenna itself, is responsible for the transmission, reception and amplification of the users’ signal. In the optical distribution network (ODN) (designated the fronthaul), the connection between the BBU and RRH is made by means of a digital radio interface in the Common Public Radio Interface (CPRI) or Open Base Station Architecture Initiative (OBSAI) for digital signals. Figure 1 describes the C-RAN architecture with its main components: BBU, ODN and RRH.

B. HYBRID FIBER RADIO SYSTEMS
Wireless optical networks that are integrated by means of solutions based on RoF systems differ in their format and might be analog or digital. Even though they are not a recent technology, they are becoming more widespread and are being investigated for the C-RAN architecture on account of their benefits and drawbacks.

Several studies have addressed the concept initially introduced by China Mobile [7], which is currently being adopted by several operators. In [8], there is an examination of the opportunities provided by the use of D-RoF in the context of C-RAN for LTE-A (Long Term Evolution).

One of the main benefits is the capacity for spectrum efficiency since the framework for processing base stations is centralized in a physical BBU located in telecommunications centers; this makes it easy to share the signal, traffic data and information in the state channels of the users that are actively using the system [9].

At all events, the implementation of an optical transport system depends on the application scenario, owing to the requirements of optical bandwidth, the complexity of the system, energy consumption, the linearity conditions and basic concerns related to ADC/DAC.

In this context, the authors of [10] investigate factors related to costs, the architectural BS design and transmission capacity, and other key features involved in radio-over-fiber transmission to analyze the configuration of the link between the CO and BS. These kinds of factors can influence the network infrastructure for both rural and urban environments [11]. Moreover, in the results shown, there is a reduction of up to 65% of energy consumption in urban areas and up to 40% in rural areas.

With regard to energy efficiency in RoF systems, in particular in denser urban and territorially larger areas where microcells are used, analog transport systems are more efficient than digital transport in terms of energy use. In other words, among the schemes investigated, RF over analog fiber technology is more efficient in terms of energy consumption [10], [12], and this has an impact on OPEX. Follows, the equipment that make up the link of the RoF schematics: in D-RoF (ADC/DAC, DPD, Clock, Management, Small signal, amplifier, Power amplifier, Feeder, Power supply and Cooling), IF-RoF (Clock, management, RF unit, Power amplifier, Power supply and Cooling) and A-RoF (Power amplifier, Power supply and Cooling).

When the costs of CAPEX/OPEX are compared between D-RoF and A-RoF, according to [13], A-RoF consistently has an advantage because of the high facility charges levied by the RoF digital links in relation the financial values and the energy consumption of equipment, taking into account the devices that constitute them. That study states that unless there is a real change in industry in the medium or long term with regard to obtaining an accessible price for photonic devices requiring high-speed analog-to-digital conversion, A-RoF remains the most attractive alternative for building a new fiber-based cellular backhaul.

One of the main issues addressed by telecommunications operators concerns the way in which radio signals are transmitted between the BBU and RRH. However, in [14], which refers to RoF, there are several schematic diagrams with technologies that have peculiar features since the details of the configurations are altered and have a direct effect on the fronthaul. These are based on the following: the signal format, chromatic dispersion, transmission distance, simplification of BS, linearity, cost of optoelectronic devices and performance in the link.

Thus, it can be determined from these comparisons that A-RoF links provide a simpler configuration than D-RoF in the BS. However, this requires using more expensive optoelectronic devices, and the nonlinear distortions and the chromatic dispersion effects impair the link performance. In view of this, A-RoF is only efficient for short-distance transmission. On the other hand, D-RoF can be cost-effective in EO/OE converters, owing to the digitization of the signal for the optical carrier, which results in a more complex structure for the BS.

Given the concerns about fiber radio systems, it should be noted that these schematic diagrams can either coexist with each other or with other systems, as shown in [15]. In view of this, an analysis must be conducted from the perspective of network planning with a view to ensuring a strategic implementation of the network for 5G.

C. PLANNING STRATEGIES
The planning of this architecture must be based on the essential features of the C-RAN, and its objective is to achieve the best possible network performance, especially with regard to operators’ business services strategies. These
include the following: a) the minimization of installation costs together with an optimization of parameters, b) the maximization of the capacity to increase the number of users who can be catered for by these services, c) the maximization of coverage and d) the minimization of energy consumption.

In this context, [1] conducts a comprehensive research analysis on planning 5G networks, which is based on academic and business studies. In [16], a comparative analysis is carried out on the installation costs of using the CPRI, Physical Layer Split (PLS) and A-RoF in the fronthaul, and in this way, establishing an optimization framework for planning a C-RAN, with the aim of reducing the total cost incurred by the BBU, fronthaul and RRHs.

D. THE DECISION STRATEGY

A case study must be evaluated before planning and effectively operating 5G networks, and it must be ensured that this is done in an orchestrated manner – a process that covers different domains, optimization methods and mathematical modeling, such as ILP (integer linear programming), which in this case are the basic ways to find solutions to optimization problems. This assessment is required since as the size of the problem increases, linear programming will not be able to find an ideal solution [17], and often, heuristic methods are used [18].

It is essential for cellular networks to note variations in the environment, take measures in the control plane, and duly be able to configure the networks. Thus, in the light of these kinds of convergences, there is a likelihood that pathways will arise that can lead to AI (artificial intelligence) as an alternative means of learning the variations, classifying the problems, predicting future challenges and finding possible solutions by interacting with one’s own particular environment [5].

Among these factors, machine learning is one of the most important subfields of AI. Depending on the nature of the objects and signals used in a machine learning system, the agent will generally be supplied with examples of inputs and outputs and will seek to determine the general rule that will map the inputs and outputs.

The use of fuzzy logic for decision making has been employed in different situations for the planning of network access deployment, especially owing to its simplicity, ease of implementation and suitable return - given the problems it has to solve. This approach can find solutions that are able to meet the requirements of the network in a satisfactory way. With regard to this, previous studies [19]-[22] are examples of how fuzzy logic can be used for decision making, either for implementing algorithms for handover, allocating routing protocols for flying ad-hoc networks (FANET) or the allocation of unmanned aerial vehicle (UAV) to overcome the problem of congested areas where there is a high volume of traffic data.

In light of the review outlined here, it should be noted that research studies on radio-over-fiber systems (especially those currently being carried out) seek to show both the benefits and drawbacks of the two main approaches: A-RoF and D-RoF.

On the basis of the analyses, it is clear that owing to the demand arising from the specifications of 5G (largely as a result of a better allocation of resources), RoF systems are being exploited so that they can be used within the new architecture. Moreover, several scenarios might be possible depending on the geographical layout and the application of the BS.

In the case of planning, there is an opportunity to use learning techniques to decide the best architecture to be used to ensure that services will be available. In other words, this approach helps in decision making with a view to determining which RoF scheme will have the best result given the cost benefits in the BBU, fronthaul and RRH sectors that are essential features in 5G.

III. METHODOLOGY

A. INITIAL CONSIDERATIONS

Certain criteria were taken into account when carrying out this study and must be complied with to ensure good network performance when installing the C-RAN. In the particular case of RoF systems, the performance metrics have begun to be evaluated to determine some of the benefits and drawbacks of these systems.

The influence of the chromatic dispersion of the fiber and the third-order intermodulation distortion (IMD3) have a direct influence on the dynamic range of the system caused by the nonlinearity in the frontal segment of the optical extremity [23], which can be measured in terms of the error vector magnitude (EVM) and is summarized in [24]. The effects are mainly manifested in analog signals, which undergo high losses and, as a result, a reduction in the link range.

The concept of fiber-wireless integration is regulated by [2], which combines the operational and performance principles of this technology. However, the installation of the architecture based on C-RAN raises the possibility of controlling and managing the methodologies in the optical center itself. This would improve the performance of the network in the allocation of resources and for reconfiguration, particularly in the context of the application of the base station, which can include configurations, specifications, demands and distances between the central and other base stations arranged in accordance with the pattern shown in Figure 1.

In Figure 1, ONUs might be base stations, heterogeneous networks or any access technology that can allow connectivity in the architecture.

On several occasions, different RoF schemes are shown to make high-speed data transmission feasible and allow more flexible and versatile systems. This can make it possible to have operational functionalities with multiple carriers that can determine the degree of efficiency of fronthaul [14].

Hence, it is worth stressing that, to ensure there is interoperability within the networks, there are factors that must be taken into account when thinking about how 5G can adopt
RoF as a technological device since this kind of installation depends on the availability of fiber.

Therefore, the cost benefits of the system should be included when devising methodologies that are capable of aggregating value for integrating the various RoF schemes.

### B. STRATEGY

During the contextualization, a timeline can be created for the methodology with the aid of fuzzy logic, with a view to attributing configurations in the communications centers when planning a 5G network. This approach regards the best strategy for the RoF infrastructure as being analog, intermediate frequency or digital.

In this situation, when carrying out the decision making, there is the attractive prospect of being able to choose what is the best RoF strategy (A-RoF, IF-RoF or D-RoF) to serve the needs of the required planning from a wide range of alternatives. The fuzzy logic adds a degree of pertinence since it seeks to determine if an element or variable belongs to the set of values linked to the dataset being evaluated.

The fuzzy decision-making system returns one of the following: A-RoF, IF-RoF or D-RoF. It consists of blocks that represent the stages that must be included to assess the degree of efficiency needed to specify if the performance requirements established by the operators are being met.

The flowchart displayed in Figure 2 shows the structure that follows the sequence of the fuzzy logic, which is aimed at deciding which RoF strategy is best suited to the planning of 5G networks with C-RANs and RoF-based fronthaul.

The flowchart starts with the planning demands entering the fuzzy logic analysis block, which has a series of inputs and will go through inferences in a set of rules so that a decision can be made about the RoF strategy. If there is a suitable architecture for a case that is being planned, then the objective is met; if not, the inputs are adapted to carry out the process again to ensure it ends with the correct specification of the architecture.

When adopting this strategy, it is assumed that the fronthaul should be optical fiber, which rules out the best route since it is only based on the link distance between the center and the station and is not related to new installations or leasing the optical sector. In this way, the scheme that each block represents will be set out as follows since each interaction represents a required route:

- **First Stage**: In the first planning stage of the network, the network requirements and metrics are set (transmission distance, deployment costs, BS simplification and link performance).

- **Initial demand of the designed scenario**: The system evaluates the received demand in accordance with the requirements of the first stage. With regard to the points specified by the network, the function is to receive information essential for the input of the system, such as link distance, installation costs, possible link performance and simplification of the base station, which are the technical metrics addressed in the RoF (digital or analog).

- **Analysis of the performance requirements in the scenario**: Through the pre-existing performance parameters of each feature of various RoF schemes, this block evaluates the degree of relevant input (fuzzification) with the pre-established fuzzy compositional rules of inference, and the input values are aggregated for all the activated rules to form intermediate output sets and make decisions with regard to the final grouping; this method produces the result in the output and is known as defuzzification. The data block for performance in 5G and the performance parameters of the network will be examined in terms of the main specifications attributed by the regulatory standards, for example [2], [24], which were obtained in the works described in [14].

- **Decision about the required conditions for the scenario**: It can be determined from the output of the system what kind of RoF technology can be best adapted to the design objectives when planning the network, or in other words, once the rules of the planned fuzzy system have been put into effect, the inference will return the technology that is suited to the planning. If the requirements are not satisfied, the inputs will have to be reviewed while taking into account the system’s inputs. These can be regarded by specialists as the performance link and the implementation costs and mean that the process will restart when it has returned to the initial stage.

- **Configuration of the BBU**: In this stage, the decision about the RoF schematic diagram has already been made both for the BBU and the BS, and they can be configured in accordance with the architecture that the RoF technology requires.

- **Final stage**: The system is complete.

### C. INPUTS

The variables are classified according to the requirements of the system – that is, they are based on observation and analysis of the signal behavior, as well as the data shown in the studies found in [14]. There has been different reported experimental work on ROF-based transport systems with an achievable CPRI-equivalent rate and EVM. By and large, the employment of analog RF signal transmission over the optical fronthaul links enables high-speed data transmission, and a similar study is carried out in [25]. However, there are other
variables such as the installation costs that are examined in [10], [13], [16], [26], and because of their great influence on decision making, these parameters have a direct effect on the scenarios. Despite this, since they are based on open-source requirements, there is a limit to the extent to which D-RoF can be regarded as better than A-RoF, and for this reason, the respective degrees of pertinence apply to the strategy that is suited to the output of the system.

The input variables are configured in a triangular form, with the exception of the link range, which is configured in a trapezoidal shape because it represents the distance in kilometers and is designed to show the transition between the schemes under study. These variables denote the methodology for installing and planning the network from the standpoint of the telecommunications operators and with regard to the objectives described in [1]. The input variables that are configured in the fuzzy logic modeling are:

1. The link performance – measured by the EVM in D-RoF systems – is related to analog-to-digital converters (ADCs). In the case of different bit resolutions, there are different optical bit error rates (bit error rate * sampling rate + preamble). This means that the greater the resolution and bit rates are, the greater the bandwidth required in the optical sector, although if the bandwidth is impaired, it still maintains good performance along the link. In A-RoF, the performance deteriorates to the extent that it increases the length of the fiber and reduces the received power. Thus, it is no longer viable for long stretches of fiber, except for short distances when it has good performance. This is because it avoids using the bandwidth caused by the conversion of ADC to DAC, which makes it an attractive alternative for these scenarios.

With regard to the performance of IF-RoF, its efficiency is reduced owing to limitations in the frequency conversion, which leads to just average performance [25]. Hence, the input variable of the link performance can be poor, average or good.

2. Transmission distance – short-term and long-term attributes. This is basically because, owing to the non-linear effects of the fiber, for distances longer than approximately 10 km, the dynamic range rapidly falls in analog links, which causes a short range in A-RoF. In contrast, these effects are attenuated in IF-RoF and D-RoF, which allow longer distances of up to 40 km [14], [25], [15].

3. Simplification of the base station - IF-RoF schemes have an average complexity because devices are supplied in the BS such as local oscillators and D-RoF schemes a high complexity because extra devices are supplied in the base station such as DAC/ADCs, but A-RoF keeps a high degree of simplification and provides only equipment related to electro-optical conversion. This leads directly to low energy consumption and installation costs [26], which makes this an attractive solution compared with the other technologies studied [14], [15], [25], and for this reason, the fuzzy variable was configured with a high average and low form of simplification.

4. Installation costs – The variable can be classified as high or low. This is because, when digital transmissions are taken into account, the cost of CPRI-based fronthaul is high; as additional transceivers are required, CAPEX/OPEX costs are higher in terms of optical electronic devices and energy consumption, i.e., when observing analog transmissions, energy efficiency establishes a low energy consumption (OPEX) in the BS and a low cost of capital invested for 5G deployment (CAPEX) in relation to digital transmission.

D. FUZZY RULES

The rules operate on classic principles, or in other words, depending on the input – in this context assigned an output – needed to allocate RoF signals in the fronthaul, it is enough to evaluate the degree of pertinence through an analysis of rules with regard to the fuzzy inferences and thus take note of the following rules in accordance with Table 2.

In a fuzzy system, the results are shown in intervals between 0 and 1. A value of 0 means complete exclusion, and a value of 1 means complete integration. The other values represent intermediary degrees of relevance. A particular feature can also belong to two or more diffuse sets defined in the same world, where the values of the combined functions for each diffuse set can be different. Thus, one element may belong more to one diffuse set and less to others. Hence, the set of rules results in the decision of A-RoF, while the appropriate conditions satisfy the metrics that measure the performance of this technology in the same way that they establish IF-RoF and D-RoF.

E. THE OUTPUT VARIABLE

The fuzzy system employed here has only one output variable that represents the three variants of RoF: A-RoF, IF-RoF and D-RoF. There are three architectures in the fuzzy output that can be chosen in accordance with the inputs. This output was configured in a triangular format to express the forms of convergence within the technologies to the extent that the input metrics are varied. Hence, the limitations in the required conditions will accommodate one of the architectures in the

### Table 1. Comparison of the inputs of the RoF schemes.

| Metrics                  | A-RoF            | IF-RoF          | D-RoF            | Reference          |
|--------------------------|------------------|----------------|------------------|--------------------|
| Transmission distance    | Short (0-10 km)  | Long (up to 40 km) | Long (up to 40 km) | [14], [25], [15]  |
| Deployment Cost          | Low              | Low            | High             | [10], [13], [16]  |
| BS Simplification        | Good             | Medium         | Complex          | [14], [25]        |
| Link Performance         | Good (h2b and up to 10 km) | Medium          | Good             | [14], [25], [15]  |
TABLE 2. Rules for the fuzzy system.

| Performance | Base Station | Distance | Cost | System  |
|-------------|--------------|----------|------|---------|
| No Good     | Good         | Long     | A-RoF|
| No Good     | Good         | Good     | A-RoF|
| Good        | Good         | Short    | A-RoF|
| Good        | Good         | Good     | A-RoF|
| Good        | medium       | Short    | No Good| A-RoF|
| Good        | medium       | Short    | Good  | A-RoF|
| Medium      | No Good      | Short    | D-RoF|
| Good        | No Good      | Short    | D-RoF|
| Good        | No Good      | Long     | D-RoF|
| Good        | No Good      | No Good  | D-RoF|
| Good        | No Good      | Long     | D-RoF|
| Medium      | Medium       | Long     | IF-RoF|
| Medium      | Medium       | Good     | IF-RoF|
| Medium      | Medium       | IF-RoF   |
| Medium      | Long         | IF-RoF   |

In the decision making that takes place at the output of the fuzzy logic, the rules of inference will be made on the basis of a combination of benefits from each technique. Defuzzification returns the RoF scheme in accordance with the need for planning by the operators. The results describe the behavior of the RoF schemes under study and take account of the metrics that influence the analysis of the choice of a particular technology when faced with the task of planning a 5G network.

It is clear that the relationship between costs and performance singles out the A-RoF as the scheme to be assigned, and the extent to which the costs are reduced means there is a convergence between the IF-RoF and D-RoF systems. When there is a suitable simplification of the BS, it is decided to select A-RoF, and when it begins to increase the complexity of the base station, then D-RoF will have the best performance. Nonetheless, with regard to the choice between performance and distance, the fuzzy rules state that the greatest distance between the telecommunications center and the base station is given by the IF-RoF and D-RoF architectures. However, in the case of IF-RoF, the performance is reduced more than that with D-RoF. On the other hand, good performance is achieved by A-RoF for short distances [14].

The simplification variable shows that the degree of complexity increases with distance since the techniques that provide better performance are those of IF-RoF and D-RoF for the long link, even though simplification is achieved in A-RoF. This simplification is related to the installation costs, or in other words, analog RoF is becoming attractive with regard to digitized versions.

This increases the cost as a result of the number of transceivers needed for transmission in IF-RoF, where a medium degree of simplification is attained through the addition of a local oscillator and where there is average performance. A comparison between the distance and the cost gives strong support to the view that shortening the length of the fiber and employing A-RoF will have an immediate effect on reducing costs. This will also lead to changes in the IF-RoF and D-RoF schemes when the distances begin to increase, even though this depends on the performance.

IV. THE CASE STUDY

The scenario used in the case study was based on a 5G deployment with a carrier frequency of less than 10 GHz, where an estimate of these cost values is made in [16], [26]. However, for the purposes of this study, an expansion of the urban area was carried out through an overlapping scenario that made use of Google Earth, and the coverage area was 18 km² in the
state of Victoria, Australia. The size of this area is consistent with that of a typical distribution area used in large-scale network planning, with an area of approximately 150 km$^2$.

This broadened the setting and made it more realistic so that different ways could be found of configuring BBUs and RRHs based on the optical fronthaul link. This is because there is usually a larger number of densely populated environments, and hence when planning the installation of new networks, several features must be taken into account, either in an urban or rural area. Figure 4 shows the used scenario.

A hundred different geographical points were selected at random on the map to specify the scenario, and the routes were calculated by the application itself, while the distances of the possible installations at the base stations were obtained from the central point. It should be noted that the fiber installations generally took place on the streets and avenues and thus could follow different routes for long distances. The points that were collected were exported to Matlab, where they could be used as input in the fuzzy system. The other variables were varied in accordance with their specifications and restrictions, and the output returns the RoF architecture that has the best performance out of the different choices.

V. ANALYSIS OF THE RESULTS

The results show that regardless of expectations about the limitations of the RoF technologies, a wide range of possibilities should be able to coexist. These include the following: the performance, fronthaul link, installation costs and aggregate value of the 5G network.

Observing the scenario under study and the basis of the data provided by [16], [26], [27], the best cost in densely populated and geographically spacious urban areas does not always provide the best solution; rather, this can be found with different configurations of the BBUs, as demonstrated in Figure 5.

The interrelationship of the performance, linkage range and simplification of the base station yielded the following results:

i) As shown in Figure 5a, in the case of simple base stations (and regardless of the performance and range), the signal is limited by the restriction of A-RoF.

ii) As shown in Figure 5b, in the case of base stations of intermediate complexity with a short range, the configuration of the architecture is IF-RoF owing to the fuzzy logic inferences. This allows both to be used while increasing the distances, but good performance is only achieved by D-RoF. iii) Figure 5c shows that when there is complexity at the base station, the system rejects the A-RoF configuration in all the scenarios. However, in the case of long distances in links that have inferior performance, there is scope for choosing IF-RoF owing to its average degree of complexity and low performance.

It was demonstrated through the case study that some of the base stations are outside the coverage zone for A-RoF. For this reason, the installation costs found in [17] followed a different pattern because the center was configured with A-RoF and D-RoF in proportion to what was decided by the designed fuzzy model. This was because out of the 100 routes collected, the model assigned 39 cases to A-RoF and the others to D-RoF by including a high-capacity link and incurring low installation costs. Thus, the best solution would not be the best cost but rather an intermediate scheme such as that shown in Figure 6.

In Figure 6, the configuration of the telecommunication center with more expensive architectures is represented in 2 charts formed of 3 columns. Chart I shows the distribution of the installations of A-RoF, IF-RoF and D-RoF; Chart II shows the representation of costs for the coexisting technologies. Column (a) shows the installation of A-RoF, (b) the ratio between the A-RoF and D-RoF installations, and (c) the setting up of installations in D-RoF.
of the architectures, and Chart II shows the proportional costs in accordance with the distribution of the architectures that were assigned by the fuzzy modeling. Column a) represents 100% A-RoF installations, Column b) shows the coexistence of A-RoF and D-RoF installations, and Column c) shows 100% D-RoF installations. Thus, when Chart I is assessed, the analysis represents the cost statements, and the best scheme was when 100% of the samples lay within the specifications of A-RoF [16]. However, by employing the fuzzy methodology for the scenario under study, it was determined that a part of the installations should be allocated for A-RoF and another part for D-RoF (39% and 61% respectively) since the installation with the best link performance is believed to incur lower costs. On the other hand, when assessing Chart II, the best installation cost was found for 100% A-RoF installations. However, the best configuration (cost/performance) in the analyzed scenario was based on the coexistence of the two architectures. This is based on the assumption that, in this case, the best cost takes into account the increase in D-RoF with regard to A-RoF, owing to the fact that CPRI requires more expensive transceivers for the fronthaul, CAPEX/OPEX costs and energy costs and given that the A-RoF access network is more efficient than other technologies [10], [13].

VI. CONCLUSION
The growing process of centralization among telecommunications networks is improving the prospects of better management, supervision and planning of access technology systems, whether at a central office, the units of users or the base stations. However, this greater degree of flexibility is beginning to cause concern in the distributed computing environment, particularly in the fronthaul, owing to the limitations of bandwidth in the sector that meets the needs of mobile data services. In an attempt to overcome the problem of overloading, technologies such as RoF are constantly being studied and advanced in academic and industrial research. This has resulted in key metrics that can be used in decision making, together with computing intelligence techniques, mainly for the purposes of a centralized form of maintenance and management.

In this study, a methodology was put forward using fuzzy logic for decision making among various forms of suitable RoF architectures in an optical fronthaul. Its purpose was to obtain the best possible solution for the installation of network planning with access to 5G in configurations of a C-RAN for the BBU and fronthaul. The performance requirements that determine the limitations of each scheme were taken into account, as well as the costs of installing and simplifying the base stations.

Finally, a case study was carried out to show the results on the basis of a realistic scenario. This included factors that influence the planning of 5G networks, such as the distance between the center and base station and the installation costs. These show that when planning a network, the cost and performance of radio-over-fiber systems must coexist to meet the needs of densely populated urban scenarios.

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