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A Techno-Economic Framework for Installing Broadband Networks in Rural and Remote Areas

MARCELA ALVES DE SOUZA[1,2], HUGO PEREIRA KURIBAYASHI[2,3], PALINE ALVES SARAIVA[1], FABRÍCIO DE SOUZA FARIAS[4], NANDAMUDI L. VIJAYKUMAR[5,6], CARLOS RENATO LISBOA FRANCÊS[2], AND JOÃO C. WEYL ALBUQUERQUE COSTA[2], (Senior Member, IEEE)

[1]Information and Communication Technology Center, Federal University of Southern and Southeastern Pará (UNIFESSPA), Marabá 68505400, Brazil
[2]Graduate Program in Electrical Engineering, Federal University of Pará (UFPA), Belém 66075-110, Brazil
[3]Faculty of Computing and Electrical Engineering, Federal University of Southern and Southeastern Pará (UNIFESSPA), Marabá 68505400, Brazil
[4]Faculty of Information Systems, Federal University of Pará (UFPA), Cametá 68400-000, Brazil
[5]Institute of Science and Technology, Federal University of São Paulo (UNIFESP), São José dos Campos 12247014, Brazil
[6]National Institute for Space Research (INPE), São José dos Campos 12227010, Brazil

Corresponding author: Marcela Alves de Souza (marcela.alves@unifesspa.edu.br)

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ABSTRACT Expanding broadband services represents a significant challenge for broadband operators, especially in light of the requirements related to the total cost of ownership of these technologies. In the last few years, this expansion has advanced significantly, but it still represents a challenge that must be overcome since there is a need to provide low-cost services to rural communities in remote areas. Issues related to geographical location, the low income of residents, and the lack of public infrastructural facilities lead to a disadvantageous relationship between the potential revenue for operators and the high costs of deploying infrastructure. Although there are several research endeavors in the literature aimed at addressing how connectivity can be provided, they do not discuss systems that take account of the specific features of these regions or that have adapted services and network applications to meet the needs of these communities. Thus, using dimensioning systems for the total cost of network ownership and taking into account capital and network operating expenses, this study establishes a technical and economic framework for the deployment of broadband networks in rural and remote areas. It also applies economic feasibility analysis techniques designed to assist decision making by interpreting the effects of any financial investment made and estimating the expected profits of the broadband operators. We also recommend the use of socioeconomic indicators to predict the potential social impact of this framework on the development of these regions. We employ a case study to demonstrate the operational features of the planned framework. Based on real data obtained from a municipality located in the Brazilian Amazon region, we show that it is possible to reduce the cost of subscribing to broadband services for end-users by reducing deployment costs and thus ensure that access to digital services can be equitably obtained.

INDEX TERMS Broadband services, rural and remote areas, total cost of ownership, feasibility analysis.

I. INTRODUCTION

In the last few decades, the Internet has ceased to be regarded as just a consumer commodity and has become consolidated as a basic human right that can foster social inclusion and lead to the equal participation of excluded people in digital society [1]. Currently, the global crisis of COVID-19 has illustrated how crucial access is for carrying out daily activities, such as working, studying, and maintaining contact with family and friends. In the area of education, for example, 94% of students worldwide have been forced to continue their studies at home, regardless of whether they are lucky enough to have telecommunications services available [2].

Telecommunications networks have been helping to supply the basic communication needs of individuals, organizations, and governments in an increasingly effective way by providing goods and services to different sectors of society. According to [3], the use of technology can help reduce poverty,

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improve access to educational services, foster job creation, and help boost gross domestic product (GDP), which is a means of measuring a country's socioeconomic development.

Given the increasing need for and growing significance of Internet services, several countries have invested heavily in implementing and improving telecommunications systems. However, despite the rapid rate of expansion of telecommunications networks in recent years, digital services are more widely available in developed countries than in developing countries, especially in large urban centers [4]. Approximately 46.4% of the world population does not have regular access to the Internet, which represents a total of 3.61 billion people [5]. Among developing countries, this digital divide is even more striking when analysed in terms of income level, age, sex, and, in particular, urban and rural geographic location [6].

In economically attractive areas, such as large urban centers, the deployment of telecommunications systems occurs naturally because of the high degree of profitability that is guaranteed by the return on investment due to the increased demand for data traffic [7]. On the other hand, in rural and remote areas, making a profit is often quite a challenging task, since their economic, geographic, and demographic conditions impose obstacles to the expansion of infrastructure. Thus, factors such as sparse population density and low per capita income can be converted into low expectations of financial return for the network operator. This low financial return, coupled with the high cost of deploying and operating telecommunications systems, has restricted these services and made them unavailable to a large part of the population [8].

Although there are several mechanisms for providing financial assistance to expand broadband networks in low-income areas, such as public funding [8], the low degree of human development and digital inclusion that is generally found in these regions suggests the need for providing services and applications that are adapted to the needs of the users. Unlike the traffic profile management of users in large urban centers, these regions require service coverage and minimum possible reliability, in addition to information and communication technology (ICT) applications that are suited to the social and economic development of the region.

In light of this, one of the main challenges for operators is to provide broadband network connectivity that is compatible with the needs of these regions but in a technically and economically sustainable way. An investigation of alternative methods that can assist in the proper planning of these networks might represent a timely and important research endeavor. Thus, a framework adapted for rural and remote settings is essential to evaluate the different types of technologies, deployment mechanisms, and business models.

The analysis of investment opportunities within a time scale is crucial to making a complete assessment of the financial viability of a network planning project, such as its negative cash flow. Such efforts are difficult because of the challenge of giving due weight to the particular requirements of and applications in these areas and may indicate (or accentuate) operators' lack of commercial interest in exploiting these regions. On the other hand, the potential financial benefits should be evaluated not only from the standpoint of the network operator but also in terms of the socioeconomic needs of the local inhabitants. Moreover, the relationship between average per capita income and average revenue per user (ARPU) can be used to evaluate these planning projects and assist in reducing the social inequalities that hamper human development in these regions.

In the related literature, there are several studies aimed at adopting network planning approaches for rural and/or remote areas [9]–[11]. However, to the best of our knowledge, there is a lack of initiatives that *a)* address the challenges of planning broadband services in an integrated manner; *b)* take into account the need for ICT services and applications that are adapted to the needs of the users in these regions; or *c)* use realistic geographic information as input data for the provision of planned telecommunications systems. In view of this, this article conducts an analysis of the main challenges related to the provision of telecommunications services in rural and remote areas and establishes a framework that aims to evaluate (both technically and economically) the process of planning telecommunications services in these areas while taking note of what is realistically feasible for the conditions of the Brazilian Amazon. The main features of the framework include the following:

- Classical modelling techniques, such as graph theory, to define interconnection scenarios; decision-making tools based on computational intelligence paradigms and a database powered by socioeconomic data to meet the demand for data traffic;
- Issues related to the development of a realistic system for modelling cities, which includes a city map to obtain the best structural design;
- The use of a photovoltaic system to supply clean and sustainable energy and analyse the technical and economic aspects of this technology;
- Algorithms and analytical models for traffic prediction including greenfield deployment used for the installation of an IT system and brownfield migration for access and transport networks, as well as the assessment of the total cost of ownership of the installed system;
- The use of a virtualized infrastructure as an alternative to reducing costs incurred by network deployment and operation;
- The aggregation of real databases that include demographic and geographic information or information about the existing network infrastructure;
- Adapted models of payback and net present value (NPV) aiming at evaluating different scenarios from the financial perspective of the operator, as well as from the standpoint of the end user;
- Validation of the proposed scheme and the use of a municipality located in the Brazilian Amazon region as a case study.

The rest of this article is structured as follows. Works related to this study are discussed in Section II. Some of the main challenges related to this framework are set out in Section III. Our vision and proposed technical-economic framework are detailed in section IV. Section V describes the case study for the introduction of the framework, as well as the numerical results obtained. Finally, Section VI concludes the study by making some final considerations.

II. RELATED WORK

Research on the deployment of broadband networks in rural areas has attracted a great deal of attention in recent years. Several works in the literature establish frameworks aimed at analyzing technologies, deployment scenarios, emergencies, regulatory policies, and business models [12]–[15]. Reference [12] employ a techno-economic framework for regression analyses of key factors of the implementation and adoption of broadband services in rural areas, with a special emphasis on the digital inclusion of the communities involved. Reference [13] set out a sociotechnical framework that integrates potential technological solutions to reduce the degree of digital exclusion in rural areas. The authors list a set of factors that must be taken into account and integrated to guide the implementation process in rural areas. In [14], the authors establish a framework that can be applied in any country to assist in formulating national and international policies aimed at reducing the digital divide. The strategies used by the authors include the sharing of the network infrastructure and different fiber or microwave technologies for the backhaul. Reference [15] address different deployment strategies that can improve the viability of high-speed broadband access at low cost, potentially using 4G or 5G. Costs are estimated based on several factors: the choice of technology, sharing of infrastructure, spectrum price, and taxation.

The planning of communication networks, including that in rural and remote areas, relies on models for estimating and forecasting data traffic. In [16], the authors carry out a study that employs a multidimensional model to predict user demand for data traffic. The authors provide evidence to support the strategy based on the assumption that relying only on technical data from operators is not sufficient to estimate the demand in these regions. Among the most notable parameters included are the following: population density, mobile device transmission capacity, user type, and average subscription rates. Reference [17] provide analytical models to estimate the demand for data traffic from internet of things (IoT) applications in rural communities in Mexico, and these include public statistical information from the region, such as the number of residents and households, among other factors. In [18], machine learning concepts were applied to predict data in locations where traffic demand is unknown or has a high degree of uncertainty. The method uses satellite imagery to estimate telecommunications demand metrics, including the adoption of cell phones and expenses associated with mobile services.

In addition to estimating traffic demand for network planning, it is necessary to find sustainable and low-cost solutions for these regions. Thus, studies analyse the technical and economic viability of the network in underdeveloped rural regions by using different technologies for access and transport [19]–[22]. In [19], the authors carry out an analysis of the cost of implementing a CDMA450-based radio network to estimate the cost of spectrum licensing, as well as the effects of the cost of government-subsidized handsets. Reference [20] discusses the use of WiLD links for backhaul connectivity over long distances in rural areas. The author justifies the choice of the technologies involved by pointing out the potential reduction of operational expenses since the equipment is easy to install and operate. Reference [21] examine the deployment of voice and data services for rural areas, including 3G small cells and WiFi for Long Distances (WiLD) and Worldwide Interoperability for Microwave Access (WiMAX). In [22], the authors address issues related to sharing a backhaul infrastructure between network operators, including communities that own and manage an available wireless network.

Another element considered in several works in the literature is the unreliable or nonexistent supply of electricity in rural areas. To address this issue, several studies consider the use of photovoltaic systems in rural areas [23]–[25]. In [23], the authors propose an architecture composed of unmanned aerial vehicles (UAVs) equipped with base stations to provide service coverage through terrestrial sites. The architecture includes the use of photovoltaic panels and solar batteries to recharge UAVs and power these sites. Reference [24] carry out a feasibility study on the use of photovoltaic systems applied to GSM mobile telephony in remote areas in order to determine an economical way to achieve environmental sustainability, that is, replacing the supply of electricity with utilities. Reference [25] analyse the deployment of 5G technologies in rural areas with low financial returns to consider low-cost strategies for the implementation of these networks. Among the main discussions raised by the authors, we highlight the implementation of 5G nodes powered by a photovoltaic system.

Unlike the related works, our paper includes a discussion that highlights the importance of understanding the socioeconomic characteristics of rural and remote regions for the implementation of telecommunications networks. To the best of our knowledge, there is a lack of initiatives that incorporate all these elements in an integrated manner. Thus, our scheme differs from those of other studies in the following ways:

1) We examine important socioeconomic factors that define the demand profile, not only those perceived by the operator but also (among other features) the age group of the population, the number of schools, the total number of health centers and the number of households. The purpose of this approach is to model and project the demand for data traffic so that the potential suppressed demand inherent in these regions can be taken into account;

2) We evaluate different deployment strategies, which make use of legacy technologies, as well as 5G-based deployments;
3) We list alternative deployment strategies that can lead to the reduction of network costs, such as the analysis of greenfield/brownfield scenarios, the adoption of photovoltaic systems, and the exploitation of shared central office infrastructures through a neutral host and a virtualized infrastructure;
4) We analyse the question of economic viability from the perspective of users in these regions to assess the impact of subscription fees on the average income of the population.

III. CHALLENGES

Several challenges related to network service provision in rural and remote areas must be taken into consideration and solved by taking initiatives to broaden the connectivity of these regions.

A. INSTALLATION AND OPERATIONS COSTS

The low penetration of public infrastructure (such as the introduction of highways, electricity and postal services) tends to increase costs related to capital expenditure (CAPEX) since there is often a need for investment to adapt or construct the additional civil infrastructure required for the installation of telecommunication services.

With regard to operational expenditure (OPEX), examples of cost components include *a)* the long distances from large urban centers or even parts of these rural communities that are relatively inaccessible, *b)* the displacement of employees of the broadband operators, *c)* the transportation of spare parts or expansion project equipment, and *d)* the resolution of operational problems that require action in the field; these challenges are considerably different from those of implementation in large urban centers.

To illustrate these challenges, we can cite several examples. The first is the Republic of Sri Lanka, which launched the Rural Infrastructure Development Program (RIDP) in 2016. The objective of the program is to raise the socioeconomic level of rural Sri Lanka through the improvement or expansion of highways, the development of a water supply system, and the implementation of basic sanitation projects and thus make it easier to install a telecommunications system in these areas [6]. In the Republic of Guinea, telecommunications operators face difficulties installing communications systems in rural and remote areas because of poor or nonexistent public services networks [26]. This makes the deployment of telecommunication networks a non-profit-making enterprise and hence unsuitable for private initiatives. In China [27], the greatest challenge for the deployment and development of rural broadband is the high cost of building and maintaining telecommunications networks, and although there is private investment and government funds for the deployment of these networks, there is still a lack of sustainable business models and methodologies.

B. LOW POPULATION DENSITY AND POVERTY

A large portion of rural and remote areas are characterized by low rates of population density, which is often coupled with low per capita income among the population, which together add to the difficulty of providing connectivity in these regions. In Brazil, for example, the income obtained in urban areas is approximately twice as high as the income obtained in rural areas. A low per capita income means a low ARPU; this has the potential to result in reduced gross revenue for the operator and makes the distribution of OPEX from the mobile communication system quite a challenging task. For example, in the Republic of Congo, more than 75% of the population lives in rural and isolated areas and is without access to ICT applications and services. The main reason for this is the high cost of acquiring devices that have Internet access resources [28].

In the case of Latin America, the low average income of the population in some countries causes a considerable difference between them in terms of the number of people who have access to mobile telephone services. From the user's standpoint, the TCO (total cost of ownership) for mobile services consists of capital expenditure, which is generally linked to the acquisition of mobile devices and expenses incurred by data and voice services. In the case of 40% of the population with low purchasing power who live in countries such as Guatemala, Bolivia, and Ecuador, the TCO indices represent 15% of the average income. On the other hand, in the case of the wealthiest 20% of the population, it reaches values between 1 and 4% of the average income of the population [29].

The expansion of telecommunications services in rural and remote areas from a traditional perspective can represent a low return on financial investment. This leads to a low ARPU and a long return on investment (ROI), thus increasing the obstacles to the implementation or expansion of services in these regions [30]. According to [31], an estimated 4.5 billion people have an annual income of less than US $ 1,500, and they live mainly in disadvantaged rural areas. Thus, although there is a lack of interest from operators and the scale of this market is low, the market trends follow this path due to the large number of users in these regions.

C. ELECTRICITY SUPPLY

Several rural locations have outdated electricity transmission and distribution systems, resulting in failures in supply and poor-quality transmission. Broadband operators must devote a proportion of their financial resources to the acquisition and installation of protection systems, battery clusters, and electric power generators. This may represent a significant increase in CAPEX expenditure for the implementation of the projects. There are also issues related to the weather, such as storms or adverse climate conditions, which, combined with the risk of damage and destruction of equipment in remote areas, can lead to an increase in capital expenditure for telecommunications networks.

The use of energy generators also tends to increase the costs incurred through the operation of telecommunication systems (OPEX), since most countries find that the generation of energy by employing engines is more expensive than obtaining it through a conventional supply chain matrix in the country. In addition to being costly, the burning of fossil fuels gives rise to the emission of greenhouse gases (GHGs), which leads to a significant increase in the carbon footprint of the ICT sector [32].

D. DIGITAL INCLUSION

Digital inclusion can be defined as a set of processes that lead to the development of cultural attributes related to the use of technology. These attributes are required not only for Internet access but also for the regular browsing of electronic content, the consumption of digital services, the assessment and creation of online content or advanced features of mobile devices [33].

According to [34], almost 40% of nonusers in eight countries in Latin America state that they do not use Internet services because they need better knowledge and skills to do so. Nevertheless, according to the same survey, more than seven out of ten people state that they have never used online banking services to make transfers or payments or have never made use of any electronic government service. Countries from other continents, such as the Republic of Nepal and the Central African Republic, list ICT literacy as one of the main obstacles to extending network services to rural and remote communities [6].

In the case of Brazil (the largest country in Latin America), data from [35], including Brazilian households with no use of the Internet, highlight the following reasons for this lack of use: a lack of interest in using the Internet (34.9%), the expense of Internet services (28.7%) and a lack of knowledge of how to use the Internet (22.0%).

It can be inferred from the above that low levels of digital inclusion act as inhibitors in the use of telecommunications services. Moreover, the lack of digital inclusion generates considerable pent-up demand from users for data traffic in these regions. This phenomenon has serious social implications for the people involved, as well as financial implications for network operators. This phenomenon is aggravated by the low population density of these regions, which leads to low expectations of financial revenue for services that require connectivity. Thus, clearly, there is a need to adopt strategies that take into account these difficulties, which requires a better method of planning and implementing these services. These might include the following: the creation of tourist villages [36], the growth of agriculture [37], an improvement in logistics and service provision [38], financial inclusion [39], and the dissemination and adoption of digital innovations in rural microenterprises [40], among other factors.

E. GEOGRAPHY AND COVERAGE

In [6], the following countries – Costa Rica, Panama, Sudan, Kenya, Congo, Afghanistan, Venezuela, and Brazil – list geographical accessibility as one of the main obstacles to the provision of broadband services in rural and remote regions. Factors such as geographic distance, the conditions of the terrain, forested areas, and the poor standard of the transport system are highlighted.

Communities located in remote regions of the Amazon, for example, face serious challenges in the provision of basic services, as well as education, health, and telecommunications services, because of the difficulty of reaching these regions. Although the coverage rate for telecommunications services can be regarded as significant in Latin America and the Caribbean, the coverage gap is equivalent to a population of 64 million inhabitants, many of whom reside in remote areas with a low population density [34].

IV. OUR VISION

We decided to establish our framework because broadband Internet services are a primary need, and their installation can be guaranteed by government entities or through the funding schemes of private companies. However, this undertaking can be made feasible only through the reduction of the necessary costs of implementing and operating the network, but its results will be very beneficial since the greater use of these services by people will generate employment and income opportunities through agriculture and tourism.

A. MAIN PILLARS

1) DEMAND ESTIMATION AND DATA TRAFFIC FORECAST

We believe that the widespread availability of telecommunications services can foster the socioeconomic development of rural and remote regions and simultaneously increase the interest and demand for these types of services by making the main economic activities carried out in these regions attractive and profitable.

ICT services and applications must be adapted to the specific needs of users in these regions to provide basic infrastructural facilities, such as those related to education and health [6]. This approach will involve meeting different requirements for reliability, coverage, and bandwidth from those found in dense urban regions. While in the case of urban areas, it is often important to maximize data rates or minimize the delay experienced by subscribers, in the case of rural and remote areas, the minimum amount of network resources must be provided to ensure basic coverage rather than aiming to achieve high data rates [41].

As shown in Tables 1 and 2 for urban areas, a large volume of broadband traffic is generated by advanced Internet applications, which entails increasingly strict requirements for bandwidth, capacity, and delay, since installation in rural regions needs careful planning to adapt to the specific conditions of the region (i.e., this can directly influence factors such as the traffic profile, types of technologies, business model and the consequent TCO of the network).

These communities generally need content to be published in their own language, which is relevant to their

TABLE 1. Comparison among urban and rural scenarios.

	Urban Scenario	Rural and Remote Scenarios
Service Type	4K Streaming, AR/VR, Tactile Internet, IoT	SD Streaming, e-health, e-learning, web browsing
Network Constraints	Maximize bandwidth, minimize delay, coverage	Coverage, guaranteed bandwidth
User Density	High	Low
Energy sources	Power grid	(Unreliable) Power grid, renewable sources
Business model	Return on Investment	Subsidized by the government

TABLE 2. Application profile.

Scenario	Examples	Latency (ms)	Data rate (Mbps)	Reference
Urban	RA/RV	10.0	100.0	[42], [43]
	Factory automation	20.0	1.0	
	Tactile Internet	1.0	200.0	
	4K Streaming	< 30.0	10.0 - 25.0	[44], [45]
Rural	e-agriculture	60.0	0.001	[42], [43]
	e-Health	40.0	2.0	
	Environmental monitoring	1000.0	1.0	
	e-Learning (SD Streaming)	< 40.0	1.5	[44], [45]
	Web browsing	< 80	0.5	-

local interests. The authors [33] list these factors as one of the main obstacles to digital inclusion and the expansion of telecommunications services in these rural regions. Hence, ICT services and applications based on IoT and machine-to-machine (M2M) communications (i.e., e-health, e-commerce, e-learning, e-government), among others, can be used to enhance the social, economic, and cultural development of these regions. The adoption and financing of these applications can be conducted by local governments to increase the demand for data traffic in these locations and thus make it financially feasible for network operators to install these services.

2) PHOTOVOLTAIC SYSTEM

Regarding the challenges of regular electricity supply, the adoption of renewable energy sources must be considered; however, the impact of using such technologies in dimensioning the network's TCO must be evaluated. In this context, the adoption of photovoltaic technologies can be promising, given the potential availability of solar radiation, as well as the technological evolution of this equipment and its popularization process. Thus, to reduce implementation costs, photovoltaic equipment or even electrical protection equipment can be installed in the homes of residents through agreements with the operator to reduce the risk of depredation and theft of equipment; the counterpart may be the provision of electricity and data services to such residents [46].

3) WIRELESS ACCESS NETWORKS

The deployment or expansion of wireless access networks is of great significance in light of factors such as population density and digital inclusion. According to the global survey carried out by ITU-D [6], which listed the technologies that are used to connect rural and remote areas, approximately 59% of countries responded that they used wireless technologies (fixed or mobile) such as 2G, 3G, WiMax, Wi-Fi or Satellite/V-Sat for access. This approach makes it possible to cover vast territorial areas at a lower cost than wired approaches. Thus, the use of mobile devices provides Internet access facilities without the need for the installation or operation of additional devices, such as modems or Wi-Fi access points, by communities still lacking digital inclusion, in addition to potentially reducing network installation and operational costs [34].

The network operator may decide to design an entirely new network infrastructure (greenfield), but the costs of implementing this may be higher than those found in scenarios where either a part or all of the existing infrastructure can be used (brownfield). Greenfield scenarios can be employed when there is no telecommunications system in a particular location or when there is a technological incompatibility that prevents the use of an infrastructure [47]. The adoption of brownfield scenarios depends on the exploitation of legacy technologies that can be used to reduce the costs of implementation.

4) NEUTRAL HOST AND VIRTUALIZED INFRASTRUCTURE

A neutral host involves managing a network infrastructure to host any entity that uses it to provide its services for its end users. From the standpoint of the network operator, deployments based on neutral hosts can reduce the implementation and operational costs of the web. Local governments, companies, and local providers can become owners of radio and ICT facilities to rent or assign local connectivity and computing resources to broadband operators through multi-lease services [48], [49].

Solutions based on software-defined networks (SDNs) and virtualized network functions (NFVs) in rural areas offer significant advantages and opportunities to reduce CAPEX by approximately 40% and OPEX by 30% [50]. This approach can reduce the dependence on expensive solutions from network equipment suppliers by replacing network functions with software-based implementations running on low-cost multifunctional hardware. This paradigm ensures flexible network management and better visibility to improve overall network performance, manageability, and the security of the network infrastructure [51].

B. OVERALL ARCHITECTURE

This techno-economic framework aims to assist the task of dimensioning the total expenses and investments necessary to implement or expand communication networks in rural and remote areas. Not only must the TCO of the network be

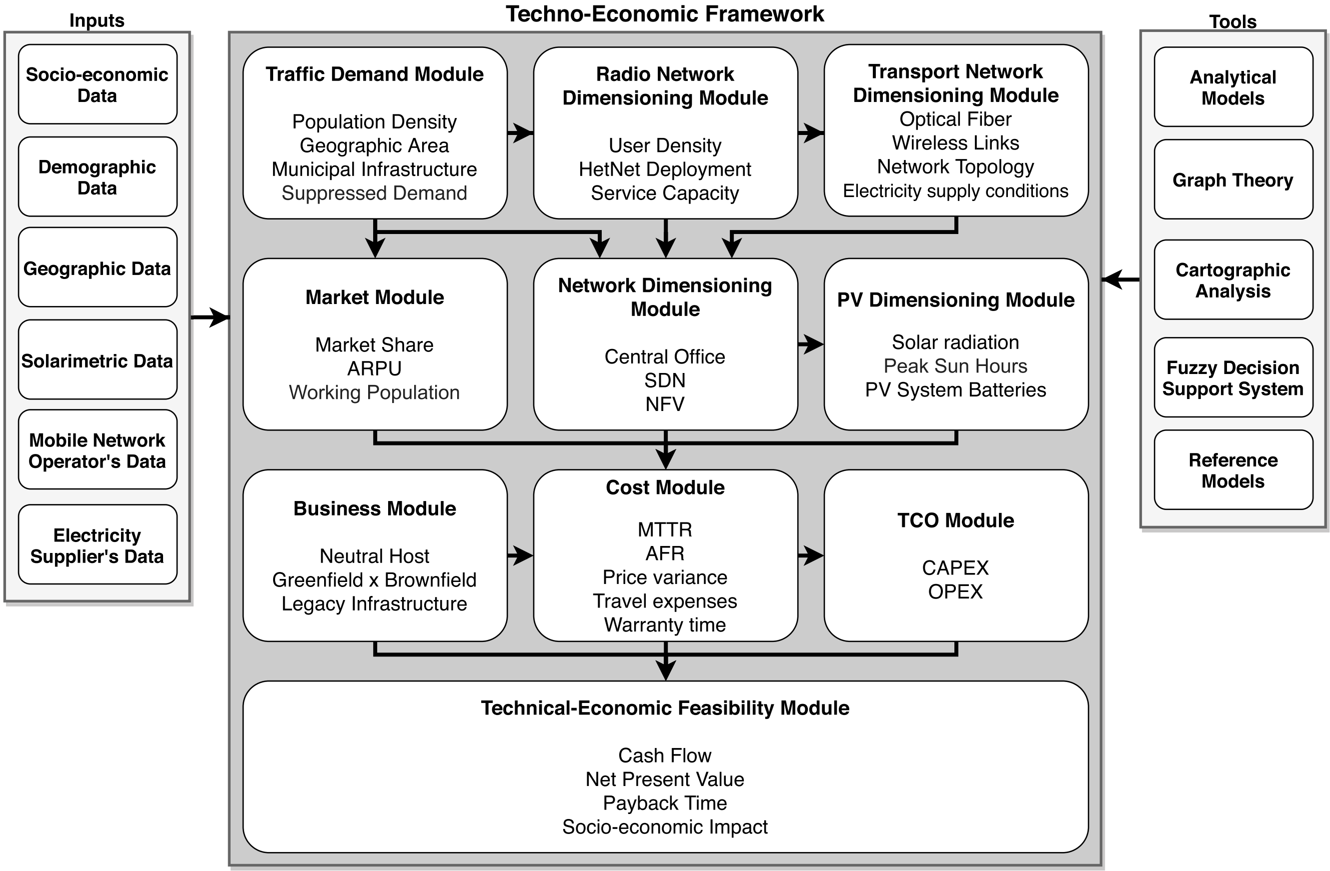


FIGURE 1. General architecture of the techno-economic framework for installing networks in rural and remote areas.

evaluated, but the economic viability of the project and possible socioeconomic effects of the implementation must be estimated. This research complements the concepts outlined in [52], [53] by considering demographic, geographic, and socioeconomic factors to define the ICT services and applications adapted to the population's needs in these regions. Although [52] is a relevant study on the deployment of 5G transport networks, its scope does not include the evaluation of specific aspects of rural and remote areas. We believe these specific characteristics, such as low human development and infrastructure problems, and other issues, tend to influence the technical-economic feasibility process.

Fig. 1 shows the general architecture of the framework and its modules. As inputs, data and information based on the socioeconomic, demographic, and geographical factors of these regions are used. Solarimetric data are drawn on for the dimensioning of the photovoltaic system, as well as information related to the local supply of electricity, if available. The data on the mobile network operators at the locations are used to estimate the existing service capacity and to design deployment scenarios based on cost-effectiveness measures.

The framework uses analytical models, algorithms, and graph theory concepts and employs cartographic and geographic analytical techniques. Reference models from the literature and a fuzzy-based decision support system combined with radio and transport dimensioning algorithms seek to choose the proper type of base station for a geographical area under deployment investigation.

The model adopted for rural areas covers the various territorial spaces that make up the municipality, such as towns and villages, in addition to the urban center. These spaces are classified by analyzing the territorial dimensions and the number of inhabitants. However, for the sake of convenience, in the remainder of this work, we will only employ the term locality to refer to any type of territorial space in a municipality located in a rural and remote zone. Thus, we define M as a set of municipalities, such that $M = \{m_1, m_2, \ldots, m_i\}$. Each element of M represents a municipality in a rural and remote area and can be designed by means of a connected, nondirected graph, such that m_i is represented by Eq. (1):

$$m_i = G(N_i, E_i), \forall m_i \in M, \tag{1}$$

where N_i is a set representing all the localities of municipality m_i, such that $N_i = \{a_1, a_2, \ldots, a_n, c_i\}$. The n-th locality ofN_i, denoted by a_n, is linked to a tuple $(A_n, \rho_n, \varepsilon_n, \gamma_n)$, such that A_n represents the territorial area A_n, ρ_n represents the population density [inhabitants/km^2], ϵ_n denotes a logical value to express the availability of electrical power, while γ_n represents a logical value to denote the pre-existence of some infrastructure of broadband network in the locality. For the entire set N_i, there is one (and only one) element denoted by c_i (i.e., $\exists! c_i \in N_i$), representing municipality m_i. In this context, this framework assumes that the headquarters c_i of the municipality is the location where all the transport links must converge (either directly or indirectly) and hosts the networks central office (CO). We also assume that c_i is provided with a backbone infrastructure capable of meeting the demand of all locations belonging to the set N_i, representing a possible point of presence (PoP).

1) TRAFFIC DEMAND MODULE

The traffic demand module aims to characterize the average traffic demand per area [Mbps/km^2]. The result of this module is obtained through the application of long-term traffic models [54], [55], which are adapted to the reality of a given region. In this context, this module considers two types of mobile subscribers. The first type refers to subscribers of conventional data services, and their number is inferred from data such as population density, the percentage of active users during peak hours and the share of the population with access or ability to use devices with access capacity to the mobile network [56]. The second type of subscriber refers to those associated with applications to be used by the municipality's public services infrastructure. Such service infrastructure includes applications based on IoT and M2M platforms in the context of applications for e-learning and e-health, among others. Such applications are estimated based on [17], which considers public statistical information, such as the number of inhabitants, homes, vehicles, and commercial establishments, in addition to information on municipal infrastructures, such as the number of schools, hospitals, and public servants.

This module also considers an effect of pent-up demand on the number of subscribers, given that there is a problem of urban-rural equity related to the deployment of broadband in these regions [57], [58]. For this, the estimated user density [users/km^2] is modelled as a time series in the shape of a Gompertz curve. Thus, it is possible to consider the growth in the number of users as being slower at the beginning and at the end of the analysis time (reaching saturation) compared to the other observation periods.

The demand for data traffic from locality a_n is represented by $\tau_{n,t}$ [Mbps/km^2] and can be obtained from Eq. (2). The term t refers to the year of analysis, within a total time of T years ($t \in T$). Each grouping houses a set of users of mobile networks and a set of municipal entities, such as schools, health posts, public security units, governance and commercial establishments, which make use of conventional Internet applications and applications based on IoT and M2M platforms. The demand for data traffic per year from the n-th location ($\tau_{n,t}$) can be defined as

$$\tau_{n,t} = d^{user}_{n,t}\alpha_n \sum_j r_{j,t}s_j + \sum_z d^{gov}_{n,z,t}\alpha_{n,z}r_z, \tag{2}$$

where $d^{user}_{n,t}$ represents the density of mobile users [users/km^2] in year t, α_n represents the percentage of active users at peak hours, r_j represents the average data rate generated by mobile terminals of type j [Mbps], and s_j represents the fraction of users using terminals of type j. Based on the definitions from [54], three different mobile terminal types are considered: mobile PCs, tablets and smartphones. Terminals are divided into two groups in terms of the data traffic demand needed by the users, i.e., heavy and ordinary users, where the average requests of an ordinary terminal capacity are equivalent to 1/8 of those classified as heavy. Thus, the term $r_{j,t}$ can be computed as

$$r_{j,t} = h_t \cdot r^{heavy}_j + (1 - h_t) \cdot r^{ordinary}_j, \tag{3}$$

where the term h_t represents the proportion of heavy terminals for year t. In addition, the density of mobile users $d_{n,t}$ [users/km^2] can be expressed by Eq. (4):

$$d^{user}_{n,t} = \xi_t \cdot \theta_i \cdot \rho_n, \tag{4}$$

where ξ_t represents the projection of potential users for Internet services, θ_i represents the population of m_i with potential access or ability to use mobile devices, and ρ_n denotes the population density of this locality. Additionally, the term $\xi(t)$ represents the Gompertz curve, according to Eq. (5):

$$\xi_t = \mu \cdot e^{-\beta e^{-\sigma \cdot t}}, \tag{5}$$

where the parameters μ, β and σ are utilized to adjust the growth project of potential users for Internet services over time. In particular, the parameter μ determines the final rate of potential users, σ represents the growth rate of the number of these terminals, and the parameter β represents the initial rate of adoption. Therefore, the higher σ is, the faster the proportion of mobile users that increase over time in the locality.

Still, considering Eq. (2), the term $d^{gov}_{n,z,t}$ denotes the density of terminals used by the municipal entities in year t, such as IoT and M2M applications, while z denotes the types of used applications. The parameter $\alpha_{n,z}$ represents the percentage of active terminals, and r_z represents the average rate of data for applications of type z. The term $d^{gov}_{n,z,t}$ can be obtained from:

$$d^{gov}_{n,z,t} = \frac{\xi_{z,t}N_{n,z}}{A_n}, \tag{6}$$

where $\xi_{z,t}$ represents the Gompertz curve defined in Eq. (5) to represent the rate of adoption of terminals of IoT and M2M applications, $N_{n,z}$ denotes that potential quantitative of terminals of type z and A_n represents the territorial area of the n-th locality. Consequently, the total traffic demand of municipality m_i can be represented by $\sum_{\forall n \in N_i} \tau_{n,t}$, and from the combination of Eqs. (2-6), it is possible to estimate a forecast of data traffic of a given municipality for any year t.

2) RADIO NETWORK DIMENSIONING MODULE

Expansion Strategy: The purpose of this module is to define the types of radio access technology to be used on the network, as well as the types of equipment to be installed. Using data from the survey of existing operator infrastructure, it is possible to estimate the current service capacity (if any) and design it according to the ICT services and applications adapted to the needs of users and to estimates made by the demand module of traffic. Consequently, it may be possible to design a technology expansion or upgrade and thus promote a reduction in implementation costs by partially using the existing infrastructure (e.g., towers and electrical cabling, among other systems). Parameters such as user density [users/km^2] and the existing service capacity are considered in this module. Finally, this module considers radio deployment strategies based on new radio technologies, such as 5G. However, this module considers an eventual time of maturation of such technologies [59] to allow the degree of penetration of 5G-enabled devices to develop, given the context of the social, economic and cultural challenges of these regions.

For all localities a_n of N_i, if the term γ_n is true, then there is pre-existing legacy radio infrastructure covering the locality in question to some extent. Based on the traffic demand defined in Eq. (2) and considering the service capacity existing in the group, the network traffic demand to be expanded in year t ($\tau_{n,exp,t}$) can be expressed as

$$\tau_{n,exp,t} = (1 + \varphi_{RM})\tau_{n,t} - \frac{C_{n,t}}{A_n}, \tag{7}$$

where φ_{RM} is a parameter representing a reserve service margin to guarantee the service of users and network applications during peak traffic. The term C_n represents the accumulated service capacity of BSs existing in the locality [Mbps], i.e., $C_{n,t} = \sum_b C^{BS}_{b,t}$, where b denotes the types of BSs existing in the locality a_n. If the group does not have any type of radio service capacity ($C_{n,t} = 0$), this framework assumes the implementation of an outdoor BS to provide basic coverage in the locality. This outdoor BS can be of the macro (MBS) or micro BS (MiBS) type.

Fuzzy System: The module uses an expert system based on AI to define the choice between the types of BSs presented. Information such as the territorial area (A_n) of the location and mobile network technology available in year t (and its estimated coverage capacity) are considered by the system. In particular, the module considers the use of a fuzzy system to define this choice process. Fuzzy systems are useful for managing imprecision and uncertainty in a system's reasoning process, with partial and automatic optimization of network parameters being possible [60]. Fig. 2 presents the architecture of the fuzzy system used by this module.

Data on the locality area (A_n), mobile network technologies available for deployment and path loss models that estimate the coverage area of a BS [61]–[63] are used as inputs. The fuzzification subsystem receives system variables, and an association function is calculated for each entry in the fuzzy system. The database subsystem defines the fuzzy association functions that allow degrees of association to fuzzy sets to be assigned. This attribution is built from concepts that are subjectively defined and based on specialized knowledge. The inference mechanism identifies rules to be triggered and calculates the fuzzy values of the output variables using a

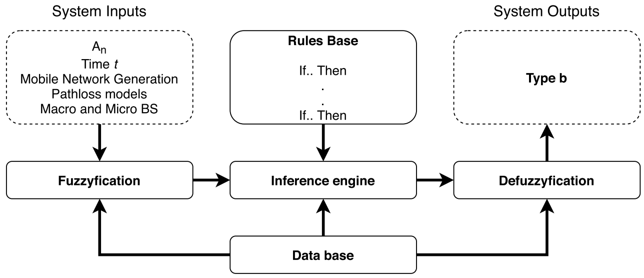


FIGURE 2. Illustration of general fuzzy logic architecture with inputs and output used by the RAN dimensioning module.

max-min inference method [64]. Then, the outputs obtained for each rule are combined into a single set using a fuzzy aggregation operator. The rule with the highest degree of truth is selected, and then, the association function to be activated is determined to specify the type of BS to be implemented in the locality.

From the definition of Eq. (7), the term $\tau_{n,exp,t}$ can assume positive or negative values. If $\tau_{n,exp,t}$ assumes positive values ($\tau_{n,exp,t} > 0$), there is a need to expand the installed capacity. Otherwise ($\tau_{n,exp,t} \leq 0$), the capacity of the existing access network in the locality is considered sufficient to meet the traffic demand in year t.

If technological updating is possible, this framework assumes the upgrade of the BS radio interface (i.e., from a 3G to 4G interface, for example). From the eventual update process, if the condition $\tau_{n,exp} > 0$ persists, the implantation of new BSs is considered; however, implantation is based on increased capacity and not on coverage.

We consider two possible strategies for implementing new BSs in this work, following [65]: (*i*) the homogeneous implementation of macro BSs and (*ii*) the implementation of small BSs (SBS). The maturation time of new radio technologies is represented by the parameter ζ_i, which represents a period in years, after which the network operator will start to implement 5G ($t \geq \zeta_n$) deployments. The total BSs of a certain type that need to be implanted in year t ($N^{BS}_{b,t}$) can be computed according to Eq. (8):

$$N^{BS}_{b,t} = \frac{\tau_{n,exp,t} \cdot A_n}{C^{BS}_{b,t}}. \tag{8}$$

The general operation of the radio network sizing module is summarized by Algorithm 1. Line 3 recovers the term N_i, which represents all locations in municipality m_i, as defined by Eq. 1. The algorithm performs the main loop between lines 4-31. The stopping criterion for this loop is the maximum analysis time T. The internal loop in lines 5-30 represents the dimensioning of the radio network being computed individually for each location a_n. Lines 6-8 compute the area of the locality, the demand for data traffic, and whether there is a preimplanted infrastructure in year t. Between lines 9-13, if there is no pre-existing infrastructure, an outdoor BS (MBS or MiBS) is implemented using the fuzzy system that makes up the module. Line 14 defines the type of BS to be deployed

Algorithm 1: RAN Dimensioning Algorithm

1 Input: m_i, φ_{RM}, ζ_i, *strategy*;
2 **begin**
3 $N_i \leftarrow getLocalidades(m_i)$;
4 **for** $t \leftarrow 0$ **to** T **do**
5 **for** $n \leftarrow 1$ **to** $|N_i|$ **do**
6 $A_n \leftarrow landArea(a_n)$;
7 $\tau_{n,t} \leftarrow trafficDemand(a_n, t)$;
8 $\gamma_n \leftarrow isThereLegacyRAN(a_n)$;
9 **if** γ_n *is False* **then**
10 $b \leftarrow fuzzy(A_n, t)$;
11 $BS \leftarrow newBS(b)$;
12 $a_n \leftarrow addBS(BS, a_n, t)$;
13 **end**
14 $b \leftarrow deploymentType(strategy, \zeta_i, t)$;
15 $C_{n,t} \leftarrow capacity(a_n)$;
16 $\tau_{n,exp,t} \leftarrow expand(\tau_{n,t}, C_{n,t}, \varphi_{RM}, A_n)$;
17 **while** γ_n *is True and* $\tau_{n,exp,t} > 0$ **do**
18 $BS \leftarrow getLegacyBS(a_n)$;
19 $a_n \leftarrow upgrade(t, a_n, BS)$;
20 $C_{n,t} \leftarrow capacity(a_n)$;
21 $\tau_{n,exp,t} \leftarrow expand(\tau_{n,t}, C_{n,t}, \varphi_{RM}, A_n)$;
22 $\gamma_n \leftarrow isThereLegacyRAN(a_n)$;
23 **end**
24 **if** $\tau_{n,exp,t} > 0$ **then**
25 $N_b^{BS} \leftarrow totalBS(\tau_{n,exp,t}, C_{b,t}^{BS})$;
26 $BSs \leftarrow newBS(t, b, N_b^{BS})$;
27 $a_n \leftarrow addBS(t, BSs, a_n)$;
28 $C_{n,t} \leftarrow capacity(a_n)$;
29 **end**
30 **end**
31 **end**
32 **end**

by capacity, and line 15 recovers the capacity of the BSs existing in the location. Line 16 calculates the traffic capacity to be expanded in the locality ($\tau_{n,exp,t}$). The loop in lines 17-23 assesses whether the existing service capacity is capable of meeting the traffic demand for year t. If not, the existing BSs are upgraded to more recent generations, while nothing is done if the existing service capacity can meet the demand. Finally, lines 25-28 are reached if the capacity to be implemented in the location is still greater than the existing service capacity, even after the updates. In this case, based on $\tau_{n,exp,t}$, a number of BSs N_b^{BS} are dimensioned and implanted in location a_n.

3) TRANSPORT NETWORK DIMENSIONING MODULE

The objective of this module is to define the technologies and topology of the transport segment, together with the types of equipment that must be installed in each location to establish communication to the CO. Given the potential heterogeneous geographic conditions or the high population dispersion generally associated with these regions, we assume in this framework a fully wireless (microwave/millimeter-wave)-based deployment, where a pair of antennas is deployed for each microwave link. For this, the module takes into account the output of the radio dimensioning module, as well as the communication topology to be established between the localities of the municipality.

Wireless technology offers cost-benefit and flexibility compatible with implementation in rural regions and usually operates in the microwave/millimeter-wave 6-42 GHz bands, in addition to having a communication scheme based on line-of-sight (LOS) [65]. Fig. 3 presents the reference architecture of wireless implantation considered by this module. Each BS is equipped with a antenna. For MBSs or MiBSs, the communications tower of the radio structure is also used for fixing the antenna. For SBSs, installation is carried out with fastening structures based on rods to guarantee the conditions of LOS. As shown, the communication topology is point-to-point (PtP), with links organized in a tree.

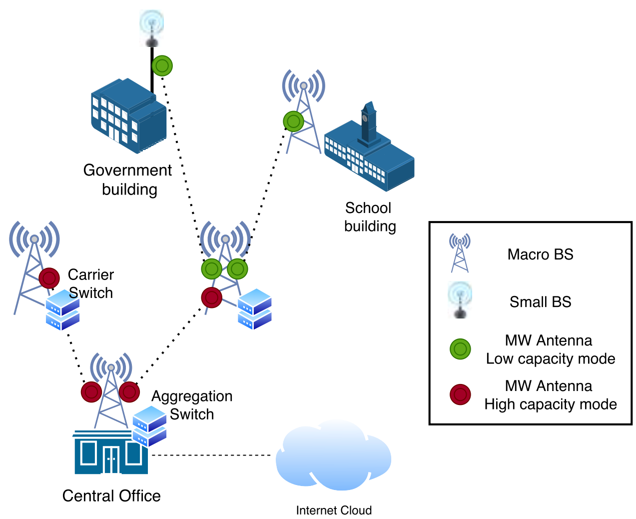


FIGURE 3. Wireless transport architecture for rural and remote areas.

This framework considers that the network is equipped with two levels of wireless hubs. Each first-level hub concentrates data traffic through a carrier switch and forwards this traffic to the second-level hub. The number of carrier switches in each N_t^{CS} hub in year t can be defined as

$$N_t^{CS} = \lceil \frac{N_t^{MWL}}{N_{ports}^{CS}} \rceil, \qquad (9)$$

where N_t^{MWL} denotes the number of wireless links associated with the hub and N_{ports}^{CS} represents the number of ports on a carrier switch. This module considers the propagation models presented in [66] to dimension the microwave links to consider the models of attenuation by rain according to ITU-R P.530 [67] and thus determine the types of antennas, antenna size and expected transmission capacity for a given region.

It is also predicted that the locality may or may not have access to electricity infrastructure, given that the majority of the population without access to electricity lives in rural

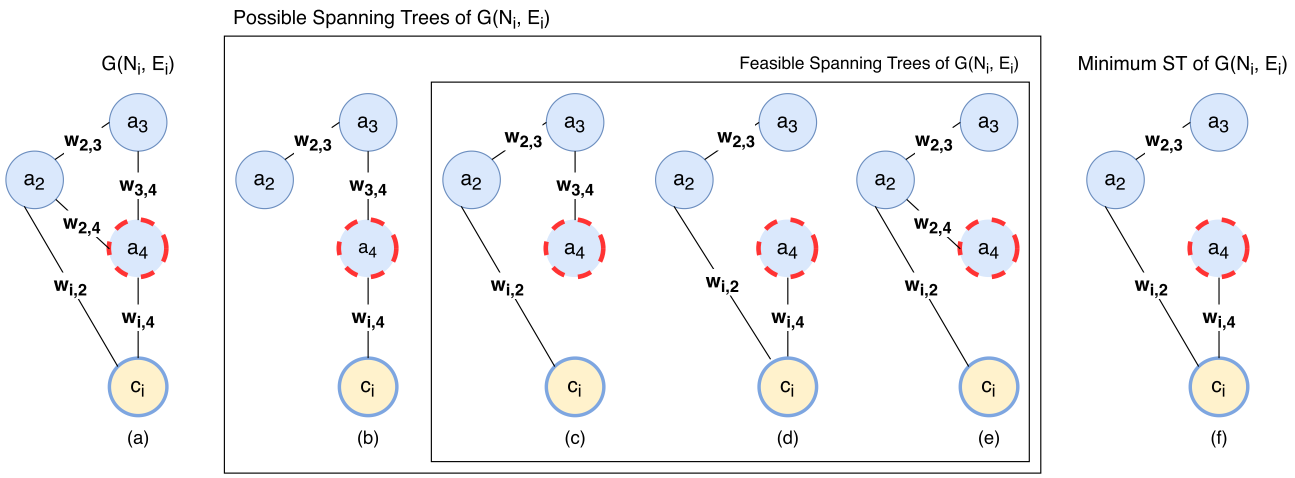


FIGURE 4. **Representation of the transport network topology definition process, considering the availability of electricity in the localities.**

areas of developing countries [68]. Thus, this inefficient supply can cause a reduction in the reliability of the network's service within the locality, as well as in neighboring localities, depending on the transport topology adopted. Thus, this framework module also seeks to represent, through graph theory concepts, the effects caused by these energy inefficiency issues.

Minimum Spanning Tree: Considering the definition of Eq. (1), E_i represents the set of edges of graph $G(N_i, E_i)$ for $E_i = \{e_1, e_2, \ldots, e_l\}$ to represent the physical paths between the elements of N_i, such as road and river routes, among others. The l-th element of E_i, denoted by e_l, represents a tuple (a_p, w_{pq}, a_q), $\forall a_p, a_q \in N_i, p \neq q$, such that w_{pq} represents a weighting of cost and distance between a_p and a_q locations. Considering the cost definition of a graph, G is associated with a cost function, defined as the sum of the weights of the edges that make up G $(\sum w_{p,q}, \forall e_l \in E_i)$.

The space for finding solutions to this type of problem is considered complex due to the number of nodes and edges associated with the graph, thus requiring high computational processing power. Thus, to minimize this complexity, the concept of a spanning tree is used, which in turn is applied to the nondirected graph G, in which any subgraph of G is a tree, i.e., a connected nondirected graph without circuits. This tree can be defined as a spanning tree if it contains all the vertices of G. As trees are connected, every undirected graph with a spanning tree is connected. Conversely, every connected undirected graph has at least one G_{ST} spanning tree. When obtaining at least one G_{ST} spanning tree of G, when applying the cyclic exchange operation, it is possible to obtain all other G spanning trees.

Fig. 4(a) exemplifies the representation of any graph G, while Figures 4(b), (c), (d) and (e) show some of the possible spanning trees obtained from G. In the scheme presented, the a_4 location is distinguished from the others, as it does not have a regular electricity supply ($\varepsilon_4 \leftarrow False$). Thus, despite being one of the possible G spanning trees, the tree presented by Fig. 4(b) is not considered viable according to the transport dimensioning module. When applying the concept of cost to each of the trees considered viable, any tree that has a minimum cost will be considered the minimum generating tree (MST), as represented by Fig. 4(f), which illustrates that one of the viable trees spanned from G has the minimum cost, thus reducing computational effort and optimizing the generation of results.

The functioning of the transport topology definition mechanism is summarized in Algorithm 2. The algorithm has as input the graph that represents a given municipality and the identification of which location does not have electricity (a_n), as in Fig. 4(a). In line 3, the G_{ST} set is initialized as an empty set. If graph G has cycles, for each cycle existing in G, an edge is removed, keeping the graph connected. If there

Algorithm 2: Topology Definition Algorithm

1 Input: G, a_n;
Result: G_{MST}
2 **begin**
3 initialize $G_{ST} \leftarrow \{\}$;
4 **while** *G has Cycles* **do**
5 $cycle \leftarrow getCycle(G)$;
6 $G \leftarrow delEdges(cycle, G)$;
7 **end**
8 $G_{ST} \leftarrow append(G)$;
9 $edges_k \leftarrow excludedEdges(G)$;
10 **for** $k \leftarrow 1$ **to** $|edges_k|$ **do**
11 $cycle \leftarrow fundamentalCycle(G', edges_k)$;
12 $STs \leftarrow cyclicExchange(cycle)$;
13 $G_{ST} \leftarrow append(STs)$;
14 **end**
15 $G_{ST} \leftarrow update(G_{ST}, a_n)$;
16 $G_{MST} \leftarrow min(G_{ST})$;
17 **end**

are still more cycles, the operation is repeated continuously until the last cycle is removed from G, according to lines 4-7. Finally, G_{ST} stores the initial G generating tree (line 8). Thus, lines 9-14 seek to obtain the other G generating trees. In line 9, the term $edges_k$ stores the set of all edges that were removed from G and that are not present in G_{ST}.

The loop of lines 10-14 individually adds each of the elements of $edges_k$ to the G_{ST} spanning tree. Each addition forms a fundamental cycle in G_{ST} (line 11). For each fundamental cycle, the cyclic exchange operation is performed, which individually removes the other edges that make up the fundamental cycle (line 12). Each removal generates a new spanning tree to be stored in G_{ST} (line 13). Line 15 performs the update of the G_{ST} set by removing all spanning trees/topologies that have locations without regular electricity supply as nonleaf nodes. Finally, among all the spanning trees stored in G_{ST}, line 16 selects the one that has the minimum cost and consolidates it in G_{MST}.

4) NETWORK DIMENSIONING MODULE

From the inputs received from the previous modules, this module seeks to consolidate the amount of equipment needed for the network to function, as well as to estimate the volume of new infrastructure that must be implemented by dimensioning the equipment necessary for the operation of the CO, based on the concept of neutral hosting. For this, the module performs sizing based on SDN and NFV technologies [69], [70]. Through this approach, it tends to be possible to adapt the functions related to the evolved packet core (EPC) in a multioperator environment through virtualization to create several independent EPCs in the same physical infrastructure. Thus, this approach can increase the efficiency of the financial resources invested through the sharing of the infrastructure and potentially reduce the associated operating costs [22]. The module also considers EPC elements distributed by several virtual servers (VSs) running on physical servers (PSs) for general use. This paradigm tends to remove the components that originally perform these operations on purpose-built devices to maintain mainly general-purpose equipment installed in the CO.

Given the need for analysis from a technical-economic point of view, this quantity of equipment is dimensioned on an annual scale to consider the periodic expansion of the network, which tends to be facilitated by these software-based deployments. This module seeks to estimate variables related to the network maintenance and repair processes. Finally, this module of the framework still performs the dimensioning of the potential energy consumption of the network to forward to the dimensioning module of the photovoltaic system. To characterize the composition of physical servers in the CO, we define the estimated number of physical servers needed in year t as N_t^{PS}, which is computed as

$$N_t^{PS} = \left\lceil \frac{\sum_n \tau_{n,t} A_n}{C^{VS} N_{PS}^{VS}} \right\rceil, \tag{10}$$

where C^{VS} represents the individual service capacity of a VS [Mbps/virtual server] and N_{PS}^{VS} denotes the average number of competing virtual instances on a physical server [no. of virtual instances/physical server]. Despite the use of virtualized components through SDN and NFV, a minimum number of bare metal switches is still required to provide physical connectivity between network components and aggregate traffic to be routed to the Internet. Thus, the number of aggregation switches N_t^{AS} in year t is computed as

$$N_t^{AS} = \left\lceil \frac{N_t^{PS}}{N_{ports}^{AS}} \right\rceil, \tag{11}$$

where N_{ports}^{AS} denotes the number of ports on an aggregation switch. This equipment needs to be stored and installed in a specific structure in the CO. In this context, we assume the CO is re-architected as a data center, given the context of virtualization inherent to the use of SDN and NFV technologies [71]. With this model, gains in agility tend to be possible, given the ability to elastically deploy services according to traffic demand. In this context, we assume that this deployment model is based on the use of modularized containerized data centers in the form of micro data centers (μDC). The use of μDC in the context of telecommunications network operators is associated with the reduction of implementation costs and improvements in the efficiency of use of the electricity consumed [72].

Consequently, we denote the maximum capacity of the equipment installation of a μDC by $L^{\mu DC}$, expressed in rack units [U]. As the μDC infrastructure can be expanded, μDC quantitative in the year t, $N_t^{\mu DC}$ can be obtained by

$$N_t^{\mu DC} = \left\lceil \frac{L^{PS} N_t^{PS} + L^{AS} N_t^{AS}}{L^{\mu DC}} \right\rceil, \tag{12}$$

where the terms L^{PS} and L^{AS} denote the utilized space in the equipment rack by each physical server and aggregation switch, respectively.

5) PHOTOVOLTAIC SYSTEM DIMENSIONING MODULE

The objective of this module is the dimensioning of the photovoltaic system (PVS) to be used to meet the energy consumption of the network equipment. For this, this module considers our previous methodology for dimensioning an on-grid PVS, applied to the context of Hetnets [73] to decrease the operator's OPEX and reduce carbon dioxide (CO_2) in the atmosphere. However, given the potential unreliability or availability of electricity supply in rural or remote regions [68], we have extended this methodology and considered the dimensioning of an off-grid PVS [74].

Due to the limited availability of data around certain regions' energy infrastructure, this framework module could use a composite map of the global power grid using publicly available open data generated through open-source tools similar to [75]. However, given the ease of access to data from the region under analysis, this module of the framework considers data from the local electric utilities and the total energy demand of the network, consolidated by the network dimensioning module.

In a complementary way, this module performs the dimensioning of a PVS for each locality of the considered municipality. This dimensioning takes into account only the energy demand for the network equipment installed in the locality, including radio and transport equipment, or CO equipment, when the locality refers to the municipality's headquarters. If the location does not have any type of regular energy supply, we consider the implementation of an off-grid PVS. However, if there is a regular supply of electricity, this module considers the adoption of an on-grid PVS to further consider the reliability of this supply, given the criteria of continuity of the service provided by the electricity utility.

To define the degree of supply reliability, we use the concepts of average interruption duration (I_{AD}) and average interruption frequency (I_{AF}). The term I_{AD} denotes the interruption time [hours] for which a locality remains without regular electricity supply. This amount of time in general is presented on an annual scale [hours/year]. The term I_{AF} represents the number of power interruption events in a given year. Thus, for a municipality or locality to be considered reliable by this module, such indicators must be below the maximum limits previously established, i.e., $(1+\varphi_{En})I_{AD} < I_{AD}^{Max}$ and $(1+\varphi_{En})I_{AF} < I_{AF}^{Max}$, where φ_{En} defines an additional safety margin ($\varphi_{En} > 0$). If the presented condition is not satisfied, the module considers the electric power supply to be unreliable, despite being available.

Based on the above, for locations with unreliable electricity supply, this framework also takes into account the implementation of a battery bank to store the energy load of the network in expected periods of interruption, based on parameters I_{AD} and I_{AF}. On the other hand, if the PVS to be implanted is off grid, this dimensioning of the battery bank takes into account the average hour/day in which it is not possible to use solar radiation. The dimensioning of the number of stationary batteries to be installed in the battery bank can be calculated according to the following expression:

$$N_t^{SB} = \left\lceil \frac{P_t^{Net} T_{usage}^{SB}}{C^{SB}} \right\rceil, \tag{13}$$

where P_t^{Net} and T_{usage}^{SB} represent the total potential of the network [W] and the daily average time PVS does not generate electricity [hours]. In particular, in localities with unreliable electricity supply, we assume that T_{usage}^{SB} is calculated from I_{AD} and I_{AF}, i.e., $T_{usage}^{SB} = (1+\varphi_{SB})\frac{I_{AD}}{I_{AF}}$, where φ_{SB} represents a scale factor to ensure the safety margin for the battery bank ($\varphi_{SB} > 0$). Additionally, C^{SB} represents the useful autonomy capacity of a stationary battery [Wh] and can be computed by

$$C^{SB} = C_{rated}^{SB} P^{DoD} E^{SB}, \tag{14}$$

where C_{rated}^{BS} denotes the nominal capacity of the battery [Wh], P^{DoD} defines the maximum discharge depth [%] and E^{BS} refers to the global efficiency of the battery [%].

6) MARKET MODULE

This module of the framework considers indicators related to the economic market to assess financial viability, such as the average price of subscription to services or even the economically active portion of the population. This module also seeks to consider the market share of the network operator to estimate the volume of financial revenues. Thus, the module aims to support the dimensioning of the financial flow of the operator to be considered in the cost module. The gross financial income obtained by the operator F_t^{inc} for year t can be defined by

$$F_t^{inc} = \lambda_t (S_{fee,t}^{user} N_t^{user} I_{wp} + S_{fee,t}^{gov} N_t^{gov}), \tag{15}$$

where λ_t represents the market share of the network operator, while $S_{fee,t}^{user}$ and $S_{fee,t}^{gov}$ denote average data service subscription fees for conventional users and government entities, respectively. The term N_t^{user} can be defined as the number of conventional subscribers in year t, and I_{wp} denotes the economically active share of the population. Similarly, the term N_t^{gov} can be defined as the number of government subscriptions in year t. Eq. (16) presents the ARPU [$/user] modelling used in this module:

$$ARPU_t = \frac{F_t^{inc}}{N_t^{user} + N_t^{gov}}. \tag{16}$$

7) BUSINESS MODULE

This module seeks to relate parameters associated with the business models that can be used by network operators to assess their impact on the costs of implementing and operating the network. Based on the existing infrastructure data, this module seeks to evaluate the investment models to be considered by analyzing the design of greenfield and brownfield scenarios. This analysis is conducted considering each of the localities of a municipality to evaluate these alternative scenarios from the perspective of financial costs in the subsequent modules.

8) COST MODULE

This module seeks to model, on a time scale, the cost variables associated with the network TCO. One of the variables considered is the volume of maintenance and repairs required for the network infrastructure. In this sense, it considers the use of any equipment warranty that can reduce expenses related to equipment damage. In the case of solar inverters, for example, the use of the warranty coverage time tends to concentrate expenses related to repairs after the end of the warranty period.

This module also considers that expenses related to the costs of wages, infrastructure rent, and electricity often have inflationary behaviour over time, while expenses related to the acquisition of hardware components generally suffer a reduction due to factors such as popularization and maturity of the company and technology involved. Thus, this price variation process must be considered when dimensioning the network's implementation and operation costs. Thus, the cost module uses a linear model to calculate the cost variation, as [76]:

$$Pr_t = Pr_0 + \chi Pr_{t-1}, \quad (17)$$

where Pr_t represents the price of an item in year t and Pr_0 represents the price in year 0 of project implantation. The parameter χ refers to the factor of updating the price. By assuming negative values, χ can be applied to calculate expenses of acquiring hardware, which usually drops over time. On the other hand, positive values can calculate the variation of expenses, such as salaries, power costs, and rent. In addition, broadband operators must frequently comply with SLA agreements related to the minimum parameters of availability and service interruption. Thus, this module considers payment of eventual financial fines due to unavailability, which affects the fulfillment of the considered SLA levels.

9) TCO MODULE

This module seeks to dimension the network's TCO, as the sum of CAPEX and OPEX expenses, on a time analysis scale. For CAPEX expenses, the module considers all financial investments for the acquisition, installation, and infrastructure costs of the equipment associated with the network. Because installation is potentially carried out in places with difficult access to or a long distance from large urban centers, the installation fee is parameterized with a distance factor, which also has a direct influence on maintenance costs. For the definition of OPEX, this module seeks to consider expenses related to network operation and maintenance time. For this, we consider the costs of electricity, spectrum licensing, rental of physical space, operation, and monitoring. Maintenance costs include expenses for preventive and corrective repairs and maintenance on all components associated with the network. The details of each cost component are modelled in detail below.

Equipment Cost: The cost of Co_{Eq} is the sum of all expenses related to the acquisition of equipment associated with the Eq_P and its installation Eq_I in their respective locations of use, as follows:

$$Co_{Eq} = Eq_P + Eq_I. \quad (18)$$

The cost of acquiring equipment Eq_P can be defined as

$$Eq_P = \sum_t Eq_{P,t}^{RAN} + Eq_{P,t}^{MW} + Eq_{P,t}^{CO} + Eq_{P,t}^{PVS}, \quad (19)$$

where the terms $Eq_{P,t}^{RAN}$, $Eq_{P,t}^{MW}$, $Eq_{P,t}^{CO}$, and $Eq_{P,t}^{PVS}$, respectively, define the costs of acquiring equipment with respect to the radio network, transport network, of CO and PVS in year t. This annual acquisition occurs due to the gradual increase in traffic demand (modelled by the Gompertz curve), leading to consequent updates of the required capacities. Thus, new network elements are added whenever necessary. The term $Eq_{P,t}^{RAN}$ can be defined as

$$Eq_{P,t}^{RAN} = \sum_b N_{b,t}^{BS} Pr_{b,t}^{BS}, \quad (20)$$

where $N_{b,t}^{BS}$ and $Pr_{b,t}^{BS}$ refer to the quantity of BSs of type b updated or implanted and their respective financial associated costs. The term $Eq_{P,t}^{MW}$ can be calculated as

$$Eq_{P,t}^{MW} = N_t^{CS} Pr_t^{CS} + \sum_j 2N_{j,t}^{MWL} Pr_{j,t}^{MWA} \quad (21)$$

where N_t^{CS} and Pr_t^{CS} represent the quantity and price of acquiring carrier switches, respectively. The terms $N_{j,t}^{MWL}$ and $Pr_{j,t}^{MWA}$ indicate the quantity of links of type j and the unit price of the antenna for this type of link. The term $Eq_{P,t}^{CO}$ is computed as

$$Eq_{P,t}^{CO} = \lambda_t (N_t^{PS} Pr_t^{PS} + N_t^{AS} Pr_t^{AS}), \quad (22)$$

where N_t^{PS} and Pr_t^{PS} represent the quantity and the price of new physical installed serves, respectively, whereas terms N_t^{AS} and Pr_t^{AS} define the quantity of newly acquired aggregated switches and the unit price of acquiring such switches, respectively. Finally, the cost of photovoltaic equipment $Eq_{P,t}^{PVS}$ is defined as

$$Eq_{P,t}^{PVS} = N_t^{SP} Pr_t^{SP} + N_t^{SI} Pr_t^{SI} + N_t^{SB} Pr_t^{SB}, \quad (23)$$

where N_t^{SP}, N_t^{SI} and N_t^{SB} respectively, the number of solar panels, inverters and new stationary batteries installed, and Pr_t^{SP}, Pr_t^{SI} and Pr_t^{SB} denote the unit purchase price of this equipment, in that order. Since Eq_P defines the quantity of equipment to be purchased for the network, we assume that the Eq_I installation costs are based on the installation and testing time for each type of equipment. In this way, Eq_I can be expressed as

$$Eq_I = N_{tech} \sum_t S_t (T_{I,t}^{RAN} + T_{I,t}^{MW} + T_{I,t}^{CO} + T_{I,t}^{PVS}), \quad (24)$$

where N_{tech} represents the number of technicians needed for the installation process and is computed from the total number of N_{team} teams and the number of technicians per team N_{team}^{tech} ($N_{tech} = N_{team} N_{team}^{tech}$). Additionally, S_t represents the average hourly wages of a single installation technician in year t, while the terms $T_{I,t}^{RAN}$, $T_{I,t}^{MW}$, $T_{I,t}^{CO}$, and $T_{I,t}^{PVS}$ define the estimated time for the installation of radio, transport, CO and PVS network equipment, respectively. The term $T_{I,t}^{RAN}$ can be computed as

$$T_{I,t}^{RAN} = \sum_b (N_{b,t}^{BS} T_{I,b}^{BS} + 2T^{Tr}), \quad (25)$$

where $N_{b,t}^{BS}$ denotes the number of BSs of type b to be installed, $T_{I,b}^{BS}$ represents the associated installation time, and T^{Tr} denotes the average travel time to the location of installation. The term $T_{I,t}^{MW}$ can be obtained as follows:

$$T_{I,t}^{MW} = N_t^{CS} T_I^{CS} + \sum_j 2(N_{j,t}^{MWL} T_{I,j}^{MWA} + T^{Tr}), \quad (26)$$

where N_t^{CS} and T_I^{CS} define the number of carrier switches and the installation time for each switch. The term $N_{j,t}^{MWL}$ defines the number of links of type j, while $T_{I,j}^{MWA}$ represents the installation time of an antenna of this type of link. Additionally, the installation time of equipment CO ($T_{I,t}^{CO}$) in year t can be defined as

$$T_{I,t}^{CO} = \lambda_t (N_t^{PS} T_I^{PS} + N_t^{AS} T_I^{AS} + 2T^{Tr}), \quad (27)$$

where N_t^{PS} represents the number of physical servers deployed and T_I^{PS} denotes the installation time for each server. The parameter N_t^{AS} represents the number of aggregation switches to be installed, while T_I^{AS} symbolizes the installation time for each switch. Finally, the term $T_{I,t}^{PVS}$ is modelled from

$$T_{I,t}^{PVS} = N_t^{SP} T_I^{SP} + N_t^{SI} T_I^{SI} + N_t^{SB} T_I^{SB} + 2T^{Tr}, \quad (28)$$

where N_t^{SP} represents the number of solar panels deployed and T_I^{SP} denotes the installation time for each panel. Similarly, N_t^{SI} represents the number of solar inverters, T_I^{SI} defines the installation time for each inverter, N_t^{SB} represents the total number of implanted stationary batteries and T_I^{SB} represents the installation time for each battery.

Infrastructure Cost: The infrastructure costs of Co_{infra} include necessary investments to implement equipment associated with the network. For example, for the radio network, these expenses are concentrated on the installation of communication towers, while for PVS, these expenses include the costs of fixing the structures of the solar panels.

$$Co_{Infra} = \sum_t N_t^{CT} Pr_t^{CT} + N_t^{MH} Pr_t^{MH} + \lambda_t (N_t^{\mu DC} Pr_t^{\mu DC}) + N_t^{SP} Pr_t^{FS}. \quad (29)$$

In the Eq. (29), the terms N_t^{CT} and Pr_t^{CT} refer to the number of communication towers and their respective unitary costs, N_t^{MH} denotes the number of poles for fixing antennas and Pr_t^{MH} represents the unit cost of each pole. The terms $N_t^{\mu DC}$ and $Pr_t^{\mu DC}$ define the quantity and unit price of a μDC. Finally, the term Pr_t^{FS} denotes the expenses associated with repairing the structure of solar panels at the panel installation site.

Energy Cost: Electricity costs Co_{En} make up the network's OPEX, despite the adoption of PVS. For off-grid PVSs, this cost item is assumed to be null ($Co_{En} = 0$), while for on-grid PVSs, these costs are based on the mandatory payment of a minimum service availability fee from the electric utility and the amount of energy generated by the PVS. Thus, unlike the other TCO cost items, electricity costs represent potential revenues for the network operator, as follows:

$$Co_{En} = \sum_t (Pr_{in,t}^{kWh} Con_t^{Net}) - Pr_{out,t}^{kWh} T_{oper}^{Net} (En_t^{CO} + \sum_b N_{b,t}^{BS} P_b^{BS} + \sum_j 2N_{j,t}^{MWL} P_j^{MWA}), \quad (30)$$

where $Pr_{in,t}^{kWh}$ represents the electricity purchase tariff from the dealership [\$/kWh] and Con_t^{Net} represents the minimum consumption to be acquired from this dealership [kWh]. The term $Pr_{out,t}^{kWh}$ defines the sale price of the energy generated by PVS [\$/kWh], T_{oper}^{Net} defines the annual network operation time [hours], and En_t^{CO} defines the energy consumption of the CO in year t. Additionally, the term P_b^{BS} defines the nominal consumption power of a BS of type b [kW], and P_j^{MWA} represents the nominal consumption power of an antenna of type j [kW]. The term Con_t^{Net} can be obtained as follows:

$$Con_t^{Net} = N_t^{NM} Con_{Min}^{NM}, \quad (31)$$

where N_t^{NM} defines the number of bidirectional meters used and Con_{Min}^{NM} represents a minimum consumption allowance to be acquired from the dealership per bidirectional meter [kWh]. Additionally, En_t^{CO} can be computed as

$$En_t^{CO} = \lambda_t (N_t^{PS} P^{PS} + N_t^{AS} P^{AS} + N_t^{\mu DC} P^{\mu DC}), \quad (32)$$

where P^{PS}, P^{AS} and $P^{\mu DC}$ represent the nominal consumption power of a physical server, aggregation switch, and a μDC.

Spectrum Cost: Spectrum costs (Co_{SL}) include expenses related to the licensing of the wireless (microwave/millimeter-wave) spectrum. From the data of the transport dimensioning module, it is possible to obtain the number of links and their respective types. Thus, we consider the methodology presented in [52] for the calculation of transmission network licensing costs to analyse these costs annually and observe their impact on the network's OPEX.

Maintenance Cost: The maintenance costs Co_M include the annual cost of preventive maintenance activities for all equipment associated with the network. Additionally, expenses related to monitoring and full-time operation are included. Such expenses are based mainly on the cost of remunerating the technical team responsible for this monitoring process. Thus, Co_M can be calculated according to the following expression:

$$Co_M = \sum_t \lambda_t M_t^{CO} + M_t^{RAN} + M_t^{MW} + M_t^{PVS} + Mon_t, \quad (33)$$

where the terms M_t^{CO}, M_t^{RAN}, M_t^{MW} and M_t^{PVS} represent the costs of maintaining the CO, the radio network, the transport segment, and the PVS in year t. The term Mon_t defines expenses related to network monitoring and includes the costs of licensing the monitoring software used in the CO, as [52]. The term M_t^{CO} can be computed as follows:

$$M_t^{CO} = (N_t^{\mu DC} T_M^{\mu DC} + N_t^{PS} T_M^{PS} + N_t^{AS} T_M^{AS} + 2T^{Tr}) S_t + N_t^{\mu DC} Pr_{M,t}^{\mu DC} + N_t^{PS} Pr_{M,t}^{PS} + N_t^{AS} Pr_{M,t}^{AS}, \quad (34)$$

where the terms $T_M^{\mu DC}$, T_M^{PS} and T_M^{AS} represent the maintenance times for equipment associated with CO, μDC, physical servers and aggregation switches, respectively. The terms $Pr_{M,t}^{\mu DC}$, $Pr_{M,t}^{PS}$ and $Pr_{M,t}^{AS}$ represent fixed maintenance costs, which are often related to the replacement of components, such as power supplies, cabling and materials needed to cool the equipment. In a complementary way, M_t^{RAN} represents the maintenance costs of the RAN and can be obtained from the following expression:

$$M_t^{RAN} = \sum_b (N_{b,t}^{BS} T_{M,t}^{BS} + 2T^{Tr}) S_t, \quad (35)$$

where $T(M,t)^B S$ refers to the maintenance time of a BS of type b. In addition, the estimated maintenance time of the PVS in year t is modelled by $M_t^P VS$, computed according to

$$M_t^{PVS} = (N_t^{SP} T_{M,t}^{SP} + N_t^{SI} T_{M,t}^{SI} + N_t^{SB} T_{M,t}^{SB} + 2T^{Tr}) S_t, \quad (36)$$

where the terms $T_{M,t}^{SP}$, $T_{M,t}^{SI}$ and $T_{M,t}^{SB}$ are associated with the maintenance times for solar panels, inverters and stationary batteries. Considering the PVS, such maintenance activities include the regular cleaning of solar panels, the calibration of their positioning, and the preventive replacement of various components, such as cables, electrical connections and other low-cost components.

Finally, the costs associated with maintaining the transmission network (M_t^{MW}) are modelled according to the approach presented in [52].

Floor Space Cost: The costs of renting Co_{FS} physical space are modelled as an annual fee paid by the operator for the accommodation of equipment associated with the network of facilities in the localities of the municipality. The term Co_{FS} can be calculated according to the following expression:

$$Co_{FS} = \sum_t (\lambda_t N_t^{\mu DC} A_{\mu DC} Pr_t^{Out} + \sum_b N_{b,t}^{BS} A_b^{BS} Pr_{b,t}^{Out|In} + N_t^{SP} A_{SP} Pr_t^{Out}), \quad (37)$$

where $A_{\mu DC}$ denotes the physical area required for the installation of a μDC [m^2] and Pr_t^{Out} represents the annual outdoor space rental fee to be paid by the operator [\$/m^2]. Additionally, $Pr_{b,t}^{Out|In}$ denotes the rental rate applied to the BSs location [\$/m^2]. If type b of the BS is of the outdoor type $Pr_{b,t}^{Out|In}$, it assumes the value of a fee for outdoor spaces; otherwise, the rental fee for indoor spaces is considered. Finally, A_b^{BS} and A_{SP} denote the physical area used for installing BSs of type b [m^2] and the physical area occupied by a single solar panel [m^2], respectively.

Fault Management Cost: While maintenance expenses include the preventive cost of maintenance activities, failure management costs include expenses related to the repair of failures that may occur in the equipment associated with the network. The total number of failures per year for each type of equipment can be calculated from the annualized failure rate (AFR) of each component, together with the quantity of each piece of equipment. We count the average repair time (MTTR) of each piece of equipment in the network to parameterize the labour expenses necessary for the effective repair of the equipment considered. In general, we denote the type of network equipment to be repaired and can therefore represent any equipment (BSs, antennas, and inverters, among others). In this way, $N_{i,t}$ represents the total of type i equipment to be repaired in year t, thus allowing the computation of Co_{FM} failure management costs as follows:

$$Co_{FM} = \sum_t \sum_i ((MTTR_i + 2T^{Tr}) N_{tech} S_t + Pr_{i,t}^{Eq}) AFR_i N_{i,t} + Penalty_t, \quad (38)$$

where $MTTR_i$ denotes the average repair time for equipment of type i and $Pr_{i,t}^{Eq}$ represents the respective purchase price for replacing the damaged equipment. Additionally, AFR_i denotes the annualized failure rate of type i equipment, while the term $Penalty_t$ quantifies the eventual payment of fines that the operator must bear when service interruptions are higher than a maximum threshold defined by the network's SLA. Thus, we express by T_t^{Un} the network downtime in year t [hours]. If T_t^{Un} is higher than a maximum threshold $T_{Max,t}^{Un}$ ($T_t^{Un} > T_{Max,t}^{Un}$), the operator is subject to a financial fine, modelled as follows:

$$Penalty_t = Pr_t^{Penalty} (T_t^{Un} - T_{Max,t}^{Un}), \quad (39)$$

where $Pr_t^{Penalty}$ refers to the financial penalty per hour for the downtime in year t [\$/h].

Finally, the total CAPEX expenses of the network are expressed by $CAPEX = Co_{Eq} + Co_{Infra}$, while the total costs of OPEX are expressed by $OPEX = Co_{En} + Co_{SL} + Co_M + Co_{FS} + Co_{FM}$. Consequently, the TCO considered in this framework is based on the sum of the presented costs of all the items.

10) TECHNICAL-ECONOMIC FEASIBILITY MODULE

From all inputs, this framework module seeks to assess the financial viability of the network deployment project. With this module, it is possible to make long-term investment decisions to assist in the evaluation of the project's financial return. Hence, it is possible to evaluate the profitability of the project and make it more attractive to network operators. To this end, one of the metrics used in this module is based on the use of the net present value (NPV) of the network implementation project. The NPV is a method that consists of bringing to zero the date ($t = 0$), all the cash flows of an investment project and adding them to the value of the initial investment. This method also considers the use of the minimum rate of attractiveness of return (MARR) for the project, which is a factor that estimates the present value of future cash flow, considering the value of revenues and the risk or uncertainties of these future revenues. In this way, the network's NPV can be obtained as follows:

$$NPV = \sum_t \frac{CF_t}{(1 + MARR)^t}, \quad (40)$$

where CF_t represents the network's cash flow in year t, where $CF_t = TCO_t - F_t^{inc}$. Potential financial benefits should be assessed not only from the perspective of the network operator but also from the point of view of the population. The relationship between the average income per capita of the local population and the ARPU can be used to assess the feasibility of implantation from a socioeconomic perspective to potentially contribute to the reduction of social inequalities and human development in these regions [3]. Thus, this module seeks to evaluate the SI_t socioeconomic index on an annual basis, according to Eq. (41):

$$SI_t = \frac{ARPU_t^{user}}{PCI_t}. \tag{41}$$

where the term $ARPU_t^{user}$ represents the average revenue per user considering only the number of conventional mobile users in the network, i.e., the number of terminals based on IoT/M2M applications is disregarded. The PCI_t parameter denotes the average income per capita of the local population in year t. Assuming that $PCI_t \geq ARPU_t$, the lower the value of SI_t, the lower the estimated financial impact of the cost of telecommunications on the population's income, which tends to facilitate the process of adopting such technologies and the consequent use of pent-up demand from these regions.

V. CASE STUDY

This section describes a case study that demonstrates how our techno-economic framework can be applied to dimension the network's TCO by assessing a) the feasibility of the implementation and b) any associated socioeconomic effects during an analytical period of 10 years ($t \in [0, 9]$).

A. SOCIOECONOMICS OF THE MUNICIPALITY

With regard to the choice of municipality, we adopt a realistic geographic model that takes into account the territorial dynamics that often prevail in rural and remote regions of developing countries. To achieve this objective, we examine the municipality of Faro (Brazil), located in the Amazon Regional Complex in South America (as shown in Fig. 5). This municipality is selected because of its demographic and socioeconomic characteristics, in addition to the fact that it has limited broadband services. In terms of the instruments employed for the classification and characterization of rural and urban spaces, the Brazilian Institute of Geography and Statistics (IBGE) categorizes Faro as a rural-remote municipality on account of its demographic density and its limited accessibility to large nearby urban centers [77].

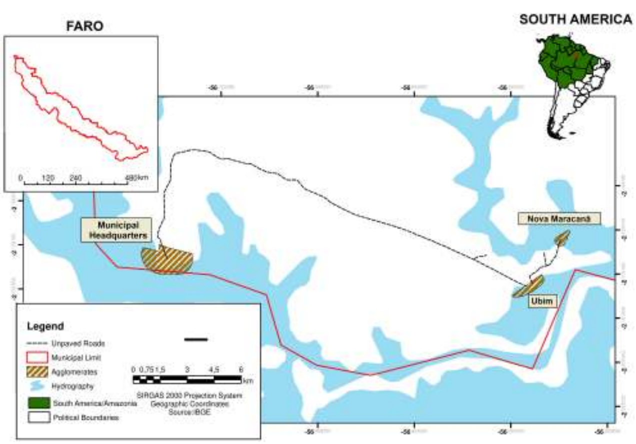


FIGURE 5. Cartographic representation of Faro (Brazil).

Faro has a territorial area of approximately 11,771 km^2 and a total population of 8,177 inhabitants. Approximately 94.78% of the population is under the age of 65, while 75% of this population lives in the towns with the highest degree of urbanization in the municipality: municipal headquarters, Ubim and Nova Maracanã [78], [79]. These three locations have electricity supply from a local concessionaire, with continuity of supply indexes at $I_{AD} = 15.02h$ and $I_{AF} = 9.12$ [80]. The Human Development Index (MHDI) of Faro is 0.563, which places this municipality in the range of low human development (MHDI between 0.500 and 0.599). The economically active region of Faro corresponds to approximately 56.01% of the population ($I_{wp} = 0.56$) and consists of largely informal workers ([81].

Faro has a ratio of 1 public employee to every 12.88 inhabitants, and approximately 48% of these employees work in the municipal health system [82]. Although Faro's average per capita income grew by 136.46% between 1990 and 2010, it is currently projected at R$ 522.50 (approximately US $ 100.67 per person), which means that at least 30.39% of the population is living in extreme poverty. In the Gini index, an instrument used to measure the degree of concentration of income, Faro has a value of 0.56. In addition, Faro has a school-age population of 38%, although it only has one public school located at the municipal headquarters [78].

B. TRAFFIC FORECAST

For the dimensioning of the traffic forecasting of the localities of the municipality, we adopt a rate of active users of 16% ($\alpha_n = 0.16$), applied to conventional network users [65]. When defining the average data rate generated by mobile terminals ($r_{j,t}$) and the fraction of mobile users (s_j), we adopt the definitions provided by [56]. We assume that the proportion of the rural population that was able to gain access to the network or had the necessary skills to use mobile devices θ_i is 0.65 (the range of the population of Faro between the ages of 15 and 65). To define the Gompertz curve ξ_t (Eq. 5), we consider that the parameters μ, β and σ assume the values 0.8, 5.0 and 0.55, respectively [17]. Thus, we find that there was a moderate growth rate for mobile users, which tended to intensify more sharply in the second half of the period of analysis.

With regard to government services based on IoT and M2M applications, we adopt the application profile displayed in Table 3. These applications are categorized into types of services so that the parameters used in the Gompertz curve are specified for each type of application, as well as the required data rate (r_z) [Mbps]. For the definition of the term $N_{n,z}$, which represents the number of potential terminals using the z application, we draw on demographic and socioeconomic data for Faro, and thus, $N_{n,z}$ takes on specific values for each type of application according to the data for each location.

According to Table 3, in the case of e-health applications, the values of $N_{n,z}$ are estimated from the total population over

TABLE 3. Data for government applications collected from [78], [79], [81]–[85].

Service	z-Application	r_z	μ_z	β_z	σ_z	α_z	$N_{n,z}$			Basis for the calculation
							Municipal Headquarters	Ubim	Nova Maracanã	
e-Health	Health monitoring	1.0	1.0	15	0.35	1.0	343	18	86	Population above the age of 65
	Telemedicine	25.0	1.0	15	0.55	0.4	6	1	1	Estimated number of doctors
	Web browsing	2.0	1.0	5	0.55	0.5	190	9	37	Existing health professionals
e-Learning	SD streaming	13.9	0.8	10	0.55	0.16	645	28	124	Number of e-Learning students
	Web browsing	2.0	1.0	5	0.45	0.16	2,786	119	533	Number of students and teachers
e-Gov	Road monitoring	8.0	1.0	10	0.55	1.0	177	21	49	Number of crossroads in the district
	Web browsing	2.0	1.0	5	0.55	0.16	397	17	76	Number of civil servants
e-Finance	ATMs	2.0	1.0	5	0.45	0.16	10	0	0	Number of bank branches and ATMs
	Payment services	2.0	0.8	5	0.45	0.16	2,280	96	435	Number of informal workers
Smart City	Electricity measurement	0.1	1.0	15	0.55	1.0	1,063	47	213	Number of households
	Water measurement	0.1	1.0	15	0.55	1.0	1,063	47	213	Number of households
	GPS tracking	0.1	0.8	5	0.45	1.0	109	5	21	Number of motorized vehicles

the age of 65 and the estimated number of doctors and other existing health professionals in each location. With regard to e-learning applications, estimates are used for the number of students and teachers, in addition to the number of potential students in distance education. Data such as the number of civil servants and the total number of street crossings in each location are used to estimate e-government applications, while in the case of e-finance applications, the estimates are based on the total number of informal workers or even the number of available ATMs. Finally, with regard to smart city applications, the numbers of homes and motor vehicles in each location are used to estimate the term $N_{n,z}$.

C. NETWORK DIMENSIONING

From the survey data of the existing network infrastructure, it can be seen that the municipal headquarters has three MBSs installed, one with a 3G interface and two with a 2G interface [86], while Ubim and Nova Maracanã do not have any telecommunications systems. Thus, for municipal headquarters, the radio dimensioning module of the framework might make infrastructure upgrades for later generations, such as LTE-A (Release-10), LTE-A Pro (Release-13) and 5G-NR (Release-16). In the case of technologies based on 5G, we assume a maturation time of 5 years ($\zeta_i = 4$ due to the set of challenges listed in Section III.

For the dimensioning of the traffic capacity expansion $\tau_{n,exp,t}$, we assume a reserve service margin of 20% ($\varphi_{RM} = 0.2$). We also adopt two strategies for the installation of the radio network: homogeneous (using only MBSs) and heterogeneous (using macro and micro BSs to provide coverage and SBSs to provide indoor capacity; HetNet). With regard to positioning an SBS (and its respective antenna), we assume that it is possible to install it on the premises of municipal sites, such as schools and hospitals, to reduce the installation costs. When making the estimates of coverage, energy consumption and service capacity of BSs, we use the parameters shown in [61], [63], [73], [87].

On the basis of the cartographic, geographic and electricity data of the locations, the dimensioning module of the transport network defines the topology that will be used in Faro. The dimensioning carried out proves the existence of two high capacity MW links, which create a LOS tree topology, to connect Ubim to Nova Maracanã (1.35 km) and the latter to the headquarters (15.65 km), where CO is installed. When estimating the distances of the links and the attenuation models by precipitation of the ITU-R P.530 [67], the module suggests that these links can operate in the range of 6-13 GHz, with 60 cm disks, to attain a precipitation rate of 75.9 mm/h. For low capacity links, we decide to use links in the 15-42 GHz band with 30 or 60 cm discs.

In the case of the automated network sizing module, we assume the implementation of modular μDCs with a useful installation capacity of 42 Us each. Each of the μDCs has cooling infrastructure services, electrical management, and remote monitoring and fault control tools. X64 processors are used for the characterization of the physical servers [72]; on a conservative estimate, each physical server is capable of supporting a maximum of 10 virtual instances simultaneously ($N_{PS}^{VS} = 10$). We estimate that each physical server and aggregation switch occupy a space of 2U and 1U, respectively.

D. PHOTOVOLTAIC SYSTEM

The PVS sizing module requires the use of an on-grid system in each location in such a way that each system is dimensioned for the energy demand of the network devices installed in the location. The battery bank is dimensioned on the basis of the Faro energy availability indicators and the maximum limits established for the Municipality $I_{AD}^{Max} = 21$, $I_{AF}^{Max} = 35$, $\varphi_{En} = 0.4$ and $\varphi_{SB} = 0.2$. On the question of harnessing solar energy radiation, we assume annual average values of 4.651 Wh/m^2.day [88] and 5.0 hours of peak sun [89], values compatible with the region where Faro is located. When dimensioning the battery bank, we assume that each stationary battery has a capacity of 2.64 kWh ($C_{rated}^{SB} = 2.64$), a maximum discharge depth of 60.0% ($P^{DoD} = 0.6$) and an overall efficiency of 80% (E^{SB}). For the installation site of the photovoltaic devices, we assume that they are located close to the main BS of each location so that they can make use of part of the existing infrastructure. Each solar panel has an area of 1.91 m^2, while the inverter can share the cabin together with the BS. The other parameters required for dimensioning the PVS are the same as those adopted in our previous study [73].

E. MARKET AND BUSINESS

On the basis of the information about the existing network system in Faro, we believe there are at least two network operators, so the module market is expressed as $\lambda_t = 0.5$. In a complementary way, in the business module, we adopt two implementation approaches: greenfield and brownfield. In the case of the greenfield scenario, we disregard the potential existence of a legacy infrastructure and require the immediate installation of infrastructure. In brownfield scenarios, if the location already has a pre-existing infrastructure, the network is expanded on it. The business module includes the implementation of 5G technology to decide whether to take into account the technology maturation time (ζ_i). On the basis of this assumption, we list four deployment scenarios, which are described in detail below:

- BF+5GS scenario: the brownfield implementation strategy and maturation time for the implementation of 5G technology. If the location does not have any type of legacy infrastructure, we adopt a greenfield deployment approach;
- GF+5GS scenario: the greenfield implementation strategy and maturation time for the implementation of 5G technology. Although the location has a partial pre-existing infrastructure, these resources are disregarded when evaluating a deployment method based on LTE-A BSs;
- BF+5GF scenario: the brownfield deployment strategy and immediate 5G deployment, i.e., when there is a need to expand the network's service capacity, the existing BSs are upgraded directly to 5G-based technologies;
- GF+5GS scenario: a greenfield deployment strategy and immediate 5G technology deployment.

F. TECHNICAL-ECONOMICAL FEASIBILITY

In the case of the cost module, we assume that equipment acquisition expenses have a readjustment coefficient of -7% per year ($\chi = -0.07$), while other expenses, such as rent, penalties, and human resources, have a readjustment factor that increases by 3% per year ($\chi = 0.03$). We assume that the minimum network availability time corresponds to 90% of the total network operation time in one year $T_{Max,t}^{Un} = 7,884$h, according to data on the regulation of telecommunications services in Brazilian territory [90]. Based on data from existing network operators in Faro, we can infer that the average network availability is 8,320h (94.97%). Thus, the expenses for Faro related to the payment of penalties have not been calculated ($Penalty_t = 0$).

The TCO sizing module involved standardizing the cost parameters in monetary units, as shown in Table 4. In this context, we assume that the financial value related to the update of a BS radio interface is based on a percentage of the purchase value of the new BS, since its potential use is a part of the infrastructure. Thus, for all cases of technological updating (when possible), we assume the application of a base percentage of 40%. That is, when upgrading a BS to a newer radio interface, we include only 40% of the purchase price of this new BS (Pr_b^{BS}). We assume an annualized failure rate (AFR) of 0.0584 for any network device, while the other parameters related to the network installation, maintenance and operational procedures are summarized in Table 5.

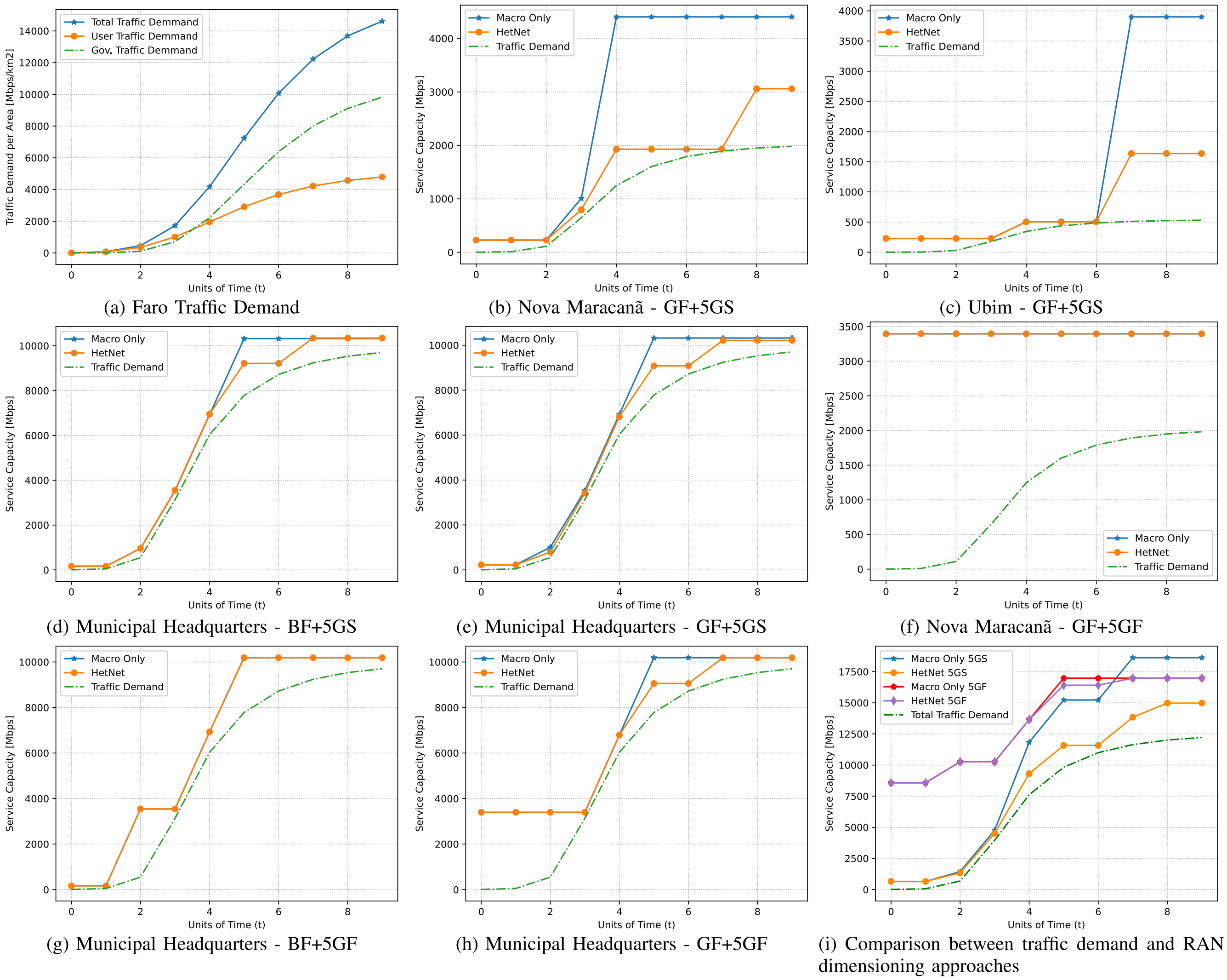
TABLE 4. Standardized cost parameters.

Component/Parameter	Value
MBS/MiBS LTE-A (Pr_b^{BS})	$3.71 \cdot 10^{-1}/1.85 \cdot 10^{-1}$
SBS LTE-A (Pr_b^{BS})	$5.57 \cdot 10^{-2}$
MBS/MiBS LTE-A Pro (Pr_b^{BS})	$4.01 \cdot 10^{-1}/2.05 \cdot 10^{-1}$
SBS LTE-A Pro (Pr_b^{BS})	$6.01 \cdot 10^{-2}$
MBS/MiBS 5G-NR (Pr_b^{BS})	$4.36 \cdot 10^{-1}/2.18 \cdot 10^{-1}$
SBS 5G-NR (Pr_b^{BS})	$6.54 \cdot 10^{-2}$
Carrier/Aggr. SW (Pr^{CS}/Pr^{AS})	$1.86 \cdot 10^{-2}/2.72 \cdot 10^{-2}$
Small/Large MW antenna (Pr_j^{MWA})	$5.19 \cdot 10^{-3}/2.07 \cdot 10^{-2}$
MW Antenna Hast	$2.66 \cdot 10^{-3}$
μDC/Physical Server ($Pr^{\mu DC}/Pr^{PS}$)	$4.54 \cdot 10^{-1}/1.27 \cdot 10^{-1}$
MBS/MiBS comm. tower (Pr^{CT})	1.0/0.5
Solar Panel/Fixing structure (Pr^{SP}/Pr^{FS})	$1.52 \cdot 10^{-3}/3.38 \cdot 10^{-4}$
Stationary Battery/Inverter (Pr^{SB}/Pr^{SI})	$2.54 \cdot 10^{-3}/5.31 \cdot 10^{-2}$
Technician salary/hour (S_t)	$4.72 \cdot 10^{-4}$
Energy cost/kWh ($P_{in}^{kWh}/P_{out}^{kWh}$)	$1.56 \cdot 10^{-6}/1.15 \cdot 10^{-6}$
Indoor yearly rental fee/m^2 (Pr^{Out})	$1.77 \cdot 10^{-4}$
Outdoor yearly rental fee/m^2 (Pr^{In})	$3.54 \cdot 10^{-5}$
Penalty fee/hour ($Penalty$)	$9.09 \cdot 10^{-3}$
User/Gov subscription fee (S^{user}/S^{gov})	$4.54 \cdot 10^{-5}/5.45 \cdot 10^{-5}$
Small/Large MW spectrum leasing/year	$7.24 \cdot 10^{-4}/1.81 \cdot 10^{-3}$
Per Capita Income (PCI)	$9.5 \cdot 10^{-4}$

With regard to the module of the techno-economic feasibility framework, we assume a minimum rate of return of 10% ($MARR = 0.1$) [52], while we adopt Eq. (21) to predict the evolution of the value of average income per capita during the period of analysis by including an update factor of 5% per year ($\chi = 0.05$).

G. NUMERICAL RESULTS

Traffic Forecasting and Network Installation: Fig. 6 shows the results of the traffic demand forecasts for Faro and their effect on radio network dimensioning. With regard to this,



(a) Faro Traffic Demand
(b) Nova Maracanã - GF+5GS
(c) Ubim - GF+5GS
(d) Municipal Headquarters - BF+5GS
(e) Municipal Headquarters - GF+5GS
(f) Nova Maracanã - GF+5GF
(g) Municipal Headquarters - BF+5GF
(h) Municipal Headquarters - GF+5GF
(i) Comparison between traffic demand and RAN dimensioning approaches

FIGURE 6. Forecasts of the traffic demand and radio network dimensioning for the locations of Faro.

Fig. 6a demonstrates the evolution of the types of signatures included in system modelling, and we can see that the traffic demand for government applications is initially lower than the demand for conventional users because of the low adoption rate of IoT/M2M applications in the first years of the analysis time. However, owing to the parameters included in the traffic demand module, the traffic of IoT/M2M applications progressively increases with an approximate CAGR of 123.60% to meet the traffic demands of conventional users. This trend corresponds to the traffic expectations predicted for the coming years, caused by the advent of 5G networks and IoT/M2M technologies [43], [91].

Figures 6b and 6c show the dimensioning of the radio network in the installation of GF+5GS for Nova Maracanã (Fig. 6b) and Ubim (Fig. 6c). Since these locations do not have a pre-existing network infrastructure, the framework infers that it is impossible to apply brownfield scenarios, and thus, the BF+5GS and GF+5GS scenarios have the same results for both locations. Thus, for convenience, we show only the results of the GF+5GS scenario, although when examining the consolidated results for Faro, we use data from all the scenarios and locations described in the case study. The radio network sizing module foresees the installation of an outdoor BS LTE-A in both locations for the provision of basic coverage in year 0. That is, the implementation of an MBS for the macro-only approach and an MiBS for HetNet approach in both locations. For Nova Maracanã (Fig. 6b), the specialist system predicts that this single BS will be able to meet the traffic demand until Year 4. The upgrade of the radio interface is evaluated for the macro-only strategy, and once the upgrade to LTE-A Pro is no longer sufficient to carry out the service in the locality, the upgrade to 5G-NR is performed, without the need for any future upgrade or deployment in this scenario. The HetNet approach allows the upgrade of MiBS to 5G-NR in Year 4 and subsequently the implementation of an SBS 5G-NR in Year 8. In a complementary way, (Fig. 6c),

TABLE 5. Network installation, maintenance and operation parameters.

Component/Parameter	Value
Number of Team (N_{team})	1
Number of tech per team (N_{team}^{tech})	2
Cost change factor - salary (χ)	7%
Cost change factor - hardware (χ)	-3%
uDC area (m^2)	14.78
MBS/MiBS cell site area (m^2)	50.0/25.0
Min. Power Consumption kWh/year (Con_{Min}^{NM})	1, 200
MBS/MiBS instl. time/MTTR ($T_I^{BS}/MTTR_b^{BS}$)	10.0/1.0
SBS instl. time/MTTR ($T_I^{BS}/MTTR_b^{BS}$)	1.0/0.5
MW antenna instl. time/MTTR ($T_I^{MWA}/MTTR_j^{MWA}$)	3.0/0.5
MW antenna instl. time/MTTR ($T_I^{MWA}/MTTR_j^{MWA}$)	6.0/1.0
Carrier SW instl. time/MTTR ($T_I^{CS}/MTTR^{CS}$)	1.0/0.5
Aggregation SW instl. time/MTTR ($T_I^{AS}/MTTR^{AS}$)	1.0/0.5
Physical Server instl. time/MTTR ($T_I^{PS}/MTTR^{PS}$)	2.0/1.0
Solar Panel install. time/MTTR ($T_I^{SP}/MTTR^{SP}$)	0.5/0.1
Solar Inverter instl. time/MTTR ($T_I^{SI}/MTTR^{SI}$)	2.0/0.5
Stationary Battery instl. time/MTTR ($T_I^{SB}/MTTR^{SB}$)	0.5/0.1
Annualized Failure Rate (AFR)	0.0584

the BS outdoor design is upgraded for Ubim to an LTE-A Pro interface in Year 4, and no future updates or deployments are required for Ubim. Thus, from the standpoint of meeting the traffic demand, it is not necessary to implement technologies based on 5G or any other additional BS, whether MBS or SBS. For this reason, the macro-only and HetNet curves overlap in Fig. 6c.

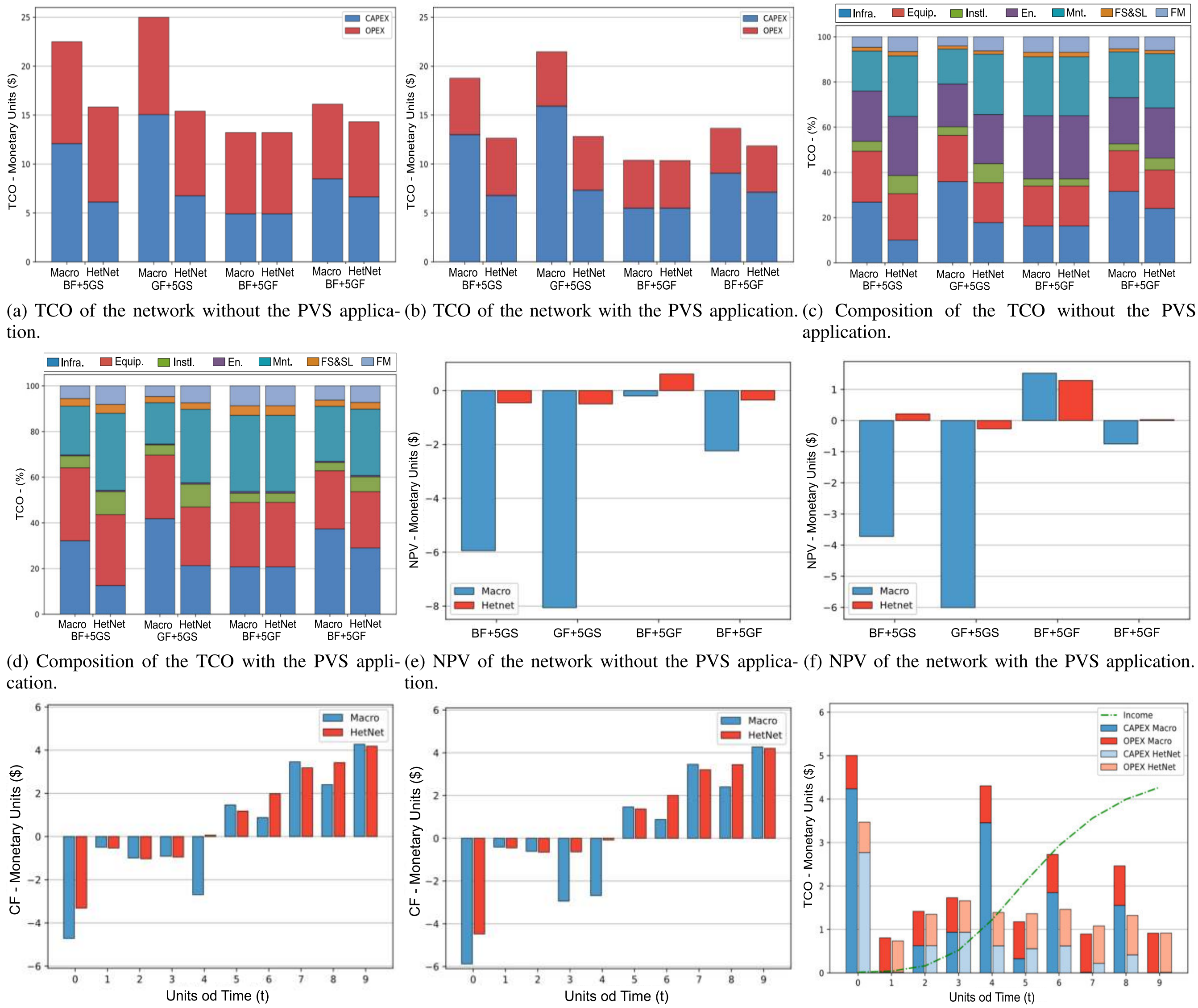
Figures 6d and 6e show the application of the BF+5GS and GF+5GS scenarios for the Faro Municipal Headquarters. In the case of the BF+5GS scenario, the framework takes into account the existing network infrastructure at the headquarters. Between years 0 and 3, the three existing BSs are progressively updated, and at the end of year 3, they all have an LTE-A Pro interface. From Year 4 onwards, it is necessary to implement new BSs to expand the service capacity. The macro-only approach implements three more 5G-NR MBSs until the end of the analysis period, while the HetNet approach provides for the additional deployment of four 5G-NR SBSs. On the other hand, although the GF+5GS scenario (Fig. 6e) disregards the pre-existing network infrastructure, it is also expected to implement a total of three LTE-A Pro MBSs by Year 3 through the macro-only approach, as well as in the BF+5GS scenario. In the case of the HetNet approach in GF+5GS (Fig. 6e), the implementation of SBSs only occurs from Year 3; however, this is the scenario that is most expected to be implemented by SBSs until the end of the reporting analysis period.

The application of the GF+5GF scenario for Nova Maracanã is shown in Fig. 6f. In this scenario, a single MBS 5G-NR is deployed in Year 0 to provide basic coverage in the locality and adopts both radio installation approaches (macro-only and HetNet). Owing to the high service capacity of the BS that is implemented, no further upgrade or installation will be necessary for the following years. Since the application of the GF+5GF scenario for Ubim behaves in a way that is similar to that observed in Nova Maracanã, for purposes of convenience, we will confine this study to examining only one of the forecasts. Again, we would like to point out that these locations do not have a pre-existing network infrastructure, so there is no possibility of applying brownfield scenarios. In view of this, the BF+5GF and GF+5GF scenarios provide the same results for Ubim and Nova Maracanã.

Figures 6g and 6h show the application of the BF+5GF and GF+5GF scenarios at the municipal headquarters of Faro. In the case of the BF+5GF scenario, successive updates are made to the radio interface of the existing MBSs, and it is not necessary to implement new BSs in any of the radio installation approaches, which again explains the overlapping curves in Fig. 6g. On the other hand, in scenario 6h, both the macro-only and HetNet approaches start with the implementation of an outdoor MBS 5G-NR, which should meet the traffic demand until Year 4. As a result, both strategies carry out the implementation of a different number of BSs but culminate by attaining the same service capacity in Year 8.

Fig. 6i compares the scenarios that are displayed to highlight the differences between the traffic handling capacities of scenarios that seek the deployment of 5G technologies only after a period of maturation (BF+5GS and GF+5GS) and scenarios that carry out this installation immediately (BF+5GF and GF+5GF). We examine the average service capacity between each pair of scenarios to understand the different types of radio installation (macro-only and HetNet). As shown in Fig. 6i, in the 5GS scenarios, there is a smaller difference between the capacity of the radio network and the required traffic demand, with a special emphasis on the first years of the analysis time. In particular, with regard to the HetNet 5GS scenario, greater granularity in terms of types of BS and service capabilities should bring about a greater adherence to the traffic demand curve. On the other hand, the distance observed in the 5GF scenarios is explained mainly by the implementation of 5G technologies in Ubim and Nova Maracanã. In light of the relatively low traffic demand, even with the adoption of IoT/M2M applications, the service capacity ends up being significantly higher than the required traffic demand, as represented by Fig. 6f.

Total Cost of Property and Technical-Economical Feasibility: Figures 7a and 7b show the total cost of ownership of the network for each of the alternative scenarios under consideration. In particular, Fig. 7a demonstrates the TCO of the network without taking note of the application of the PVS, while Fig. 7b shows the effects of the installation of the PVS in the network. With regard to Fig. 7a, it should first be pointed out that all the approaches based on the implementation of macro-only radio have a significantly higher TCO value than those based on HetNet. However, there is an exception in the specific case of the BF+5GF scenarios, which have the same levels of TCO for the macro-only and HetNet strategies because the set of BSs existing at the headquarters (when updated directly to 5G-NR) can meet the entire traffic demand from this location without the need to implement a new BS (whether an MBS or SBS). In the Nova Maracanã and Ubim, a single outdoor BS is required to provide



(a) TCO of the network without the PVS application.

(b) TCO of the network with the PVS application.

(c) Composition of the TCO without the PVS application.

(d) Composition of the TCO with the PVS application.

(e) NPV of the network without the PVS application.

(f) NPV of the network with the PVS application.

(g) Cash flow BF+5GS with the PVS.

(h) Cash flow GF+5GS with the PVS.

(i) Evolving pattern of TCO in the HetNet scenario.

FIGURE 7. Representation of TCO, NPV, CF and the evolving pattern of TCO for the scenarios examined in this study.

capacity and coverage in each of these locations. We find a difference of 110% between the most expensive scenario (Macro GF+5GS) and the scenarios with the lowest TCO levels (Macro and HetNet BF+5GF). Thus, although all the scenarios are capable of meeting the projected traffic demand, there are significant differences between the observed TCO values.

When applying PVS to the network (Fig. 7b), there is a considerable reduction in the TCO of the network, according to the data shown in Fig. 7a. The average reduction observed is approximately 18.97% for all the scenarios but ranges between 16.05 and 21.87% since each scenario has a different energy demand, which directly influences the PVS dimensioning and the TCO network. It should be noted that after the application of PVS, the composition of the TCO undergoes a significant change. While in the results in Fig. 7a, in general, there is a greater proportion of OPEX expenses in all the scenarios, from the application of PVS, there is a noticeable reduction in OPEX costs and an increase in CAPEX expenditure (average of 7.1%) resulting from the installation of the PVS components. In addition to the above, Figures 7c and 7d verify the results achieved by the framework, as they show the percentage composition of the TCO for scenarios without and with the application of PVS, respectively. From the results obtained, the cost elements that are included are infrastructure (Infra.), equipment/hardware (Equip.), installation expenses (Instl.), energy (En.), maintenance (Mnt.), rent of physical space and spectrum (FS&SL), and fault management (FM). In particular, in the case of Fig. 7d, the energy component (En.) refers to the mandatory cost of the minimum electricity supply rate of the local concessionaire, although the energy consumed by the network is generated entirely by the PVS of the network.

Fig. 7e shows the NPV of the network for all scenarios. Most of these scenarios are not profitable from the standpoint of the network operator because of the negative NPV obtained from a discounted cash flow (MARR $=$ 10%). This behaviour corresponds to the difficulties discussed in the literature regarding the installation of telecommunications services in rural and remote areas. It should also be noted that the macro-only scenarios are much less satisfactory than the HetNet deployment scenarios. Although the HetNet BF+5GF scenario is profitable from the operator's financial perspective, the immediate deployment of 5G technology may not be technically feasible because of the low penetration of compatible devices. Thus, Fig. 7f shows the NPV, which includes the application of PVS in the network. In this case, the HetNet BF+5GS scenario will be profitable for the network operator since there is a significant reduction in energy expenses. This trend may show that the application of alternative technologies applied to the reduction of network expenses could be a key factor that makes the process of technical and economic installation viable for network operators in rural and remote regions.

It is worth noting that the accumulated TCO of the HetNet BF+5GS and GF+5GS approaches (Fig. 7b) entails approximately the same level of investment even though only the BF+5GS scenario shows a positive NPV in Fig. 7f. This behaviour suggests that the dimensioning of the TCO alone is not sufficient to assess the feasibility of installing the network. In this case, the project's cash flow arrangement and the joint effect of the MARR may be factors in decision-making when undertaking the project. Although the TCO accumulated over the analysis period is approximately the same for the HetNet BF+5GS and GF+5GS approaches, the cash flow of the brownfield approach (BF+5GS) is less pronounced than that observed in the greenfield approach (GF+5GS). This observation is based on the lower degree of investment in implementation at the beginning of the analysis time (Fig. 7g), with regard to the cash flow observed in Fig. 7h. This time difference at the time of the investment application, combined with a discounted cash flow, is sufficient to cause a positive NPV for the HetNet BF+5GS approach, as seen in Fig. 7f.

Fig. 7i shows the evolving pattern of TCO during the analysis period in comparison with the network operator's gross revenue for the BF+5GS together with the PVS scenario. Although a large amount of investment is required during the analysis period in this scenario (with a special emphasis on the first years of the installation of the network), it has been noted that the gross revenue becomes significantly higher than the expenses incurred for the implementation and operation of the network beginning in Year 5. Although the framework has technical and economic significance for the network operator, the views of the local community must also be taken into account. To this end, we adopt the SI term, which defines the relationship between the average per capita income of the population (PCI) and the average revenue per user (ARPU) of the operator, in terms of Eq. 41. Based on data from [33], it has been suggested that ARPU represents only 5% of the PCI of developed countries ($SI = 0.05$), while for developing countries, this level is in the range of 20% ($SI = 0.2$). In the case of rural and remote regions, this behaviour can be attributed to the need for the network operator to maximize NPV or at least make it positive by increasing the tariffs charged to end users.

A Socio-Economic Perspective: On the basis of the results of the application of the framework in the context of the municipality of Faro and the value of the subscription fees outlined in Table 1, the SI term has an approximate value of 16.07% ($SI = 0.1607$). This result can be considered promising since Faro is located in a region of low human development, where the SI should be at the level of 20%. Although still far below the level of developed countries, this difference may represent a decisive factor in the implementation and take advantage of the suppressed demand from users in these regions. A significant reduction in end-user subscription fees or an excessive increase in the rate of government applications may be unrealistic or even financially unsustainable for the network operator.

Fig. 8 shows the variation of the monthly subscription fees of conventional users, together with the NPV forecast for each case in the scenario involving HetNet BF+5GS with PVS. In this context, it should be noted that the reduction in the subscription fee means better IS values, although the NPV begins to assume negative values, which makes the installation project impracticable. On the other hand, if the subscription fee of users increases by 35%, despite the NPV assuming a positive value, the SI term assumes values above 20%, which tends to be undesirable from the perspective of end users and hampers the expansion of traffic demand during the analysis period.

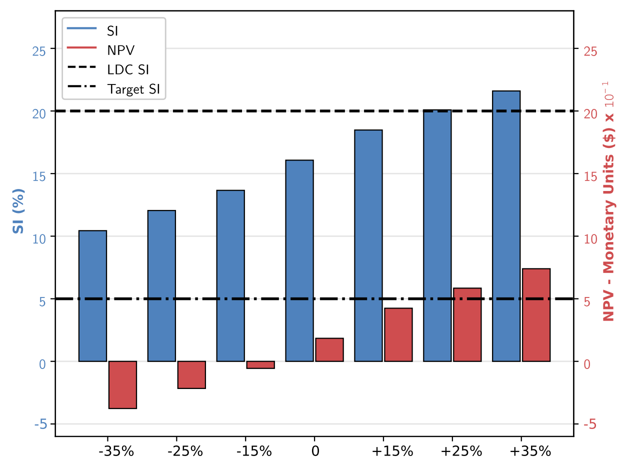


FIGURE 8. **Representation of variations in users subscription rates and their implications for the NPV of the network.**

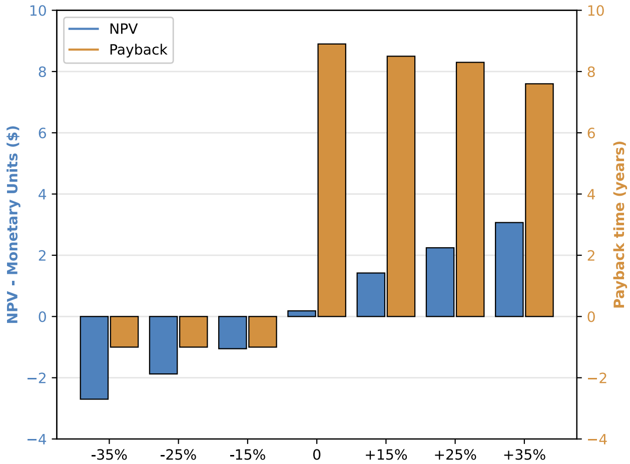


FIGURE 9. Representation of variations in subscription rates of government agencies and the estimated payback time for the network.

Fig. 9 shows the relationship between the variation in the subscription rate of government applications and the estimated payback time of the network, again with regard to the HetNet BF+5GS scenario with PVS. If this subscription fee suffers any negative adjustment, the NPV tends to assume negative values, which makes the deployment project unattractive to the network operator. In these cases, there is no payback since the network's sources of revenue are unable to offset previous investment in implementation. These cases are denoted by the negative column in the representation of the payback in Fig. 9. On the other hand, by increasing the subscription fee to 35% or more, the payback time is reduced by approximately 2 years, and the NPV increases by approximately 1.665%. Thus, in view of the set of assumptions and opportunities offered, funding strategies by government entities can be important for the installation of network services in rural and remote regions.

H. LIMITATIONS OF THE STUDY

Some aspects could be improved in the future when planning a technical-economic feasibility study of broadband services for rural and remote areas.

First, we worked with several assumptions for traffic demand forecasting and cost analysis. Although these assumptions reflect real data collected from the Brazilian government's official information sources, there is a need to develop strategies to incorporate uncertainty variables inherent in the forecasting process. Moreover, to the best of our knowledge, the parameter costs are compatible with rural and remote regions in the Brazilian Amazon. Other areas might have different cost drivers, which could lead to different conclusions.

Second, in the study case, we parametrized the proposed models with real static data related to the reality in the municipality. To improve this input process and make the proposed approach more extendable, the development of a data layer can include online queries of public databases, such as those on electricity availability in a specific region, population density, and other information.

Finally, the proposed framework does not consider specific technical issues related to the deployment of links under LOS conditions. While globally, there is an extensive adoption of wireless (microwave/millimeter-wave)-based technologies, we assume that the related technical challenges of deploying these technologies are quite difficult to overcome and hence have not been explicitly considered in this work.

VI. CONCLUSION AND FUTURE WORK

This work has established a comprehensive techno-economic framework that is capable of scaling the deployment and/or expansion of network infrastructure through the adoption of ICT services adapted to the demographic, socioeconomic and geographical characteristics of rural and remote regions. This scheme has the capacity for generalization and can potentially be applied to any scenario of rural and remote areas in developing countries.

With regard to gaining access to networks, the framework includes fiber and wireless connections, with the latter being employed particularly in remote regions where the former does not exist - a typical scenario in the Brazilian Amazon. The connection topology is defined by means of graph theory, which makes use of the existence of infrastructural facilities (mainly energy). A specialist system based on fuzzy rules assists in the decision about how to install the technology and takes into account technical and socioeconomic factors. The network design takes note of trends in virtualized (NFV and SDN) and shared (neutral host) networks to reduce CAPEX and OPEX costs.

In this way, by being based on current technological concepts, the framework is able to efficiently evaluate the potential use of existing telecommunications systems and adopt approaches for the installation of homogeneous and heterogeneous networks, in addition to implementing a photovoltaic system to reduce operating costs. This work included a case study of the installation of communication networks in a municipality in the Brazilian Amazon region. It was shown that the application of brownfield scenarios, the implementation of HetNets and the use of technologies based on 5G after a period of technological maturation are practicable alternatives that are technically and economically viable for network operators.

With regard to the population of Faro, there is a reasonable relationship between the average income per capita and the average revenue per user envisaged by the operator, which is below the average of developing countries. This shows how the choice of technologies, business models and low-cost strategies adapted to these regions are important for planning rural connectivity. In view of this, the framework offers promising results, as it is able to balance the degree of financial investment necessary for the network operator with the requirements of end users and may lead to the reduction of subscription costs or better data franchise business plans.

Finally, future research work should include the definition of geomorphological models. They are also an exciting area to examine to provide proper LOS condition analysis and a sensitivity analysis study in traffic forecasting models to weigh uncertainties. Furthermore, currently planned future work includes examining supply-side costs, market segmentation parameters, service penetration per customer segment, and new deployment strategies. This future work will add more detail on network costs and improve the proposed model's adherence to the reality of these rural and remote regions.

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MARCELA ALVES DE SOUZA received the B.S. degree in information systems from the Federal University of Pará (UFPA), Marabá, Brazil, in 2012, and the M.S. degree in electrical engineering with an emphasis on applied computing from UFPA, Belém, Brazil, in 2016, where she is currently pursuing the Ph.D. degree. Since 2014, she has been an Information Technology Analyst with the Information and Communication Technology Center, UNIFESSPA. She has experience in information systems, software analysis, and development, process modeling, and database administration. Her research interests include energy efficiency, wireless mobile networks, energy harvesting, and techno-economic analysis.

HUGO PEREIRA KURIBAYASHI received the B.S. and M.S. degrees in computer science from the Federal University of Pará (UFPA), Belém, Brazil, in 2007 and 2011, respectively, where he is currently pursuing the Ph.D. degree in electrical engineering with an emphasis on applied computing. He is currently an Assistant Professor with the Faculty of Computing and Electrical Engineering, Federal University of South and Southeast Pará (UNIFESSPA). His research interests include next-generation networks, energy efficiency, smart radio resource management for wireless mobile networks, and the Internet of Things.

PALINE ALVES SARAIVA received the B.S. degree in information systems from the Federal University of Pará (UFPA), Marabá, Brazil, in 2012, the master's degree in systems engineering from the Escola Superior Aberta do Brasil, in 2016, and the M.S. degree in electrical engineering with an emphasis on applied computing from UFPA, in 2020. Since 2014, she has been an Information Technology Analyst with the Information and Communication Technology Center, UNIFESSPA, where she has performing software development activities. She has experience in information systems, software development, programming languages, and agile methods.

FABRÍCIO DE SOUZA FARIAS received the Ph.D. degree from the Universidade Federal do Par (UFPA), Brazil, in 2016. He has been a Professor with the Faculty of Information Systems, UFPA, Cameta, since 2014. His research interests include data mining, HetNets, mobile backhaul, digital TV, and DSL networks.

NANDAMUDI L. VIJAYKUMAR received the master's degree in applied computing and the Ph.D. degree in informatics. He has worked for almost 40 years at the National Institute for Space Research (INPE) retiring in May 2017. He has participated in a Postdoctoral Program, funded by European Union, at the University College Cork (UCC), Cork, Ireland, to evaluate effects of Climate Change for Coastal Environment. He is currently a Computational Technologist. He is also a Visiting Associate Professor with the Federal University of São Paulo (UNIFESP)/Campus São José dos Campos. His research interests include formal models for performance evaluation and software testing, computational modeling of coastal environment, data science, smart cities and geotechnologies. He has published 57 articles in journals and 125 papers in international and national conferences. He has supervised 14 Ph.D. and 13 M.Sc. students in the area of applied computing.

CARLOS RENATO LISBOA FRANCÊS received the B.S. degree in computer science from the Federal University of Pará (UFPA), in 1995, and the M.S. and Ph.D. degrees from the University of São Paulo, Brazil, in 1998 and 2001, respectively. He held a postdoctoral position at the Institute for Systems and Computer Engineering, Technology and Science, Porto, Portugal, in 2012. He is currently an Associate Professor with the Telecommunication and Computer Engineering Department, UFPA. His research interests include performance evaluation, optimization, Markov processes, and artificial intelligence models.

JOÃO C. WEYL ALBUQUERQUE COSTA (Senior Member, IEEE) received the B.Sc. degree in electrical engineering from the Federal University of Pará (UFPA), Belém, Brazil, in 1981, the M.Sc. degree in electrical engineering from the Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil, in 1989, and the Ph.D. degree in electrical engineering from the State University of Campinas, Campinas, Brazil, in 1994. He is currently a Professor with the Institute of Technology, UFPA, and a Researcher with the Brazilian Research Funding Agency National Council for Scientific and Technological Development, Brasilia, Brazil. His current research interests include broadband systems and optical sensors.