OPTIMIZATION OF BACKHAUL NETWORKS FOR INTERNET ACCESS IN HIGH ANDEAN AREAS OF CAJAMARCA

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Summary
Internet access in rural areas of Cajamarca, specifically in the high Andean areas, faces significant restrictions due to poor telecommunications infrastructure, which produces digital disparities that harm education, the economy, and social inclusion. The purpose of this research was to create and implement a Backhaul network that improves connectivity in the high Andean districts, analyzing its technical feasibility and its possible effect on the quality of service. An applied methodological approach was used, with a quantitative approach and an experimental design, which included the study of traffic, network structure and the choice of appropriate equipment for areas of difficult geographical access. The findings indicated that the network presented increases the available bandwidth, decreases latency and ensures greater stability in data transmission, which enables more efficient access to the internet in remote communities. In summary, the implementation of a Backhaul network is shown to be an appropriate option to reduce the digital divide in rural areas, promoting technological inclusion and social progress in the high Andean regions.

Keywords: Broadband Network, Internet Access, High Andean Rural Districts Cajamarca, CAPEX, OPEX.

1. Introduction

Access to the internet is a crucial aspect today for the social, economic and cultural progress of countries, as it directly affects education, competitiveness and the participation of citizens in the digital age. However, the inequality in the distribution of technological infrastructure has generated a notable digital divide, especially in rural areas and areas with difficult geographical access, where the availability of the internet is still scarce or even non-existent. In Latin America, this phenomenon has been the subject of numerous studies that highlight how the lack of connection widens structural inequalities and limits opportunities for advancement for disadvantaged communities (Becerra and Astudillo, 2020). In Peru, despite initiatives to improve telecommunications infrastructure, coverage in high Andean areas remains limited, restricting access to essential digital services and placing large sectors of the population at a disadvantage (Organization of American States, 2021).

The region of Cajamarca, with its irregular terrain and the dispersion of its inhabitants, faces this challenge in a particular way. Districts in the high Andean areas have limited connectivity that affects not only access to information and communication, but also the provision of services in education, health, and public administration through digital platforms. This lack of connectivity represents a significant obstacle to achieving the 2030 Agenda and the Sustainable Development Goals, which promote the reduction of inequalities and universal access to information and communication technologies (UN, 2019). The situation requires technological solutions that adapt to the geographical and socioeconomic context, in order to overcome the current limitations and offer a stable, accessible and quality internet service.

In this context, the implementation of backhaul networks emerges as a viable and efficient option to improve connectivity in rural areas. These networks are designed as intermediate transmission systems that connect local access networks with the telecommunications core, and have proven to be effective in improving bandwidth, reducing latency, and expanding coverage in complex situations (Alfaro, Quintero, & Rodríguez, 2019; Singh, Sharma, & Misra, 2021). Several recent studies indicate that the development of backhaul infrastructure, whether through wireless or hybrid technologies, is a fundamental strategy to ensure the sustainability and scalability of the service in communities with low population density (Cao, Zhao, & Wang, 2022). In addition, research carried out in hard-to-reach areas has shown that this type of solution not only improves technical connectivity, but also generates positive effects on social and economic indicators, promoting digital inclusion and territorial cohesion (Torres & Villanueva, 2023).

Despite the advances in concepts and technology, the digital divide in Cajamarca continues to be a major limitation that slows down development opportunities. The lack of a solid infrastructure that allows the efficient sending of data from provincial capitals to rural areas becomes an obstacle to digital integration in the region. This problem raises the central question of the research: how can a backhaul network help improve internet access in the high Andean districts of Cajamarca? From this main question, the following specific questions arise: what is the current state of internet coverage in the high Andean districts of Cajamarca? , what technical characteristics should a backhaul network have to adapt to the geographical and socioeconomic conditions of the region? , and to what extent can the proposed network ensure improvements in aspects such as bandwidth, latency and service stability?

The answers to these questions are not only important in the technical field, but also have a considerable societal impact. Recent research has shown that the existence of digital infrastructure in historically marginalized areas translates into greater opportunities to access online education, the creation of new rural business initiatives, and the strengthening of social cohesion through digital participation (Mendoza, Palacios, & Ramírez, 2021). Therefore, addressing the challenge of connectivity in Cajamarca from a technical and practical approach represents an important contribution to both telecommunications engineering and the reduction of social inequalities.

The objective of this study is to demonstrate that the design and implementation of a backhaul network adapted to the geographical characteristics of Cajamarca offers a viable and efficient solution to reduce the digital divide. The study proposes a practical approach that combines the analysis of current service conditions, the identification of key technical parameters and the assessment of the potential impact of the network on improving internet access. Thus, the work not only intends to suggest a technical alternative, but also to contribute to the academic debate and to formulate public policies that promote digital inclusion in rural areas of Peru and Latin America.

2. Objectives

2.1 General objective

To evaluate the economic and technical feasibility of a backhaul network designed to adapt to the specific geographical conditions of two rural high Andean districts of Cajamarca, in order to improve Internet access.

2.2 Specific objectives

- To analyze the geographical, demographic, and economic conditions of the high Andean rural districts of Cajamarca in order to adapt the design of the backhaul networks.
- To develop a backhaul network model that optimizes coverage and quality of service in high Andean rural districts of Cajamarca.
- To evaluate the economic viability of backhaul network projects in high Andean rural districts of Cajamarca, through the analysis of Net Present Value

3. Methodology

3.1 Focus, scope, and design

3.1.1 Research Approach

The study will take a mixed approach, with an emphasis on quantitative and qualitative analysis of secondary data. This approach will allow a comprehensive understanding of the geographical and socioeconomic conditions of the high Andean rural districts of Cajamarca, as well as the applicable broadband network technologies, without the need for on-site primary data collection.

3.1.2 Scope of the investigation

The research will focus on the design of broadband networks capable of overcoming the challenges imposed by the topography and economic constraints of the high Andean rural districts of Cajamarca. Existing secondary data on telecommunications infrastructure, socio-economic conditions, and relevant case studies will be analysed to formulate technically and economically viable solutions.

3.1.3 Research design

- Literature review: A thorough literature review will be conducted, including previous project reports, academic studies, and technical documentation on broadband network deployments in similar contexts.
- Document analysis: Evaluation of public policies, reports from telecommunications operators, and official statistics to understand the current connectivity landscape in the target districts.
- Modeling and simulation:

- Use of simulation software such as Link Planner, to model the design of broadband networks, considering the topography and demographic characteristics of the districts.
- Technical and economic feasibility analysis by using financial analysis tools (Excel and financial programs in Python) to estimate the NPV and IRR of the proposed models.

- Case study analysis: Selection and analysis of case studies that have faced similar challenges, extracting lessons learned and effective practices applicable to the districts of Cajamarca.
- Expert consultations: To reinforce the robustness of the study, consultations will be carried out with experts in telecommunications and rural development through electronic communication, seeking to validate the network design proposals and their economic implications.

3.1.4 Validation of the proposal.

The validation process will include the comparison of the results of the simulation and financial analysis with the information and patterns identified in the reviewed literature and expert consultations. This approach will ensure that the proposals are not only technically and economically feasible, but also realistic and applicable in the specific context of the high Andean rural districts of Cajamarca.

3.2 Population and sample

3.2.1 Population

The study population included households and public institutions (such as schools and health centers), located in the rural high Andean districts of Cajamarca, that lacked adequate access to broadband internet services.

3.2.2 Sample

Given the geographical dispersion and logistical challenges of the selected districts, a non-probabilistic sampling was chosen for convenience. The sample included households and public entities of the RNNFO's Cajamarca Regional Project, in two specific districts: Sitacocha and Tongod, which adequately represented the topographical and socioeconomic diversity of the region.

3.2.3 Sampling Type

A non-probabilistic convenience sampling was used, selected due to geographical and access limitations in the high Andean districts. This method made it possible to study the areas where it was most easily accessible within the limits of the budget and the scope of the project, while gathering valuable information on the implementation of technology and the feasibility of wireless networks in these challenging conditions.

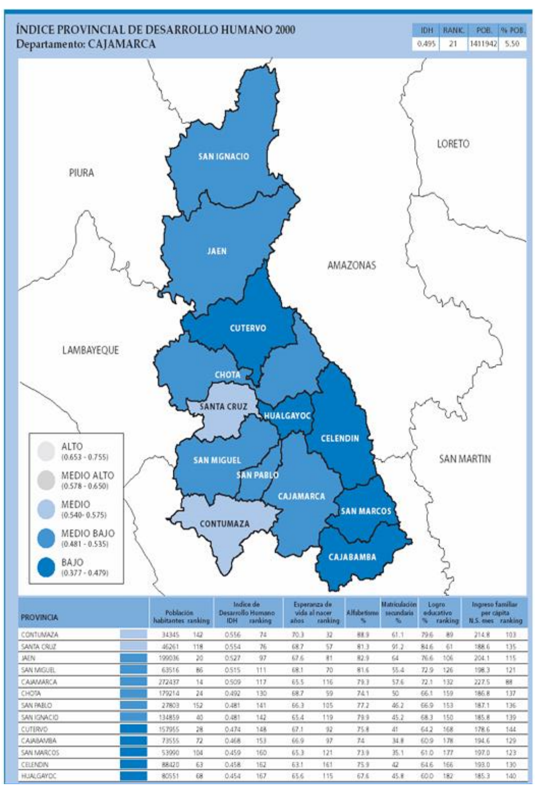
4. Results and analysis

4.1 Backhaul Network Results and Analysis

In this research focused on improving Internet access in rural high Andean districts of Cajamarca, particularly in Sitacocha and Tongod, significant results have been obtained that underscore the complexity and the need for specific solutions for each area. It consolidates and summarizes essential findings to provide a clear view of the current state and challenges faced by these communities regarding Internet connectivity.

4.1.1 Context and justification

Cajamarca, a region with vast potential, but limited by its accessibility to basic services such as the Internet, presents a unique scenario for the deployment of broadband networks. The districts of Sitacocha and Tongod, with their diverse geography and demographic conditions, represent a particular challenge for the implementation of telecommunications infrastructures. According to the IPE (2023), it has faced significant challenges in terms of poverty, remaining the second poorest region in the country for the last 15 years, only surpassed by Huancavelica. Districts such as Tongod and Sitacocha, with poverty levels of 45.3% and 40.2% respectively (INEI, 2018), underscore the urgent need for this intervention. Sitacocha in Cajabamba and Tongod in Santa Cruz belong to the axis of economic and territorial integration of the stagnant and marginal areas of Cajamarca, respectively (GRC, 2015). The following figure shows the map of the human development index, which shows the low development index in the provinces of San Miguel and Cajabamba.



PROVINCIA	Población habitantes	ranking	Indice de Desarrollo Humano IDH	ranking	Esperanza de vida al nacer años	ranking	Alfabetismo %	Matriculación secundaria %	Logro educativo %	ranking	Ingreso familiar per cápita N.S. mes	ranking
CONTUMAZA	34345	142	0.556	74	70.3	32	88.9	61.1	79.6	89	214.8	103
SANTA CRUZ	46261	118	0.554	76	68.7	57	81.3	91.2	84.6	61	188.6	135
JAEN	199036	20	0.527	97	67.6	81	82.9	64	76.6	106	204.1	115
SAN MIGUEL	63516	86	0.515	111	68.1	70	81.6	55.4	72.9	126	198.3	121
CAJAMARCA	272437	14	0.509	117	65.5	116	79.3	57.6	72.1	132	227.5	88
CHOTA	179214	24	0.492	130	68.7	59	74.1	50	66.1	159	186.8	137
SAN PABLO	27803	152	0.481	141	66.3	105	77.2	46.2	66.9	153	187.1	136
SAN IGNACIO	134859	40	0.481	142	65.4	119	79.9	45.2	68.3	150	185.8	139
CUTERVO	157955	28	0.474	148	67.1	92	75.8	41	64.2	168	178.6	144
CAJABAMBA	73555	72	0.468	153	66.9	97	74	34.8	60.9	178	194.6	129
SAN MARCOS	53990	104	0.459	160	65.3	121	73.9	35.1	61.0	177	197.0	123
CELENDIN	88420	63	0.458	162	63.1	161	75.9	42	64.6	166	193.0	130
HUALGAYOC	80551	68	0.454	167	65.6	115	67.6	45.8	60.0	182	185.3	140

Figure. 1 Map of Cajamarca, Extracted from GRC (2015)

The figures. 2 and 3 illustrate the provinces of San Miguel and Cajabamba respectively, highlighting the location of the districts of Tongod and Sitacocha. It is relevant to note that RDNFO connection nodes are implemented in both districts (Fitel, 2018), see Figure 10. This infrastructure assumes that the costs associated with installing and providing internet service in these areas could be significantly reduced (Lam, Yin, & Zhang, 2022), thus facilitating broadband access and supporting service expansion in the region.

Figure 2 Location of Tongod district - map of Peru. Excerpted from GRC (2017)

Figure. 2 Location Sitacocha district - map of Peru. Extracted from Caballero (2018)

4.1.2. Geographical, demographic and housing configuration.

CCPP Tongod.

Tongod district, with an average altitude of 2,688 meters, is home to a population of 1,251 inhabitants spread over 260 households, resulting in an average of approximately 2.25 persons per household. This average varies significantly between population centers; for example, Pisit has the lowest average number of people per household with 0.92, while El Chito shows the highest value with 3.33 people per household.

Code	CCPP/Caserío	Natural regi	Altitude (M.S.N.M.)	Population	Housing	People x housi
061112	**Tongod District**			**2 688**	**1 251**	
1	Tongod	Quechua	2 628	586	260	2.25
2	La Palma	Quechua	2 467	39	16	2.44
3	The Lucuma	Quechua	2 525	210	82	2.56
4	Chilal de la Merced	Quechua	2 736	287	106	2.71
5	That horco	Quechua	2 617	220	84	2.62
6	Quitahuasi	Quechua	2 894	109	70	1.56
7	La Laguna	Quechua	3 238	72	37	1.95
8	Chaullagon	Quechua	2 667	19	13	1.46
9	Tongod Alto	Quechua	2 925	38	25	1.52
10	Chuclla Pampa	Quechua	3 299	128	54	2.37
11	Bancuyoc	Sunni	3 582	40	31	1.29
12	The Crown	Quechua	3 303	101	32	3.16
13	The Triumph	Quechua	3 151	61	27	2.26
14	Pisit	Quechua	3 256	81	88	0.92
15	Andean Lily	Quechua	3 355	54	20	2.70
16	El Chito	Quechua	2 706	30	9	3.33
17	The Well	Quechua	2 654	43	28	1.54
18	About Conga	Quechua	3 250	12	7	1.71
19	High Viewpoint	Quechua	2 716	154	62	2.48
20	The Capulí	Quechua	2 620	74	28	2.64
21	La Merced	Quechua	2 653	117	60	1.95
22	Free People	Quechua	2 681	60	26	2.31
23	Garay	Sunni	3 688	61	46	1.33
24	Santa Ana	Quechua	2 645	92	40	2.30

Table 1. Population centers and housing in the district of Tongod

Source: Prepared by the authors with INEI 2017 data

The Table. 1 details the demographic and geographical characteristics of the population centers within the Tongod District, focusing on key aspects such as the natural region, altitude, total population, number of dwellings and the average number of people per household. The altitude of these centers varies considerably, from 2,467 meters above sea level in La Palma to 3,688 meters in Garay, reflecting the geographical diversity of the district that is mostly found in the Quechua natural region, with some areas in Suni.

The distribution of population and housing reveals both concentrations and dispersions of inhabitants across the district, suggesting areas of higher and lower population density that could influence the planning of services and infrastructure. For example, Tongod, the largest population center, has 586 people and 260 homes, standing out as the main population center of the district. On the other hand, centers such as Sur Conga and Bancuyoc, with 12 and 40 inhabitants respectively, represent the smallest settlements, which could reflect unique challenges in terms of accessibility and provision of basic services.

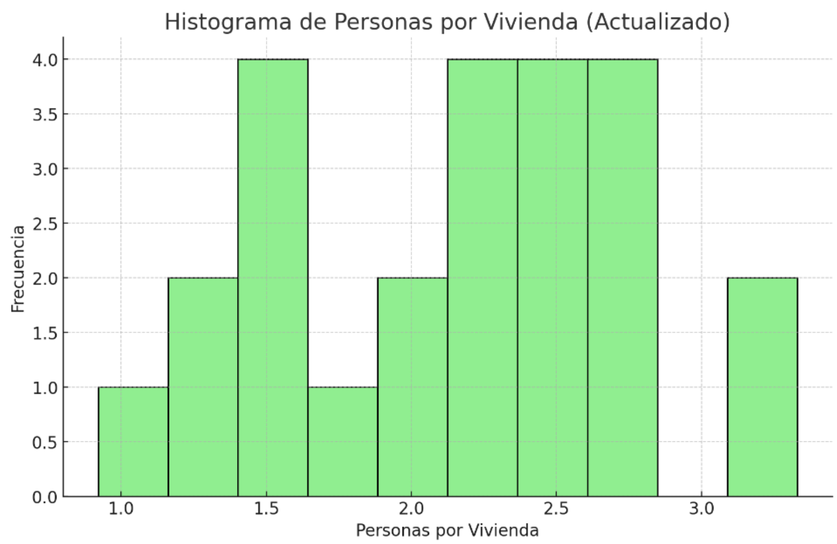


Figure. 3 Histogram population by dwelling in the CCPP Tongod. Own elaboration.In original Spanish language

The Figure. 4 indicates that 80% of the data is between the values of approximately 1.37 and 2.71 people per household. This means that the lowest 10% of data is below 1.37 persons per household, and the highest 10% of data is above 2.71 persons per household, leaving the central 80% of data within this range.

Tongod, the largest population center, has 586 people and 260 homes, standing out as the main population center of the district. On the other hand, population centers such as Sur Conga and Bancuyoc, with 12 and 40 inhabitants respectively, represent the smallest settlements, which could reflect unique challenges in terms of accessibility and provision of basic services.

From the above, we can conclude that both districts are characterized by a varied geography, from fertile valleys to Andean mountains (Alcántara & GRC, 2011; Pulgar, 2020), which pose significant obstacles to the deployment of networks (Leija Hernández, López Bonilla, & Iturri Hinojosa, 2014). Sitacocha, with a population of 8910, and Tongod, with 4891 residents (INEI, 2022b), show low population density, which requires careful planning to ensure effective network coverage (ITU, 2012). In addition, for the calculations of effective bandwidth or throughput per dwelling in Sitacocha we can work with dwellings of 4 inhabitants and in Tongod dwellings of 3 inhabitants.

CCPP Sitacocha.

We are going to present the geographical, demographic and housing data of Sitacocha in the first place. The following table provides a comprehensive view of the population centers within the District of Sitacocha, based on data obtained from INEI (2017). Highlighting the classification of each population center by its location in different natural regions, in addition to detailing its altitude, total population, number of homes and the average number of people per home. A remarkable diversity is observed in the altitude of these centers, ranging from 1,205 meters above sea level in Santa Ana to 3,693 meters in Suro Chico, reflecting the varied topography and the different climatic conditions faced by the communities. In the Table. 2, Lluchubamba is identified as the population center with the largest number of inhabitants, with 1,896 people, which indicates that it is a key area for the targeting of services and resources. Likewise, the number of dwellings per population center shows a considerable variation, which implies different needs in terms of infrastructure and basic services. The lowest number of people per household is recorded in Sitacocha with an average of 1.40, which could indicate a higher prevalence of single-person households or a lower density of occupancy in the dwellings. On the other hand, the highest value is found in Santa Rosa De Jocos, with an average of 4.58 people per household, suggesting larger households or a higher density of family occupancy, which may be indicative of extended family traditions, limitations in access to housing, or a preference for extended family life in that area.

Code	CCPP/ Hamlet	Natural region	Altitude (M.S.N.M.)	Population	Housing.	People/ housing
060204	Sitacocha District			4300	2247	
1	Lluchubamba	Quechua	3 209	1 896	696	2.72
2	Sitacocha	Quechua	2 964	189	135	1.40
3	Santa Ana	Appearance	1 205	169	47	3.60
4	Tingo Grande	Appearance	1 091	115	47	2.45
5	Santa Rosa	Appearance	1 167	730	188	3.88
6	San Martin	Quechua	3 017	111	71	1.56
7	Marcamachay	Quechua	2 679	101	57	1.77
8	Ask	Quechua	2 995	162	71	2.28
9	Saint Ursula	Quechua	2 912	101	38	2.66
10	Cochapamba	Quechua	3 032	107	42	2.55
11	Huacra	Quechua	3 056	101	44	2.30
12	Huamborco	Quechua	2 854	309	92	3.36
13	San Juan	Quechua	2 696	154	54	2.85
14	Shocorco	Quechua	2 906	167	42	3.98
15	Santa Rosa de	Quechua	2 672	220	48	4.58

	Jocos					
16	Bellavista	Quechua	2 791	220	82	2.68
17	San Isidro de Jocos	Quechua	2 826	424	131	3.24
18	Cochapampa	Quechua	3 246	220	98	2.24
19	Jalcahuasi	Quechua	2 825	192	76	2.53
20	Pucarita	Appearance	1 274	143	47	3.04
21	Chillin	Quechua	2 886	127	53	2.40
22	Moraspamba	Quechua	2 628	156	45	3.47
23	Suro Chico	Sunni	3 693	82	43	1.91

Table 2 Population centers with a population of more than 100 inhabitants – Sitacocha

This table. 2 details the demographic and geographical characteristics of the population centers within the Tongod District, focusing on key aspects such as the natural region, altitude, total population, number of dwellings and the average number of people per dwelling. The altitude of these centers varies considerably, from 2,467 meters above sea level in La Palma to 3,688 meters in Garay, reflecting the geographical diversity of the district that is mostly found in the Quechua natural region, with some areas in Suni.

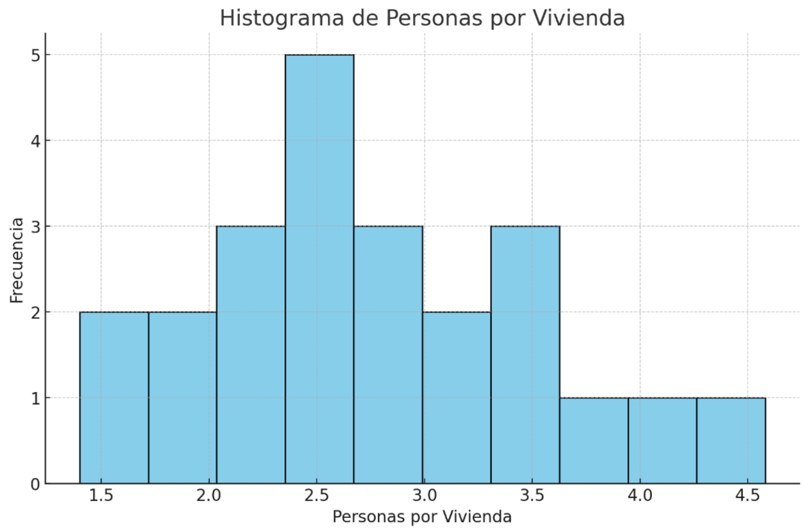


Figure 5 Histogram of population by dwelling in the CCPP of Sitacocha. Own elaboration.In original Spanishlanguage

From the Figure. 5, for the people-per-household dataset, 80% of the data is between the values of approximately 1.80 and 3.82 persons per household. This indicates that the lowest 10% of data are below 1.80 persons per household, and the highest 10% of data are above 3.82 persons per household, placing the central 80% of data within this range

4.1.3 Current CCPP internet coverage Tongod and Sitacocha.

In the diagnosis of Internet provision in the areas of Tongod and Sitacocha, in the region of Cajamarca, significant challenges are evident in terms of the coverage and accessibility of both fixed and mobile Internet services.

Currently, in the CCPPs of the high Andean rural districts of Sitacocha and Tongod, there is no backhaul network, only internet access with mobile phone operators, PCS, in the district capitals, mainly. A consolidation of the findings is presented below:

Situation in Tongod District: Connectivity Challenges.

In Tongod district, the Internet connectivity situation faces significant barriers, evidenced by the confirmation of the main fixed Internet service providers about the lack of coverage in this area. This lack of fixed internet access highlights the region's reliance on mobile connectivity solutions.

According to the information provided by Osiptel (2023), the available mobile coverage is limited and concentrated in a few locations. Movistar and Bitel emerge as the only providers that offer services at specific points in the district, which highlights restricted mobile connectivity. This limitation in coverage directly affects residents' ability to access essential services online and slows down socioeconomic, educational, and health development in the region.

A peculiar aspect in Tongod is the wireless Internet option available in the district capital, where users can access 100 Gbps for 85 soles, using the mobile phone infrastructure. Although this offer represents an alternative to online connectivity, its dependence on the mobile network and the pricing model based on data consumption may not fully meet the needs of all users, especially for those whose Internet demands exceed the established threshold. Table 3 shows the mobile phone operators in the CCPPs of Tongod district.

|	CCPP/Caserío	Operator	Telephony Mobile	Technology Mobile
061112	Tongod District			
1	Tongod	Movistar / Bitel	Yes	Movistar 2G / Bitel 3 and 4G
2	La Palma	---	No	---
3	The Lucuma	---	No	---
4	Chilal de la Merced	Movistar	Yes	Movistar 2G
5	That horco	Movistar	Yes	Movistar 2G
6	Quitahuasi	---	No	---
7	La Laguna	---	No	---
8	Chaullagon	---	No	---
9	Tongod Alto	---	No	---
10	Chuclla Pampa	---	No	---
11	Bancuyoc	---	No	---
12	The Crown	---	No	---
13	The Triumph	---	No	---
14	Pisit	---	No	---
15	Andean Lily	---	No	---
16	El Chito	---	No	---
17	The Well	---	No	---

18	About Conga	---	No	---
19	High Viewpoint	Bitel	Yes	Bitel 3G and 4G
20	The Capulí	Bitel	Yes	Bitel 4G
21	La Merced	Bitel	Yes	Bitel 4G
22	Free People	---	No	---
23	Garay	---	No	---
24	Santa Ana	Bitel	Yes	Bitel 4G

Table 3. CCPP Tongods vs mobile operators
Source: National Georeferenced Data Platform – Geo Peru

In Figure. 6 and Figure 7, the histogram of existing telephony and mobile technology is shown:

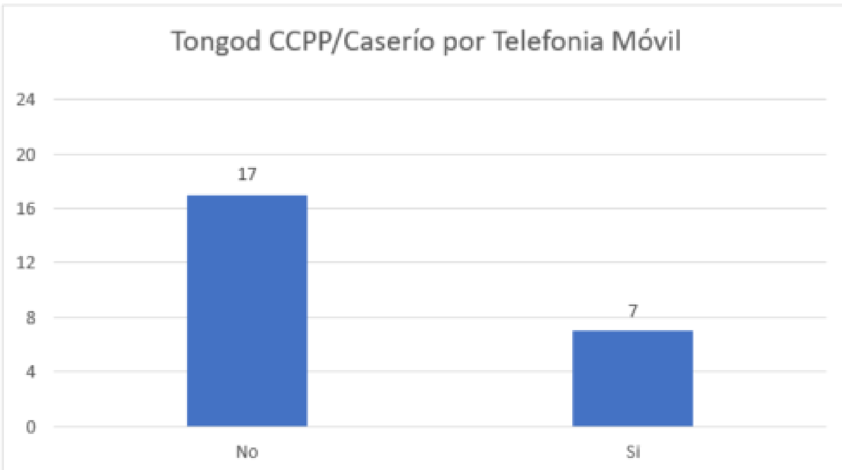


Figure. 4 Mobile telephony histogram – CCPP Tongod. Own elaboration.*In original Spanish language*

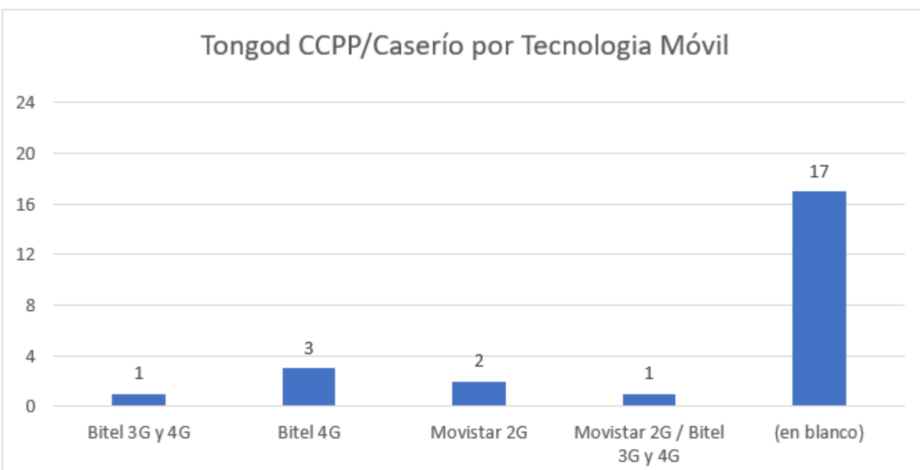


Figure. 5 Mobile technology histogram – CCPP Tongod. Own elaboration.*In original Spanish language*

Situation in Sitacocha and surrounding areas.

A notable lack of fixed Internet services was identified in key locations such as Lluchubamba and Sitacocha, following direct consultations with the main operators in Peru: Bitel, Claro, and Movistar. These operators confirmed the absence of fixed Internet coverage not only in these localities but also in other areas with considerable population density, such as Santa Rosa and Huamborco. The research extended to mobile phone coverage, revealing that Bitel has the largest presence in the region, albeit limited to certain locations, while Movistar and Claro offer coverage in a smaller range of areas.

Table 4 shows the mobile phone operators in the CCPPs of the district of Sitacocha.

Code	CCPP/Caserío	Natural region	Operator	Mobile	Technology Mobile
060204	Sitacocha District				
1	Lluchubamba	Quechua	Claro, Movistar, Bitel	Yes	Claro 3G / Movistar 2G / Bitel 3G and 4G
2	Sitacocha	Quechua	Bitel	Yes	Bitel 3G and 4G
3	Santa Ana	Appearance	---	No	---
4	Tingo Grande	Appearance	---	No	---
5	Santa Rosa	Appearance	Movistar	Yes	Movistar 2G
6	San Martin	Quechua	---	No	---
7	Marcamachay	Quechua	---	No	---
8	Ask	Quechua	---	No	---
9	Saint Ursula	Quechua	---	No	---
10	Cochapamba	Quechua	Bitel	Yes	Bitel 3G and 4G
11	Huacra	Quechua	---	No	---
12	Huamborco	Quechua	---	No	---
13	San Juan	Quechua	---	No	---
14	Shocorco	Quechua	---	No	---
15	Santa Rosa De Jocos	Quechua	Bitel	Yes	Bitel 3G and 4G
16	Bellavista	Quechua	Bitel	Yes	Bitel 3G and 4G
17	San Isidro De Jocos	Quechua	Movistar, Bitel	Yes	Movistar 2G / Bitel 3G and 4G
18	Cochapampa	Quechua	---	No	---

Table 4. CCPP Sitacocha vs mobile phone operators

Source: National Georeferenced Data Platform – Geo Peru

In Figure. 8 and Figure 9, the histogram of existing telephony and mobile technology is shown:

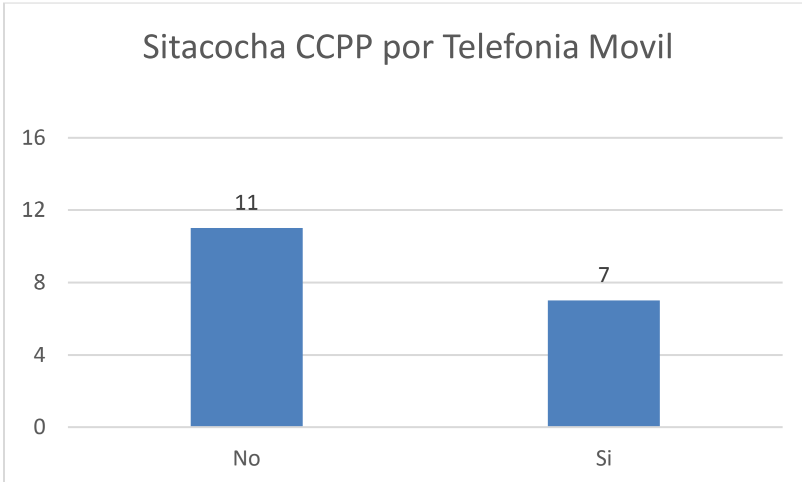


Figure 8 Mobile telephony histogram – CCPP Sitacocha. Ownelaboration.In original Spanishlanguage

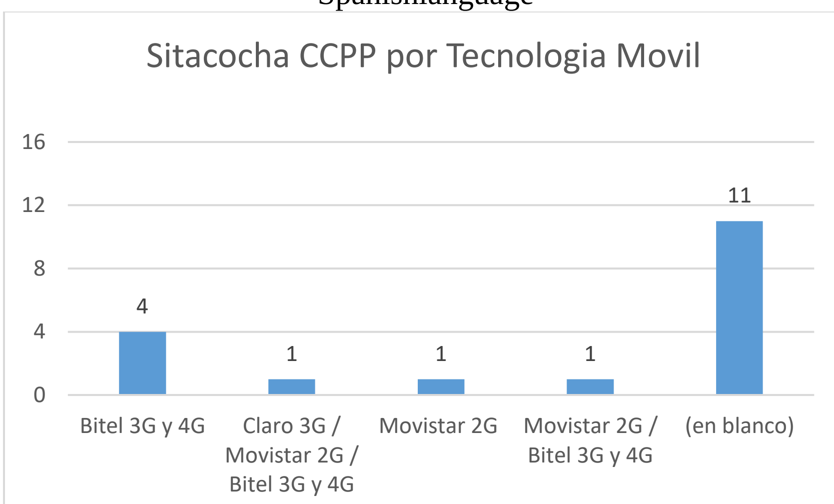


Figure 9 Mobile technology histogram – CCPP Sitacocha. Own elaboration.In original Spanishlanguage

Satellite Internet.

Companies such as Gilat Peru, HughesNet, Viasat, and Tuenti (Telefónica) offer various satellite internet solutions that promise to overcome physical barriers by providing wide coverage in these high Andean areas. These options vary in costs and speeds, allowing for some flexibility depending on the specific needs of each community. On the other hand, Starlink (2024) stands out for its innovative proposal using satellites in low Earth orbit (LEO), offering competitive download speeds and reduced latencies, although with a higher initial cost compared to other technologies.

When comparing technologies in terms of latency, speed, and cost, it is observed that each has advantages and limitations. 4G technology, for example, offers a cost-effective option with good latency and speeds suitable for general use, limited by coverage and potential network congestion. Terrestrial wireless radio links present a viable alternative with low latencies and high-speed capabilities at a reasonable cost, especially suitable for fixed installations in areas with limited infrastructure (ITU, 2012). In contrast, satellite access, especially through LEO technologies such as Starlink, provides an extensive coverage solution with significant improvements in latency and speed, albeit at a higher initial cost.
For the communities of Tongod and Sitacocha, the optimal strategy may involve a combination of these technologies. Deploying satellite solutions can ensure widespread coverage, while using 4G or radio links in more populated areas could optimize performance and costs. Detailed planning, considering connectivity needs, available budget, and existing infrastructure, along with actively seeking financing or grant options, is critical to facilitate the effective deployment of these integrated solutions (Kokez, 2020).

4.2. Backhaul Network

4.2.1. Location of population centers.

The Tables are presented. 5 and 6 of population centers of Sitacocha and Tongod, with their respective geographic coordinates, which provides essential data to identify strategic locations for the installation of telecommunications infrastructure, allowing a detailed analysis of coverage, facilitates the planning of optimal routes for the laying of fiber optics and helps to estimate the demand for services based on population density and the presence of institutions.

Item	CCPP	CCPP Type	Latitude	Longitude	Institutions	Guy
1	Tongod	Urban	-6.755689	-78.82592	4	2 I.E., 1 CCSS, 1 Commissioner.
2	La Palma	Rural	-6.708501	-78.80779	0	0
3	The Lucuma	Rural	-6.713667	-78.82226	2	1 I.E.
4	Chilal de la Merced	Rural	-6.73232	-78.8397	0	
5	That horco	Rural	-6.743801	-78.81133	1	1 I.E.
6	Quitahuasi	Rural	-6.771329	-78.83171	0	0
7	Caserio la Laguna	Rural	-6.75902	-78.85383	0	0
8	Chaullagon	Rural	-6.789972	-78.79725	0	0
9	A. Tongod	Rural	-6.79123	-78.8168	0	0
10	Chuclla Pampa	Rural	-6.828001	-78.83078	0	0
11	Bancuyoc	Rural	-6.855267	-78.8769	0	0
12	Crown	Rural	-6.814788	-78.82613	0	0
13	The Triumph	Rural	-6.807504	-78.81438	0	0
14	Pisit	Rural	-6.817365	-78.86475	0	0
15	Andean Lily	Rural	-6.842594	-78.83266	0	0

16	El Chito	Rural	-6.711952	-78.79726	0	0
17	The Well	Rural	-6.725025	-78.81603	0	0
18	About Conga	Rural	-6.749077	-78.85078	0	0
19	High Viewpoint	Rural	-6.765491	-78.83743	0	0
20	Free People	Rural	-6.770849	-78.81127	0	0
21	Santa Ana	Rural	-6.751077	-78.83155	0	0

Table 5. Coordinates of the CCPP Tongod – occupied dwellings
Source: Own elaboration

	de	tude	stitutions
ıbamba	572	9550	1 CCSS, ımissioner
cha	452	7194	1 CCSS
Ana	852	5012	
Grande	005	3437	
Rosa	762	8468	
artin	068	3183	
machay	058	8628	
	257	5188	
Jrsula	720	4807	
pamba	897	1643	
a	375	9447	
borco	137	5095	
an	038	0810	
rco	097	2795	
Rosa de	737	3652	
ista	392	6873	
idro de	655	8436	
pampa	252	3218	
uasi	458	0855	
ta	500	3400	
ı	608	9287	
pampa	513	7387	
Chico	683	2102	

Table 6. Coordinates of the CCPP Sitacocha – occupied dwellings
Source: Own elaboration

Once the coordinates of the Population Centers (CCPP) were obtained, we used Google Earth to locate them accurately on the map as shown in Figures 9 and 10. This tool allows us to visualize the exact location of each population center, providing a clear perspective of its geographical distribution. This process is essential for interventions in areas such as telecommunications infrastructure. The ability to accurately locate CCPPs using Google Earth enriches the decision-making process, ensuring that development initiatives are well-informed and geographically relevant.

Figure 9 Tongod CCPP location. Own elaborationusing Google Earth.In original Spanishlanguage

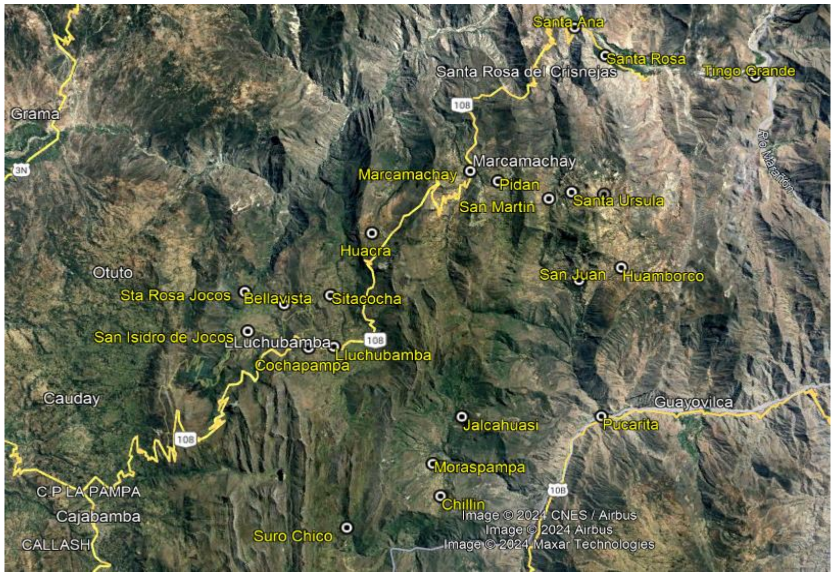


Figure 10 Sitacocha CCPP location. Own elaboration using Google Earth.In original Spanish language

4.2.2 Development of the network model.

The development of a wireless network model optimized for areas with varied topographical conditions represents a significant challenge, especially in geographically diverse regions such as mountains, valleys, and scattered rural areas. This model requires precise adaptability to the peculiarities of the terrain to ensure effective and reliable connectivity for users. From experience, an approach is proposed that contemplates the support of some technologies including fiber optics.

Detailed terrain assessment and mapping

The initial process of our project meticulously focused on the analysis of the terrain within the districts of Tongod and Sitacocha, areas notoriously marked by their complex topography. Using the Google Earth Pro tool, we were able to gain a detailed perspective of the local geography, which was crucial in identifying major terrain-related challenges such as steep elevations, tall buildings, and areas of dense vegetation, all factors that could affect wireless signal transmission.

With this knowledge in hand, we proceeded to define the optimal locations to locate the transmission towers in both Tongod and Sitacocha. The line-of-sight (LoS) functionality offered by Google Earth Pro proved to be an invaluable resource in ensuring that each location chosen for the towers allowed for effective wireless communication, thus facilitating optimized coverage and minimizing areas with weak or non-existent signals.

This careful selection and planning process allowed us to identify the most suitable locations for key infrastructure, such as towers and antennas, allowing us to tailor our network design to meet the specific coverage needs in Tongod and Sitacocha. By overcoming the challenges presented by the natural and built environment, we have been able to craft both efficient and effective network design.

In Sitacocha, it was identified that the starting point would be the capital, Suchubamba, from where direct connections are deployed to key towns such as Shojorco, Santa Rosa de

Jocos, San Isidro de Jocos, and Bellavista, thus guaranteeing broad and effective coverage. Strategically, additional nodes were placed throughout the region to ensure direct visibility and, therefore, connectivity between several remote locations, overcoming the inherent geographical challenges of the region.

In Tongod, the effort was mirrored, starting with a main connection node in the district capital, extending coverage to key areas, and ensuring reliable, high-quality communication services for these communities through carefully planned wireless infrastructure. The utilization of Google Earth Pro in the initial planning phase has provided a solid and accurate foundation for the deployment of our wireless network, ensuring that the proposed infrastructure aligns perfectly with the geographic and topographical features of Tongod and Sitacocha, and establishing the necessary conditions to deliver reliable, high-quality communication services to these communities.

4.3 Results of the technical performance of the Backhaul network

The evaluation of the backhaul network created for the high Andean districts of Cajamarca has made it possible to detect notable improvements in all key performance indicators, which validates the technical feasibility of the proposal and its possible influence on the reduction of the digital divide.

First, in relation to bandwidth, the findings indicate that the current infrastructure in the districts analyzed only provided an elementary service, with speeds well below what was necessary to simultaneously serve homes, schools and health centers. In the initial phase, the average effective capacity did not reach the minimums recommended by international organizations such as the International Telecommunication Union (ITU), restricting access to quality digital resources. The implementation of the backhaul network allowed a considerable increase in the available bandwidth, achieving speeds that facilitate the smooth transmission of multimedia content, the realization of videoconferences and the use of online educational platforms. This change is important because it transforms a limited and unreliable service into a real connectivity option for rural communities.

When it comes to latency, a significant improvement was also observed. Before implementing the proposal, response times exceeded 200 ms on average, which negatively affected the user experience by causing obvious delays in navigation, interruptions in video calls and restrictions on access to interactive services. After the backhaul was executed, latency was significantly reduced, approaching international standards for medium and high-quality connections. This means that users can now access applications that require quick responses, such as real-time teaching platforms, telemedicine or online administrative procedures.

Connection stability was another critical aspect in the evaluation. The original infrastructure exhibited frequent packet loss, resulting in interruptions and problems in data transmission. These limitations affected the reliability of the service, causing frustration among users and preventing its use in educational or institutional contexts. With the proposal of the new network, the tests showed a noticeable reduction in packet losses, as well as a significant decrease in the rate of transmission errors. The service achieved a much higher level of continuity, an essential aspect in communities where internet disruptions often lead to digital isolation that limits local development.

Another important point is the solution's expandability and replication. The proposed scheme not only meets the current demands of the high Andean districts analyzed, but also allows its extension to other localities that present similar geographical characteristics. This property ensures that the initiative is not limited to a single example, but that it is transformed into a model of technological intervention that can be applied in different rural contexts in Peru and Latin America. The use of modular equipment and the flexible adaptation of the network structure make it possible to adjust the network to various requirements and budgets, which reinforces the viability of the project.

From a global perspective, the findings show that the backhaul network not only improves technical indicators such as bandwidth capacity, latency, and stability, but also contributes significantly to reducing the digital divide. This is manifested in the real possibility of including the high Andean districts in the digital environment, promoting fair access to education, health care and public services. Similarly, the implementation of this solution supports the right of communities to access information and to participate equally in the digital society, turning the proposal into a strategy with both a social and technological impact.

4.4 Expected Impact of Backhaul Network Implementation

The implementation of the backhaul network in the high Andean districts of Cajamarca not only represents an improvement in the technical parameters of connectivity, but also projects a set of social, educational, economic and technological impacts of great relevance. These expected impacts reflect the proposal's ability to transform the reality of communities that have historically been marginalized from access to quality internet.

In the educational field, the increase in bandwidth and the decrease in latency generate suitable conditions for the incorporation of online teaching platforms, virtual libraries and collaborative learning tools. In the previous situation, students in these communities had very limited access to digital resources, which accentuated the gap compared to their urban peers. With the backhaul network, it is expected that students and teachers will be able to participate in virtual classes, access multimedia content without interruptions and strengthen the teaching-learning process, thus contributing to a more inclusive and equitable education.

In the healthcare sector, enhanced connectivity enables the implementation of telemedicine services, remote consultations, and access to up-to-date medical databases. This is crucial in remote districts where hospital care is limited and transfers to urban centers are often costly and complicated. The possibility of remote diagnoses and virtual consultations increases the coverage and quality of the local health system, improving care for vulnerable populations.

From an economic perspective, the backhaul network offers new opportunities for local entrepreneurship and the insertion of small producers in digital markets. By having stable internet, residents can access e-commerce platforms, virtual training and digital financial services. Not only does this diversify revenue streams, but it also fosters the region's competitiveness, integrating local producers into broader value chains and reducing the commercial isolation of communities.

In the field of public management, reliable connectivity makes it possible for local governments to implement digital administration systems, online procedures, and citizen participation mechanisms. This favors transparency, streamlines administrative processes and facilitates the access of residents to State services, thus reinforcing governance and efficiency in public management.

Finally, in terms of social cohesion and territorial development, the expected impact lies in the progressive reduction of the digital divide that has historically affected high Andean communities. Digital integration strengthens citizens' right to access information, favors social inclusion, and promotes territorial equity. In addition, the scalability of the designed model allows the Cajamarca experience to be replicated in other rural regions of Peru and Latin America, which amplifies the scope of the proposal and makes it a strategic alternative for connectivity in isolated territories.

Overall, the expected impacts of the implementation of the backhaul network transcend the merely technical, configuring itself as an integral contribution to the sustainable development of the high Andean districts, in accordance with the digital inclusion objectives established by international organizations and with the United Nations 2030 Agenda.

5. Conclusions

The development of this study has made it possible to verify that the creation of a backhaul network is presented as a robust technical solution and adequate to the needs of the mountain districts of Cajamarca, a region that has historically faced severe difficulties in terms of connectivity. The initial analysis showed that the existing telecommunications infrastructure was insufficient to meet the growing demand for digital services, evidencing limitations in bandwidth, high latencies and problems in service stability. In this context, the elaborated proposal demonstrated that it is possible to overcome these limitations by implementing well-planned backhaul technologies, achieving a significant improvement in the technical indicators that affect the quality of connectivity.

The findings indicate that the proposed network significantly increased the available bandwidth capacity, which enables access to online learning platforms, multimedia resources and data transmission services with acceptable quality. Similarly, the decrease in latency achieved ensures more competitive response times, facilitating the use of interactive applications and participation in real-time activities, such as videoconferences and virtual classes. Likewise, the improvement in connection stability, reflected in the reduction of packet losses and service interruptions, reinforces the reliability of internet access, a fundamental aspect for communities that depend on this resource to integrate into the digital environment.

Beyond the technical achievements, the impact of the backhaul network is expected to go beyond the merely technological. In the field of education, a significant improvement in teaching and learning processes is expected by ensuring access to updated digital content, interactive resources and distance education modalities that help reduce the gap between students in rural and urban areas. In the health sector, connectivity facilitates access to telemedicine services, remote consultations and medical databases, which improves care in areas where face-to-face health resources are limited. In the economic area, the existence of a reliable internet promotes the linking of small producers and local entrepreneurs with e-commerce platforms, online training and digital microfinance systems, contributing to boost the region's economy. Finally, in terms of public management, the network will allow local governments to offer electronic services, online procedures and citizen participation mechanisms that reinforce transparency and efficiency in administration.

The analysis also showed that the developed network model has a character that allows scaling and replication, which adds significant value for its application in other areas that present similar geographical and socioeconomic conditions. The adaptability of the suggested structure, together with the ability to incorporate mixed technologies, makes the network a sustainable and flexible option for different rural connectivity situations. This discovery is crucial, as it not only provides a specific solution for Cajamarca, but also lays the groundwork for carrying out the same experience in other communities in Peru and Latin America facing similar challenges.

However, it is important to recognize the limitations that need to be taken into account in future implementation projects. Among these limitations are expenses related to physical and technological infrastructure, the need to ensure continuous and specialized maintenance, as well as the dependence on public policies that encourage and finance investment in telecommunications in rural areas. In addition, external factors such as extreme weather and the availability of electricity in isolated regions can affect the viability of the proposal. Therefore, it is suggested to investigate options that integrate renewable energy sources, such as solar or wind, to ensure continuity of service in remote environments with limited energy infrastructures.

The main contribution of this study is to demonstrate that the digital divide in the high Andean areas is not an insurmountable obstacle, but an opportunity to innovate in the design and implementation of technological solutions that fit particular contexts. The suggested backhaul network not only addresses technical shortcomings, but is also projected as a means for social inclusion and the strengthening of sustainable territorial development. Thus, progress is made in meeting the objectives of the United Nations 2030 Agenda, especially those related to the reduction of inequalities and universal access to information and communication technologies.

In summary, the conclusions of this research allow us to conclude that the proposed backhaul network represents a viable, scalable and socially relevant option to improve internet access in high Andean districts of Cajamarca. Its technical advantages are combined with significant social and economic effects, underscoring the need to join efforts between the State, the private sector and local communities to ensure its effective and sustainable implementation in the long term. Thus, the research not only contributes to the field of telecommunications engineering, but also represents a key step towards the creation of a fairer, more inclusive and equitable digital society.

6. Recommendations

Based on the results obtained, the following suggestions are presented to guide the effective implementation of the proposed backhaul network and to strengthen future research:

Public policies and state management

- Local and regional authorities in Cajamarca should prioritize investment in telecommunications infrastructure in rural areas, incorporating backhaul projects into their territorial development and digital inclusion plans.

- It is recommended to promote subsidy programs and financing models that combine public and private resources, so that implementation costs can be reduced and the long-term viability of the project can be guaranteed.

- It is advisable to create more flexible regulations that facilitate the participation of small operators and community entities, thus ensuring that rural communities have competing connectivity options.

Technical and operational aspects

- It is suggested to complement the backhaul infrastructure with renewable energies, such as solar or wind, to reduce the impact of energy problems in hard-to-reach areas.
- It is crucial to implement technical training programs for local staff who will be responsible for maintaining the network, in order to reduce dependence on external providers and ensure continuous service.
- It is recommended to regularly monitor critical network parameters such as bandwidth, latency, and stability using intelligent management systems to identify problems in a timely manner and improve performance.

Social and Community Impact

- It is proposed that the benefited communities participate in the design, management and evaluation of the service, promoting co-responsibility and social ownership of the project.
- It is essential to create digital education programs for students, educators and the general population, so that the improvement in connectivity really translates into greater opportunities in education, health and entrepreneurship.
- It is suggested to link the implementation of the network with local economic development projects, such as e-commerce platforms focused on rural farmers, which will maximize the positive impact on community well-being.

Lines of future research

- Expand the research through a cost-benefit analysis that includes projections on the economic sustainability of the network in different scenarios of population growth and digital demand.
- Conduct comparative studies in other high Andean and Amazonian regions to validate the scalability of the model and propose a national standard for rural connectivity.
- Investigate the potential of integrating emerging technologies, such as 5G networks, low-orbit satellites, and artificial intelligence solutions for dynamic data traffic management.

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