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Integrated Technical and Economic Analysis of Open RAN for Remote eHealth in Brazil

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Abstract Traditional radio access networks (RANs) are often characterized by rigid, proprietary architectures, high capital (CAPEX) and operational (OPEX) expenditures, and vendor lock-in. These limitations hinder cost-effective deployments in remote and underserved regions. In this paper, we evaluate the potential of Open RAN, a flexible and disaggregated networking paradigm leveraging virtualization and multi-vendor interoperability, to bridge the healthcare gap in Brazil through remote eHealth applications. Focusing on the mobile specialist practice (MSP) use case, we introduce a total cost of ownership model that integrates both CAPEX and OPEX across urban, suburban, and rural deployment scenarios, thereby addressing a critical gap in current network economic models. Additionally, we explore a detailed taxonomy of MSP sub-use cases that delineates the technical requirements for high-definition video streaming, haptic feedback, and remote diagnostics. We conducted laboratory experiments on a 5G Open RAN testbed using real ultrasound equipment in collaboration with Samsung, Beneficência Portuguesa (one of the largest private healthcare hubs in Latin America), and InovaHC (the innovation center of the region's largest hospital). These experiments demonstrated that our approach meets stringent performance indicators such as low latency, robust throughput, and reliable packet delivery under diverse backhaul conditions. The results further indicate that Open RAN can substantially reduce deployment costs while ensuring high-performance remote medical services. These findings provide valuable insights for advancing field trials, refining economic models, and guiding future policy initiatives.

Keywords: eHealth, mobile specialist practice, Open RAN, remote diagnostics, total cost of ownership.

1 Introduction

One of the most prominent applications driving the evolution of current and future mobile network generations is digital health [Suraci *et al*., 2022]. Conceptually, the World Health Organization (WHO) defines eHealth as the cost-effective and secure use of information and communications technologies in support of health and health-related fields [World Health Organization, 2024]. This includes healthcare services, health surveillance, health literature, as well as health education, knowledge and research. Indeed, eHealth has been adopted widely to provide e-diagnosis and e-treatment services, whose benefits are attributed to the reduced time and manpower costs [Zhang *et al*., 2021]. Unfortunately, due to the weakness of prior generations of cellular networks, the goals of eHealth have not yet been fully accomplished [Zhang *et al*., 2021]. The 3rd Generation Partnership Project (3GPP) has set standards for various eHealth use cases as part of the development of future generations of cellular systems via some technical specifications (TSs) and technical reports (TRs), such as TS 22.261 [3GPP, 2024b], TS 22.104 [3GPP, 2024a], TR 22.826 [3GPP, 2021], among others, which outline and specify the main key performance indicators (KPIs) that should be met in order for the systems to comply with the foreseen applications [3GPP, 2024a,b, 2021]. Currently, the fifth generation (5G) of mobile systems is promised to be the solution for many ambitions of the eHealth sector, offering ultra-reliable low-latency communications (URLLC), enhanced mobile broadband (eMBB), and massive machine type communications (mMTC), thus being adopted worldwide.

Among the many countries where 5G has been deployed, Brazil stands out as a key example of its impact on the eHealth sector in remote areas. Occupying a continental-scale territory in South America, Brazil exhibits a medical workforce density that deviates significantly from the ideal. It is observed that its urban centers have a significantly higher concentration of physicians compared to remote, underserved areas of the country [Federal Council of Medicine (CFM) of Brazil, 2024]. In this context, eHealth applications emerge as a crucial solution for delivering medical assistance to areas that would otherwise lack adequate healthcare services. In particular, the mobile specialist practice (MSP) use case, as outlined in 3GPP TR 22.826 [3GPP, 2021], emerges as a potential solution to this challenge, offering means to overcome the irregular medical density problem. Unfortunately, the costs associated with such a solution may pose a challenge for its implementation in Brazil and in other nations with similar characteristics.

One of the main challenges in making the MSP viable in countries like Brazil is the nation's vast territory. The significant distances between urban centers and remote communities can lead to technical and cost-related limitations. This situation suggests a practical approach to categorize the MSP into two sub-use cases: urban centers and isolated communities. These categories take into account the unique challenges that may arise due to the large distances between regions, including bandwidth limitations and high latency. In order to overcome these challenges, new technological solutions should be explored.

A promising solution to address the technical and cost limitations of various use cases is the concept of open radio access network (RAN) [Polese *et al*., 2023; Ahad *et al*., 2019; Trifonov *et al*., 2022; Riyanto *et al*., 2023]. This approach has emerged as a way to shift from the traditional RAN to a new paradigm for future mobile communications. Open RAN deployments utilize disaggregated, virtualized, and software-based components that are connected through open, well-defined interfaces, enabling interoperability across different vendors [Polese *et al*., 2023]. For instance, this new paradigm could be effectively applied to the MSP use case to help address Brazil's irregular medical density distribution. More recently, we conducted an incipient investigation in a 5G Open RAN environment [Parente *et al*., 2025] demonstrating the feasibility of remote ultrasound settings. That seminal study did not comprise deployment costs and a deep analysis of technical system behavior in diverse geographical scenarios.

In this paper, we introduce a new integrated techno-economic methodology to validate the deployment of Open RAN for eHealth in remote areas, providing a practical deployment framework and using Brazil as an important case study. The proposal expands upon previous findings by not only providing deeper empirical technical evaluations but also addressing the economic dimension often overlooked in technical trials. Our contributions include: (i) an original total cost of ownership (TCO) model specifically tailored for the Open RAN paradigm within the eHealth vertical, filling a critical gap in current network economic models; (ii) a new detailed taxonomy for eHealth use cases based on 3GPP TR 22.826, utilized to define the stringent KPIs for the MSP use case; (iii) a new mapping of Open RAN deployment models (Suburban, Rural 1, and Rural 2) that directly address the infrastructure challenges of remote regions, such as bandwidth limitations and high latency; and (iv) a rigorous technical and empirical validation of our solution, thus moving from theory to practice. In collaboration with Samsung and leading medical centers (Beneficência Portuguesa and InovaHC), we conducted experiments on a 5G Open RAN testbed using real-world medical ultrasound equipment (Samsung V6 and HM70 EVO). Our laboratory results deliver two key findings: first, we demonstrate that the Open RAN architecture meets the stringent throughput and latency KPIs for remote echocardiogram examinations; second, we confirm this performance is maintained under realistic remote conditions, including satellite backhaul and, most importantly, over long-distance (up to 10 km) open fronthaul links, proving the technical feasibility of centralized Open RAN architectures for vast geographical areas such as those in Brazil.

In the sequel, the paper is organized as follows. Section 2 presents a deep literature review with several related works in the eHealth vertical. Section 3 introduces the problem statement and motivation, covering a new proposed taxonomy for eHealth use cases based on the 3GPP technical standardization, a detailed analysis of the MSP use case and its inherent challenges, as well as a description of an illustrative case study in Brazil. Section 4 proposes new technical and economic Open RAN solutions to overcome the challenges of the MSP use case in remote areas. Section 5 presents a laboratory setup along with an insightful and comprehensive discussion on the use of Open RAN in remote eHealth. Finally, Section 6 concludes the paper.

2 State of the Art in eHealth and Open RAN: A Literature Review

Digital health is one of the leading applications of emerging wireless networks [Suraci *et al*., 2022]. According to the WHO, the scope of eHealth is broad, integrating e-diagnosis, e-treatment, and remote patient monitoring to fundamentally improve the accessibility and operational efficiency of healthcare systems. 3GPP specifications and reports, notably TS 22.104, TS 22.261, and TR 22.826, detail the KPIs required for these applications [3GPP, 2024b,a, 2021] and form the technical foundation enabling the delivery of high-quality eHealth services.

The evolution of 5G technology has introduced the key features mMTC, URLLC, and eMBB, which are fundamental for supporting advanced eHealth applications. The standardization of these features has demanded a significant effort from 3GPP. In particular, TS 22.104 outlines use cases for "connected hospitals or medical facilities," with a specific emphasis on robotic surgeries, thereby underscoring the critical concerns regarding reliability and availability for high-stakes medical applications. Furthermore, TS 22.261 addresses broader 5G use case requirements relevant to eHealth, while TR 22.826 delves deeper into the healthcare vertical by presenting use cases such as remote surgery and emergency medical services. These documents collectively highlight how 5G's technical advances can support the demanding performance requirements of critical healthcare services.

Various research efforts have explored real-world applications of 5G in healthcare and emphasized the role of 5G in enhancing telemedicine, remote patient monitoring, and emergency response services. For instance, [Padmashree and Nayak, 2020] provides a comprehensive overview of 5G applications in healthcare, and [Georgiou *et al*., 2021] investigates specific use cases such as remote health monitoring and telemedicine. Both studies highlight the increasing importance of privacy and security as healthcare data become more integrated with 5G networks. The COVID-19 pandemic further accelerated the adoption of 5G technologies in healthcare, with [Moglia *et al*., 2022] showing how 5G enabled rapid deployments of tele-ultrasound and patient monitoring technologies, proving essential in mitigating the challenges posed by the pandemic.

In terms of technical challenges, studies such as [Zhang *et al*., 2021] and [Antevski *et al*., 2021] focus on how 5G addresses latency and bandwidth issues, particularly in critical applications like emergency healthcare and augmented reality for medical responders. These findings demonstrate significant improvements over fourth generation (4G) and illustrate 5G's potential to transform critical care delivery.

The exploration of network slicing and other advanced 5G features in healthcare continues to gain traction. For example, the article [Gharba *et al*., 2021] (part of the Vinni project) demonstrates how network slicing can improve latency and throughput in mobile ultrasound applications, while [Bianzino *et al*., 2023] examines future scenarios involving smart ambulances and rescue operations powered by next-generation networks. Furthermore, the role of artificial intelligence (AI) in optimizing 5G networks for healthcare is a growing area of interest. The study in [Trifonov *et al*., 2022] highlights how AI and Open RAN can be leveraged to enhance the management of Internet of medical things (IoMT) devices, with a focus on power efficiency and device longevity.

In exploring the deployment of 5G, studies have also emphasized the role of Open RAN in reducing costs and improving flexibility. The study in [Riyanto *et al*., 2023] offers a techno-economic analysis of 5G Open RAN deployment in dense urban environments, demonstrating a 38% reduction in capital expenditure (CAPEX) when compared to traditional RAN solutions. Although this study focuses on urban environments, its economic implications extend to rural and remote contexts where reducing infrastructure costs is critical for eHealth networks. The flexibility afforded by Open RAN through multivendor integration plays a vital role in delivering cost-effective and scalable network solutions in underserved regions. Additionally, [Kondrashov *et al*., 2023] provides a comparative analysis of the TCO for distributed RAN (D-RAN), centralized RAN (C-RAN), and Open RAN architectures, highlighting significant cost efficiencies of Open RAN in scenarios with limited infrastructure resources.

Security and interoperability are further critical challenges in Open RAN deployments. Recent studies and industry reports have highlighted these issues [Liyanage *et al*., 2023]. In multi-vendor environments, ensuring robust security is essential for protecting sensitive eHealth data [de Oliveira *et al*., 2023]. Standardization efforts led by the O-RAN Alliance, including open interface specifications and recommended security protocols, are aimed at mitigating these risks [Alavirad *et al*., 2023]. Nonetheless, gaps such as inconsistent security implementations and inadequate interoperability testing have been identified [Klement *et al*., 2024; Krasniqi *et al*., 2023], underscoring the need for continuous security audits and rigorous testing.

In addition, [de Oliveira *et al*., 2023] is particularly relevant to our investigation as it examines the application of Open RAN in Brazil, specifically in remote ultrasound and tomography trials, addressing challenges in expanding these services to underserved regions. However, it lacks an analysis of the associated deployment costs and a taxonomic organization of the existing eHealth use cases.

In a recent preliminary investigation within a 5G Open RAN environment, we successfully established the technical feasibility of remote ultrasound configurations [Parente *et al*., 2025]. As a seminal study, it did not account for the multifaceted economic and structural requirements in practical deployments.

While the reviewed studies have significantly advanced our understanding of 5G applications in healthcare and demonstrated the cost benefits of Open RAN in urban settings, they leave an important gap. Specifically, there is a need for a comprehensive analysis that integrates both technical performance and economic viability of deploying Open RAN in underserved remote areas, such as those in Brazil. This research aims to fill such a gap by evaluating the MSP use case through a novel TCO model and tailored deployment strategies.

3 Problem Statement and Motivation

3.1 eHealth Taxonomy

In the eHealth vertical, we can outline many different use cases that have been considered in the context of 5G. Their taxonomy has been structured based on different categories, including requirements, communication technologies, objectives, performance measures, approaches, and others [Ahad *et al*., 2019]. For instance, a taxonomy based on system requirements may include critical KPIs such as availability, reliability, latency, bit rate, survival time, service area, among others: while some use cases require stringent KPIs for reliability and latency (URLLC), others may prioritize high levels of bit rate (eMBB). Another important taxonomic criterium is the communications technologies used in eHealth, which may include either static or mobile applications, each one working on local or remote scenarios. These scenarios have been particularly explored in the TR 22.826 considering the following use cases [3GPP, 2021]:

- MSP;
- Patient monitoring inside ambulances (PMIA);
- Emergency care–ultrasound examination and remote interventional support in static ambulances (EC);
- Cardiac telemetry outside the hospital (CTOH);
- Cardiac telemetry inside the hospital–care facility (CTIH);
- Duplicating video on additional monitors (DVAM);
- Augmented reality assisted surgery (ARAS);
- Robotic aided surgery (RAS);
- Communication quality of service (QoS) requirement for robotic telesurgery (QoS-RT).

We organize these use cases in a taxonomic fashion as shown in Figures 1, 2, and 3, where the acronyms are defined in Tables 4, 5, and 6, shown in Appendix A. In these figures, from the left to the right, we have (i) the main categories (URLLC, eMBB, or mMTC), then (ii) the several use cases considered in the TR 22.826 that fall into a specific category, (iii) a sub-use case, and finally (iv) the corresponding required KPIs.

The taxonomy proposed herein for the eHealth use cases is based on service demand (URLLC for reliability and latency requirements, eMBB for high bit rates, and mMTC for

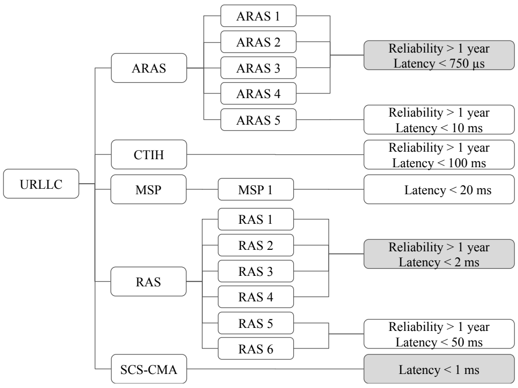


Figure 1. Taxonomy based on URLLC KPIs.

networks with massive components). The use cases defined in TR 22.826 are divided into different subcategories or sub-use cases, depending on aspects like related video resolution, number of active UEs, etc. These sub-use cases are identified in this article by different index numbers and are considered in the taxonomic classification. Note that some use cases are included in more than one category, since they present different critical KPIs. Our objective is to bring together important correlated aspects that need to be observed so as to deliver a suitable system solution for an application at hand. In the next section, we analyze the MSP scenario, an important use case in developing countries and in underserved areas.

3.2 MSP Use Case

The MSP use case for 5G networks is specified in the technical report 3GPP TR 22.826 [3GPP, 2021]. By proposing video examinations (i) supervised by remote medical specialists and (ii) performed over reliable connectivity, this use case can address the lack of medical specialists in remote areas.

In the MSP, a mobile specialist practice is located in a truck equipped with audio/video devices along with medical and diagnostic equipment over 5G connectivity. During the patient examination, the necessary remote experts can be contacted, thus having access to the patient information through a 5G connection. The examination may be supported by local non-specialized staff, such as medical technical assistants. This use case is a static-remote scenario, where medical specialists and patients are in different places, and devices or people are moving while the care is delivered (the truck is not in a permanent position, but it is stopped during the examination session).

It should be noted that we could propose specialization for the MSP use case. For instance, the specialist practice may not be inside a truck, but inside another vehicle, like a boat, or even fixed in an emergency temporary location. Also, the specialist practice can be located inside a building in a suburban or rural area with medical equipment resources but a lack of medical specialists (5G fixed wireless access scenario). The medical equipment itself could be a mobile equipment that moves across different service points. The described scenarios are very common in developing countries like Brazil and are relevant MSP variants.

The MSP use case is organized into seven different subcategories, each one with different KPI requisites:

1. Stereoscopic 4K 60 fps 12 bits per pixel color coded (e.g., YUV 4:1:1) real time video (lossless compressed),
2. Compressed 4K video stream,
3. Haptic feedback data stream,
4. High quality audio stream,
5. CT/MRI scan data, max 300 megabytes of DICOM data
6. Remote console for CT/MRI (XVGA compressed), and
7. Uncompressed 512x512 pixels 32 bits 20 fps video stream from ultrasound probe.

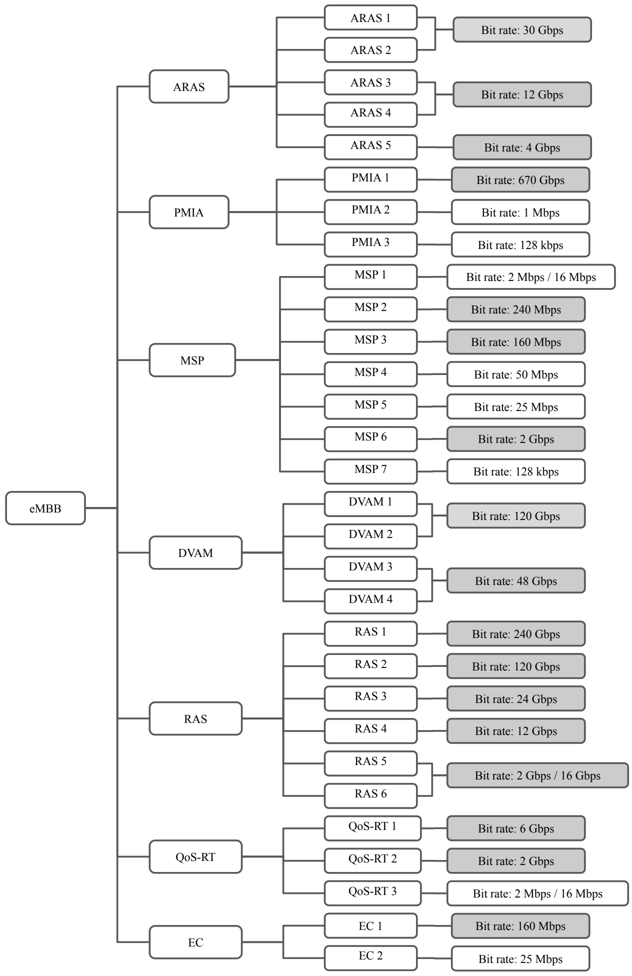


Figure 2. Taxonomy based on eMBB KPIs.

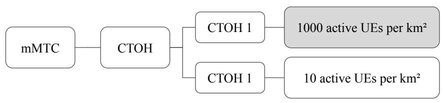


Figure 3. Taxonomy based on mMTC KPIs.

Different types of examination using different medical equipment could fit into one of the above MSP subcategories, thus leading to different KPI requisites. These KPI requisites are the first aspect that we consider in this article when defining the supported RAN deployment scenarios. The second aspect we consider is the available infrastructure to deploy the RAN network. Indeed, the area covered by the RAN could be located in urban or suburban regions with the necessary 5G infrastructure to support equipment installation or in rural (far remote) areas where such infrastructure is lacking. This infrastructure gap may include the absence of network connections for backhaul, insufficient power supply for the equipment, and a lack of buildings or towers for equipment installation. We emphasize below the distinction among urban, suburban, and rural areas since it is important to evaluate the possible deployment scenarios and their related TCO.

- Urban and suburban areas: availability of necessary infrastructure for cell installation.
- Suburban areas: limited infrastructure for cell installation.
- Rural areas: lack of necessary infrastructure for cell installation.

The rural scenario is particularly relevant in developing countries, which typically face problems related to the lack of infrastructure in remote areas. This limitation often results in higher deployment costs for 5G networks in remote areas, which can be economically prohibitive. In this context, Open RAN emerges as a viable solution to address these financial challenges due to its potential to lower both CAPEX and operational expenditure (OPEX). However, the lack of infrastructure, coupled with specific use case requirements, restricts the feasible Open RAN deployment scenarios and, as a result, limits its potential to reduce CAPEX and OPEX. This issue will be further discussed in the following sections.

3.3 MSP Implementation: Technical and Economic Challenges

The eHealth use cases explored in 3GPP TR 22.826 [3GPP, 2021] have very distinct requirements, and as presented in our taxonomic analysis, some of these requirements are quite stringent in terms of latency, availability, rate, and the number of served devices. Meeting these demanding requirements falls within the scope of 5G specifications, but fulfilling a specific requirement may limit technically feasible deployment options. Fortunately, 5G networks built on Open RAN solutions provide greater deployment flexibility by enabling distributed network functions through various split and virtualization models. The main aspects that may restrict Open RAN deployment scenarios are the following.

- Low latency and high availability: specifying aggressive low levels of latency and high levels of availability may make it unfeasible to use certain splits and/or network functions located far from the cell site.
- High rates with high user density: the need to support high user traffic with reasonably high utilization rates and user density can greatly increase the demand on the transport network, which may not be sufficient to accommodate this demand.

Additionally, as already mentioned, another point to consider in defining deployment scenarios is the available infrastructure. This aspect becomes particularly important in suburban and rural areas far from urban centers, which are very common in developing countries. Another factor that will have a significant impact is the available transport network. In more extreme cases, satellite links may be necessary, potentially rendering use cases with stringent latency or bandwidth requirements unfeasible. In milder conditions, it may be possible to install a transport infrastructure at the deployment site, noting that its installation may increase the costs, and even when installed, it may not (i) offer the rates and latencies needed to enable certain Open RAN deployment models and (ii) meet the requirements of the proposed use cases. Looking more closely at the cost of the transport network, it may be technically feasible to install it in one of the rural/suburban locations that meet any requirement or Open RAN deployment scenario, but the associated cost may be so high that it renders the deployment economically infeasible.

We emphasize that Open RAN is an approach that can reduce the TCO of cellular networks, thereby enabling economically viable service provision in previously underserved suburban and rural regions. However, we can infer from the discussion above that this TCO reduction may be compromised by the transport network deficiencies commonly found in suburban/rural scenarios. So, there is a challenge to define if an Open RAN deployment scenario can really support the use cases' technical requirements and, at the same time, fulfill the deployment economic restrictions.

It is important to highlight that current regulations aim to balance technological innovation with the safety and quality of care, ensuring that remote practices adhere to the ethical and legal principles of traditional medicine. However, in order for telemedicine to establish itself as an effective and inclusive tool, it is essential to address infrastructure and training challenges, as well as to promote regulations that continue to evolve alongside technological advancements and societal needs.

In this article, we will conduct a technical-economic analysis for the MSP use case, which is considered a priority in several countries. The same methodology could be applied as well to other eHealth use cases considered in 3GPP TR 22.826 [3GPP, 2021]. In the next section, we provide a case study analyzing the eHealth scenario in Brazil.

3.4 Demand for Physicians in Brazil: A Case Study

The regulation of telemedicine and telehealth in Brazil has evolved considerably, especially due to the demands brought about by the COVID-19 pandemic. In response to the health crisis, the Ministry of Health issued Ordinance No. 467/2020 [Ministry of Health of Brazil, 2020], which temporarily authorized the practice of telemedicine during the state of public emergency. This measure relaxed certain rules and expanded the use of digital technologies for remote medical services.

Following the end of the state of emergency, telemedicine was permanently regulated by Resolution CFM No. 2,314/2022 [Federal Council of Medicine (CFM) of Brazil, 2022c], which replaced previous CFM regulations and established new guidelines for the practice of telemedicine in Brazil mediated by communication technologies. According to this resolution, telemedicine can be exercised in the types of teleservices described in Table 1.

Table 1
Teleservices - CFM Resolution No. 2,314/2022 [Federal Council of Medicine (CFM) of Brazil, 2022c].

Teleservice	Description
Teleconsultation	Non-face-to-face medical consultation, mediated by TDICs (Digital, Information and Communication Technologies), with physician and patient located in different spaces.
Teleinterconsultation	Exchange of information and opinions between physicians, with the help of TDICs, with or without the presence of the patient, for diagnostic or therapeutic, clinical or surgical assistance.
Telediagnosis	Remote, geographic and/or temporal medical procedure, with the transmission of graphics, images and data to issue a report or opinion by a physician with a specialist qualification record (RQE) in the area related to the procedure, in response to the request of the attending physician.
Telesurgery	Performing a surgical procedure remotely, using robotic equipment and mediated by safe interactive technologies. Robotic surgery is regulated by Resolution CFM No. 2,311/2022 [Federal Council of Medicine (CFM) of Brazil, 2022b].
Telemonitoring or medical telesurveillance	Act carried out under coordination, indication, guidance and supervision by a physician for remote monitoring or surveillance of health and/or disease parameters, through clinical evaluation and/or direct acquisition of images, signals and data from equipment and/or aggregated devices or implantable in patients at home, in a medical clinic specializing in chemical dependency, in a long-term care institution for the elderly, in clinical or home hospitalization or when transferring the patient until their arrival at the health establishment. Telemonitoring includes the collection of clinical data, its transmission, processing and management, without the patient having to travel to a health unit.
Telescreening	Act carried out by a physician, with assessment of the patient's symptoms, remotely, for outpatient or hospital regulation, with definition and direction of the patient to the appropriate type of assistance they need or to a specialist.
Teleconsulting	Consultancy act mediated by TDICs (Digital, Information and Communication Technologies) between physicians, managers and other professionals, with the purpose of providing clarifications on administrative procedures and health actions.
Teleconference	Medical teleconferencing via synchronous video transmission, of a medical procedure, can be carried out for the purposes of assistance, education, research and training, with authorization from the patient or their legal guardian, provided that the group receiving images, data and audio is composed exclusively of physicians and/or medical students, all duly identified and accompanied by their guardians.

Law No. 14,510/2022 [National Congress of Brazil, 2022] complements the CFM's resolutions, such as Resolution No. 2,314/2022, providing a solid foundation for the continued expansion and regulation of telemedicine in the country. With this legislation, Brazil takes an important step toward a more accessible, efficient, and technologically advanced healthcare system.

The key aspects of the regulation of telemedicine in Brazil include the following.

- Informed consent: patients must provide clear and informed consent before undergoing remote consultations or medical services. This consent may be obtained digitally.
- Medical responsibility: the professional responsibility of physicians in telemedicine is equivalent to that of in-person consultations. Physicians must ensure the quality of care and protect patient privacy and confidentiality.
- Diagnostic limitations: telemedicine should not replace in-person care when a physical examination is essential for an accurate diagnosis.
- Data security: protecting patient data is a priority. The systems used must comply with Brazil's General Data Protection Law (LGPD) to safeguard the integrity and confidentiality of medical information. Resolution CFM No. 2,309/2022 [Federal Council of Medicine (CFM) of Brazil, 2022a] establishes rules for publishing and sharing data from registered physicians in light of the LGPD, the public interest, and the legal powers conferred on the Medical Council.

According to the most recent data made available by the Federal Council of Medicine (CFM) of Brazil [Federal Council of Medicine (CFM) of Brazil, 2024], the number of physicians in the country has consistently increased since the 2000s. In 2010, Brazil had around 370 thousand physicians. In 2023, this number exceeded 570 thousand professionals, a significant growth driven by several factors and policies, including expansion of medical schools and training, incentives for physicians to stay in underserved areas, and government programs such as "Mais Médicos" [Federal Government of Brazil, 2024]. This trend is depicted in Figures 4 and 5, which show the evolution of the number of physicians in Brazil from 1990 to 2023 [Federal Council of Medicine (CFM) of Brazil, 2024]. Such evolution highlights a significant change over the last few decades, both in terms of absolute numbers and in terms of the density of physicians per 1,000 inhabitants. Specifically, the density of physicians per 1,000 inhabitants is illustrated in Figure 4 [Federal Council of Medicine (CFM) of Brazil, 2024]. In 2010, the national density was approximately 1.6 physicians per 1,000 inhabitants. In 2023, this rate rose to around 2.8 physicians per 1,000 inhabitants, which represents a significant advance.

Unfortunately, the growth in the medical density has not been uniform throughout the national territory. Despite the increase in the number and in the density of physicians per inhabitant, Brazil still faces challenges related to the unequal distribution between the different regions of the country. The demographic density of physicians by state shows significant variations, reflecting regional inequalities to access healthcare services. Recent data from CFM of Brazil [Federal Council of Medicine (CFM) of Brazil, 2024] show that the Southeast and South regions have the highest concentration, while the North and Northeast regions face a relative shortage of these professionals. This scenario is depicted in Figure 6, which shows the density of physicians per 1,000 inhabitants in each state of Brazil. While the Southeast and South regions concentrate the majority, with densities well above the national average of 2.81, other regions such as the North and Northeast ones still face a relative shortage of professionals, besides decentralization efforts.

In the Southeast region, states such as São Paulo (SP), Rio de Janeiro (RJ), and Espírito Santo (ES) lead in density, with numbers that exceed three physicians per 1,000 inhabitants. Considering the Southern region, the states Rio Grande do Sul (RS) and Paraná (PR) also have high densities, although slightly lower than those in the Southeast. The developed health infrastructure and the presence of large urban centers contribute to this concentration. In the Central-West region, the Federal District (DF) stands out with a high density of physicians, thanks to the concentration of public healthcare services and the offer of medical specializations. In the Northeast region, despite improvements in recent years, state such as Maranhão (MA) still have one of the lowest densities of physicians, with less than 1.5 professionals per 1,000 inhabitants, reflecting historical challenges in the medical distribution. In the Northern region, states such as Pará (PA) and Amazonas (AM) face significant difficulties in attracting and retaining physicians, especially in rural and difficult-to-access

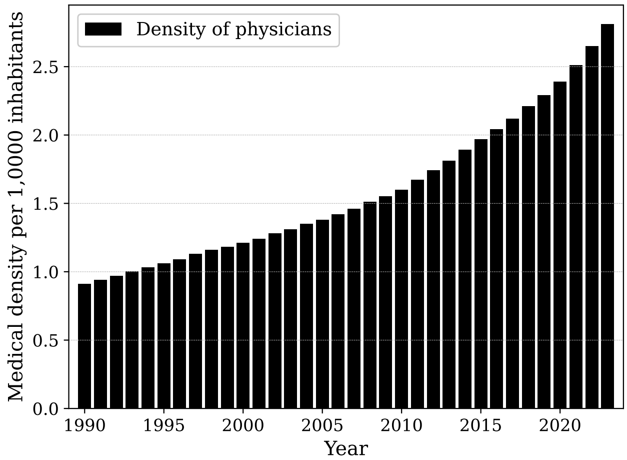


Figure 4. Evolution in the density of physicians per thousand inhabitants [Federal Council of Medicine (CFM) of Brazil, 2024].

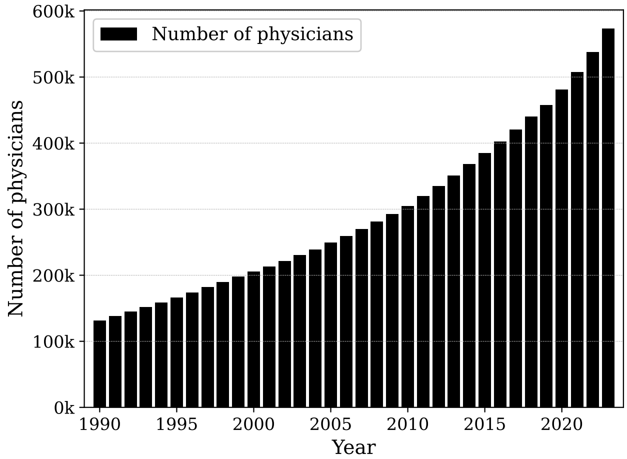


Figure 5. Evolution in the number of physicians per thousand inhabitants [Federal Council of Medicine (CFM) of Brazil, 2024].

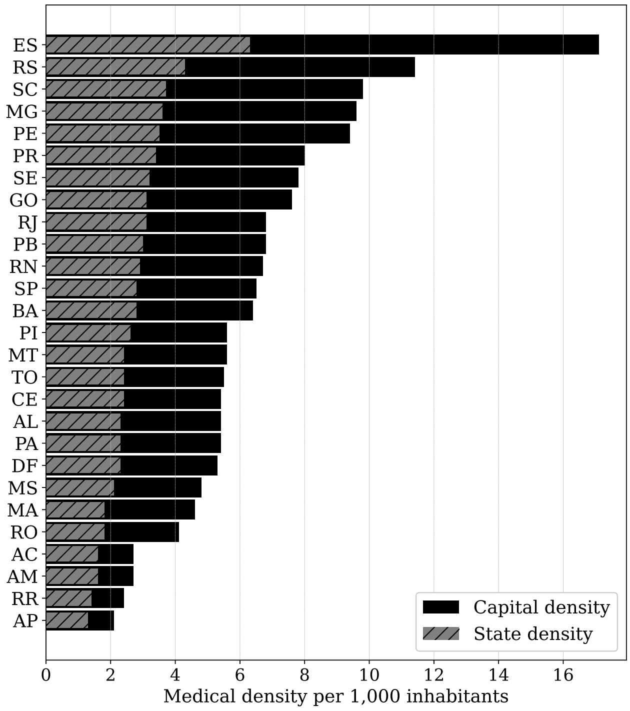


Figure 6. Density of physicians per Brazilian state [Federal Council of Medicine (CFM) of Brazil, 2024].

areas. Figure 6 shows the density of physicians per 1,000 inhabitants in each state and capital city of Brazil. The comparison between the density of physicians in the capitals of Brazilian states and the density of physicians considering the entire state, which includes rural and difficult-to-access areas, reveals significant disparities, highlighting the concentration of health professionals in central urban areas. Although there are public policies aimed at distributing physicians to needy regions, such as the "Mais Médicos" program [Federal Government of Brazil, 2024], these initiatives often fail to completely balance the distribution of professionals, resulting in the persistent concentration of physicians in capital cities. Urban areas typically exhibit a higher concentration of physicians due to multiple factors, including the presence of large hospitals, specialized clinics, research institutions, and medical schools. These facilities offer healthcare professionals enhanced opportunities for employment, specialization, and career advancement. Conversely, rural regions frequently experience a shortage of medical practitioners. Limited resources, inadequate infrastructure, and reduced opportunities for professional development make these areas less attractive to healthcare workers. Logistical constraints and challenges in ensuring the delivery of high-quality medical care further contribute to the low physician density in such locations. Additionally, the concentration of healthcare services in major hospitals situated in urban centers results in substantial travel burdens, even for relatively routine procedures such as follow-up examinations, screenings, or medical check-ups.

The use of telemedicine technologies can help mitigate physician shortages in rural areas by allowing patients to receive specialized care remotely without the need to travel to urban areas. Investing in technological infrastructure is crucial to ensuring that rural communities have access to these solutions. Furthermore, considering urban areas, large hospital centers also have to provide care for emergency cases, which means that standard cases like aftercare examinations, screenings or medical check-ups get lower priorities, and thus long waiting times are quite usual.

In this context, the MSP use case can be considered as a possible solution to provide or improve medical care not only in rural and difficult-to-access areas, but also in suburban and urban areas of Brazil and other nations with similar characteristics. In the next section, we propose innovative solutions to make the MSP a viable use case.

4 Technical and Economic Analysis

Traditional, vendor-locked RAN architectures often face high costs and limited scalability, especially in remote areas. Open RAN provides a more flexible, virtualized alternative that significantly improves vendor interoperability and lowers TCO. This section introduces Open RAN deployment models for urban, suburban, and rural environments, accompanied by a rigorous TCO analysis. To account for Brazil's vast and varied landscape, our framework incorporates modular designs and centralized management for easier upgrades and network control [Liyanage *et al.*, 2023]. Success in remote eHealth applications thus depends on balancing technical

Table 2
TPD scenarios

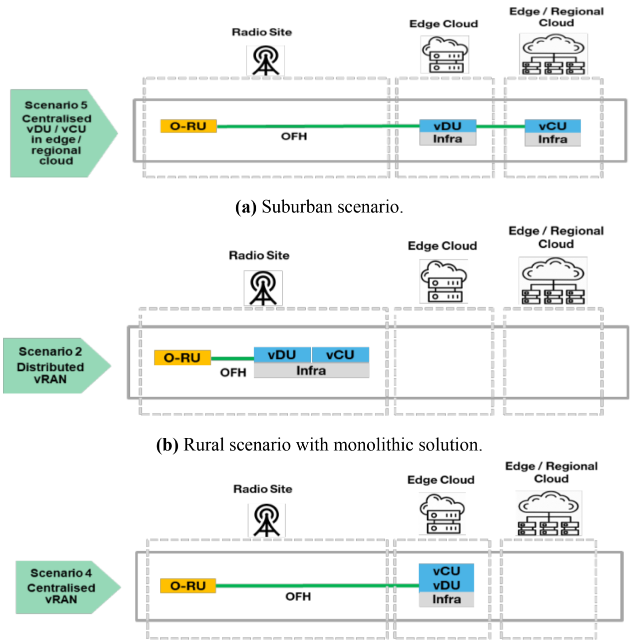
Scenario	Description
Macro distributed	RAN components are physically distributed near users
Macro centralized	RAN components are centralized in data centers or cloud hubs
RAN sharing/MOCN	RAN sharing among multiple operators using the MOCN architecture
RAN sharing/MORAN distributed	MORAN with physically distributed RAN components
RAN sharing/MORAN centralized	MORAN with centralized RAN components
RAN sharing management	Shared RAN managed independently by operators
Indoor/Mono-operator	Indoor RAN operated by a single operator
Indoor/Multi-operator	Indoor RAN shared among multiple operators
Outdoor small cell	Small cells deployed outdoors
Legacy RAT (2G/3G)	Support for older radio access technologies within Open RAN

system behavior with long-term economic sustainability.

4.1 Deployment Models

The disaggregated and virtualized nature of Open RAN supports a diverse array of implementation strategies. As outlined in the Open RAN MoU Group's Technical Priorities Document (TPD), while the radio unit (RU) is located at the cell site, other network functions offer deployment flexibility, ranging from local on-site installations to hosting within edge or centralized regional clouds [Open RAN MoU, 2024]. Table 2 summarizes these TPD scenarios, which include configurations such as macro distributed, macro centralized, various RAN sharing architectures (e.g., multi-operator core network (MOCN) and multi-operator RAN (MORAN) in both distributed and centralized forms), as well as indoor deployments and support for legacy radio access technologies (RATs), i.e., second generation (2G) and third generation (3G).

In the context of MSP use cases requiring outdoor coverage, the optimal architecture largely relies on the existing infrastructure. For suburban environments equipped with fiber-optic backhaul and established cell sites, a hybrid configuration is advantageous. This model integrates a cloud-hosted centralized unit (CU) with an edge-deployed distributed unit (DU), effectively balancing low-latency performance and high throughput with the economic benefits of centralized orchestration, as depicted in Figure 7a. In contrast, the limited fiber availability in rural regions requires the adoption of alternative transport solutions, such as satellite or point-to-point wireless links. To address these constraints, we evaluate two distinct topologies: Rural 1 (Figure 7b), where all network elements are deployed on-site, and Rural 2 (Figure 7c), which centralizes control functions (CU/DU) at the network edge.



(a) Suburban scenario.

(b) Rural scenario with monolithic solution.

(c) Rural scenario with centralized CU/DU.

Figure 7. Network architecture diagrams for suburban and rural scenarios [Open RAN MoU, 2024].

4.2 Total Cost of Ownership Analysis

The economic feasibility of our proposed deployment models is evaluated through a comprehensive TCO analysis based on the following relationship:

$$\text{TCO} = \text{CAPEX} + (\text{OPEX} \times \text{YEARS}).$$

In our context, CAPEX includes the costs associated with hardware procurement, software licenses, installation, and the deployment of supporting infrastructure such as towers and antennas. OPEX encompasses maintenance, energy consumption, cooling, and leasing costs. The open and modular architecture of Open RAN enables vendor flexibility and facilitates incremental upgrades, thereby reducing the overall TCO.

Our TCO analysis evaluates multiple deployment scenarios over one- and five-year periods, based on vendor quotations (excluding taxes). The analysis includes a suburban configuration, two rural configurations (Rural 1 with on-site deployment and Rural 2 with a centralized CU/DU) and a traditional D-RAN architecture. Table 3 provides a detailed breakdown of cost components across these scenarios, and Figures 8a and 8b illustrate the TCO for deployments with one site and three sites, respectively.

In the suburban scenario, where the DU is deployed at the network edge and the CU is hosted in the cloud, the estimated one-year TCO is \$47,031.71 (see Figure 8a). In rural areas, the absence of fiber forces the use of satellite backhaul, resulting in a one-year TCO of \$48,911.60 for Rural 1 and \$52,465.15 for Rural 2. In comparison, the traditional D-RAN configuration achieves a one-year TCO of \$47,677.18, which serves as a benchmark threshold, indicated by a vertical dashed line in Figure 8. When comparing the Rural 2 or Suburban scenarios with traditional RAN, we observe that the economic advantage of the Open RAN solution becomes evident when scaling to a larger number of sites. This advantage stems from the ability to share centralized CU/DU resources across multiple RUs, which significantly reduces the TCO as the network grows. A similar analysis applies to the five-year time frame.

4.3 Key Modeling Assumptions

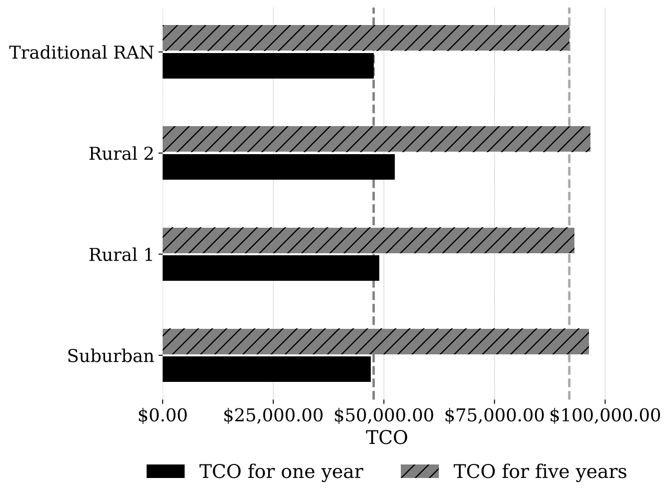
Our deployment strategies rely on open, standardized interfaces as specified by the O-RAN Alliance to guarantee multi-vendor interoperability. To safeguard sensitive healthcare data, our approach incorporates robust authentication, encryption, and continuous interoperability testing. The TCO estimates presented here are derived from fixed assumptions based on local vendor quotations and regulatory data: for instance, a fiber installation cost of $357.14 per kilometer and a tower cost of $5,357.14. These baseline values provide a controlled framework for our analysis. Of course, real-world deployments may exhibit variations due to market fluctuations and regional differences. Additionally, our TCO calculations are based on controlled laboratory experiments, and scaling to larger networks may introduce further complexities not captured in this study. Strategies such as modular design and centralized management are intended to mitigate these challenges over time.

5 Initial Solution Assessment

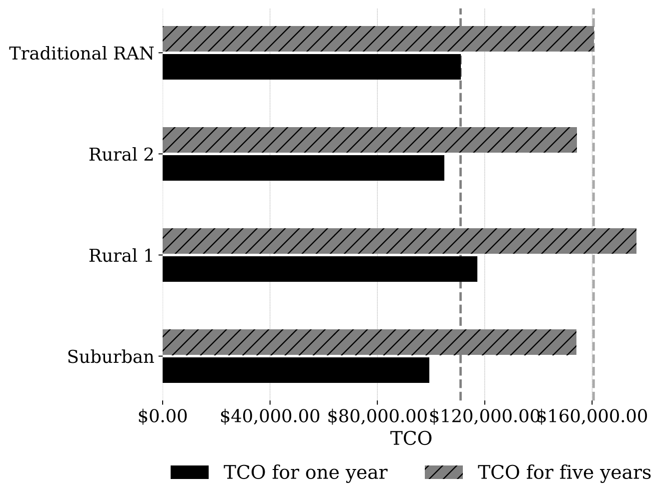
Laboratory experiments were conducted to evaluate the implementation outcomes of Open RAN networks, focusing on the specific MSP scenario. In collaboration with the medical area partners "Beneficência Portuguesa" and "InovaHC", the chosen target medical application was the remote echocardiogram examination. The tests utilized ultrasound equipment developed by Samsung, which connects to the Internet for data transmission and reception. The experimental setup enabled the measurement of key metrics, such as latency and throughput, in addition to capturing packets for detailed traffic analysis. This approach allowed the characterization of traffic patterns that will closely resemble those expected in future field tests.

For traffic analysis, we selected three primary metrics, namely, packet size, throughput, and inter-packet interval (IPI), as detailed below.

- **Packet size**: The amount of data that a packet carries during transmission. It includes both the payload and headers, characterizing the traffic profile generated by the remote ultrasound application. It also provides cross-layer insights into how this traffic interacts with the Open RAN transport and radio resources.
- **Throughput**: Represents the amount of bytes transmitted within a defined time window. During the experiments, a 1-second window was observed to provide more consistent results for analysis, and it was adopted as the standard interval for measurements.
- **IPI**: Measures the temporal spacing between transmitted packets, an essential metric for evaluating traffic behavior and its impact on connected devices. This analysis is particularly relevant in scenarios where energy optimization is critical, such as hospital environments with multiple connected devices.



(a) TCO for one site.



(b) TCO for three sites.

Figure 8. TCO model for Open RAN sites.

With these metrics, the laboratory tests provided a robust foundation for validating the project's assumptions, ensuring that the Open RAN network can adequately meet the traffic demands of the MSP scenario in real-world deployments.

5.1 Testbed Scenarios

To evaluate the feasibility of ultrasound data transmission over a 5G network, we conducted laboratory tests using two distinct Samsung ultrasound devices with different characteristics: the V6 and the HM70 EVO. While both are mobile and could be moved to different service points, the V6 is a more robust device equipped with an application (Samsung's Sonosync client) for video and audio streaming, remote operation of the equipment and upload of selected images and information. The HM70 EVO is a more portable device that lacks the video and audio streaming and remote operation capabilities but allows the upload of images and medical information to a server. For the HM70 EVO, closer support of the local staff was necessary to operate the equipment and to configure an alternative streaming solution. This involved connecting a notebook to the device for image capture and subsequent transmission via Teams.

The tests with 5G were divided into three scenarios, as

Table 3
TCO evaluation

Name	CAPEX/OPEX	Scenario[†]			
		Suburban ($)	Rural 1 ($)	Rural 2 ($)	D-RAN ($)
Backhaul optical fiber	CAPEX	17.85	**17.85**	-	-
Backhaul optical transport (per year)	OPEX	1,284.00	-	-	-
Backhaul satellite equipment	CAPEX	-	4,737.00	4,737.00	4,737.00
Access to satellite network (per year)	OPEX	-	8,421.00	8,421.00	8,421.00
Fiber connection to the RU per kilometer (fronthaul)	CAPEX	**357.14**	-	**357.14**	**357.14**
DU	CAPEX	7,910.00	-	-	-
RU	CAPEX	**7,000.00**	**7,000.00**	**7,000.00**	-
CU/DU/RU	CAPEX	-	-	-	**18,000.00**
CU/DU	CAPEX	-	**9,917.94**	9,917.94	-
Power consumption RU (watt-hour per year)	OPEX	**669.61**	**669.61**	**669.61**	**669.61**
Power consumption DU/CU (watt-hour per year)	OPEX	-	**721.12**	721.12	-
Power consumption DU (watt-hour per year)	OPEX	360.56	-	-	-
Software and licenses CU and DU per site	CAPEX	**5,500.00**	**5,500.00**	**5,500.00**	-
Maintenance and support (per year)	OPEX	535.71	535.71	535.71	1,785.71
Integration and configuration	CAPEX	892.85	892.85	892.85	892.85
Acquisition and installation cost of the tower on the site	CAPEX	**5,357.14**	**5,357.14**	**5,357.14**	**5,357.14**
Antenna cost for three sectors	CAPEX	**2,303.55**	**2,303.55**	**2,303.55**	**2,303.55**
RF splitter	CAPEX	**671.08**	**671.08**	**671.08**	**671.08**
Frequency band licensing (per year)	OPEX	178.57	**178.57**	178.57	178.57
Site cooling unit cost	CAPEX	392.85	392.85	392.85	-
Site cooling power consumption (watt-hour per year)	OPEX	506.05	**506.05**	506.05	-
Data center CU rent (per year)	OPEX	8,791.21	-	-	-
Power supply and uninterruptible power supply	CAPEX	**392.85**	**392.85**	**392.85**	**392.85**
Energy and cabinet	CAPEX	**446.42**	**446.42**	**446.42**	**446.42**
Battery	CAPEX	**250.00**	**250.00**	**250.00**	**250.00**

[†] Boldface values may vary for a larger number of sites.

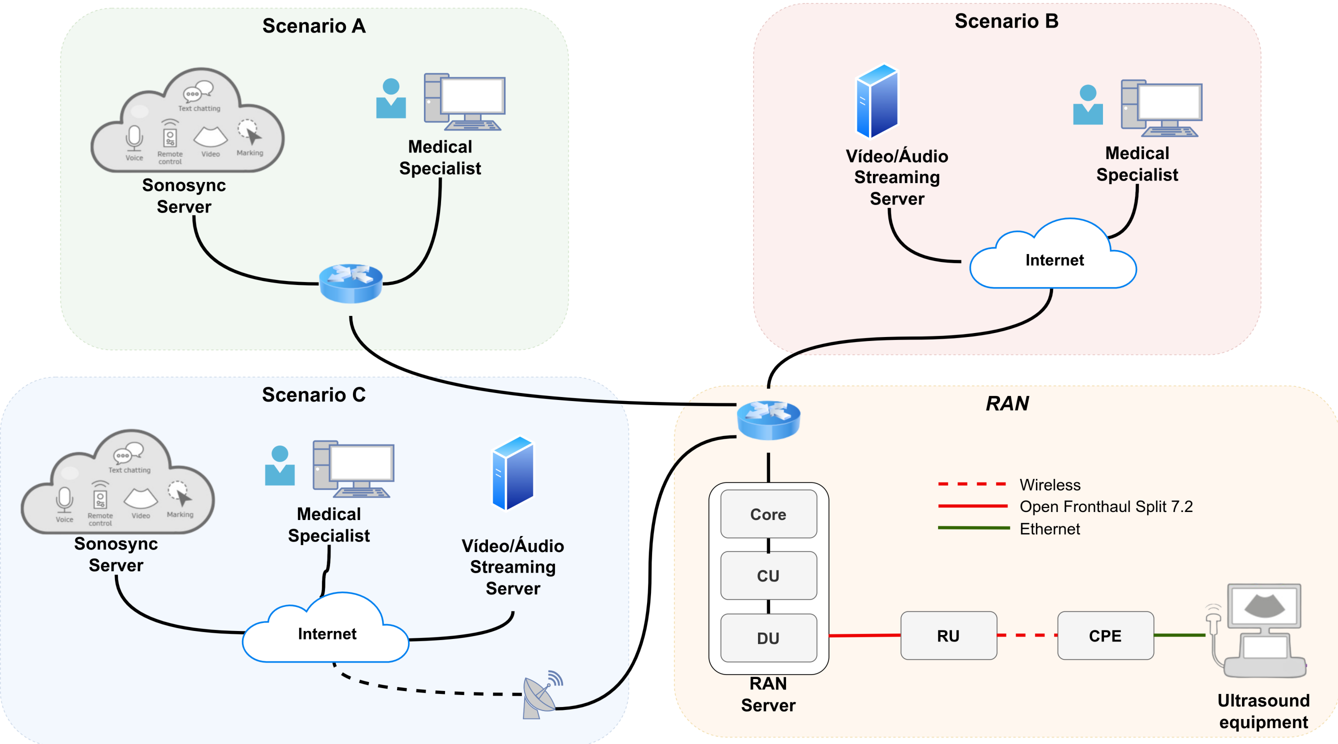


Figure 9. Open RAN Scenarios.

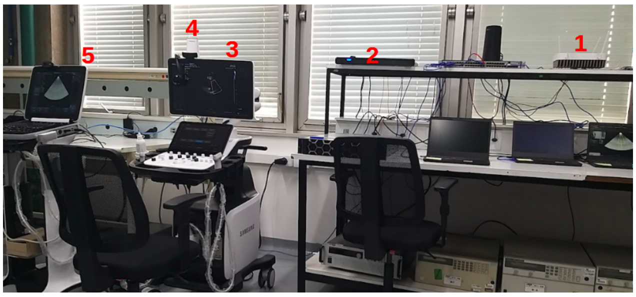


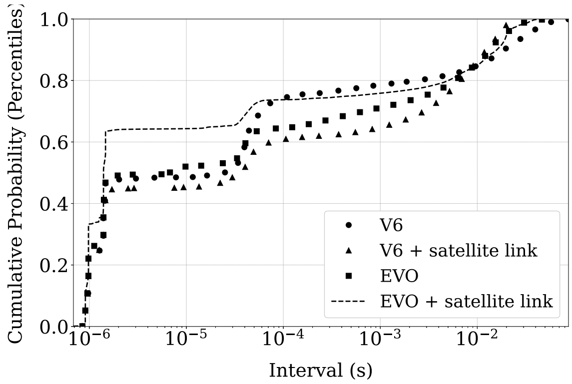
Figure 10. Laboratory setup.

depicted in Figure 9. In Scenario A, the setup focused on the V6 device, utilizing the Sonosync client for streaming and remote control. Scenario B examined the HM70 EVO device, which required the addition of a notebook for image capture and the use of Teams for data transmission. Finally, Scenario C introduced a setup where the connection between the Core and the Internet was established via satellite. This last scenario included both the V6 (using the Sonosync client) and the HM70 EVO (streaming via Teams), allowing a comparative evaluation of the impact of satellite connectivity on the system's performance. The 5G Open RAN setup was configured to use Band 78, with 100 MHz of channel bandwidth operating in 3700 MHz, prioritizing uplink traffic.

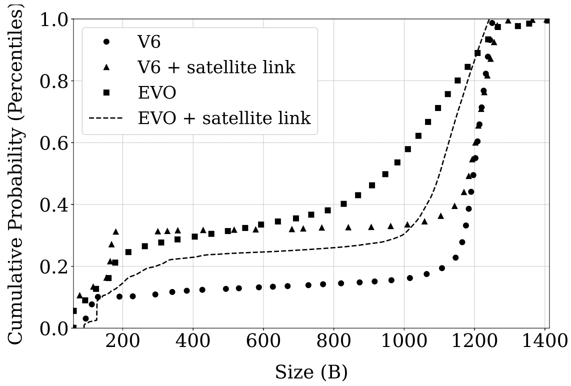
Figure 10 provides a detailed view of the laboratory environment and the equipment used during the tests. The photo highlights the main components with numbered labels: (1) the O-RU, (2) the Core/CU/DU, (3) the V6 ultrasound device, (4) the CPE with fixed wireless access capabilities, and (5) the HM70 EVO ultrasound device. For comparison, the same tests were conducted without using the 5G network, where the devices were directly connected to a switch that linked them to the streaming server and the remote specialist's computer.

5.2 Testbed Results and Discussion

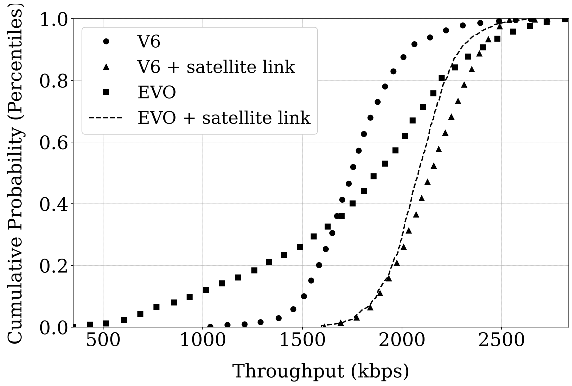
To define specific requisites for the echocardiogram remote examination using Samsung devices, our team was supported by a medical specialist who evaluated the quality of the remote examination using the equipment. For this evaluation, we considered throughput and latency as the key requisite parameters and introduced a variable throughput limitation between the equipment and the streaming/remote control servers based on switch throughput limitation. In the same way, we introduced a variable artificial latency between the equipment and the servers using latency configurable software data queues. For the V6 equipment, we worked with the medical specialist to determine the empirical quality of experience (QoE) thresholds for this specific remote examination. The specialist evaluated the video, audio, and remote control as *satisfactory* up to a limit of 5 Mbps of throughput. Regarding latency, the specialist identified two distinct QoE thresholds: the audio/video stream was acceptable up to 50 ms, while the remote control of the equipment was deemed fully usable and satisfactory with latencies up to 25 ms. A similar QoE threshold was found for the HM70 EVO equipment, which was satisfactory up to 5 Mbps and 50 ms for its audio/video stream. It is important to note that this empirically-derived 25 ms QoE requirement for remote control is less stringent than the formal 20 ms 3GPP KPI specified for URLLC-based



(a) CDF of IPI for different scenarios.



(b) CDF of packet size for different scenarios.



(c) CDF of throughput for different scenarios.

Figure 11. CDF of metrics at V6 and HM70 EVO operating with 5G connections.

MSP sub-use cases, such as those involving haptic feedback (see Figure 1). This finding indicates a specialization of the MSP use case for remote echocardiography, suggesting that 5G eMBB (or potentially even Open RAN 4G) could adequately support this application, allowing for a higher density of active equipment per cell. In summary, the medical specialist confirmed that the overall remote examination using both the V6 and HM70 EVO over our 5G Open RAN testbed was fully satisfactory.

We investigated a myriad of possible configurations for the scenarios under consideration. Figure 11 shows the three network traffic metrics for V6 and HM70 EVO equipment with fiber and satellite xHauls. While several comparisons can be drawn from that figure, we remind the reader that our main objective herein is to analyze whether our setup meets the network requirements for the MSP use case specialized for echocardiogram remote examination. Another point to consider is that the laboratory tests focused on the Open RAN

5G rural deployment scenarios for the proposed use case, comparing the use of transport network by fiber with the transport network by LEO satellite links.

Regarding the IPI, note from Figure 11a that 5G connections at HM70 EVO and V6 for IPI levels higher than 10 μs exhibit a similar behavior with either fiber or satellite xHaul. This indicates certain stability in packet delivery when using either xHaul, despite the 5G sensitivity to congestion and interference. This sheds light on how the setup meets QoS requirements to ensure low and predictable latencies, particularly for latency-sensitive applications with voice and video services. As for the packet size in Figure 11b, its CDF at EVO with satellite xHaul and V6 (with fiber or satellite xHaul) centers around typical values, thereby suggesting predominantly mixed traffic with standard packets. On the other hand, we observe greater variability at the HM70 EVO setup with fiber xHaul, which can reflect an MS Teams client characteristic of varying the packet size more compared to the V6 Sonosync client thus requiring the optimization of the maximum transmission unit configurations to avoid excessive fragmentation, especially in mobile networks. In terms of throughput, as depicted in Figure 11c, the 80th percentile for V6 throughput is lower than 5 Mbps, which was the threshold identified by the medical specialist as satisfactory for conducting the remote examination. If we look at the throughput along the test, we can see some few throughput peaks higher than 3 Mbps. These throughput peaks are relevant and influence the QoE for the remote medical examination.

An unexpected result was observed in the 80th percentile throughput: for V6 using the 5G Open RAN setup with satellite xHaul, the throughput was higher than that of V6 using the same setup with Ethernet cable xHaul. This outcome can be partially explained by variations in user interaction, such as movements and speech, during the remote medical examination, which can influence throughput. While it was not possible to fully eliminate these variations, they are considered typical events in real-world remote medical scenarios.

For the HM70 EVO, the 80th percentile throughput was below 5 Mbps, with throughput peaks exceeding 3 Mbps throughout the test. When comparing the HM70 EVO performance over satellite xHaul versus Ethernet cable xHaul, the 80th percentile values were similar. However, the distribution curve revealed lower throughput variability with the satellite link. This behavior may be attributed to increased traffic buffering over the satellite connection, which tends to smooth out short-term fluctuations at lower throughput levels. We should also highlight that, while these results were obtained using ten kilometers of fiber, tests conducted with four kilometers of fiber have not significantly impacted the results whatsoever.

Measurements using iperf3 in TCP mode related to the total 5G Open RAN link throughput indicated 202 Mbps in uplink and 366 Mbps in downlink. Using UDP mode, the measured downlink throughput was 227 Mbps in uplink and 380 Mbps in downlink. Latency measurements with ping tools indicated 12 ms of RTT in the laboratory network using the 5G link. These throughput and latency levels could be enough to support many simultaneous remote echocardiogram examinations using the same 5G Open RAN setup. Considering the MSP sub-use cases as defined in 3GPP, these measurements would be enough to support MSP 1, MSP 3, MSP 4, MSP 5 and MSP 7. Probably it would be possible to optimize the setup uplink to achieve 240 Mbps and support MSP 2, but MSP 6 would be possible to support only using FR2 frequency bands.

6 Conclusion

Open RAN technology emerges as a pivotal framework for the evolution of remote healthcare, demonstrating that disaggregated and virtualized network architectures can effectively mitigate geographical barriers to medical access. In this work, we presented a comprehensive evaluation of Open RAN architectures for eHealth services, using Brazil's diverse landscape as an important case study. By mapping an original eHealth taxonomy to 3GPP use cases, we addressed the specific challenges of expansive geography and infrastructural gaps. Our analysis identifies optimal deployment models for suburban and rural sectors, specifically assessing the scalability of up to three cell sites, while introducing a rigorous TCO framework to measure economic feasibility against legacy RAN standards. The results reveal that the economic viability of Open RAN is contingent upon resource sharing, specifically demonstrating cost-efficiency when a single DU serves three or more RUs.

Validation through a 5G Open RAN testbed with real-time ultrasound transmission confirms that the architecture meets stringent clinical requirements, even with an open fronthaul span of 10 km. A pivotal finding is the near-parity between satellite and wired backhaul performance, proving that satellite-integrated Open RAN is a transformative solution for bridging the healthcare divide in the world's most isolated regions.

Our tests using 10 km and 4 km fiber links, alongside baseline direct-wired controls, demonstrate robust throughput and low latency. These results provide valuable insights and opportunities for further advancements. While large-scale deployments present additional complexities, future optimization can address real-world factors such as satellite link performance under adverse weather, interference management, and multi-site coordination. For example, refining adaptive techniques can help mitigate jitter and packet loss in satellite links, ensuring consistent performance even in challenging conditions. Building on these findings, future work will expand to the following:

(i) Multi-site field trials to evaluate diverse propagation conditions and traffic loads.
(ii) Dedicated security assessments to validate the effectiveness of open-interface authentication and encryption under real operational threats.
(iii) Scalability simulations to confirm that the system can adapt to higher user densities, additional frequency bands, and more complex scheduling.
(iv) Strategies to counteract performance variability introduced by environmental factors, such as adaptive buffering techniques and dynamic channel allocation algorithms.

The integration of a flexible, cost-effective Open RAN framework with a robust technical-economic analysis is essential to overcoming the healthcare disparities in remote regions. Our comprehensive study includes detailed literature review, MSP taxonomy, deployment strategies, TCO analysis, and laboratory evaluations, demonstrating that such an integrated approach can significantly enhance remote eHealth delivery in Brazil and other similar countries. While our controlled laboratory experiments demonstrate the promising technical and economic viability of Open RAN for remote eHealth, future work will focus on extensive field trials and further studies to refine deployment strategies, validate the economic model under field conditions, and address scalability, security, and interoperability issues. These efforts will be crucial to transforming remote healthcare delivery into a robust, cost-effective, and sustainable reality.

A Sub-Use Case Descriptions

This appendix includes Tables 4, 5, and 6 to provide detailed descriptions for the sub-use case acronyms referenced in the eHealth taxonomy figures.

Table 4
Description of URLLC sub-use cases [3GPP, 2021]

Sub-Use Case	Description
ARAS 1	4K (3840x2160 pixels) 120 fps HDR 10bits real-time video stream with lossless compression: uplink direction with one active UE
ARAS 2	4K (3840x2160 pixels) 120 fps HDR 10bits real-time video stream with lossless compression: downlink direction with up to 10 active UEs
ARAS 3	Uncompressed 4K (3840x2160 pixels) 120 fps HDR 10bits real-time video stream: uplink direction with one active UE
ARAS 4	Uncompressed 4K (3840x2160 pixels) 120 fps HDR 10bits real-time video stream: downlink direction with up to 10 active UEs
ARAS 5	3D 256 x 256 x 256 voxels 24 bits 10 fps ultrasound unicast data stream
MSP 1	Haptic feedback data stream
RAS 1	Stereoscopic 4K (3840x2160 pixels) 120 fps HDR 10bits real-time video stream with lossless compression
RAS 2	Stereoscopic uncompressed 8K (7680x4320 pixels) 120 fps HDR 10bits real-time video stream
RAS 3	Haptic feedback data stream
RAS 4	Motion control data stream
RAS 5	4K (3840x2160 pixels) 120 fps HDR 10bits real-time video stream with lossless compression
RAS 6	Uncompressed 8K (7680x4320 pixels) 120 fps HDR 10bits real-time video stream

Table 5
Description of eMBB sub-use cases [3GPP, 2021]

Sub-Use Case	Description
ARAS 1	4K (3840x2160 pixels) 120 fps HDR 10bits real-time video stream with lossless compression: uplink direction with one active UE
ARAS 2	4K (3840x2160 pixels) 120 fps HDR 10bits real-time video stream with lossless compression: downlink direction with up to 10 active UEs
ARAS 3	Uncompressed 4K (3840x2160 pixels) 120 fps HDR 10bits real-time video stream: uplink direction with one active UE
ARAS 4	Uncompressed 4K (3840x2160 pixels) 120 fps HDR 10bits real-time video stream: downlink direction with up to 10 active UEs
ARAS 5	3D 256 x 256 x 256 voxels 24 bits 10 fps ultrasound unicast data stream
MSP 1	Haptic feedback data stream
MSP 2	CT/MRI scan data, max 300Mbyte of DICOM data
MSP 3	Uncompressed
MSP 4	Remote console for CT/MRI (XVGA compressed)
MSP 5	Compressed 4K video stream
MSP 6	Stereoscopic 4K
MSP 7	High quality audio stream
DVAM 1	Uncompressed 8K (7680x4320 pixels) 120 fps HDR 10bits real-time video stream: uplink direction with one active UE
DVAM 2	Uncompressed 8K (7680x4320 pixels) 120 fps HDR 10bits real-time video stream: downlink direction with up to 10 active UEs
DVAM 3	8K (7680x4320 pixels) 120 fps HDR 10bits real-time video stream with lossless compression: uplink direction with one active UE
DVAM 4	8K (7680x4320 pixels) 120 fps HDR 10bits real-time video stream with lossless compression: downlink direction with up to 10 active UEs
RAS 1	Stereoscopic uncompressed 8K (7680x4320 pixels) 120 fps HDR 10bits real-time video stream
RAS 2	Uncompressed 8K (7680x4320 pixels) 120 fps HDR 10bits real-time video stream
RAS 3	Stereoscopic 4K (3840x2160 pixels) 120 fps HDR 10bits real-time video stream with lossless compression
RAS 4	4K (3840x2160 pixels) 120 fps HDR 10bits real-time video stream with lossless compression
RAS 5	Motion control data stream
RAS 6	Haptic feedback data stream
QoS-RT 1	Stereoscopic 4K 60 fps HDR 10bits frame packed real time video (lossless compressed)
QoS-RT 2	4K 60 fps 12 bits per pixel color coded (e.g. YUV 4:1:1) real time video (lossless compressed)
QoS-RT 3	Haptic Feedback
EC 1	Uncompressed
EC 2	Compressed 4K

Table 6
Description of mMTC sub-use cases [3GPP, 2021]

Sub-Use Case	Description
CTOH 1	Area with hospital
CTOH 2	Suburban area

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Authors' Contributions

F. R. A. Parente, D. A. B. Fonseca, S. M. Sakai, E. J. Bonon, F. M. F. Rocha, and F. M. A. Junior contributed to the conceptualization and experimental design of this study. R. T. Zansávio and R. K. Y. Aoki performed additional experiments and evaluations. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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