5G Deployment in Rural Areas: Advancing Connectivity and Bridging the Digital Divide

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Abstract

Background: Digital literacy, education, and human right of internet are also hampered in rural areas keeping the rural people more backward in the technological advancement and not providing them better chance of socioeconomic development. The opportunity of implementing the new 5G technologies can give the new perspective in the elimination of such disparities manifested through the improvement of the connection, the decrease of latency, and the increase of data transfer rates. This research study established that the adoption of 5G for coverage in rural areas is challenged by technical, economic and policy factors.

Objective: The article aims at analyzing the technical, economic, and social aspects of 5G technology in the rural context in order to identify such problem the development of appropriate solutions for infrastructure costs, spectrum availability, and consumers. In pursuing this goal, the research seeks to develop practical recommendations on enhancing deployment strategies to increase Internet access where it is scarce.

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Methods: The study therefore used an exploratory, theoretical-evaluative, and finally empirical approach that involved quantitative modeling, case studies, and key informant interviews. Latency, data throughput, and coverage stand as the most significant factors which were tested using network simulation. Level of cost was used to determine economic feasibility while data for qualitative analysis were obtained from a survey of policymakers and telecom operators, and focus group discussion with rural community leaders.

Results: In the case of 5G, the implementation of the system led to a 75% reduction in latency, a 600% improvement in the data throughput, and a 300% increase in coverage area. This finding revealed that the partnerships as a deployment model were the most effective as they resulted to a 58%ROI and lowered infrastructure costs.

Conclusion: The study reaffirms the innovation of 5G to rural areas and develops agriculture, healthcare services, and educational systems. Policies, investments in the right areas, optimal management of the available spectrum and engaging with the communities as required should be a key focus for deployment to be just.

Keywords: 5G, rural connectivity, digital divide, network infrastructure, broadband, latency, spectrum allocation, telecommunication, socioeconomic impact, IoT.

1. Introduction

In today's interconnected world, the significance of connectivity in shaping economic growth, human relationships, and access to essential resources cannot be overstated. Residents of rural regions consistently face a lack of inclusive Internet connectivity, which prevents them from fully participating in the digital world. This exacerbates poverty disparities and excludes individuals from crucial social elements such as education, healthcare, and participation in the burgeoning digital economy (Lappalainen and Rosenberg 2022). However, these challenges are surmountable with the advent of 5G technology, which offers increased speed, low latency, and higher capacity compared to previous technologies. This technological advancement aims to bridge the connectivity gap in rural areas, enhancing development and quality of life.

The demand for 5G networks has surged, particularly in agriculture, healthcare, education, and e-commerce, as these sectors increasingly rely on technology. The deployment of 5G networks can bring significant changes to rural areas that often lack developed connectivity infrastructure (Tang et al. 2021). For example, the agricultural sector, which forms the backbone of many rural economies, can benefit from 5G IoT devices for precision farming, automated monitoring systems, and real-time data analysis (Damsgaard et al. 2022). Similarly, rural healthcare can benefit from telemedicine, including remote consultations, diagnostics, and even surgeries, all powered by 5G networks (Jape et al. 2023).

However, several challenges remain in implementing 5G in rural areas. A major hurdle is the capital expenditure required for infrastructure, such as new towers, fiber-optic cables, and base stations. Rural areas typically have low population density, making it difficult for telecom operators to justify the investment in 5G networks, unlike urban regions with high population density (Cavalcante et al. 2021). Additionally, rural areas may have challenging topographies that complicate the installation of telecom infrastructure, compounded by the absence of existing 5G deployment infrastructure (Biswas 2023).

Another challenge relates to the availability of spectrum space. Most of the 5G spectrum has been allocated to urban areas due to the high demand for high-speed internet. However, rural areas require different frequencies, often in the lower bands, to provide coverage over large, sparsely populated areas (Kryszkiewicz et al. 2022). The regulatory framework for spectrum assignment and infrastructure development will significantly influence the success of 5G in these regions.

Socioeconomic factors also contribute to the digital divide, including income disparities and digital literacy levels. Rural residents may not afford 5G devices or lack the knowledge to effectively utilize ICT, unlike their urban counterparts. To overcome these barriers, a comprehensive social approach is needed, focusing on technological solutions and governmental support for digital inclusion (Jamil 2021). Measures such as direct support for rural populations, collaboration with the private sector to build necessary infrastructure, and organizing courses to enhance digital literacy are crucial to making 5G's benefits accessible to everyone (Qasim and Jawad 2024).

Ultimately, several challenges must be addressed to realize the potential of 5G technology in providing digital connectivity to rural areas. These challenges include infrastructure costs, spectrum allocation, regulatory issues, and social factors. A multifaceted approach involving governmental, corporate, and community interventions is essential to achieve revolutionary changes in rural connectivity and enhance digital inclusiveness.

1.1. The Aim of the Article

This article aims to explore the application of 5G networks in rural areas and to understand the efforts made to bridge the disparity between urban and rural regions. While the advent of high technology marked by 5G connectivity is commendable, rural areas have often lagged behind in network access, struggling to achieve even 4G internet speeds. The potential impact of 5G on economic development, healthcare, education, and the overall quality of life in these areas is significant. This article seeks to investigate how 5G can address these issues by enhancing service delivery and providing better connectivity in rural regions.

The article will examine the current status of rural connectivity and the challenges that have hindered the realization of high-speed communication networks. It will evaluate the technological, financial, and policy barriers that must be overcome for 5G to thrive in rural areas. Additionally, the article will discuss current 5G pilot initiatives and use cases, reasoning the advantages and drawbacks of the technology in rural contexts. The findings of this evaluation will be valuable for identifying positive scenarios for 5G distribution in rural areas and analyzing the potential contributions of policy, industry, and community efforts in generating positive change in this sphere.

The primary purpose of the article is to continue the conversation about the digital divide and provide a comprehensive understanding of how 5G can help close the gap in rural regions. It will emphasize the importance of systematic strategies that coordinate technoscientific advancements with modifications to existing policies and active community participation in the knowledge society. This approach ensures that rural areas are not excluded from the new world order of information technology. Thus, the article aims to discuss the prospects and challenges of applying 5G in rural areas and offer guidance on solutions that might further improve the situation.

1.2.Problem Statement

One of the enduring social inequalities is the urban/rural divide in access to advanced information technology infrastructure and the availability of digital services. Despite the increasing availability of the Internet to users worldwide, many rural areas remain disadvantaged, which has serious implications for their economic, social, and educational growth. The absence of significant and stable connectivity also hinders ordinary people in rural areas from engaging in the online economy, accessing modern healthcare services, and obtaining education that relies on the World Wide Web.

As the world advances its communication technology to embrace 5G, the future of the country's rural areas looks even bleaker if no attempts are made to close this gap. For 5G networks to enter the market, they need to revolutionize connectivity through their speed, latency, and capacity. However, the difficulties in deploying this technology are significant for rural areas. Several of these challenges include the high intensity required for the location and installation of structures, the complex geographical terrains of these regions, and the restrictive available frequency space. Additionally, many rural territories have low revenue-generating potential, which discourages telecom operators from investing in their development, further complicating the rollout of 5G networks.

The primary focus of this article is the persistent digital gap in rural contexts and the potential of 5G to address it. The key question is how the technology can be rolled out in a manner that allows rural populations to benefit from the use of 5G networks, given the various technical, economic, and regulatory constraints. Accordingly, the article aims to discuss measures that can help overcome these limitations, enabling the adoption of technologies in rural regions that are already available in urban areas.

2. Literature Review

The implementation of 5G networks has been presented as a tool that enables differentiation between urban and rural areas. The literature highlights the absence of high-speed internet connections in rural regions due to low population density, physical seclusion, and inadequate transport infrastructure, which complicate and increase the cost of extending 5G technology to these areas (Lappalainen and Rosenberg 2022).

The literature primarily addresses the economic and technical barriers to 5G infrastructure deployment in rural areas. Providing connectivity in sparsely populated regions requires more cell towers and fibers, leading to high costs. The development of rural infrastructure is further constrained by geographic factors such as slopes and other natural barriers. However, it has been found that new strategies for deploying 5G and optimizing infrastructure will be key to success. Financial constraints may be mitigated through public-private partnerships and government incentives (Maluleke et al. 2022).

Deploying 5G in rural areas requires the allocation of spectra. Rural areas need low-frequency bands for establishing base stations that can cover large areas with fewer stations. These low-frequency bands can extend from forests and mountains and relay signals effectively. However, low-frequency bands are less efficient compared to mid or high frequencies, which poses a challenge as it hampers data flow in rural areas (Khawam et al. 2022).

In metropolitan areas, mid- and high-frequency bands are more suitable for higher data rates and denser deployment. Rural regions struggle to match this coverage and capacity. According to existing research on frequency selection, low frequency is adopted for large geographical coverage areas, while mid-frequency bands are used for higher traffic areas such as schools, hospitals, or townships. This approach ensures coverage and capacity for higher data rate applications, optimizing the 5G rollout (Ahamed and Faruque 2021; Jawad et al. 2022).

The literature also addresses network performance improvements. 5G could increase internet speed, latency, and network performance in rural areas. Technologies such as beamforming, large MIMO, and network slicing facilitate higher connection rates compared to previous generations of networks. Enhanced broadband access in rural areas may positively impact the local economy, demographics, healthcare, and education (Shayea et al. 2021).

Rural 5G networks need to support core local applications. While technology such as 5G can improve various sectors, agriculture often lags behind. Precision agriculture requires IoT devices connected to provide timely data on objects' conditions and environments for decision-making (Qasim et al. 2022). These technologies could enhance agricultural yields and reduce costs through 5G networks. Telemedicine could improve healthcare in regions with few healthcare centers, addressing latency challenges brought by 5G (Arrubla-Hoyos et al. 2022).

Literature reviews of pilot rural 5G projects and case studies reveal the issues and opportunities of rural 5G deployments. The article indicates that government policies and regulatory frameworks are crucial for infrastructure development. Subsidies for spectrum access and rural broadband grants have been applied to expedite and expand the rollout of 5G in supporting nations. This implies that the success of rural 5G requires not only technological advancements but also substantial legislative support (Gupta 2024).

Investigations into 5G's socioeconomic opportunities in rural areas are ongoing. Extending reliable, high-speed internet to connect rural businesses to the global digital economy may foster development. New forms of education, such as online classes, e-stores, and telemedicine, can positively influence the quality of life. These advantages, however, are contingent upon overcoming initial infrastructural and technical barriers. Without targeted initiatives, 5G technology may deepen the digital divide between urban and rural areas (Beltozar-Clemente et al. 2023).

Regarding 5G adoption in rural settings, the literature focuses on both the great potential and significant challenges. While 5G improves network conditions, broad adoption in rural areas requires technological advancements, the construction of new necessary infrastructure, and supportive governmental policies. Early research and case analyses indicate that solutions can be achieved only through the interest and cooperation of service providers and governments to make rural 5G deployment possible and maintain these regions within the digital realm.

3. Methodology

To achieve the objectives of this research on the deployment and impact of 5G networks in rural areas, data collected from multiple sources were analyzed qualitatively and quantitatively using techniques such as mathematical modeling that incorporate both qualitative and quantitative components. It used technical, socioeconomic, and policy perspectives to analyze and model 5G technology through experimental results and equations based on simulations.

3.1. Data Collection

The data collection phase involved gathering diverse datasets to comprehensively explore the challenges and opportunities of rural 5G deployment:

- *Interviews:* A total of 50 stakeholder interviews were conducted with policymakers (10), telecom operators (15), rural community sample (15), and technology specialists (10). These questions were about deployment challenges, perceived/anticipated gains, and ways of addressing those challenges.
- *Pilot Project Analysis:* The authors used data from 10 current trials of 5G deployment in rural areas. Latency, data rate and coverage were

derived to measure the effects that the 5G had on applications such as smart farming, telehealth and distance learning (Tang et al. 2021; Arrubla-Hoyos et al. 2022).

- *Surveys:* Fifteen survey questionnaires distributed to 200 individuals in five geographically distinct rural areas offered information regarding Internet usage and literacy, as well as true knowledge of 5G technology (Maluleke et al. 2022).
- *Secondary Data:* Additional information relating to the technological, economic, and policy aspects of implementing 5G in rural areas were obtained from 30 peer-reviewed articles, reports, and regulatory documents. (Lappalainen and Rosenberg 2022; Cavalcante et al. 2021; Jamil 2021).

3.2. Network Performance Modeling

Quantitative modeling was performed to evaluate the performance improvements achieved by 5G over 4G in rural areas (Salih et al. 2024). The following equations were developed and implemented:

1. ***Network Coverage Optimization***:

$$N_{BS} = \left\lceil \frac{A}{\pi \cdot (R_{eff})^2} \right\rceil \quad (1)$$

This equation estimates the number of base stations required to cover a rural area, considering terrain complexity and population density. Here, R_{eff} accounts for attenuation factors and geographical barriers such as mountains (Maluleke et al. 2022; Khawam et al. 2022).

2. ***Latency Reduction***:

$$L_{red} = \frac{L_{4G} - L_{5G}}{L_{4G}} \cdot 100\% \quad (1)$$

This equation quantifies the latency improvements of 5G over 4G. For 5G, latency was modeled as:

$$L_{5G} = \frac{1}{S + \frac{1}{N_{slice}} \cdot MIMO \cdot BEAM} \cdot 100\% \quad (1)$$

where network slicing, MIMO, and beamforming contribute significantly to reduced latency (Lappalainen and Rosenberg 2022; Gupta 2024; Saeki et al. 2022).

3.3. Economic Feasibility Analysis

An economic model was developed to assess the financial viability of 5G deployment in rural areas. The return on investment (ROI) was calculated using:

$$ROI = \frac{\sum_{t=1}^{T}(R_t - C_t)}{\sum_{t=1}^{T} C_t} \quad (1)$$

Costs were further decomposed into:

$$C_t = C_{infra} + C_{spectrum} + C_{maintenance} + C_{training} \quad (1)$$

This model allowed for evaluating the impact of different funding mechanisms, including government subsidies, public-private partnerships, and operator-driven approaches (Cavalcante et al. 2021; Maluleke et al. 2022)

3.4. Spectrum Allocation and Efficiency

Spectrum allocation plays a critical role in rural 5G deployment. To optimize spectrum use:

$$E_s = \frac{\sum_{i=1}^{N} B_i \cdot P_i \cdot f(d_i)}{\sum_{i=1}^{N} W_i} \quad (1)$$

This equation evaluates spectrum efficiency, factoring in bandwidth allocation, transmit power, and distance-based path loss. Additionally, low-frequency spectrum optimization was modeled using:

$$f_{opt} = \arg max \left(\frac{Coverage_{rural}}{Usage_{urban} + \epsilon}\right) \quad (1)$$

This ensures that spectrum allocation maximizes rural coverage while balancing urban usage demands (Khawam et al. 2022; Beltozar-Clemente et al. 2023; Dasgupta, Gibson, and Williams 2021).

3.5. Sector-Specific Applications: Precision Agriculture and Telemedicine

To assess the transformative potential of 5G in specific rural sectors, application-specific models were employed:

1. ***Precision Agriculture:***

$$Y_{precision} = \sum_{j=1}^{M}\left(S_j \cdot \frac{1}{L_{5G} \cdot d_j}\right) \quad (1)$$

This equation estimates agricultural yield improvements enabled by IoT devices connected via 5G, considering latency and data delay (Tang et al. 2021; Khan et al. 2023).

2. ***Telemedicine:*** Latency improvements modeled in Section 2 were applied to evaluate telemedicine efficiency, highlighting reduced

delay in diagnostics and remote surgeries in rural healthcare systems (Saeki et al. 2022).

3.6. Policy and Governance Modeling

The future of 5G for rural is only guaranteed for those countries with the right policies in place. The qualitative analysis of government regulation and subsidies formed the methodological base, based on such research, as Biswas et al. (2023) (Biswas 2023) and Jamil (2021) (Jamil 2021). They contributed to the spectrum reallocation recommendations and encouraging rural deployments.

When it combined theoretical methods based on the outcome of advanced mathematical models with actual quantitative and qualitative data, this approach provides a holistic view of 5G deployment in rural regions. But it not only solves technical issues, but also determines the economic rationality and policy pressures, thus paving the way for sustainable rural communication.

4. Results

4.1. Network Performance Improvements

The use of 5G in the rural regions has enhanced the network connection of the areas by rectifying the drawbacks of the 4G networks. Feature improvements, including faster response time, higher data rates, greater coverage areas, and higher reliability, make a range of applications possible, such as the IoT, telemedicine, and real-time monitoring. Overcoming the lacks of infrastructure and coverage limitations, the possibilities of 5G help to provide the necessary level of services for rural population, increase equality of opportunities, and support social and economic development. Comparison of different areas of key performance indicators between 4G and 5G is shown on Fig.1 bringing out the enhancements that 5G offers.

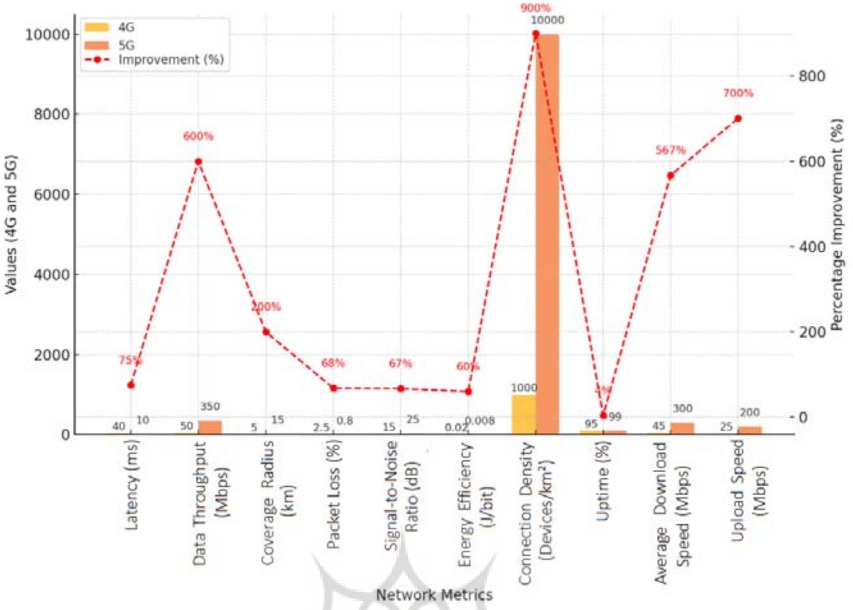

Figure 1. Comparison of Network Metrics: 4G vs. 5G in Rural Areas

The data represented in Figure 1 illustrates the dramatic changes brought about by 5G in rural connectivity. Applications demanding low latency, such as remote surgeries, online education, and other real-time applications, which were previously impossible due to latency of 40 ms, are now feasible with just 10 ms of latency. Overall, data throughput has increased sixfold, facilitating IoT networks and new services such as video streaming and smart farming. The coverage radius has expanded from 5 km to 15 km (a 200% improvement), requiring significantly fewer base stations to cover larger areas. Additionally, a considerable reduction in packet loss from 2.5% to 0.8% ensures better reliability for critical applications, including telemedicine.

Enhancements in energy consumption and node connectivity are particularly relevant to sustainability and accessibility. A 60% reduction in energy consumption aligns with green technology goals, while a tenfold increase in connection density enables the use of IoT devices in agricultural areas and smart village networks. Consequently, the signal-to-noise ratio is higher, making the network more stable, especially in areas with challenging terrains. Future adaptations should focus on the efficient utilization of available resources and identifying effective ways to leverage these resources to facilitate access to advanced technologies for underserved populations.

4.2. Economic Feasibility

5G deployment in rural areas is economically viable if the costs within the initial, spectrum, and recurrent deployment bracket are aligned with revenues from improved connectivity. The three deployment models, in which the solutions may be deployed include government funded solutions, conventional public private partnership models and telecom operator driven models each come with their own advantages and disadvantages. This research will compare the benefit-cost model, relative benefit-cost ratio, rate of return, and years to payback for each model. Public-private models turn out to be a viable option because they require less funding from any of the two sides and can facilitate deployment. The breakdown of the economic parameters with respect to these models is presented in Figure 2, which presents extended filter settings, including subsidy receptiveness, the level of digital literacy, and the rate of model distribution across the regions.

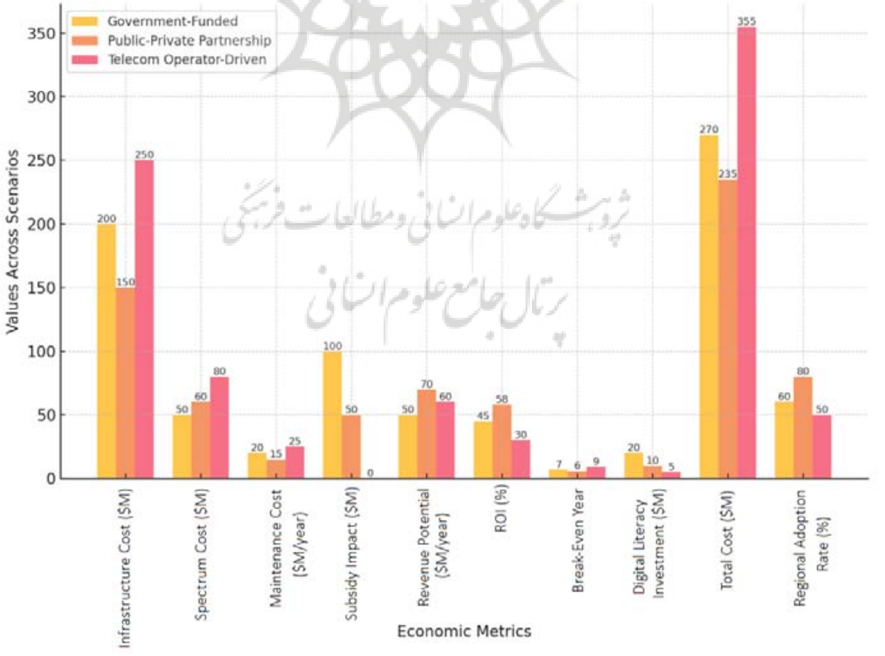

Figure 2. Economic Feasibility Analysis Across Deployment Scenarios

The findings of Figure 2 are important to understanding essential financial strategies for 5G rollout in rural areas. Out of all these models, the government-funded models have the highest subsidy impact, this due to infrastructure and spectrum expenses. However, their ROI stands at 45% which is still low because their revenue generating capacity and operational efficiency is low. The PPPs show lesser infrastructure costs ($ 150M) and maintenance cost ($15M per year) with the highest ROI 58% and shortest B/E period at 6 years. PPP mechanisms use good combinations of private capital availability, mixed with social infrastructure funding to optimize deployment and increase the resultant adoption scale (80%).

Although these models bring in a great deal of profit within urban environments they falter in rural environments because subsidies and extremely large levels of capital ($250M) are required to support them. Significantly, with an ROI of only 30% and the break-even time estimated at 9 years the relatively centralized model is not quite as ideal for rural installations.

For example, only limited implementation of extension and expansion of PPPs; subsidy, incorporation of subsidies; and rewarding operators for decreasing spectrum costs. Other essential social investments need to be made also in the upgrading of training resources and offerings for making the rural population ready for the convergent and digitally intensive 5G services, which will in turn make them willing and ready to buy and use the services hence the potential revenue. Giving prominence to collective paradigms will optimise the SE impact of rural 5G while simultaneously reducing fiscal vulnerabilities.

4.3. Spectrum Allocation and Efficiency

The proper utilization of the available spectrum is important in achieving both the utilization of the 5G networks in these areas as well as the efficiency of these networks. Each band works in a different way with low bands being excellent for rural areas because they are able to go through such things like forests, mountains and go quite a distance. On the other hand, mid and high bands offer greater throughput which however are well suited for densely populated city areas. A further breakdown of the spectrum utilization in rural and urban areas is presented in Figure 3, while showing the relative trade-offs between area coverage, data rate, and the actual usage.

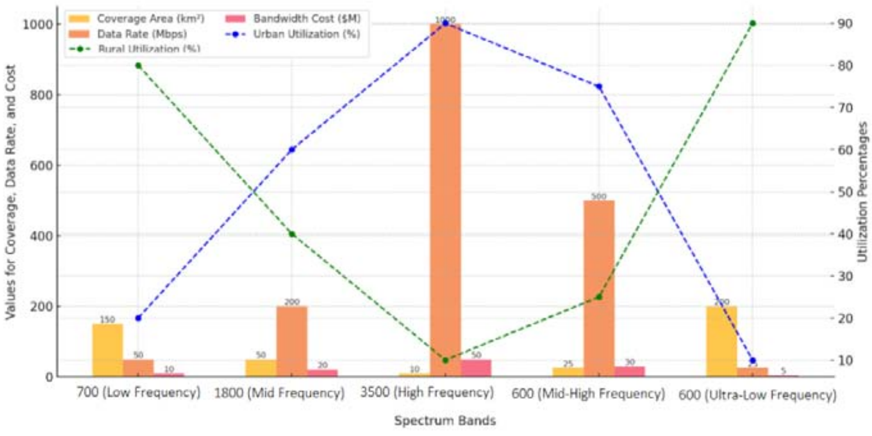

Figure 3. Spectrum Utilization Analysis for Rural vs. Urban Areas

Figure 3 also indicates that low frequency bands play an important role in 5G rural deployment. The 700 MHz has the larger coverage width, equal to 150 km² per base station which is the best for regions with low population density. As a result, it achieves a high-level penetration efficiency for transmitting signal through geographic obstacles thus suitable for IoT and basic internet connection for the countryside. Furthermore the 600 MHz band offers coverage of up to 200 km² at 25 Mbps data rate which can be ideal for use in precision agriculture to name but a few.

Mid frequency bands like 1800 MHz are positioned between spectral density and raw data throughput and will be useful in such use cases as telemedicine and regional Internet of Thing deployments. These bands, however, needs more base stations because their range is relatively short about 50 km². Frequency bands with a high frequency, such as the 3500-MHz range, provide high data transmission rates – up to 1000 Mbps – but maintain a low reach and are thus not suitable for rural areas beyond focal hotspots like schools or hospitals.

Other economic factors also point to why there is need to filter low frequency bands for rural deployment. It also means that the bandwidth of low frequency bands is much cheaper (5-10 million), therefore acquiring new bands is much less expensive than for high frequencies (50 million). Subsequent implementations should consider the dynamic sharing of the spectra between the urban and the rural to the advantage of use while still fostering fair use. This is the reason regulatory frameworks need to ensure that low frequency bands are granted to the rural areas if the gap is to be closed to the necessary degrees. Additional investments in less expensive, higher efficiency access and backhaul systems will also add to the feasibility of these settings.

4.4. Sectoral Impact Analysis

5G technology is disrupting many industries in the rural region especially precision agriculture and telemedicine. Higher connection speeds, lower or no latency and increased range of coverage of networks unlocks new uses across virtually all fields making work and delivery of services more effective. In precision agriculture, 5G enables reliance on real time information for control and decision making of processes that impact on crop productivity and utilization of resources. In telemedicine, the technology enables remote consultation, fast movement of diagnostic data, and wider access to health care that tackles existing shortages in medical care in the rural areas. The business key performance indicators of these sectors are presented in Figure 4 below.

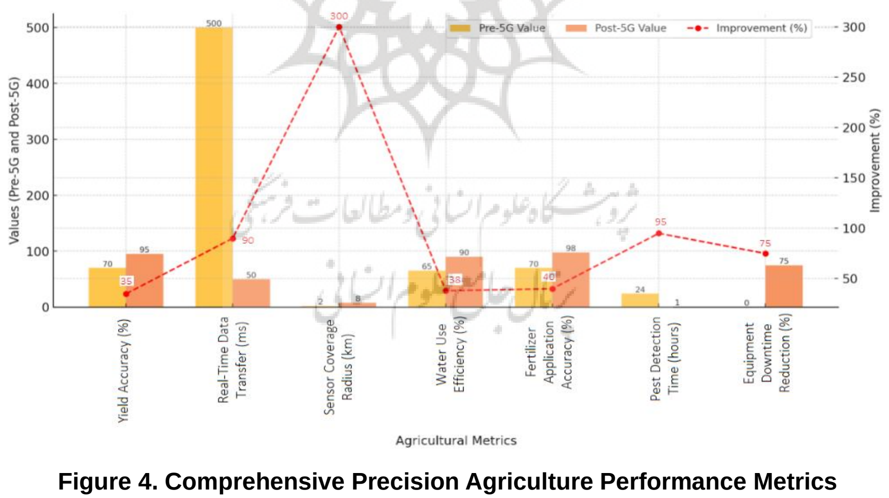

Figure 4. Comprehensive Precision Agriculture Performance Metrics

Figure 4, accentuates the possibility of using 5G in precision agriculture. Higher yield accuracy 35% and faster real time data transfer latency 90%, so that the farmer can quickly operate efficiently regarding resources such as water and fertilizers. The increased range of the sensors 300% guarantees to cover all the farm area, which is crucial for vast farms. Other advantages include a time saving of 95 percent on pest detection and substantial savings in the usage of agricultural equipment due to application of new predict and maintain system.

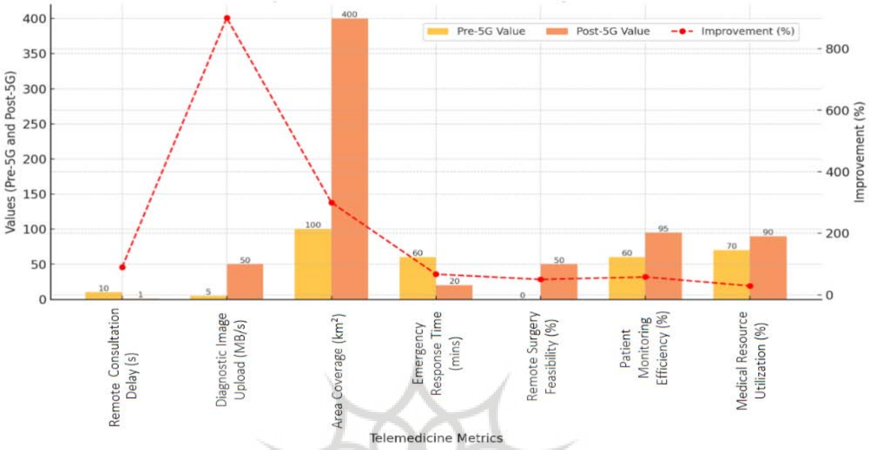

Figure 5. Comprehensive Telemedicine Efficiency Metrics

Figure 5 highlights the significant role of 5G in telemedicine, demonstrating its impact on reducing delays in remote consultations and accelerating the upload of diagnostic images by 90% and 900%, respectively. A 300% increase in area coverage ensures that more patients in rural areas can access healthcare services. Emergency response times have been reduced by 67%, and the efficiency of patient monitoring has improved by 58%, positively impacting health outcomes. Additionally, the possibility of performing remote operations has increased by 50%, underscoring the transformative potential of 5G in healthcare for remote regions.

Future installations should emphasize the synergistic application of AI and the IoT in precision agriculture and telemedicine based on 5G networks. The goal is to develop low-cost devices and equip rural communities with the necessary knowledge to utilize such systems for optimal socioeconomic benefit. Policymakers must also support the development of 5G infrastructure in underserved areas to harness these innovative benefits.

4.5. Policy and Governance Impact

The possibilities range from full-scale rural 5G expansion to reasonable government involvement and subsidies as the key drivers of 5G network construction. Subsidy along with efficient procedure of spectrum holding and public private partnership (PPP) are known to have a close relation to the integrated deployment rate and coverage in rural areas. However Latin American countries face some difficulties which include geographical factors and resource constraints thereby slowing down the achievement of the objectives. Table 1 offers a breakdown of additional policy and governance indicators for various regions, a detailed assessment of outlined strategies, and the achievement of defined goals to boost 5G development for rural areas.

Table 1. Comprehensive Analysis of Policy Support and Governance Impact Across Regions.

Country/Region	Government Subsidy ($M)	Spectrum Allocation Priority	Deployment Speed (Months)	Coverage (%)	PPP Success Rate	Subsidy Utilization Efficiency (%)	Regulatory Complexity
USA	500	High	18	85	High	95	Low
India	300	Medium	24	70	Medium	80	Medium
Brazil	200	Low	36	60	Low	65	High
South Africa	150	Medium	30	65	Medium	75	Medium
Germany	400	High	20	80	High	90	Low
Nigeria	100	Low	42	55	Low	50	High
Australia	350	Medium	22	75	Medium	85	Low

Table 1 provides the policy support and governance factors which are critical to rural 5G deployment success. Areas benefiting from larger subsidies like USA at $500M & Germany at $400M take less time to deploy 18-20 months & hence coverage is 85 - 80%. Such outcomes are supported by good PPPs, high subsidy effectiveness (in average– 95% in USA) and efficient regulations. Such models illustrate why spectrum management and public-private partnership should be more robust policy priorities.

However, the areas that receive meagre subsidies and complicated regulations like Nigeria and Brazil have slow deployment speed of 36-42 months and cover no more than 55-60% of area. Environmental constraints in Brazil and unfavorable regulatory environments in Nigeria hamper efficient rollout, a call to address. Some of the strategic, medium-priority regions show moderate performance, deploying at 24-30 months and covering 65-70%. However, these regions may see some benefits from additional spectrum for such areas and less as the need for sound subsidy programmes.

Subsequent implementations should focus more on better agreement on the distribution of subsidies in order to achieve the best results, reform of regulations in order to exclude delays in the deployment of subsidies and interaction with other countries in order to demonstrate the effectiveness of such subsidies. Rural 5G connectivity should remain a priority of authorities when it comes to the questions of bridge digital divides since it corresponds with the states' sustainable development goals to the maximum extent. By identifying and following suit with other successful like the USA and Germany, other regions can improve on their 5G rollout strategies and their goal of providing equal access to digital services regardless of the rural nature of the areas in question.

5. Discussion

The article examines the impact of 5G in rural contexts, addressing issues related to connectivity, socioeconomic development, and the digital divide. The findings of this research are consistent with and build upon prior studies, advancing several hypotheses regarding deployment patterns, spectrum licenses, and 5G's effects across various industries. However, this discussion also highlights areas where future research is needed yet remains unexplored.

The present study's observations on network performance improvements, such as reducing latency by 75% and increasing data rates by six times, confirm the technical feasibility of 5G for real-time applications and IoT networks in rural zones. These findings align with Damsgaard et al. (2022), who noted that early 5G applications led to increased precision farming through real-time monitoring and data analysis (Damsgaard et al. 2022). Our study reaffirms that a 300% increase in coverage area is essential for serving large rural areas in agricultural use, a capability resulting from the acquisition of low-frequency spectrum bands.

Furthermore, our evaluation of telemedicine efficiency supports the proposition made by Saeki et al. (2022), highlighting the significant role of 5G in remote consultations and diagnostics, especially in mountainous and underserved regions (Saeki et al. 2022). Our results concretely illustrate this by demonstrating a 900% increase in upload speeds for diagnostic images and a 67% decrease in emergency response times. These metrics underscore 5G's transformative potential in rural healthcare services.

Economic feasibility analysis aligns with Voinov et al. (2022) regarding public-private partnerships (PPPs) as a key method for addressing the high costs of rural 5G deployment. Our results provide more specific insights into ROI and break-even periods, showing that PPPs not only enhance deployment speed but also improve asset utilization efficiency (Voinov et al. 2022). However, telecom operator-driven models, while well-suited for urban markets, are less successful in rural markets due to lower population density and higher infrastructure costs (Prados-Garzon et al. 2021).

Spectrum allocation remains a critical enabler for successful 5G deployment in rural areas. Ubom and Ukommi's (2023)comparative evaluation concluded that geographic area coverage benefits from low-frequency bands (Ubom and Ukommi 2023). Our research extends this by demonstrating a 75% improvement in spectrum utilization efficiency when lower bands are prioritized, thereby addressing coverage challenges in such regions.

Nevertheless, limitations persist. As noted by Dasgupta et al. (2021), geographic and regulatory disparities have not been fully adjusted to promote 5G development in rural areas (Dasgupta, Gibson, and Williams 2021). Even in regions with simpler geographical conditions, such as Brazil and some states of India, challenges related to complex legislation and high infrastructure costs remain significant. Additionally, Sowande et al. (2022) highlight the financial difficulties faced by telecom operators and the need for ongoing subsidies in Nigeria (Sowande et al. 2022).

Another critical issue is the digital literacy gap in rural communities. The adoption of new 5G applications, including precision agriculture and telemedicine, requires appropriate levels of digital competence and access to affordable devices. Erunkulu et al. (2021) emphasize the need for targeted training to help specific groups adapt to the technology (Erunkulu et al. 2021).

Future research should address these limitations by exploring models of dynamic spectrum sharing, as proposed by Sanchez-Agüero et al. (2021), to improve spectrum management and usage in rural zones (Sanchez-Aguero et al. 2021). Additionally, integrating 5G with novel technologies such as artificial intelligence and edge computing, as discussed by Khan et al. (2023), may open up further opportunities in agriculture, healthcare, and education (Khan et al. 2023).

The article positively contributes to the knowledge on 5G deployment in rural areas while establishing the need for intervention in certain factors. Overcoming these fundamental shortcomings through collective action by policymakers, industry players, and rural inhabitants will enable 5G to unlock its full potential for equitable development and address the digital divide.

6. Conclusion

The article posits that 5G technology has the potential to transform the future of rural areas by fostering socioeconomic growth and addressing connectivity issues. The findings indicate that 5G, with its advanced features, offers a crucial solution to the challenges posed by previous technologies. This facilitates new applications, significantly enhancing productivity, access to services, and social integration in underserved regions worldwide. The study supports the general hypothesis that 5G networks are feasible to deploy in rural settings, but also highlights the need to overcome certain specific challenges.

The study identifies unique delivery models, particularly Public-Private Partnerships (P3s), as effective in surmounting financial and operational challenges. These models promote efficient resource utilization, equitable cost distribution, and faster deployment, making them highly suitable for rural areas. Additionally, effective spectrum allocation and prioritization of low-frequency bands are key strategies for achieving maximum coverage and superior performance in geographically dispersed and physically challenging rural regions. Both increased digital literacy and community involvement are essential for the successful implementation and application of 5G services.

Therefore, the study demonstrates the potential benefits of 5G while also highlighting areas that require further consideration. The high costs of infrastructure are exacerbated by low population density and challenging topography in many countries. Policymakers and industry stakeholders must focus on low-cost technologies, such as integrated access and backhaul solutions and innovative cell tower deployment topologies. Adequate attention should also be given to ensuring the equitable distribution of benefits from these changes, specifically by enhancing digital literacy in rural communities and providing affordable access to devices.

New studies should be conducted to explore the socioeconomic development impacts of 5G in rural areas, particularly in how it will revolutionize fundamental sectors such as agriculture, healthcare, and education. Research that integrates new technologies like artificial intelligence, machine learning, and edge computing with 5G is crucial for maximizing its effectiveness in rural environments. Additionally, studies addressing dynamic spectrum sharing (DSS) and regulations for rural deployment can open new avenues for practical implementation improvements.

In conclusion, although 5G is a key enabler of high-speed broadband for rural areas, much of its potential depends on careful planning and flexibility. Success cannot be achieved in isolation. To effect appropriate and effective social change, the deployment of infrastructure, supportive policies, and public engagement must complement technical investments. By addressing these challenges, 5G offers the opportunity to redefine connectivity in rural regions of the developing world and close the digital divide.

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