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EDITED BY
Dimitris Varoutas,
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REVIEWED BY
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Northumbria University, United Kingdom
Nikolaos Nomikos,
National and Kapodistrian University of Athens, Greece
Muhtahir Oloyede,
University of Ilorin, Nigeria

*CORRESPONDENCE
Shruthi Koratagere Anantha Kumar
✉ k.a.shruthi@strath.ac.uk

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Techno-economic assessment of 5G infrastructure sharing business models in rural areas

Shruthi Koratagere Anantha Kumar[1,2]* and Edward J. Oughton[2,3]

[1]StrathSDR lab, Department of Electronics and Electrical Engineering, University of Strathclyde, Glasgow, United Kingdom, [2]Department of Geography & Geoinformation Science Department, George Mason University, Fairfax, VA, United States, [3]Environmental Change Institute, University of Oxford, Oxford, United Kingdom

How cost-efficient are potential infrastructure sharing business models for the 5G era (and beyond)? This significant question needs to be addressed if we are to deliver universal affordable broadband in line with Target 9.1 of the UN Sustainable Development Goals. Although almost two-thirds of the global population is now connected, many users still lack access to high-speed and reliable broadband connectivity. Indeed, some of the largest connectivity issues are associated with those living in areas of low economic viability. Consequently, this assessment evaluates the cost implications of different infrastructure sharing business models using a techno-economic assessment framework. The results indicate that a rural 5G neutral host network (NHN) strategy helps to reduce total cost between 10 and 50% compared with other sharing strategies. We also find that, compared to a baseline strategy with *No Sharing*, the net present value of rural 5G sharing strategies can earn between 30 and 90% more profit. The network upgrades to 5G using various sharing strategies are most sensitive to changes in the average revenue per user, the adoption rate, and the amount of existing site infrastructure. For example, the results from this study show that a 20% variation in demand revenue is estimated to increase the net present value of the sharing strategies by 2–5 times compared to the *No Sharing* strategy. Similarly, a 10% increase in existing infrastructure lowers the net present value by 8–30%. The infrastructure sharing strategies outlined in this study have the potential to enhance network viability while bridging the digital divide in remote and rural locations.

KEYWORDS

5G, network slicing, network upgrade, rural connectivity, techno-economic feasibility, wireless and mobile technology

1. Introduction

Recent advancements in wireless broadband connectivity have greatly benefited societies and the wider global economy. Several facets of human life, particularly during the COVID pandemic, have benefited from broadband connectivity (Grijpink et al., 2020; Holmes and Burgess, 2020). Indeed, despite almost two-thirds of the world's population now being connected to the Internet, many users are still under-served and experience poor broadband connectivity (ITU, 2021, 2022). More often, it is the rural and remote areas that experience poor broadband services, if coverage is even offered at all. Rural Internet connectivity remains limited for various reasons including monetary, policy, regulatory, and technological constraints (Frias et al., 2020; Shruthi et al., 2021). Thus, building wireless broadband infrastructure is a pressing economic development issue (Freeman et al., 2016; Oughton et al., 2021; Chen et al., 2023). Importantly, wireless broadband can have a relatively low investment cost compared to other broadband communications technologies (e.g., fixed broadband networks) (Samdanis et al., 2016; Yaacoub and Alouini, 2020). However, this needs to be supported by evidence exploring cost-efficient ways to invest in the limited financial capital available, ensuring that the right technologies and business models are selected to maximize societal benefits (Luong et al., 2019; Banda et al., 2022).

The fifth generation (5G) broadband cellular network is now being widely deployed around the world, predominantly in urban and sub-urban areas where the population density is very high (Blackman and Forge, 2019). The key use cases of 5G include enhanced mobile broadband (eMBB), ultra-reliable and low latency communications (uRLLC), and massive machine type communications (mMTC) (Al-Dulaimi et al., 2018; Saarnisaari et al., 2020). However, in low-demand locations, it can be difficult for 5G to be economically viable using traditional deployment strategies due to the cost involved in meeting the demands such as high capacity and low latency performance requirements (Chiaraviglio et al., 2017; Jiang et al., 2021). One emerging technology enabled by 5G is "network slicing," which supports network virtualization and consists of independent logical networks, called slices (Ghosh et al., 2019). Slicing technology can support the deployment of shared neutral host networks (NHN) where multiple tenants/operators can co-exist on the same physical network but different virtual networks (Gomes et al., 2021). The survey on the need for sharing the telecommunication infrastructure, especially at the edge is explored in Lehr and Stocker (2023). This research brings out the need for supportive policies for end-user infrastructure sharing, especially to meet 5G performance requirements.

Currently, 5G network sharing strategies can be classified into 4 broad types: *No Sharing*, *Passive Sharing*, *Active Sharing*, and *NHN* (GSMA, 2019a). In *No Sharing*, each operator deploys their own independent network, whereas in *Passive Sharing*, multiple operators share non-electronic components, such as towers and site compounds. Alternatively, in *Active Sharing*, the operators share all passive and electronic telecommunication components, except for different spectrum bands and the network core. Finally, in a *NHN* the operators share all passive and active components between themselves and other potential slice tenants.

A recent techno-economic assessment has indicated that a 5G business case that involves infrastructure sharing can lead to an increase in operator revenue, resulting from more efficient usage of infrastructure (Schneir et al., 2019; Walia et al., 2019; Allawi et al., 2022), motivating the study of this topic. Advances in 5G techno-economic approaches have been attempting to better integrate more realistic aspects of the underlying infrastructure in engineering-economic evaluation (Smail and Weijia, 2017). Indeed, techno-economic studies often focus entirely on greenfield deployments, excluding the fact that there might already be existing infrastructure in rural locations providing basic connectivity. For example, many rural areas may have a 2G cellular infrastructure deployed, with those assets still repaying the debt used to finance the existing construction (Smail and Weijia, 2017; Kusuma and Suryanegara, 2019). In such a circumstance, where the rural community has an existing basic telecommunications network, the key questions are:

1. How should the network be upgraded to a future cellular generation (such as 5G or beyond)?
2. What level of sharing might deliver the best outcomes for the operator, users, and wider society?

Consequently, the research in this paper explores future infrastructure sharing strategies for rural areas, predicated on the notion that most locations already have at least some existing infrastructure assets providing basic connectivity (for example, 2G, 3G, or 4G). The key contribution is the estimation of quantitative viability metrics and sensitivity analysis for four different infrastructure sharing strategies to address the digital divide, especially in rural and remote areas. Given each rural area faces a unique set of challenges due to its geographic location, there is a need to investigate solutions for generic rural areas while taking into account as many variables as practical.

The key aim of this study is to analyze the cost of minimizing the digital divide over the next decade, for users within the reach of existing infrastructure. Thus, providing the higher quality of service (QoS) offered by 5G compared to legacy technologies. Indeed, the initial goal of SDG 9.1 is to build sustainable and inclusive infrastructure, especially as availability is essential to increase community adoption and digital literacy. Over the long term, as demand for wireless broadband grows in rural areas, operators may need to later pivot to other infrastructure strategies, for example, by densifying the network with small cells to serve higher traffic quantities.

This paper is organized as follows. Firstly, Section II provides an overview of the literature on different 5G network sharing strategies. The method is then presented in Section III, while Section IV presents the results. Finally, Section V discusses the advantages along with any challenges of the business models appraised, while Section VI provides conclusions.

2. Literature review

Generally, there are two main types of possible wireless broadband infrastructure approaches in rural areas:

- **Greenfield** deployment refers to a scenario where there is no form of existing broadband infrastructure in place, therefore requiring an operator to build network assets from scratch. While capital intensive to build greenfield assets, the network operator does have flexibility in what to deploy as no legacy systems are present. However, decisions need to select the most suitable and cost-efficient technology to deploy to support their requirements (ITU, 2022; Simon, 2022).
- **Brownfield** deployment refers to a scenario where some form of broadband technology is deployed. Hence, the network operator needs to upgrade the existing radio equipment and any other supporting infrastructure. While recent ITU data might demonstrate that ≥70% of the global population is now online, many of these users may lack decent high-speed Internet (ITU, 2022)

Assessments indicate that the majority of global people already live within reach of existing mobile infrastructure (Shruthi et al., 2021; Oughton, 2023). However, huge coverage and capacity problems exist due to users being *under-served*. Therefore, upgrading existing infrastructure is becoming a major focal point for overcoming the digital divide over the next decade (Commission, 2022). This will largely involve upgrading legacy 2G/3G systems to support newer cellular generations, such as enhanced 4G/5G mobile broadband. It is possible for a single 4G site to serve up to 20,000 subscribers, with up to 2,000 active devices (Parkvall, 2023). In theory, a 5G site is expected to support up to a million devices (Hossain and Hasan, 2015).

Many studies have investigated the costs of deploying and operating a nationwide 5G network and concluded that changes to rural telecommunication business models will drive enhanced connectivity (Firli et al., 2015; Jha and Saha, 2019; Kusuma and Suryanegara, 2019). Furthermore, a key observation is that MNOs take a long time to deploy near-ubiquitous coverage because the provisioning of telecommunication services is a costly procedure with a low or negative return on investment (ROI) in rural or remote rural areas (Yaghoubi et al., 2018; Cano et al., 2019). Hence, there is a need to explore different network-sharing strategies to minimize the digital divide, with the ambition of bringing the next generation of cellular technology to rural areas (e.g., 5G). Infrastructure sharing at any level eases the process of network deployment and opens up newer revenue streams (Meddour et al., 2011). The key advantage of shared infrastructure is the increased resource utilization and network capacity as a result of infrastructure along with spectrum sharing among the tenants on the network (Kliks et al., 2018; Schneir et al., 2019).

2.1. Technological aspects

In network slicing, each slice can be tailored to support the use case to be served with distinctive 5G key performance indicators (KPIs), such as for latency, data rates, error rates, minimum resource allocation, etc., (Series, 2017; Zhang, 2019). The key technology enablers for network slicing are software-defined networking (SDN), and network function virtualization (NFV), which provide the lifecycle management of network slices by dynamically instantiating, modifying, and terminating the slices as per the end-user requirements (Afolabi et al., 2018). Network slicing is integrated with multi-access edge computing (MEC) to combine the benefits offered by SDN, NFV, and service function chaining (SFC) (Mach and Becvar, 2017). This integration helps to overcome the static resource allocation issue and convert it to dynamic resource allocation while still satisfying the network performance requirements for the slice users. The key benefits offered by this integration are dynamicity and efficient use of resources (Filali et al., 2020). This technique of capacity partitioning helps reduce the overall capital expenditure (CAPEX) and operational expenditure (OPEX) while leveraging the benefits of dynamic resource sharing and allocation (Foukas et al., 2017; Shen et al., 2020).

The working definition of an *NHN* is "*a self-contained cellular network deployed by a service provider that builds and operates an integrated technology platform that is solely for sharing purposes*" (Badmus et al., 2019). This helps to reduce the duplication of resources while providing services in the same area (Matinmikko-Blue and Latva-aho, 2017). A *NHN* approach allows a single physical infrastructure to be built for multiple operators acting as tenants and could use shared spectrum bands for its operation. A survey of ongoing research on neutral hosts, especially using 5G suggests that an NHN approach can enhance capacity and coverage, especially in dense small cell deployments, with the right policies in place that encourage incumbent operators to participate (Walia et al., 2017; Maeng et al., 2020; Lähteenmäki, 2021). The potential tenants could be mobile network operators (MNOs) (Matinmikko et al., 2017; Oladejo and Falowo, 2017; Colman-Meixner et al., 2019), Internet service providers (ISPs) (Pries et al., 2016; Frank et al., 2022), communication providers (CP) (Cavalcante et al., 2021), hospitals, and other private networks (Giambene et al., 2019; Zhang et al., 2019). In a *NHN* model, each slice tenant has an end-to-end 5G virtual network with all components of a typical wireless network (Zhang et al., 2017; Kaloxylos, 2018). Indeed, many researchers have examined the challenges associated with 5G network slicing. For example, this includes evaluating different business models, deployment options, and techno-economic feasibility levels, with an approach based on an NHN using shared spectrum, being the most cost-efficient option (Ramasetty and Masilamani, 2019; Quadri et al., 2020; Bajracharya et al., 2022). As network slicing and a NHN approach encourage an open network with dynamic resource allocation, this idea is being expanded to 6G where network slicing is one of its key enablers (Cao et al., 2022).

Infrastructure sharing may also include spectrum sharing among operators, hence necessitating the need to share both underlying infrastructure costs and spectrum licensing costs for a site across the potential tenants (Meddour et al., 2011). As national operators upgrade the network, the infrastructure will use their nationally licensed or locally shared spectrum bands for operations (Matinmikko-Blue et al., 2018, 2019). The ongoing research on NHNs helps to understand the various aspects of 5G network sharing strategies, especially in terms of technology, spectrum, security, policies, regulations, and techno-economic feasibility (Khodashenas et al., 2016; Tseliou et al., 2019; Wang et al., 2019).

2.2. Rural 5G trials

Rural 5G networks can be used for a variety of purposes. For example, eMBB applications that require high bandwidth and data rates (video/voice calling, remote video monitoring, remote health care, wide-area industrial automation, video streaming, e-governance, e-commerce, and online learning). Moreover, uRLLC applications that require very low latency and low data volume (disaster management and response, control of critical services, and machine-to-machine communication). Additionally, mMTC applications that require low power and data volume (sensors and IoT devices with limitless data transmission). These applications enable the deployment of 5G in rural areas, potentially generating multiple revenue streams for infrastructure providers (InP) and ensuring network viability.

To viably deliver affordable rural connectivity there are several challenges that need to be overcome. Many issues are technological, but there are also challenges pertaining to adoption, revenue generation, and business models (Noll et al., 2018; Yusuf et al., 2021). For example, to address the digital divide, many technologies have been trialed and tested to assess their suitability, including long range Wi-Fi, 4G, unmanned aerial vehicles (UAVs), satellite systems, balloons, and TV whitespace (TVWS) (Osoro et al., 2023). However, the common shortcomings of these technologies include network performance during changing operating conditions, scalability, user roaming, high-speed data rates, reliability, data security, latency, and other performance criteria for different telecommunication operators (Fourati et al., 2022; Kumar et al., 2022; Randell-Moon and Hynes, 2022).

Moreover, to address the issue of rural connectivity, researchers have begun testing the suitability of 5G network designs to address the needs of rural use cases. Indeed, a rural 5G pilot trial that uses IEEE P2061 5G standards develops an architecture designed to support low-cost rural broadband communication using a 5G NHN without network slicing and Wi-Fi (Khaturia et al., 2020). The proposed solution utilized macro-cells to support 5G access technologies, with backhaul connectivity relying on a TVWS link and the last-mile using wireless local area networks (WLAN) (Khaturia et al., 2020). In another report by GSMA, the authors encourage sharing to reduce the digital divide using a local service provider in rural areas (Handforth, 2019). The authors find the key to minimizing the coverage gap and connecting these locations at a reasonable cost is to lower network deployment and operational costs and find newer business models. It is also important to account for risks associated with the adoption of 5G, as this has a large impact on commercial viability. The use of spectrum sharing in local 5G networks deployed by the InP is explored in Perez Guirao et al. (2017), Anderson et al. (2020). These studies highlight the benefits and ease of spectrum sharing in 5G bands, especially at higher frequencies. In another pilot trial, the 3.5 GHz band using the GSM and TV broadcast tower sites in rural areas was used for long-range coverage to provide broadband services (Lun et al., 2019). The network was able to achieve good downlink data rates even near the cell edge, however, the uplink performance was inadequate.

Many studies were carried out to investigate the costs of deploying and operating a nationwide 5G network with a duration of 10 years in different countries (Oughton and Frias, 2018; Oughton et al., 2019a,b). The conclusion was that encouraging the correct policies, technology choices, and innovations in rural telecommunication business models will drive infrastructure deployment. Ultimately, MNOs require a long time to install near-universal coverage using conventional deployment strategies since, in remote or rural locations, providing telecommunications services is a costly option with a low or negative return on investment. As a result, the research in this paper examines 5G infrastructure sharing strategies as an alternative solution for providing broadband connectivity in rural areas.

2.3. Infrastructure sharing strategies

Figure 1 shows the possible upgrade sharing strategies for existing cellular sites to 5G involving many options, ranging from *No Sharing* to either *Passive Sharing*, *Active Sharing*, or a *NHN*.

Figure 1A shows the network architecture for a *No Sharing* strategy. In this approach, the incumbent MNO has full control over the network and its equipment from end-to-end. There is no competition over the QoS provided, as typically, this type of strategy has only one operator in a rural area. It will be expensive for another operator to deploy their infrastructure, especially in places with negative or poor ROI (Jeanjean, 2022).

Figure 1B shows the network architecture for a *Passive Sharing* strategy which involves sharing of backhaul, telecommunication sites, ducts, masts, towers, equipment rooms, and related power supplies, air conditioning, and security systems. The operators using this strategy would have to work toward the goal of reducing the overall cost and agree upon a common cell plan management and upgrade. The key challenge with this strategy is finding operators with similar goals in terms of deployment locations, desired site construction materials, tower heights, network protections, and backhaul capacity requirements (Oughton and Frias, 2018; Jeanjean, 2022).

Figure 1C shows the network architecture for an *Active Sharing* strategy. This business model involves sharing radios, base stations, backhaul, telecommunication sites, ducts, masts, towers, equipment rooms and related power supplies, air conditioning, and security systems. The spectrum bands are not shared, therefore, each operator uses their licensed bands. This method is preferred by operators who have long-term contractual agreements with each other, along with clearly defined agreements regarding operational conditions. The crucial factors affecting deployment include trust among competitors and the policies laid out by the national telecommunication regulator. The challenges with this strategy include making this a long-term commitment, network complexity, and the fact that each individual operator must relinquish their own independent decision-making e.g., for network upgrades. Similar pricing plans could act as a threat to disrupt operator cooperation (Frisanco et al., 2008).

Figure 1D shows the network architecture for a *NHN* strategy which involves the sharing of spectrum, core networks, radios, base stations, backhaul, telecommunication sites, ducts, masts, towers, equipment rooms, power supplies, air conditioning, and security systems. This method involves end-to-end network sharing (at all passive and active levels, including spectrum) among the slice tenants (Samdanis et al., 2016; Gomes et al., 2021; Jeanjean, 2022). Unlike the previously articulated sharing strategies, the potential operators would have a network agreement only with the 5G NHN infrastructure operator. This strategy also allows other potential slice tenants, and the operators, to co-exist on the network (Fernandez-Fernandez et al., 2021; Lappalainen and Rosenberg, 2022). In the final *NHN* strategy, all MNOs would lease slices from the incumbent and ideally provide services at all sites. The key challenges of this strategy are similar pricing plans and market strategies, a decline in infrastructure-based competition, management of dynamic resource allocation, and the security of data on each slice (Paglierani et al., 2020; Pápai et al., 2022). An

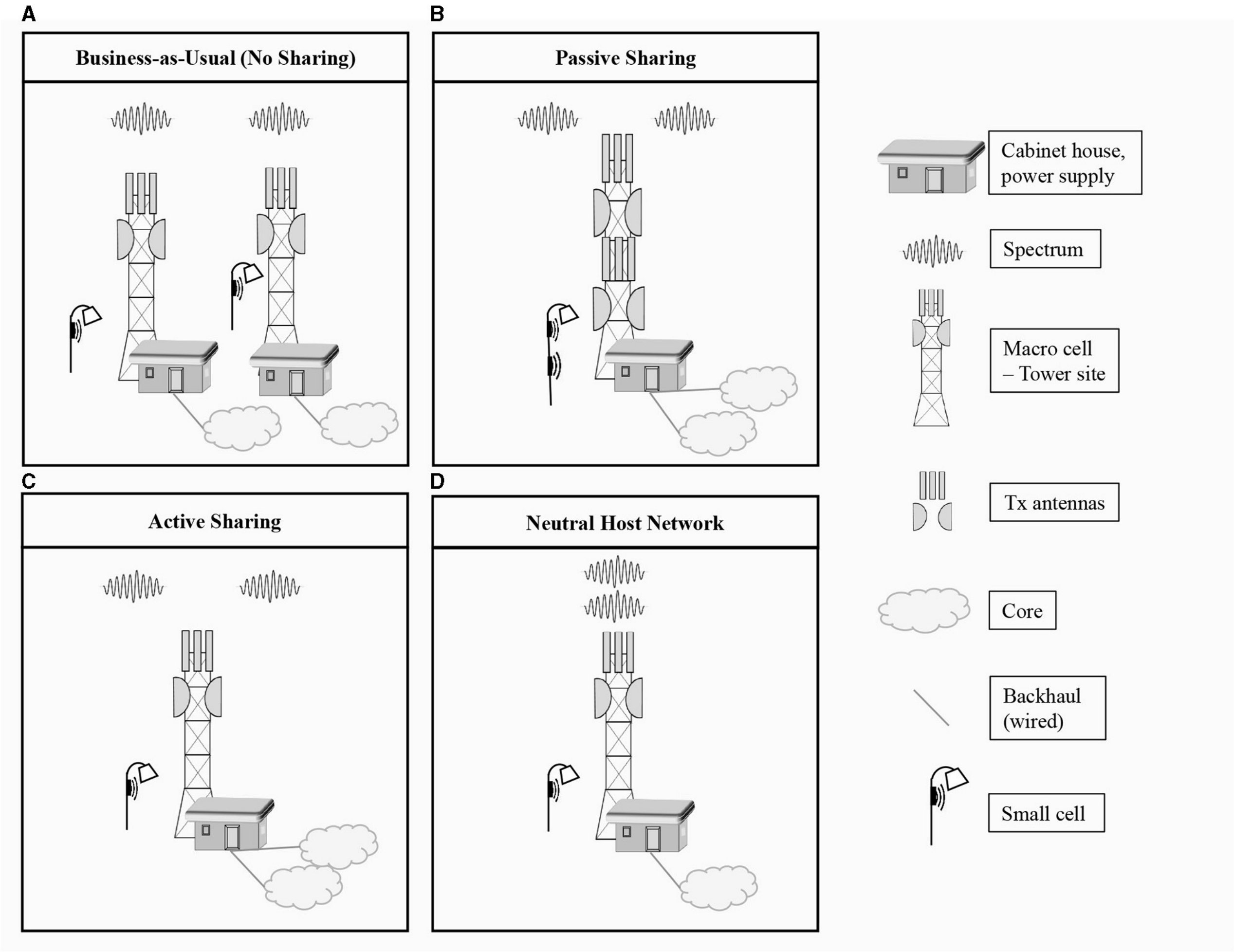

FIGURE 1
Network architecture of various sharing strategies of 5G upgrade: **(A)** no Sharing; **(B)** passive sharing; **(C)** active Sharing; **(D)** 5G NHN.

important aspect of a successful upgrade to a 5G network using a *NHN* model is cooperation among the slice tenants and their corresponding resource allocation schemes (Sanguanpuak et al., 2019; Tran and Le, 2020). These barriers and obstacles to adopting the NHN strategy should be explored as future work to stimulate discussions among stakeholders. The widespread usage of this technology lies in the slicing capabilities offered by the network, and associated security aspects (Raza et al., 2019; Psyrris et al., 2021; Sciancalepore et al., 2022).

2.4. Business models and TEA framework

A preferable first option for operators may be *No Sharing*, as it would enable absolute control over network capacity resources (GSMA, 2019b; Jeanjean, 2022). However, this is not always economically viable because of the required investment, existing debt, and potential revenue. Indeed, operators in many markets worldwide have been experiencing static or declining profits while also being saddled with sizeable existing debt payments (van Kranenburg and Hagedoorn, 2008; Veligura et al., 2020; Sahoo and Sahoo, 2022). Thus, there has been a need for MNOs to seek newer 5G revenue streams, as explored in many research papers (Oughton and Russell, 2020; Bajracharya et al., 2022). Therefore, operators may choose to explore other sharing strategies (Frisanco et al., 2008; Oughton et al., 2022b).

With a weak economic outlook for MNOs but also the need to invest in new infrastructure, the willingness for operators to share assets and spectrum bands is increasing (Matinmikko et al., 2017; Oproiu et al., 2018; Colman-Meixner et al., 2019). The MNO business models utilizing 5G network sharing strategies have been found to be cost-efficient in different deployment scenarios (Atherley, 2020; Psyrris et al., 2021; Kenechi and Stefano, 2022). In the *NHN* case, the approach supports MNOs, private networks, ISPs, and other potential tenants to co-exist without interfering with each other's operations. Studies have shown that horizontal slices support use cases while vertical slices support multi-tenancy (Kaloxylos, 2018; Lee et al., 2019; Shruthi et al., 2021).

In recent years, techno-economic assessment (TEA) frameworks have been trying to include additional simulation parameters which better match real-world deployment conditions (Bouras et al., 2020; Oughton and Russell, 2020; Frank et al.,

TABLE 1 Techno-economic assessment.

References	Adopted methods	Parameters	Findings
Oughton and Russell (2020)	Spatio-temporal simulation modeling approach	Topography, demand, existing sites, cost, NPV, cost-saving strategies	The results show that upgrading existing sites to 5G and adding small-cells, would meet eMBB demand in urban areas.
Frank et al. (2022)	Techno-economic model	Demand, adoption prediction, cost, NPV, cost-saving strategies	The results show that using 5G NFV and NHN results in cost savings of at least 53% for industrial verticals.
Bouras et al. (2020)	Techno-economic assessment	Cost, indoor user requirements from 5G, interest rate	Feasibility and sensitivity analysis was explored for using 5G NFV for distributed antenna systems (DAS) and multiple input multiple out (MIMO) for indoor coverage. The study shows the approach is energy- and cost-efficient.
Oughton et al. (2021)	Open-source techno-economic assessment	Demand, supply, least cost network upgrade strategies, subsidies	Independent analysis of the strategies for MNOs for deploying 4G and 5G would require supportive policies, especially in terms of spectrum and backhaul to minimize the deployment cost.
Pryce (2022)	Policy analysis	Topography, spectrum sharing, NHN	The study shows the need for supportive spectrum policies and neutral host service providers to minimize the digital divide.
Sahoo and Sahoo (2022)	Malmquist total factor productivity index, panel generalized method of moment	Productivity, efficiency, energy, cost	Suggests the key factors affecting the telecommunication industry include profit, demand and advertisement. However, the industry is also negatively impacted by the firm debt ratio.
Shruthi et al. (2021)	Techno-economic assessment, sensitivity analysis	Demand, supply, cost, NPV, sensitive factors	The study shows that 5G NHN could be a potential solution for greenfield rural 5G deployments in locations with no prior telecommunication services.
Ioannou et al. (2020)	Techno-economic assessment, cash flows, DCF analysis, risk and sensitivity analysis	Cost, population density, competition, policy scenarios	The research in this study shows that 4G FWA deployments in rural areas are cost-efficient and could lower upgrade costs when migrating to 5G.
Oughton and Lehr (2022)	Techno-economic models	Future uncertainties, cost, engineering specifications, data visualization	Future TEA research should ensure model uncertainty is fully quantified, and portrayed for other researchers to understand parameter variability.
Walia et al. (2017)	Techno-economic assessment	Cost, number of small cells	The results show that 4G/5G femto cells provide better coverage and also are cost efficient compared to Wi-Fi.

2022; Schneir et al., 2023). Table 1 summarizes the different TEA models and their adopted methods, parameters, and the key findings of those studies. Consumer and government pressure to provide enhanced telecommunication infrastructure, with higher data throughput per user and better overall QoS, has been encouraging operators to upgrade their networks and expand coverage (Oughton et al., 2021; Pryce, 2022). Many of the studies presented in Table 1 focus on urban deployment scenarios or specific vertical use cases. Hence, there is a need to define a generic theoretical framework of assessment to enable the techno-economic feasibility evaluation of infrastructure sharing strategies and business model options.

Typically, each rural location has a unique set of network feasibility conditions. These depend upon a range of factors, including population density, per capita income, the adoption rate, local business composition, fiber backhaul availability, and existing competition among operators (Walia et al., 2017; Kumar et al., 2022; UN, 2022). As a result, in this study, we explore the suitability and the techno-economic viability of different rural network sharing strategies. We also examine how the input parameters of the developed model affect the feasibility of 5G infrastructure sharing.

3. Method

This section will detail a method for answering the research question. We focus on solutions with sustainable data rates higher than 30 Mbps per user (Schneir and Xiong, 2016; Ioannou et al.,

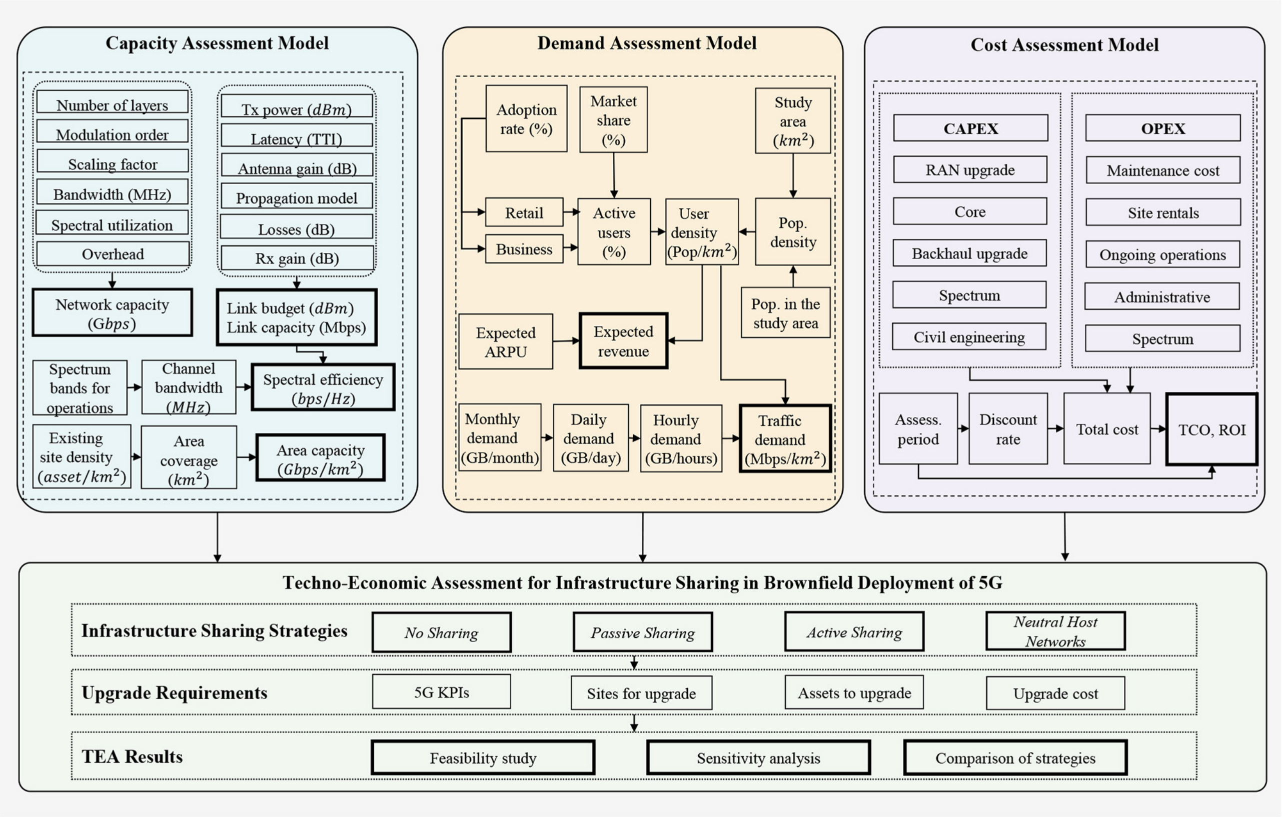

FIGURE 2
Techno-economic modeling for the assessment of 5G upgrade using different sharing strategies.

2020; ITU, 2021), for low-frequency bands (<1GHz) and mid-frequency bands (1–6 GHz). For this study, the existing backhaul could either be wireless or wired technology that may also require upgrading.

Techno-economic assessment can help determine the technical and economic requirements for the profitability of successful infrastructure deployment strategies (Oughton and Lehr, 2022). Thus, Figure 2 illustrates the techno-economic modeling framework used in this study for understanding the business case feasibility of 5G rural upgrades via different infrastructure sharing business models. The model takes inputs capturing future traffic demand, existing infrastructure assets, and network parameters and estimates the number of necessary upgrades (Jang, 2022). This model is derived from many studies across the literature (Yaghoubi et al., 2018; Schneir et al., 2019; Oughton and Lehr, 2022), and further extends the approach to include different infrastructure sharing strategies, in order to investigate their feasibility.

The incumbent operator is treated as having four key infrastructure sharing strategies to select from, depending upon the overall cost requirements in terms of CAPEX, OPEX, and existing debt. Rational network operators will aim to minimize the cost of potential infrastructure upgrades while attempting to maximize the revenue opportunity in any sharing strategy (Watson, 2002; Duan et al., 2013).

3.1. Capacity assessment

The capacity assessment helps to estimate the current level of available data traffic that existing assets are capable of transporting (Oughton et al., 2022b). Initially, incumbent operators need to assess the sites that require upgrading and their parameter requirements, such as spectrum, bandwidth, latency, 5G KPIs, network congestion during busy hours, and throughput (Ioannou et al., 2020; Oughton and Lehr, 2022). The number of site upgrades necessary can be estimated based on the number of potential future subscribers of the network, the number of concurrent users, and other possible slice tenants' applications (Duan et al., 2013; Oughton et al., 2022b). The number of sites that would require upgrading varies depending on the sharing strategies, demand assessment, and combined area of coverage.

In reality, the incumbent network operator would conduct a survey in the region of interest and list the location of each telecommunication site, its existing backhaul capacity, operating frequency bands (licensed and unlicensed bands), latency, bandwidth, throughput, data rates, busy hour traffic capacity, the population that it serves, the coverage area, the technologies supported, user plane and data plane management, servers, and other network performance indicators. With this information, it is possible the incumbent operator can analyze existing assets in detail such as cells that show high traffic congestion and hotspots where the demand is very high (Zulfadli,

TABLE 2 Modulation scheme and index.

Modulation order Q_m^i	Modulation scheme
2	QPSK
4	16 QAM
6	64 QAM
8	256 QAM
10	1024 QAM

2022). It is important to maximize the use of existing infrastructure during rural network upgrades to keep costs down (GSMA, 2019b; Frank et al., 2022; Kenechi and Stefano, 2022).

Let A km^2 be the area of study region for the network upgrade. Assume, that there are N incumbent operators, each having $x_{mc,i}$ macro cells and $x_{sc,i}$ small cells, such that $i \in N$ in the region of interest.

The overall site density in the region of interest, ρ_{site}, is given as

$$\begin{aligned} \rho_{mc,site} &= \frac{\sum_{i=1}^{N} x_{mc,i}}{A} \\ \rho_{sc,site} &= \frac{\sum_{i=1}^{N} x_{sc,i}}{A} \end{aligned} \tag{1}$$

The average coverage area per site, β km^2 is estimated as follows:

$$\begin{aligned} \beta_{mc,site} &= \frac{A}{x_{mc}} \\ \beta_{sc,site} &= \frac{A}{x_{sc}} \end{aligned} \tag{2}$$

The theoretical data throughput for a 5G site is calculated using the equation given below (Lim, 2020):

$$C_{5G} = \frac{\sum_{j=1}^{J} (\nu^{(j)} Q_m^i f^j R_{max} \frac{12 N_{PRB}^{BW(j),\mu}}{T_s^{\mu}} (1 - O_h^j)}{10^6} \tag{3}$$

where, PRB is the physical resource blocks (PRBs), J is the sum of 5G carriers in carrier aggregation, $\nu^{(j)}$ is the number of layers that a gNodeB transmitter streams to a piece of user equipment (UE), Q_m^i is the modulation order (shown in Table 2), f^j is the scaling factor, and R_{max} is a number equal to $\frac{948}{1024}$. Finally, $N_{PRB}^{BW(j),\mu}$ is the resource block allocation that is determined by the sub-carriers depending upon μ numerology and BW in bandwidth, T_s is the symbol time, and O_h is overhead.

Next, to understand the practical throughput implications of multiple 5G sites in close proximity, we need to utilize a 5G new radio (NR) link budget. Via stochastic geometry, spectral efficiency values can be estimated producing a distribution of capacity among different UEs at varying distances from a gNodeB (Lim, 2020; Jang, 2022). The NR link budget estimation considers a standard deviation of 6 dB for a rural scenario and different propagation models for rural areas (Lim, 2020; Oughton and Jha, 2021), in line with the literature (Oughton, 2020a,b). The analysis also considers interference from nearby base stations. The NR link budget per UE (in dBm), shown in Equation (4), is described in the 3GPP 38.901 standard (Lim, 2020). The link budget depends on a range of factors including climatic conditions, foliage, building clutter, distance between the transmitter and the receiver, indoor or outdoor location of the receiver, atmospheric conditions, and frequency of operations.

$$\begin{aligned} LinkBudget_{Rx,dBm} = {} & Tx_{BW} + AntennaGain_{Tx} - CableLoss_{Tx} + AntennaGain_{Rx} - \\ & CableLoss_{Rx} - PL_{propagationModel} - PenetrationLoss - \\ & FoliageLoss - BodyLoss - InterferenceMargin - \\ & RainIceMargin - SlowFadeMargin - PenetrationLoss_{indoor} - \\ & AttenutationLoss_{indoor} \end{aligned} \tag{4}$$

The 5G pathloss equations ($PL_{propagationModel}$) for the rural macro cell scenario as defined in 3GPP 38.901 standards for a line of sight (LOS), $PL_{RMA_{LOS}}$, is as given below (Ghosh et al., 2019; Jang, 2022; Lin, 2022):

$$PL_{RMA_{LOS}} = \begin{cases} PL_1, & 10m \leq d_{2D} \leq d_{BP}. \\ PL_2, & d_{BP} \leq d_{2D} \leq 10km. \end{cases} \tag{5}$$

$$\begin{aligned} PL_1 &= 20log_{10}(40\pi d_{3D} f_c/3) + \\ &\quad min(0.03h^{1.72}, 19) log_{10}(d_{3D}) - \\ &\quad min(0.044h^{1.72}, 14.77) + 0.002 log_{10}(h) d_{3D} \\ PL_2 &= PL_1(d_{BP}) + 40log_{10}(d_{3D}/d_{BP}) \\ d_{BP} &= 2\pi h_{BS} h_{UT} f_c/c \\ d_{3D} &= \sqrt{(h_{BS} - h_{UT})^2 + d_{2D}^2} \end{aligned} \tag{6}$$

where c is the speed of light, d_{2D} is the ground distance between BS and UE, h_{BS} and h_{UT} are the height of the base station and UE, respectively, and f_c is the center frequency in Hz. For PL_1 has a shadow fading of, $\sigma_{SF} = 4$, $h_{BS} = 35m$, $h_{UT} = 1.5m$, while for PL_1 has a shadow fading of, $\sigma_{SF} = 6$. These formulas are valid for $10m \leq h_{BS} \leq 150m$ and $1m \leq h_{UT} \leq 10m$.

The signal-to-noise ratio (SINR), $\gamma = 10^{LinkBudget_{Rx,dBm}}$, values are used in Equation (7) to calculate the capacity and spectral efficiency per user. The actual channel capacity per site, C bits/sec of the existing infrastructure, is estimated using bandwidth B, channel utilization χ, SINR γ, and spectral efficiency, μ (Capozzi et al., 2013). Generally, realistic channel capacity C, is lower than theoretical channel capacity C_{5G} (Abozariba et al., 2019; Lin, 2022).

$$\begin{aligned} C &= Blog_2(1 + \gamma) \\ &\quad B\mu\chi \end{aligned} \tag{7}$$

Network modeling focuses on capturing congested peak demand periods, with the network consequently able to handle traffic during less congested periods. Moreover, traffic estimation helps to understand network traffic demanded by 5G users and the ability to meet user requirements. Additionally, the network should be flexible enough to accommodate future growth in 5G demand. To understand the demand per site, 5G NR traffic modeling as well as scheduling is utilized (Benoist, 2018; Zainal, 2022).

As the number of active users on the network grows, there is a need to increase the number of gNodeB assets deployed to meet the minimum user data rate requirements (Comşa et al., 2018; Nor et al., 2022). The number of sites that are required to be upgraded is estimated using link budget analysis, traffic management, and user scheduling (Oughton et al., 2023). The incumbent operator would select the outcome which provides the maximum number of towers for the upgrade, to account for future demand from end-users and their applications (Lee et al., 2014; Amer and Puttaswamy, 2019).

3.2. Demand assessment

Data traffic demand is estimated by determining market share, anticipated smartphone users or other business subscribers, population distribution, active users exchanging traffic at peak times, the amount of traffic per user, and then the amount of traffic handled per site (Sciancalepore et al., 2017). Here, we follow the demand method applied in the digital infrastructure costing estimator (DICE) (Oughton et al., 2023). This model was developed for the analysis of universal broadband studies with the aim of quantitatively modeling the various factors described above to estimate traffic demand, which is broadly commensurate with other modeling approaches commonly found in the literature (de la Torre et al., 2020; Oughton et al., 2022b; Oughton, 2023).

Rural areas tend to have a small number of settlements, although there are a few outliers (Yaacoub and Alouini, 2020). The demand estimation also includes business subscriber data and throughput requirements for potential end-user applications, including Internet of Things (IoT) devices or other technologies for health, energy, transportation, etc. (Musacchio et al., 2006). Another major unknown parameter that affects network feasibility is the expected average revenue per user (ARPU). In theory, if an operator expects the existing ARPU to increase following the deployment of new services, then there would be a higher appetite to invest, for example, in upgrading to 5G services (Kenechi and Stefano, 2022). This situation, however, has considerable uncertainty, which requires scenario analysis (Oughton et al., 2022b). Finally, compared to consumers, business subscribers are typically expected to pay higher subscription rates (which may translate into a more reliable service, and revenue stream) (Lappalainen and Rosenberg, 2022).

In this step, the incumbent operator would estimate the potential 5G subscribers and their use cases. There would be a survey/discussion with the potential slice tenants about their application requirements that the network would need to satisfy. The incumbent operator would tabulate the demand assessment model's outputs and estimate the ARPU that end-users would be willing to pay for their services. The end-users could be business-to-business (B2B) or business-to-consumer (B2C) (Psyrris et al., 2021; Schneir et al., 2022). The number of small and macro cells that require an upgrade is dependent on this analysis.

To estimate the traffic demand that should be supported by the network over a period of T years (say, T is the study period), there is a need to include the data obtained from the demand assessment model. Let the expected average user traffic be given as δ_t GB/user/month, such that, $t \in T$. Then, the data consumed per day per user, $\delta_{t,day}$ MB/day (Oughton and Frias, 2018; Oughton and Jha, 2021). The minimum data speed required per user ζ in Mbps, during the busiest hour of the day (B_{HF}) using the conversion value of 1 Byte (B) with 8 bits (b), and 1 h with 3,600 s (Oughton et al., 2022b), is calculated as:

$$\zeta = \frac{8}{3600}\frac{1}{30}\frac{1}{1000}\delta_t B_{HF} \tag{8}$$

Then the population density, ρ_{pop} for the study area A with population P. Typically, x% of the population density, ρ_{pop} for the study area A of the P, would be the number of subscribers for a service.

Finally, the area traffic ι_{area} is estimated as (Oughton and Russell, 2020; Oughton, 2023),

$$\iota_{area} = x\zeta\frac{P}{A} \tag{9}$$

3.3. Cost assessment

This assessment includes the estimation of the cost incurred in deploying and operating the different business model options. The expenditure for a particular 5G upgrade is calculated first per site and then aggregated to a local statistical area level. A rational incumbent MNO designs and deploys a forward-looking network that accounts for future traffic demand over the next 10–20 years. The discounted total cost of ownership (TCO) ω is estimated as the sum of CAPEX ω_c and OPEX ω_o over this time horizon (Chiaraviglio et al., 2017; Ioannou et al., 2020; Oughton and Lehr, 2022). CAPEX includes the cost of the radio equipment upgrade ω_{RAN}, the backhaul upgrade (wired as well as wireless) and any labor ω_b, a small edge cloud site ω_{edge}, spectrum ω_s, and any core network upgrades necessary ω_{core}. OPEX includes the cost of power, administrative operations, core network maintenance, routine maintenance of radio equipment, operational spectrum, and edge cloud maintenance.

Generally, there is a need to upgrade the backhaul capacity to support 5G data rates. Additionally, unlike other studies which exclude current asset debts, ω_d, this assessment also includes a nominal existing debt payment per site which is closer to what is experienced in reality (Cheng et al., 2003). The debt payment factor ω_d, is not included in OPEX because it lacks the traits required for ongoing routine operations and maintenance. As a result, they are included in CAPEX, which is in accordance with the discussion with operators related to the inclusion of debt in their estimates. By adopting this parameter, analysts can more accurately reflect the level of debt owed to each operator and its impact on brownfield telecommunications deployment. Furthermore, as per standard industry practice, the backhaul cost is split between CAPEX and ongoing OPEX (Oughton et al., 2022a), while the existing debt payment is factored into CAPEX (Brach, 2016). Therefore, the modified TCO for this study is (Yaghoubi et al., 2018; Chiha et al., 2020; Oughton and Lehr, 2022).

$$\begin{aligned}\omega &= \omega_c + \omega_o \\ &= (\omega_{RAN} + \omega_b + \omega_s + \omega_{core} + \omega_d) + (\omega_o)\end{aligned} \tag{10}$$

TABLE 3 Number of physical components for upgrade per cellular sites for each sharing strategy.

Strategy	No Sharing	Passive Sharing	Active Sharing	NHN
Tower	4x	1x	1x	1x
Site	4x	1x	1x	1x
Backhaul	4x	1x	1x	1x
RAN	4x	4x	2x	1x
Spectrum	4x	4x	2x	1x
Core	4x	4x	4x	1x

3.4. Network upgrade requirements

The 5G network upgrade assessment estimates the infrastructure requirements for future assets. This model includes details about site locations, additional backhaul capacity, macro and small cell quantities, future spectrum bandwidth, expected spectral efficiency, usage of the network traffic, and slice requirements of various potential tenants. The tenants may find it desirable to obtain the resources they lease on a near-real-time basis (Sanguanpuak et al., 2019; Jeanjean, 2022). In addition, the incumbent may also need to account for upgrades to support potential future tenants.

Table 3 shows the number of physical components for upgrade per cellular site for each sharing strategy in a 4-operator scenario. The total number of sites required for the upgrade is subject to the existing coverage areas and network sharing strategy. From Table 3, it can be observed that in a *No Sharing* (baseline) deployment, most sites and base stations of the incumbent would need to be upgraded and no physical sites are shared. In a *Passive Sharing* deployment, the resources required for upgrading are reduced compared to the baseline scenario as the physical site locations and other passive components are shared among all operators, whereas the radios, spectrum, hardware, and core are not shared. Furthermore, in an *Active Sharing* approach, the operators deploy a lower number of radios and hardware components compared to *Passive Sharing*. Finally, in the *NHN* deployment, the total resources for a 5G network upgrade reduce further as end-to-end components are shared by all operators.

Let κ be the number of towers that require a network upgrade and ω be the TCO of the network upgrade. The key optimization equation to lower the TCO associated with 5G brownfield deployments in rural areas, while satisfying the aims to increase coverage (β) and data rates, (C) but minimizing the number of towers that require an upgrade, is stated as follows (Duan et al., 2013; Shruthi et al., 2021):

$$\begin{aligned} \min_{x_{mc}, x_{sc}} \quad & \omega \\ \text{s.t.} \quad & maximize \ \ \beta \\ & \zeta \ > \ C \\ & \kappa \ \leq \ x_{mc} + x_{sc} \end{aligned} \tag{11}$$

3.5. Techno-economic feasibility assessment framework

This framework performs a feasibility analysis of the possible infrastructure sharing strategies for each rural 5G business model. The results of the network upgrade requirements, specifically, the number of necessary upgrades needing to be made, are then fed forward to be combined with the potential costs of each component from the cost model, thus producing the key assessment result metrics.

The revenue per year R_i such that $i \in T$, and the total revenue, R, over the period T for ARPU Ψ_{5G} for 5G services are calculated as (Ioannou et al., 2020; Oughton et al., 2021):

$$\begin{aligned} R_i \ &= \ 12\rho_{up,sub}(\Psi_{5G} - \Psi_{old}) + 12\rho_{new5G}(\Psi_{5G}) \\ R \ &= \ \sum_{i=1}^{T} R_i \end{aligned} \tag{12}$$

where Ψ_{old} shows the ARPU for existing infrastructure, ρ_{new5G} are the additional new subscribers joining the network who require 5G KPIs for their applications, and $\rho_{up,sub}$ is the existing subscribers who upgrade their services to 5G technology who can be charged more than existing technologies. The cash flow for year i, α_i such that $i \in T$, is estimated as (Besanko and Braeutigam, 2020):

$$\alpha_i \ = \ R_i - \omega_i \tag{13}$$

where ω_i is the cost per year toward the upgrade. The incumbent operator would upgrade the network sequentially to match the network demand and earn higher revenues. For analyzing the profitability of the network upgrade to 5G using different sharing strategies, the net present value (NPV), Υ, method is used with a discount factor r and is calculated as (Ye and Tiong, 2000; Besanko and Braeutigam, 2020):

$$\Upsilon = \sum_{i=1}^{T} \frac{\alpha_i}{(1+r)^i} \tag{14}$$

when $\Upsilon = 0$, then it is a no profit-no loss scenario for the infrastructure provider. This helps in the estimation of the minimum ARPU, Ψ_{min}, at which the infrastructure provider would consider deploying the 5G network. The minimum ARPU would in turn help in determining the pricing range which the operators should charge to the end-users (Shruthi et al., 2021).

3.6. Output

As incumbent operators shift their 5G business models to rural areas, they are driven both by a desire to reduce overall TCO by maximizing current and future resources and to sell new vertical services to increase revenue (Partners, 2019; Gómez et al., 2022; Pryce, 2022). Hence, the appraisal outputs focus on population coverage in rural areas: the minimum provided speed per user in busy hours, the percentage of subscribers with 30+ Mbps peak speed, an NPV feasibility analysis, and a sensitivity analysis for uncertainties. The various costs for network upgrades for an area with an existing 2G/3G network tend to be higher than upgrades from existing 4G networks. For example, existing 4G hardware can support future infrastructure upgrades with relatively minimal software updates, lowering the upgrade cost significantly (Oughton et al., 2021; Kenechi and Stefano, 2022; Lappalainen and Rosenberg, 2022).

4. Results

In this section, the results are reported using the methodology illustrated in Figure 2. The network planning simulation was modeled using the Python model, which is available on the GitHub repository (Shruthi, 2023). The overall TCO is calculated for a 5G network upgrade over a time horizon of 10 years for a generic rural context.

4.1. Description of the study area

Consider a generic rural study area (A) of 500 km^2 with interspersed low population density villages ($<$300 people per km^2) for the time period of 2023–2032. In this study, the population density for the base scenario is 36 people per km^2. Assume there are four national MNOs, and each wants to be omnipresent within their operating country (Saha, 2020). Table 4 provides a summary of the simulation parameters and the inputs for different models. The data for the study are obtained from various sources from the literature (Oughton and Frias, 2018; Grijpink et al., 2020; Ofcom, 2020; Oughton and Jha, 2021; 5G-New-Thinking, 2022; ITU, 2022; Lappalainen and Rosenberg, 2022). Typically for rural areas, the operating frequencies are in the range of 700 MHz and 3,800 MHz (Partners, 2019). Note that a higher coverage is offered by 700 MHz (at lower throughput rates), while higher throughput rates are offered at 3,800 MHz band (but with lower coverage) (Wahyudin et al., 2021; GSA, 2022). For example, during the network upgrade the 3,800 MHz band could be used to serve a small rural hamlet with enhanced mobile broadband services, while the 700 MHz band could be used for greater wide-area coverage across the cell (e.g., for highly mobile users in vehicles). The network could use either time or frequency division duplex (TDD/FDD) as a modulation scheme.

In this evaluation, for the existing technology with a take-up rate (x), 50% of P, consider that 30% of those users would upgrade to 5G services, and an additional 20% of P would join the network for 5G services. Therefore, the rural region of interest in this study, especially sensitivity analysis, is treated as having between 1,000 to 25,000 mobile subscribers along with thousands of devices for private networks and IoT applications (Oughton and Mathur, 2021). These subscribers could belong to local businesses or corporate companies. Today, the ARPU from wireless broadband around the world ranges from $2 to $45 (ITU, 2021). Therefore, the incumbent MNO would expect a higher ARPU from the 5G services and higher data rates along with exponentially improved performance, say +20% compared to the ARPU of the 4G services (Suryanegara, 2018; Yang, 2022). But over time, the price per GB would drop, which would encourage operators to share the network, which would further encourage infrastructure sharing among the operators (Hunukumbure et al., 2022). Next, the annual increase in the subscriber base is considered to be around 4% although the rural population growth is below zero (Bank, 2021), this is because improved wireless broadband will increase the demand for connectivity for use cases such as remote job opportunities, personal communication, e-governance, farming, and healthcare facilities.

In this paper, we follow a long run incremental cost (LRIC) approach where a "hypothetical MNO" is modeled representing an entity with an average market share, average spectrum portfolio, average set of existing sites, etc. In a perfectly competitive market, each of the four MNOs would acquire roughly 25% of the entire 5G services market share, adding up to 100% of the market share. For this study, we consider the busy hour factor (B_{HF}) to be 0.15, and maintain low latency ($<$50 ms). An aspirational target for governments globally is to provide a minimum 30 Mbps average data speed per user and to increase the data usage to a minimum of 30 GB/Month per user (UN, 2022). Therefore, in this study, we consider a minimum average data speed of 30 Mbps per user and data consumption of 50 GB/month per user. Table 4 shows the modeling conditions for the study location and its simulation parameters, along with the cost for various components required for the 5G upgrade.

The average cost per site for the macro-cell and small-cell varies considerably. In this study, we estimate that a brownfield macro-cell upgrade is approximately $45,000 including RAN upgrades, core, spectrum ($0.7 per MHz at 700 MHz, and $0.03 per MHz at 3,800 MHz), and other parameters, while the greenfield small-cell deployment is around $12,000 (Osio, 2021; Oughton and Jha, 2021). The variation in the costs depends on the selected strategy and the upgrade required for the existing hardware and software components such as the core, radios, site, gNodeB, and processing units. Next, the cost of an average backhaul upgrade would be approximately $10,000 for macro-cell and greenfield deployment would cost around $5,000 for small-cell. The OPEX for the small cell could be as low as $800 per year, while the same for the macro cell would be around $2,500. The brownfield deployment already has an existing debt payment to be cleared, which is about 5% of the TCO of each site (Bhatia, 2022). Note that the debt payment is for the existing infrastructure (2G, 3G, and 4G), not the new 5G network. The study considers that the CAPEX and backhaul depreciate at a 3% rate, while the OPEX and debt payment appreciate each year at 5 and 2%, respectively (Schneir et al., 2019).

4.2. Demand-Supply estimations

Generally, there would be around 60 active users at any instance in time per site, except during congestion periods when the capacity can be expanded using virtual and cloud resources via network slicing (Chiha et al., 2020). As the number of active users grows, a corresponding rise in the number of demand requests for scheduling users takes place. Furthermore, as demand rises, SINR values decrease because resources are shared among many users (Benoist, 2018; Zulfadli, 2022).

Figure 3 reports the stochastic geometry analysis of the SINR, spectral efficiency, and channel capacity estimate of the realistic channel throughput at the cell edge for a 95% confidence interval,

TABLE 4 Simulation parameters.

Parameter	Value	Unit	References
Subscriber base growth rate	4	% per year	Schneir et al., 2019; Kenechi and Stefano, 2022
NPV discount factor	4	%	Bank and OECD, 2021
Investment duration	10	Years	-
Number of MNOs	4	-	Saha, 2020
Busy hour factor (B_{HF})	0.15	-	Steve, 2015
Rural population density	36	people per km^2	-
Area of study	500	km^2	-
Take-up	50	%	Mark, 2021; Kenechi and Stefano, 2022
Subscription growth rate	3	%	Shruthi et al., 2021; Kenechi and Stefano, 2022
ARPU for 5G wrt 4G	+20	%	Kenechi and Stefano, 2022
ARPU - retail subscribers	10 to 60	$	marketing group, 2022
Expected average user traffic	50	GB/user/month	-
Minimum user rate	30	Mbps	-
Transmission methods	5G 4x4 MIMO	-	-
Propagation model	ETSI TR 138 901	-	3GPP, 2020; Lim, 2020
Frequency reuse factor	1	-	-
Transmit power	40	dBm	Oughton and Russell, 2020
Transmitter height (macro, small)	30, 10	meters	-
Transmitter antenna type	Directional	-	Oughton and Russell, 2020
Transmitter antenna gain	16	dBi	Bouras et al., 2020
UE antenna gain	0	dBi	Oughton and Russell, 2020
Modulation	TDD/ FDD	-	-
Debt payment (of TCO required for 5G upgrade)	2	% per site	Bhatia, 2022; Morris, 2022
Spectrum ($\leq$1 GHz, >1 GHz)	0.28, 0.03	$	Grijpink et al., 2020; Osio, 2021; Oughton and Jha, 2021
Backhaul (macro cell, small cell)	10,000, 5,000	$ per km	Oughton and Frias, 2018; Oughton and Lehr, 2022
Core upgrade	10	% of RAN cost	Grijpink et al., 2020; Oughton and Lehr, 2022
Infrastructure upgrade macro cell (includes RAN, core, backhaul, spectrum, and other CAPEX components)	45,000	$ per site	Oughton and Frias, 2018; Oughton and Lehr, 2022
Infrastructure upgrade small cell (includes RAN, core, backhaul, spectrum, and other CAPEX components)	12,000	$ per site	Oughton and Frias, 2018; Oughton and Lehr, 2022
OPEX	2500	$ per site, per year	Oughton and Frias, 2018; Oughton and Lehr, 2022

for UEs operating on a 5G cell site. Indeed, there is a clear relationship between increasing UE distance from the cell site, and a decreasing SINR leading to lower spectral efficiency and thus poorer channel capacity. For the 5G network upgrade, both small- and macro-cell strategies are considered. We treat:

- macro cells as providing coverage up to 7 km,
- small cells at a mid-band frequency covering up to 3.5 km, and
- small cells with high millimeter-wave frequencies covering up to 100 m.

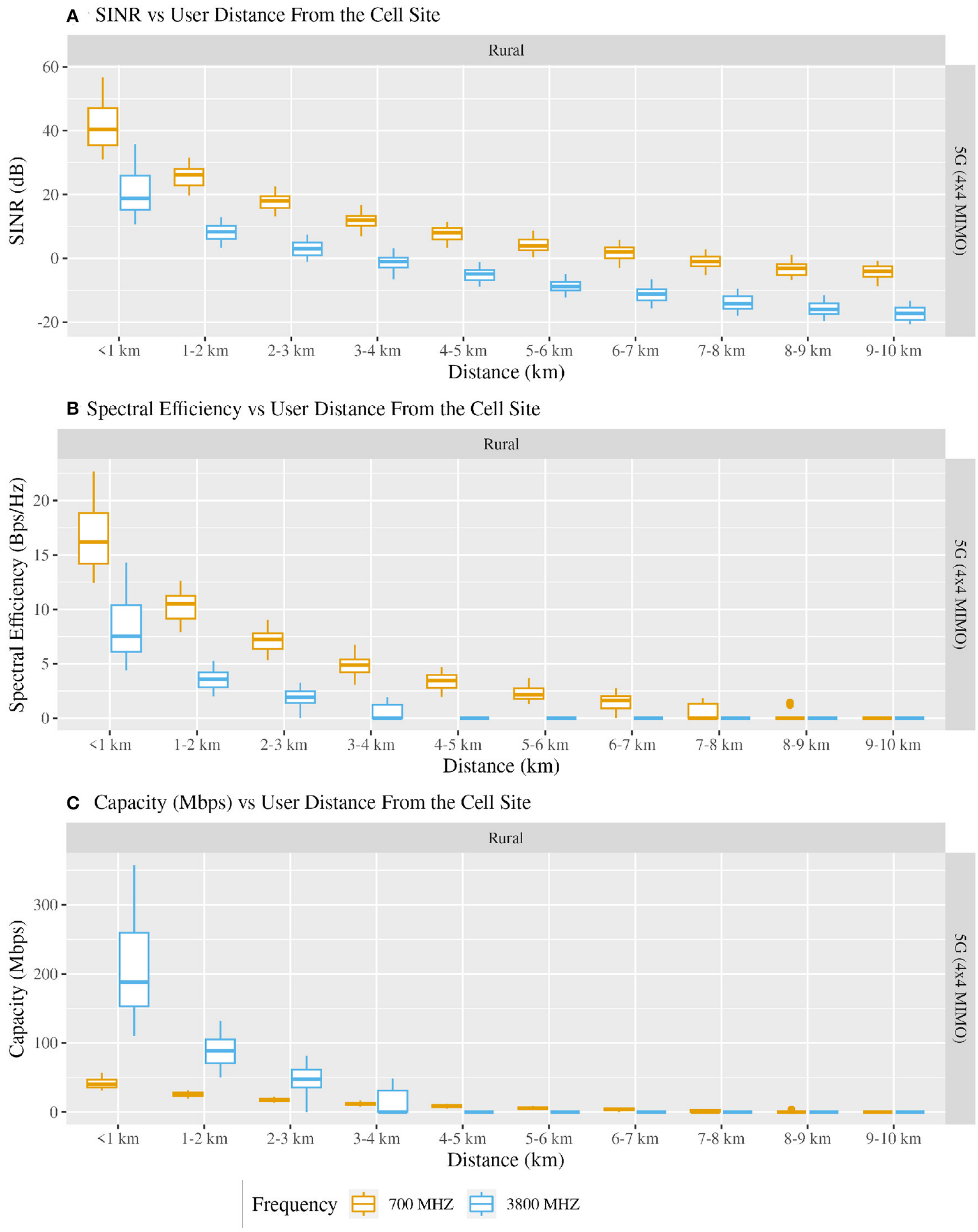

FIGURE 3
Stochastic modeling results per user in 5G cells at different frequencies: **(A)** SINR, **(B)** spectral efficiency, and **(C)** capacity.

The minimum theoretical peak cell throughput is around 177 Mbps and 1,700 Mbps at 700 MHz and 3,800 MHz frequency bands respectively, with power levels below 4 W (Biradar and Hallur, 2022; Vinogradov, 2022; Shruthi, 2023). Small cells offer higher peak data rates than macro cells but require higher quantities to provide services in the same geographic area (Wang et al., 2014). Moreover, the densification of the network by the deployment of small cells at millimeter-wave frequencies depends on the number of subscribers and the potential ROI (Wahyudin et al., 2021).

The stochastic and traffic modeling results for the base scenario of 36 people per km^2 suggest that each MNO would aim to upgrade an average of 4 macro-cells, and additionally deploy 8 small-cells, to provide maximum coverage at 30 Mbps in the brownfield rural area 5G deployment. Furthermore, the overall increase in data rates is evident only when the backhaul capacity is above 5 Gbps, specifically to support users and applications that demand more resources.

4.3. Cost savings for different sharing strategies

In this section, we explore the different infrastructure sharing strategies and their techno-economic implications. The TCO is estimated for all the 5G network upgrade sharing strategies and shows that OPEX becomes higher over time due to increased network complexity, breakdowns, repairs, and inflation. MNOs are likely to prefer different sharing strategies depending on existing demand and resource utilization. In order to meet 5G security and dynamic slicing requirements, an NHN has greater equipment requirements that must be met because multiple network operators are using the network infrastructure simultaneously (Raza et al., 2019; Sciancalepore et al., 2022). Hence, the single site cost for upgrading to the *NHN* strategy is the most expensive. In reality, an upgraded 5G network in rural areas helps to provide eMBB-related applications while supporting other 5G rural applications relating to vertical sectors, such as health and transportation.

Figure 4 shows the overall upgrading cost for all the sites for each year in the period of 2023-2032. The estimated costs shows that the TCO for *No Sharing* (baseline) is approximately $1,996,791, for *Passive Sharing* $1,459,224, for *Active Sharing* $994,446 and for *NHN* $659,864. Figure 4 and Table 3 show that for an incumbent MNO, the cost of upgrading to a rural *NHN* per site is higher compared to the incumbent MNO's upgrade to 5G per site, by 6–20% against other 5G network sharing strategies.

Moreover, Figure 4 presents the financial cost savings possible from 5G infrastructure sharing strategies. *Passive Sharing* strategies exhibit substantial savings between 10–20% for 50 GB/Month against the baseline. Meanwhile, the *Active Sharing* strategy results in savings between 20–35% for 50 GB/Month against the baseline. Lastly, a rural *NHN* provides impressive cost savings of around 35–50% against the baseline scenario.

Additionally, Figure 4 shows that for each network sharing strategy, the cost per year increases due to various factors, including inflation, the loan interest rate, and operating costs. Indeed, the cost increases by 7.6, 6, 5.6, and 5.5% for *No Sharing*, *Passive Sharing*, *Active Sharing*, and *NHN*, respectively. Also, Figure 4 shows that in the four sharing strategies, the CAPEX to OPEX ratio is around 1.9 in the first year and falls to almost 0.95 in the final year of assessment.

Figure 5 shows the minimum investment required per user toward the 5G network for a sustainable business case. It can be observed that as the number of users increases, the investment required per user decreases. For subscribers below 500, only *Active Sharing* and *NHN* strategies are profitable for the operators with per user investment less than $60, which is very high for a monthly ARPU (Taylor, 2023). As the number of subscribers increases, the minimum investment required per user falls below $10, increasing viability. When the number of subscribers is above 10,000 in the region of interest, then the minimum investment required per user is below $1.5 per subscriber. In the present scenario, the deployment is self-sustaining since the network is profitable for the operator while being affordable for end users.

4.4. Business case analysis using NPV and sensitivity analysis

Figure 6 shows the sensitivity of the NPV by varying the revenue from −93% to +100% of the baseline value at a population density of 36 people per km^2 (=18,000 people in the study area), with a subscriber growth rate of 4% per year. The results show that the increase in subscription demand leads to a commensurate rise in revenue, which overall provides an improvement in the viability of the 5G deployment across the sharing strategies. Also, the estimates in Figure 6 illustrate that the *NHN* business case is superior by at least 15% compared to other sharing strategies under the same revenue and demand conditions. For a network to be profitable at a low ARPU, say $10 per month, the subscriber base needs to be very high per cellular study area, e.g., above 20,000 subscribers per area. As the ARPU increases, say at $60, the required number of subscribers could reduce to as low as 3,400 subscribers in the *NHN* strategy for rural areas. The base scenario is calculated with a monthly APRU of $30 per subscriber. Figure 6 shows that all sharing strategies are feasible when the ARPU is higher than $40, that is, viable business models.

These results demonstrate that the techno-economic feasibility in rural areas is extremely sensitive to the number of subscribers and ARPU for the network, along with the number of towers requiring upgrading. The estimates also demonstrate the difference in the ROI for each 5G sharing strategy. Figure 6 shows that at $30, the ROI is negative for *No Sharing* and *Passive Sharing*, whereas the ROI is positive for *Active Sharing* and *NHN*.

Figure 7 shows the sensitivity analysis for the different 5G network sharing strategies. It can be observed that for a 20% increase in the ARPU, the NPV increases twice in *Passive Sharing*, 4 times in *Active Sharing*, and 5 times in *NHN* compared to the NPV of the baseline scenario (*No Sharing*). Similarly, when the existing infrastructure increases by 10%, the NPV doubles in *Passive Sharing*, trebles in *Active Sharing* and trebles in *NHN* approach compared to the NPV of the baseline scenario. The network is least sensitive to the debt repayment amount. The NPV hardly changes from the base NPV even when the debt payment parameter changes by 60% for all sharing strategies.

The results obtained in this study are compared against the existing rural connectivity studies in Oughton and Jha (2021), Laitsou et al. (2022), Oughton (2023). According to a recent study, *Active Sharing* and *Passive Sharing* strategies for 10–30 GB/month in an African scenario would reduce the cost by 48–78% and 10–44% respectively, while the same strategies in this study for 50 GB/month would reduce the cost by 20–35% and 10–20% for *Active Sharing* and *Passive Sharing*, respectively (Oughton, 2023). Meanwhile, when considering developing countries with a case study of the Indian context, the cost per user of 4 × 4 active sharing with 5–50 Mbps QoS is 70% lower compared to that of traditional LTE deployments (Oughton and Jha, 2021). These figures are slightly higher than the reduction in the investment

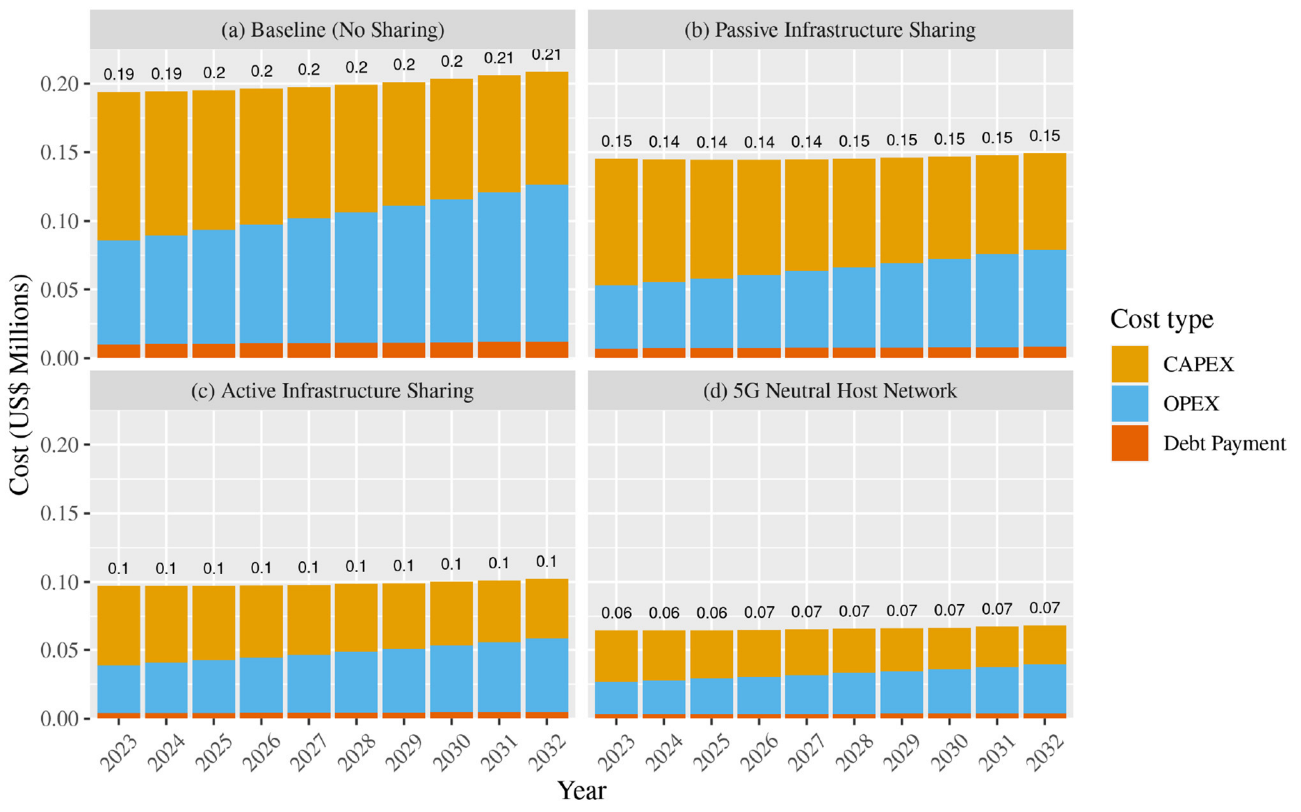

FIGURE 4

CAPEX-OPEX estimation per year for various strategies in the region of interest: **(A)** no sharing, **(B)** passive sharing, **(C)** active sharing, and **(D)** 5G NHN.

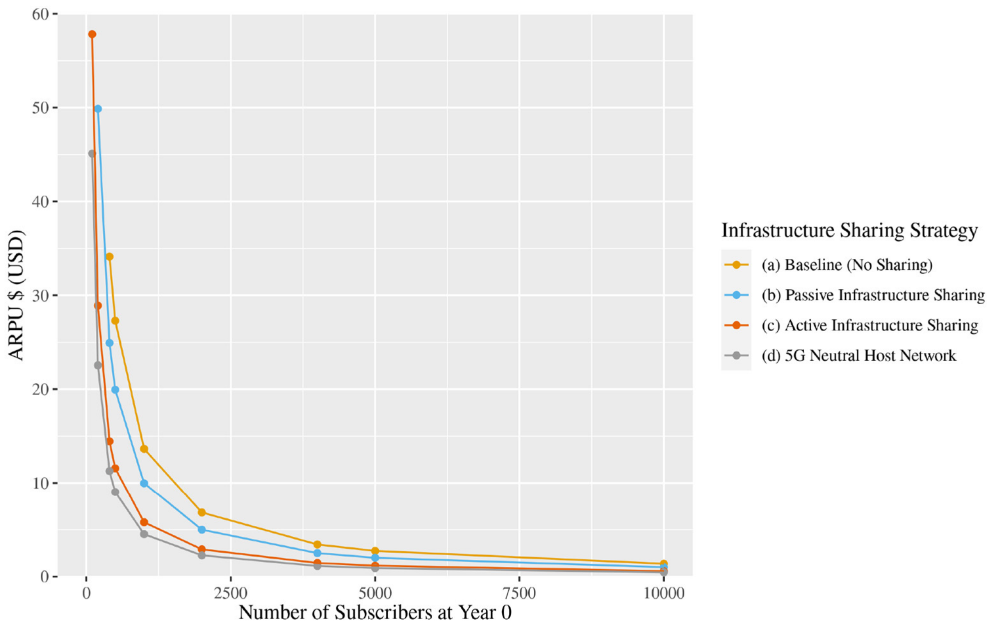

FIGURE 5

Investment per user analysis at a subscriber growth rate of 4% per year: **(A)** no sharing; **(B)** passive sharing, **(C)** active sharing, and **(D)** 5G NHN.

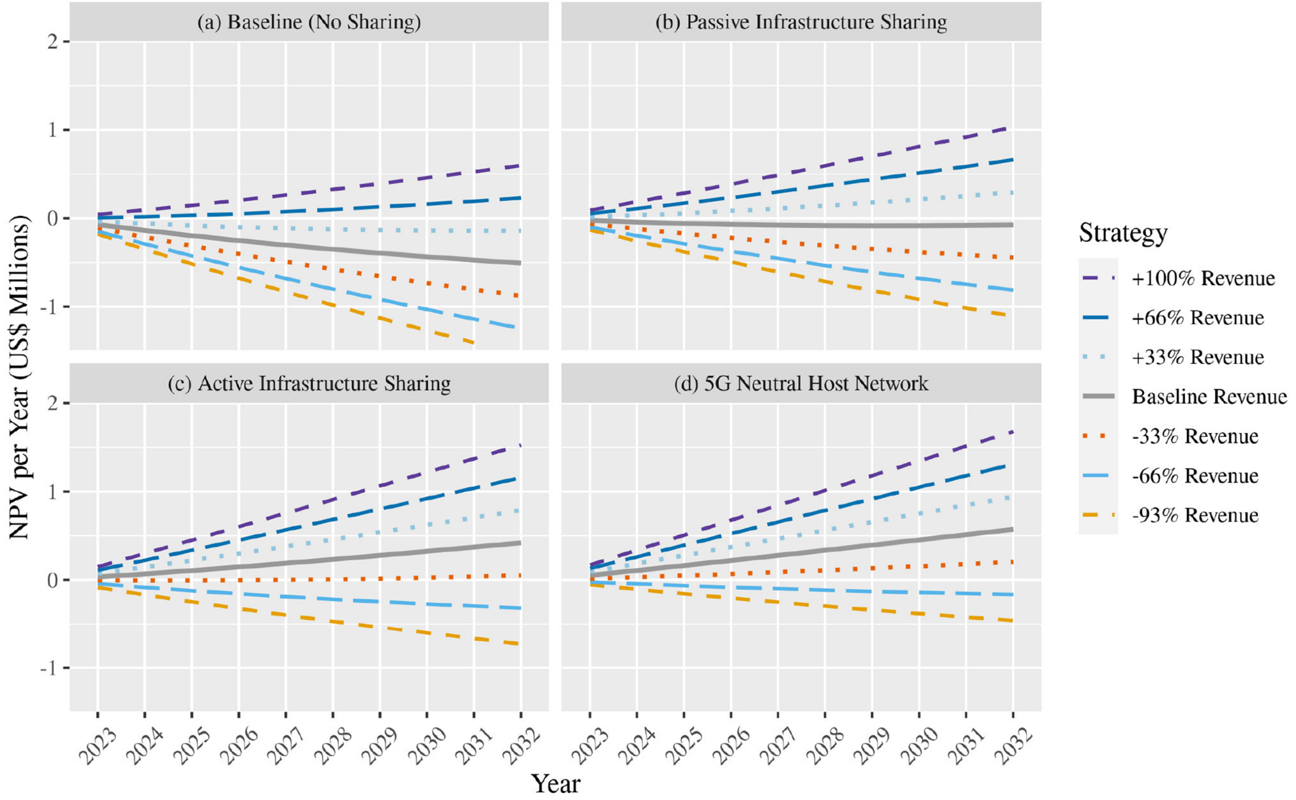

FIGURE 6
5G SC + MC upgrade using various strategies in the region of interest with varying revenue sensitivities compared to a base scenario ARPU $30 and population density of 36 people per km^2: **(A)** no sharing, **(B)** passive sharing, **(C)** active sharing, and **(D)** 5G NHN.

per user of 65% estimated here. Similarly, according to a recent study for European countries, it was shown that greenfield 5G standalone fixed wireless access without infrastructure sharing is expensive in rural areas having a cost per user over $100 per month, whereas wireless broadband using infrastructure sharing could potentially be feasible for less than $60 per month (Laitsou et al., 2022).

Studies in the literature on the successful NHN trials and initiatives have shown that a 5G *NHN* approach is beneficial to MNOs in places where the population density is very high or low, especially if there are multiple use cases targeted (Lähteenmäki, 2021). In this study, the cost savings offered by using a 5G *NHN* are approximately 35–50% compared to the baseline *No Sharing* approach. In a city-wide *NHN* deployment for an ultra-dense urban area, such as in London, the cost-savings are expected to be around 40% (GSMA, 2018; Schneir et al., 2019). Similarly, cost savings for different deployment scenarios, such as a 100-story commercial building in urban indoor and outdoor settings, were estimated to be 70 and 80%, respectively (Allawi et al., 2022). Whereas, for a university campus a *NHN* approach is estimated to result in a 20% saving (Walia et al., 2017). Finally, for an industry vertical, such as a seaport at Hamburg, a *NHN* strategy could result in up to a 50% cost saving (Schneir et al., 2022).

5. Discussing the impacts of 5G infrastructure sharing strategies

The evaluation carried out in this paper explores four major infrastructure sharing strategies for a brownfield deployment capable of supporting future technologies such as 5G (or beyond), including: *No Sharing, Passive Sharing, Active Sharing, and 5G NHN*. For the two main research questions identified, we find that the investment cost of a 5G network upgrade is significant for all network-sharing strategies tested in this analysis. However, the findings show promising business model options for different deployment strategies, which are common to all operators. An MNO could incorporate them to better reflect their goals, i.e., different levels of sharing might deliver the best outcomes for the operator, users, and broader society. For instance, they may operate their own network in some areas while sharing in others to better reflect their strategic priorities and the economics of network provision. Each incumbent MNO will appraise its asset position, possible future revenues, and the NPV for all sharing strategies to make informed strategic decisions on the most appropriate 5G deployment options. Given there will be different deployment strategies based on the demand conditions in each context, with rural and remote areas being the most challenging locations, the following discussion summarizes each one:

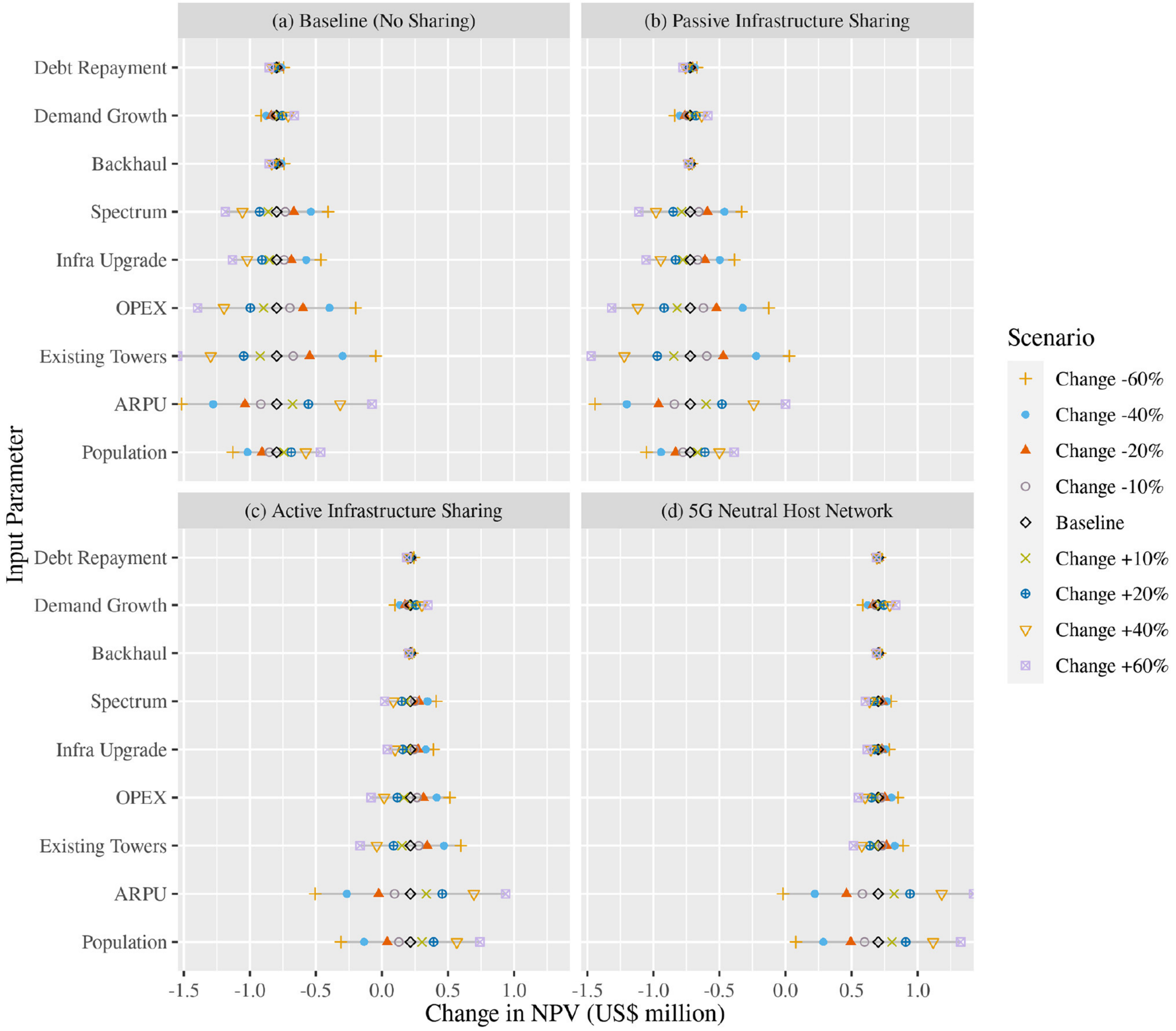

FIGURE 7
Sensitivity analysis of sharing strategies: **(A)** no sharing, **(B)** passive sharing, **(C)** active sharing, and **(D)** 5G NHN.

- **No Sharing** is suitable when the incumbent MNO has a lucrative business model. The MNO would want to retain the monopoly of being an exclusive service provider for all applications and use cases in the region of interest. In the case of a high traffic load that requires each MNO to build a network to meet these demands, maintaining this monopoly position may not have a negative impact on society as a whole.
- **Passive Sharing** is preferred when the sunk costs are high and potential ROI is lower than the *No Sharing* scenario. The operators distinguish themselves using metrics, such as coverage and QoS. The operators can still maintain control of the type of active components of the network deployment while sharing specific passive assets (e.g., the site and backhaul) to reduce costs while hopefully improving business case feasibility.
- **Active Sharing** is an appropriate option when there are fewer sites to compete or fewer available licensed spectrum bands, and operators would like to complement each other's services. One example may include the provision of national user roaming, with operators collaborating to provide reciprocal coverage in each other's service regions. Alternatively, some hard-to-serve low-demand areas may not feasibly support multiple infrastructure networks, making active sharing an attractive option.
- A **5G NHN** is the most advanced network sharing configuration and is suitable if multiple operators have a degree of trust in each other. Although it is the most cost-effective strategy, the operators leasing resources from the incumbent MNO need to be able to obtain these resources at a fair price, along with confidence in their longer-term price expectations. This option is the most viable for areas

with low subscriber counts and can cater to the full range of 5G applications. This may also be a viable option in very high-traffic areas where a single neutrally hosted network would provide a more optimal engineering design owing to reduced interference and improved cell coordination (Schneir et al., 2019, 2022; Allawi et al., 2022).

The proposed business model strategies for rural areas could prove to be attractive options (Allawi et al., 2022; Oughton, 2023). Whereas this paper focused on the cost-efficiency and viability of the proposed upgrade strategies, the one noteworthy subject not touched on which deserves attention is *governance*. MNOs generally have substantial experience in negotiating contractual terms and conditions between each other, with some operators having already entered into *passive* and/or *active* sharing agreements for infrastructure assets. However, future research needs to explore the pragmatic approaches for MNOs to undertake network sharing in practice, such as toward a company joint venture between MNOs to deploy shared infrastructure or automated policy enforcement by either regulatory bodies or other operators. These policy agreement models may differ considerably by context, in extremely high-density places (such as stadia, campuses, seaports, etc.) or rural areas with very low viability. Similar to this, the TEA model's revenue projections are likely to vary depending on the geographic context.

As a conclusion to this discussion, three key areas of research need to be examined in future studies to provide new insights into infrastructure sharing. Firstly, from an engineering perspective, a comprehensive analysis is required to define the impact of different resource allocation processes, including the control for end-users of each slice, interference management, and spectrum management. Secondly, from a microeconomic perspective, it is not yet clear what the optimal pricing plans should be and how changes in pricing affect the incumbent, tenants, end-users, and wider society. Finally, a new analysis needs to be undertaken from an industrial organization perspective to provide insight into the competitive impacts of infrastructure sharing, especially as operators move toward implementing neutrally hosted networks. Indeed, the dominant theme over the past three decades has been that more infrastructure competition is fundamentally a good thing. However, the mobile industry is now moving toward greater consolidation as a consequence of (i) changing economic circumstances and (ii) the ability to enter into the types of business models appraised in this paper.

6. Conclusion

This article presented a techno-economic assessment of 5G infrastructure sharing business models in rural areas. This began with the presentation of a theoretical model capable of assessing various infrastructure sharing strategies, and then the application of this model to a case study example. The key contribution is the provision of comparative quantitative information on the cost efficiency of the four different business model options, and their sensitivities (including *No Sharing*, *Passive Sharing*, *Active Sharing*, and *NHN*). The evaluation considered the total cost of ownership over ten years for a generic rural area.

The results indicate that the *NHN* strategy reduces the overall cost by 10–50% compared to other 5G sharing strategies. It is evident from the estimated NPV that infrastructure sharing business models can increase viability by 30–90%. However, these sharing approaches can be highly sensitive to changes in demand, as well as the level of existing available infrastructure. Given the current challenges in achieving Target 9.1 of the UN Sustainable Development Goals, the cost-saving measures explored here provide a potential solution for lowering the overall costs of the deployment in more challenging rural and remote areas. However, the implementation of infrastructure sharing strategies cannot happen in isolation and needs to be balanced against prudent technology and policy choices (by operators and governments). Without a comprehensive strategic approach to deploying wireless broadband connectivity, the aim to deliver affordable universal mobile broadband to all by 2030 will be more challenging.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://github.com/shruthiKa-kas/infrasharing5Gupgrade.

Author contributions

SK did modeling, analysis, data visualization, and writing. EO undertook data visualization and writing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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