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Techno-Economic Assessment of 5G Infrastructure Sharing Business Models in Rural Areas

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ABSTRACT How cost-efficient are potential infrastructure sharing business models for the 5G/6G era? How should telecommunication regulators formulate a national policy to improve mobile broadband connectivity? These are significant questions that need to be addressed if we are to deliver universal affordable broadband and achieve Target 9c of the UN Sustainable Development Goals. For example, over one-third of the global population has never used the Internet, with many of these users in areas of low economic viability. Consequently, this assessment evaluates the cost implications of different infrastructure sharing business models. Over a decade, the results show that a rural 5G neutral host network (NHN) strategy helps to reduce the total cost by 10-50% over "No Sharing", "Passive Sharing", or "Active Sharing" approaches. We also find that compared to a baseline strategy with "No Sharing", the net present value of rural 5G sharing strategies can earn between 30-90% 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, 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 net present value of the "No Sharing" strategy. Similarly, a 10% increase in existing infrastructure lowers the net present value by 8-30%.

INDEX TERMS 5G, network slicing, network upgrade, rural connectivity, techno-economic feasibility, wireless connectivity.

I. INTRODUCTION

The fifth generation of cellular communications ("5G") is now being widely deployed around the world, predominantly in urban and suburban areas [1]–[5]. Importantly, wireless mobile broadband can generally have a relatively low cost compared to other broadband communications technologies (e.g. fixed broadband networks) [6]–[8]. However, the economic viability of 5G can be challenging in low demand areas, mainly to satisfy strict high capacity, low latency performance requirements [9]–[12].

Currently, the key use cases of 5G include enhanced mobile broadband (eMBB), ultra-reliable and low latency communications (uRLLC), and massive machine type communications (mMTC) [11], [12]. One emerging technology enabled by 5G is "network slicing," which can support the deployment of shared neutral host networks (NHN) [13]–[15]. A "5G NHN" approach allows a single physical infrastructure to be built using shared spectrum with multiple operators acting as tenants, such as, mobile network operators (MNOs) [16]–[19], Internet service providers (ISPs) [20], [21], communication providers (CP) [22], hospitals, and other private networks [23], [24]. In a "5G NHN" model, each slice tenant has an end-to-end 5G virtual network with all components of a typical wireless network [25]–[30]. Indeed, many researchers have examined the challenges of 5G network slicing [31]–[34]. For example, different business models, deployments, techno-economic feasibility levels and challenges for NHN in private networks have been examined, with an approach based on a NHN with spectrum being the most cost-efficient option [35].

Currently, 5G network sharing strategies can be classified into 4 broad types: "No Sharing", "Passive Sharing", "Active

Sharing" and "5G NHN". 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 "5G NHN" the operators share all passive and active components between themselves and other potential slice tenants.

Recent advancements in mobile broadband connectivity have greatly benefited societies and the wider global economy. However, rural Internet connectivity remains limited for various reasons including monetary, policy, regulatory, and technological constraints [10], [36], [37]. Indeed, despite almost two-thirds of the world's population now being connected to the Internet, many users are still underserved and experiencing poor broadband connectivity. More often, it is the rural and remote areas that experience poor broadband services, if coverage is even offered at all. Thus, building wireless broadband infrastructure is a pressing economic development issue [6], [38]. However, this needs to be supported by evidence exploring cost-efficient ways to invest the limited financial capital available, ensuring the right technologies and business models are selected to maximize societal benefits [39], [40].

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 [41], [42], 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 [43], [44]. 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 [44], [45].

In such a circumstance, where the rural community has an existing basic telecommunication network, the key questions are:

i How should the network be upgraded to a future cellular generation (such as 5G/6G)?
ii 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.

This paper is organized as follows: Section II provides an overview of the literature on different 5G network sharing strategies, followed by the techno-economic feasibility method. Section III qualitatively explores the rural "5G NHN" business model, along with other sharing options for an incumbent MNO. Next, Section IV presents a quantitative theoretical techno-economic assessment of network sharing in rural areas. Section V discusses the advantages and challenges of the business models appraised in terms of helping to reduce the digital divide. Finally, Section VI provides paper conclusions and relates the findings more broadly to UN SDG Target 9c.

II. LITERATURE REVIEW

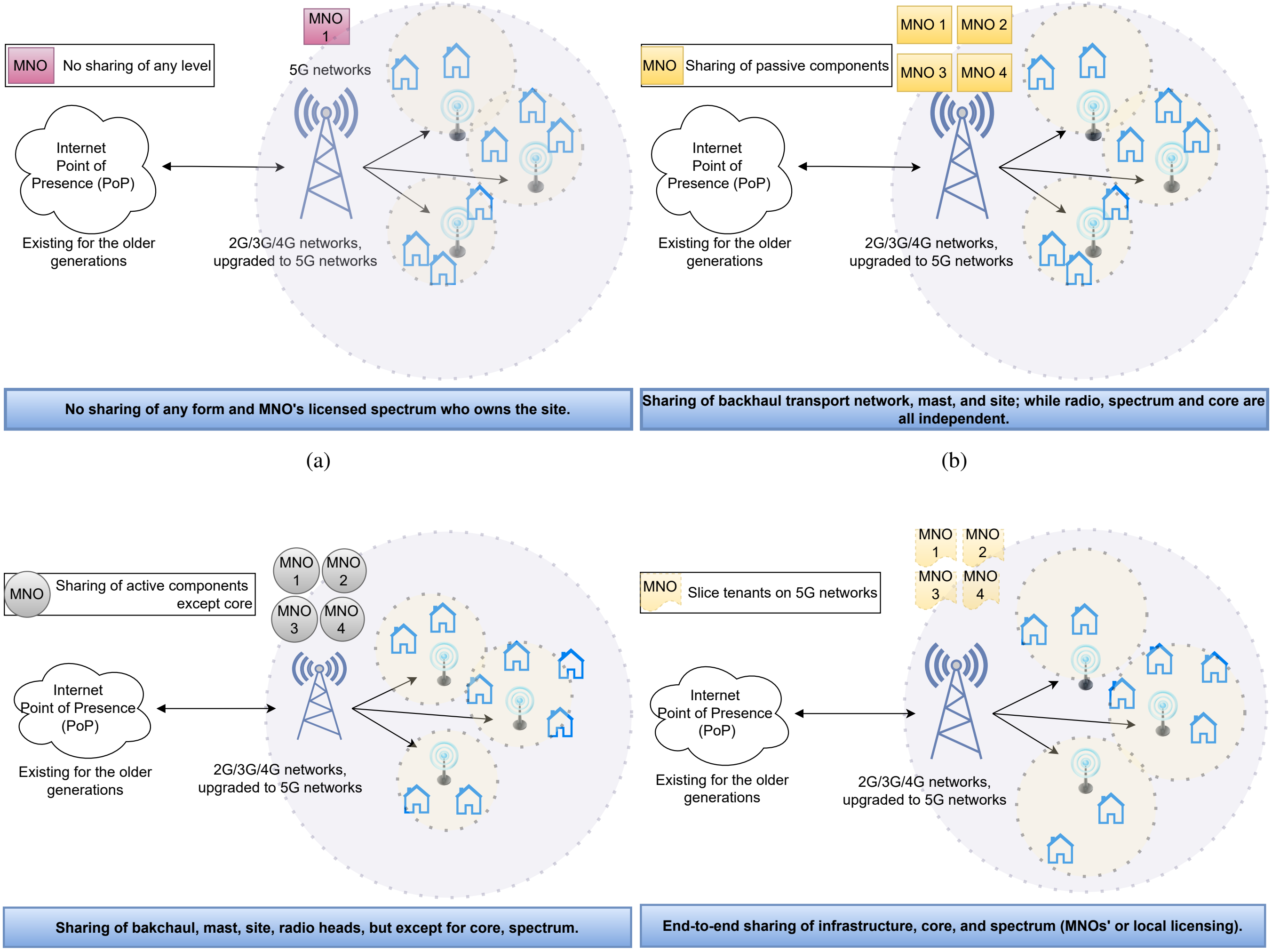
Many studies have investigated the costs of deploying and operating a nationwide 5G network and concluded that changes to rural telecommunication business models will drive enhanced connectivity [45]–[47]. Furthermore, a key observation is that MNOs take a long time to deploy near-ubiquitous coverage 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 [48], [49]. Hence, there is a need to explore different network-sharing strategies to minimize the digital divide and bring the next-generation of cellular technology to rural areas (e.g., 5G/6G).

Studies in the literature have shown that 5G infrastructure sharing is beneficial to MNOs in places where the population density is very high or low [50], [51]. 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 [52]–[55]. 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 "5G NHN".

Figure 1a shows the network architecture for a "No Sharing" strategy. In this strategy, the incumbent MNO has full control over the network and its equipment from end-to-end. There is no competition over the quality of the service (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 [56].

Figure 1b shows the network architecture for a "Passive Sharing" strategy. It 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 towards the goal of reducing the overall cost and agree upon a common cell plan. The key challenge with this strategy is finding operators with similar goals in terms of parameters such as location, material of sites, tower height, network protection, and backhaul capacity requirements [56], [57].

Figure 1c shows the network architecture for an "Active Sharing" strategy. It 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,



(a) (b)

(c) (d)

FIGURE 1: Network architecture of various sharing strategies of 5G upgrade: (a) No Sharing; (b) Passive Sharing; (c) Active Sharing; (d) 5G NHN

that is, each operator uses their licensed bands. This method is preferred by the operators who have long-term contracts with each other and have a clear laid out agreement regarding the 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 would act as a threat to disrupt the balance [58].

Figure 1d shows the network architecture for a "5G NHN" strategy. It 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 [8], [14], [56]. 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 along with the operators to use the network [14], [59]. The key challenges of this strategy are similar pricing plans, a shift in competition, pricing strategies, resource allocation, and security of data on their slice [60]–[62]. The key to the successful upgrade of the 5G network using "5G NHN" is cooperation among the slice tenants and their corresponding resource allocation schemes [14], [53], [63]. The widespread usage of this technology lies in the usage of slicing capabilities offered by the network, and its security aspects [64], [65].

The business models and the revenue generating streams for the MNOs using 5G network sharing strategies are described in the literature [66]–[68]. A preferable first option for operators may be “No Sharing”, as it would enable absolute control over network capacity resources [56], [69]. However, this is not always economically viable because reason’s such as the required investment, existing debts, and potential revenue. Therefore, operators may choose to explore other sharing strategies [10], [58]. In the “5G NHN” case, the approach supports MNOs, private networks, ISPs, and other potential tenants to co-exist without interfering with each other’s operations. Horizontal slices support use-cases while the vertical slices support multi-tenancy [27], [36], [70]. A survey of ongoing research on neutral host networks suggests that a 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 [71]–[73].

Typically, each rural location has a unique set of business models and network feasibility conditions. These depend upon a range of factors, including population density, per capita income, the adoption rate, local business composition, fibre backhaul availability and existing competition among operators [74]–[76]. 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.

In recent years, techno-economic assessments have been trying to include additional simulation parameters which better match real-world deployment conditions [20], [43], [77]. 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 [78], [79]. Indeed, operators in many markets around the world have been experiencing static or declining revenues, while also being saddled with large existing debt payments [80]–[82]. Thus, there has been the need for MNOs to seek newer 5G revenue streams as explored in many research papers [35], [43].

With a weak economic outlook for MNOs, but also the need to invest in new infrastructure, the willingness for operators to share assets is increasing [16], [83], [84]. Many of these studies focus on urban deployment scenarios or specific vertical use cases. 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.

III. METHOD

This section will detail a method for answering the research question. For this study, the existing backhaul could either be wireless or wired technology that may also require upgrading. We focus on solutions with sustainable data rates higher than 30 Mbps per user, with peak cell capacity of more than 150 Mbps for low-frequency bands (<1 GHz) and more than 1500 Mbps for high-frequency bands (<6 GHz) [85].

Techno-economic assessment can help determine the technical and economic requirements for the profitability of successful infrastructure deployment strategies [86]. Thus, Figure 2 illustrates the techno-economic modeling 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.

The incumbent operator is treated as having four key sharing strategies to select from, depending upon the overall cost requirements in terms of capital expenditure (CAPEX), operational expenditure (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 [87], [88].

A. CAPACITY ASSESSMENT MODULE

The capacity assessment module helps to estimate the current level of available data traffic that existing assets are capable of transporting. Initially, the incumbent operators need to assess the sites that require upgrading and their parameter requirements, such as spectrum, bandwidth, latency, 5G key parameter indicators (KPI), network congestion during busy hours, and throughput. The number of site upgrades necessary can be estimated based on the potential future subscribers of the network and other possible slice tenant applications [10], [87]. The number of sites that would require upgrading varies depending on the sharing strategies, demand assessment, and the 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, speed, data rates, busy hours congestion speed, the population that it serves, coverage area, technologies supported, user plane and data plane controls, servers and other network performance indicators. With this information, it is possible the incumbent operator can analyze existing assets in detail. It is important to maximize the use of existing infrastructure during rural network upgrades to keep costs down [20], [67], [69].

Assume, that there are N incumbent operators, each having $x_{mc,i}$ macro cells and $x_{sc,i}$ small cells, such that $i \epsilon N$ in the region of interest. Then, the total number of the macro cell, x_{mc}, and small cells, x_{sc} in the region of interest is given as:

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

Let A km^2 be the area of study region for the network upgrade, which has a population of P. The overall site density,

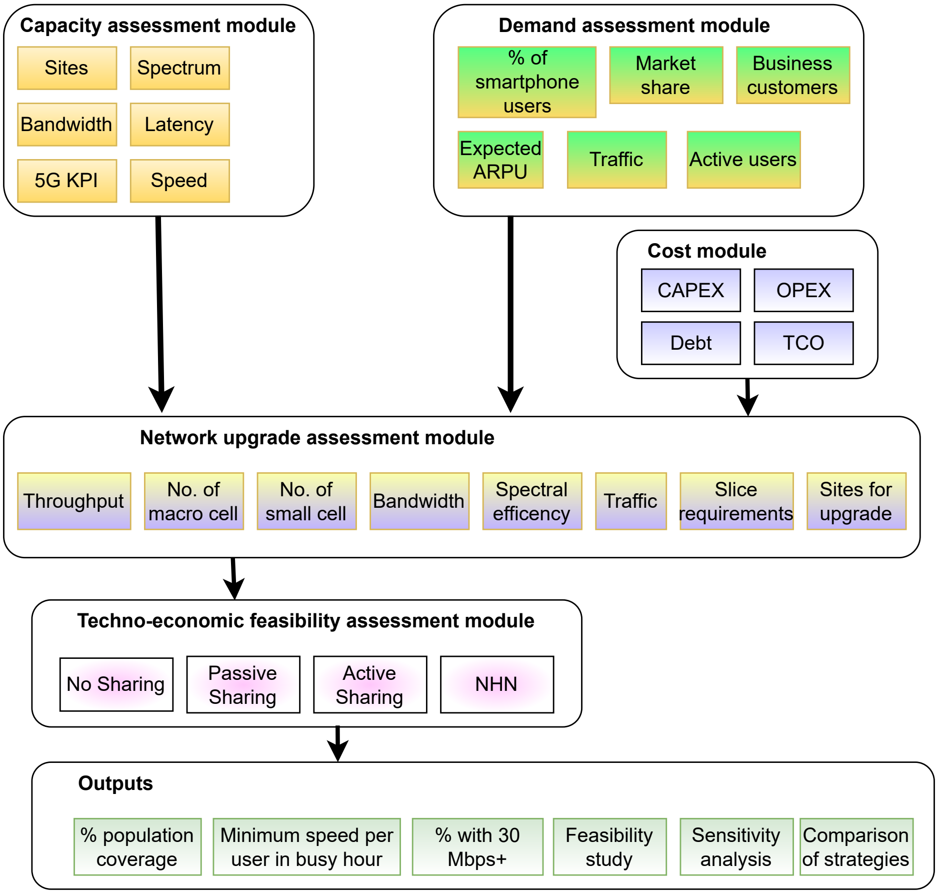


FIGURE 2: Techno-economic modeling for the assessment of 5G upgrade using different sharing strategies

ρ_{site}, is given as

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

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

$$\begin{aligned} \beta_{mc,site} &= \frac{A}{x_{mc}} \\ \beta_{sc,site} &= \frac{A}{x_{sc}} \end{aligned} \tag{3}$$

The channel capacity, C bits/sec of the existing site, is estimated using bandwidth B, signal-to-noise ratio (γ), and spectral efficiency, S.

$$C = Blog_2(1+\gamma) \tag{4}$$

B. DEMAND ASSESSMENT MODULE

Data traffic demand is estimated by determining market share, anticipated smartphone users or other business customers, population distribution, active users exchanging traffic at peak times, and amount of traffic per user, as well as the amount of traffic per user [89]. Rural areas tend to have a small number of settlements, although there are a few outliers [7]. The demand estimation also includes business customer data and throughput requirements for potential end-user applications, including internet of things (IoT) devices or other technologies for health, energy, transportation, etc. [90]. 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 [67]. This situation, however, has considerable uncertainty, which requires scenario analysis [10]. Finally, compared to consumers, business customers are typically expected to pay higher subscription rates (which may translate into more reliable service) [59].

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 module'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) [66], [84]. 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, there is a need to include the data obtained from the demand assessment module. Let the expected average user traffic be given as δ_t GB/user/month, such that, $t \epsilon T$ $(T = T_2 - T_1)$. Then, the data consumed per day per user, $\delta_{t,day}$ MB/day, is:

$$\delta_{t,day} = \frac{1}{30}\frac{1}{1000}\frac{1}{(T_2 - T_1)}\sum_{t=T_1}^{T_2}\delta_t \tag{5}$$

Accordingly, the data consumption during the busiest hour of the day is denoted by B_{HF}, $\delta_{t,day,busy}$, and is estimated as:

$$\delta_{t,day,busy} = B_{HF}\delta_{t,day} \tag{6}$$

The minimum data speed required per user ζ in Mbps using $\delta_{t,day,busy}$ MB/hour (1 Byte (B) has 8 bits (b) and 3600 seconds in one hour), is calculated as:

$$\zeta = \frac{8}{3600}\delta_{t,day,busy} \tag{7}$$

Then the population density, ρ_{pop} for the study area A with population P, is estimated as:

$$\rho_{pop} = \frac{P}{A} \tag{8}$$

Typically, $x\%$ of the P, would be the number of subscribers for a service. Hence, the subscriber density, ρ_{sub} is estimated as:

$$\rho_{sub} = x\rho_{pop} \tag{9}$$

Finally, the area traffic T_{area} is estimated as,

$$T_{area} = \zeta\rho_{sub} \tag{10}$$

C. COST MODULE

The cost module includes 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 $\omega_o$over this time horizon [86].

Unlike other studies which exclude current asset debts, this assessment also includes a nominal existing debt per site, ω_d, which is closer to what is experienced in reality. CAPEX includes the cost of the radio equipment upgrade, backhaul upgrade, and any labor, a small edge cloud site, and any core network upgrades necessary. Also, there is a need to upgrade the backhaul capacity to support 5G data rates. The backhaul cost is split between CAPEX and ongoing OPEX. By adopting this parameter, analysts can more accurately reflect the level of debt owed to each operator. OPEX includes the cost of power, equipment, administrative operations, core network maintenance, and edge cloud maintenance. Therefore, the modified TCO for this study is

$$\omega = \omega_c + \omega_o + \omega_d \tag{11}$$

D. NETWORK UPGRADE ASSESSMENT MODULE

The 5G network assessment module estimates the upgrade infrastructure requirements for future assets. This module 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 acclimate the resources they lease on a near-real-time basis [56], [63]. In addition, the incumbent may also need to account for upgrades to support potential future tenants.

The data for a 5G site is calculated using the equation given below:

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

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), $Q_m^i R_{max}$ is the modulation order, f^j is the scaling factor, 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 bandwidth BW, T_s is the symbol time, and O_h is the overhead.

The total number of sites required for the upgrade is subject to the existing coverage areas and network sharing strategy. For example, in the "No Sharing" strategy, most of the macro and small cells will need an upgrade to 5G to meet network requirements. Meanwhile, a 5G NHN sharing strategy would require the smallest number of sites for the upgrade, since it aims to increase coverage (β) and speed (C_{5G}) while minimizing the number of towers that require an upgrade.

Let γ be the number of towers that require a network upgrade and ω be the TCO of the network upgrade. The key optimization equation which needs to be solved here is:

$$\begin{aligned} \min_{x_{mc},x_{sc}} \quad & \omega \\ \text{s.t.} \quad & maximumCoverage \\ & \zeta > C \\ & \gamma \leq x_{mc} + x_{sc} \end{aligned} \tag{13}$$

E. TECHNO-ECONOMIC FEASIBILITY ASSESSMENT MODULE

This module performs the feasibility analysis of the possible sharing options for each rural 5G business model. The results of the network upgrade assessment module, 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 module, thus producing the key assessment result metrics. For analyzing the profitability of the network upgrade to 5G using different sharing strategies, the net present value (NPV) method is used. The revenue per

TABLE 1: Simulation parameters

Parameter	**Value**	**Unit**	**References**
Customer growth rate	4%	% per year	[41], [67]
NPV discount factor	4%	%	[41]
Investment duration	10	Years	-
Number of MNOs	4	-	-
Busy hour factor (B_{HF})	0.15	-	[91]
Population	15,000 to 60,000	-	
Take-up	40%	%	[67], [92], [93]
Subscription growth rate	3%	%	[36], [67]
ARPU for 5G wrt 4G	+20%	%	[67]
ARPU - retail subscribers	\$10 to \$60	\$	[94]
ARPU - business	\$100 to \$500	\$	-
Expected average user traffic	50	GB/user/month	-
SNR (signal to noise ratio)	30	dB	[43]
Spectral efficiency	30	bits/Hz	[43]
Modulation	TDD/ FDD	-	-
Capacity macro cell	177 (800 MHz, 10 MHz BW)	Mbps	[85]
Capacity small cell	1,752 (3600 MHz, 100 MHz BW)	Mbps	[85]
Existing bad loan	5% of TCO for 5G upgrade	% per site	[95]
Backhaul (macro cell, small cell)	\$10,000, \$5000	\$ per site	[57], [86]
Infrastructure upgrade macro cell	\$30,000 to \$45,000	\$ per site	[57], [86]
Infrastructure upgrade small cell	\$7,000 to \$12,000	\$ per site	[57], [86]
OPEX	\$800 to \$2500	\$ per site, per year	[57], [86]

year δ_i such that $i \,\epsilon\, T$, and the total revenue, δ, over the period T for ARPU Ψ_{5G} for 5G services are calculated as:

$$\begin{aligned} \delta_i &= 12\rho_{sub}(\Psi_{5G} - \Psi_{old}) + 12\rho_{new5G}(\Psi_{5G}) \\ \delta &= \sum_{i=1}^{T} \delta_i \end{aligned} \tag{14}$$

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. The δ_i grows each year at the rate r_{sub} as new subscribers are added to the network each year. The cash flow for year i, α_i such that $i \,\epsilon\, T$, is estimated as:

$$\alpha_i = \delta_i - \omega_i \tag{15}$$

where ω_i is the cost per year towards the upgrade. The incumbent operator would upgrade the network sequentially to match the network demand and earn higher revenues. The NPV ρ with a discount factor r is calculated as:

$$\rho = \sum_{i=1}^{T} \frac{\alpha_i}{(1+r)^i} \tag{16}$$

F. OUTPUT

Finally, the appraisal outputs focus on population coverage in rural areas: the minimum provided speed per user in the busy hour, the percentage of subscribers with 30+ Mbps peak speed, an NPV feasibility analysis, and 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 [59], [67], [78]. 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 [10], [79], [96]. Further, rural telecommunication deployment could be made more affordable by lowering TCO.

IV. RESULTS

In this section, the results are reported using the methodology illustrated in Figure 2. The overall TCO is calculated for a 5G network upgrade over a time horizon of 10 years.

A. DESCRIPTION OF THE STUDY AREA

Consider a rural study area of 500 km^2 with interspersed low population density villages, for the time period of 2023-2032. For the 5G network upgrade, both small- and macro-cell strategies are considered. We treat:

- macro cells as providing coverage up to 3 km,
- small cells at a mid-band frequency covering up to 1 km and
- small cells with high millimeter-wave frequencies covering up to 100 m.

Small cells cost less per site and offer higher speeds than macro cells. The number of small cells required per square kilometer is significantly higher than that of macro cells. The CAPEX and backhaul depreciate at a 3% rate, while the OPEX and debt payment would appreciate each year at 5% and 2% respectively [41]. The channel bandwidth depends upon the available spectrum frequency of operation as shown in Table 1.

Governments globally target 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 [76]. Therefore, in this study, we consider a minimum average data speed of 30 Mbps per user and data consumption of 50 GB/month

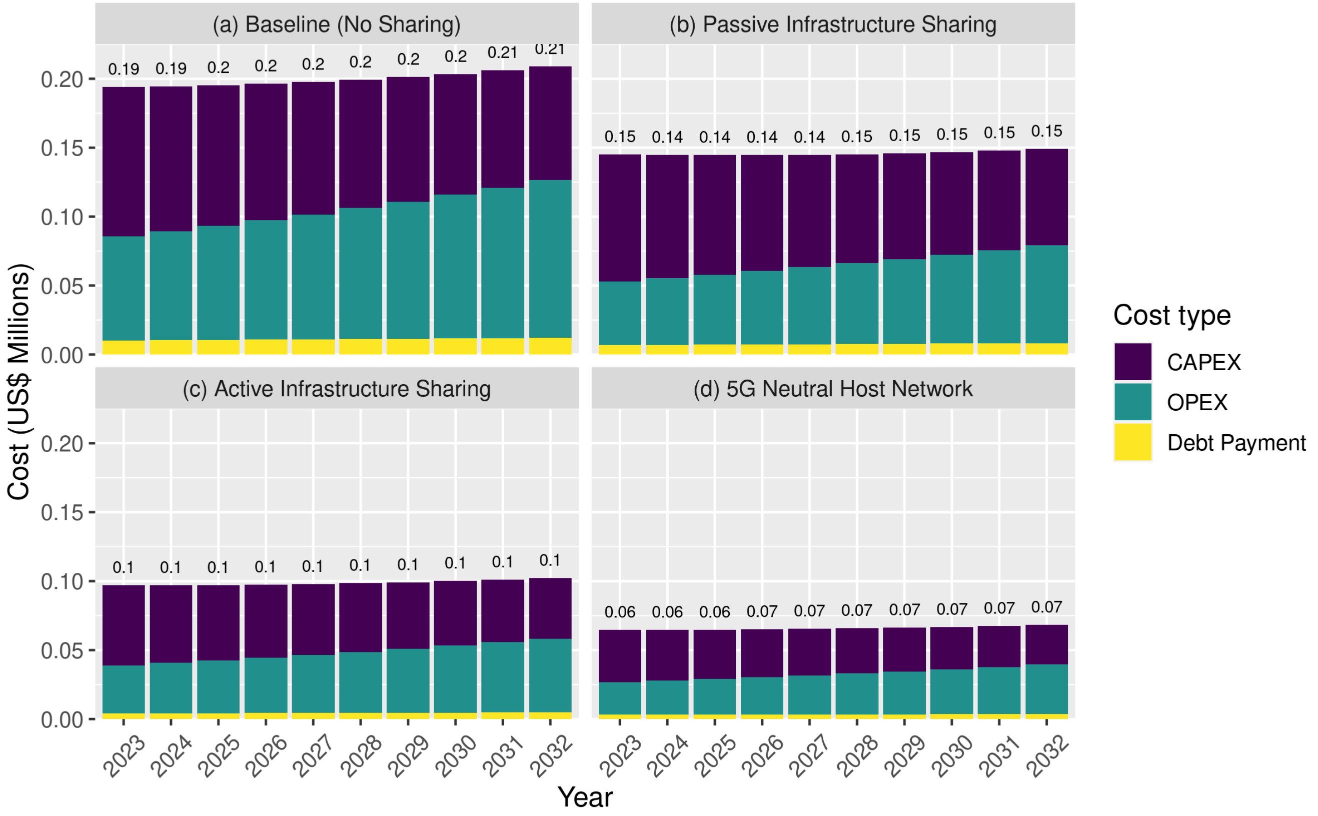


FIGURE 3: CAPEX-OPEX estimation per year for various strategies in the region of interest

per user. Table 1 shows the modeling conditions for the study location and its simulation parameters, along with the cost for various components required for the 5G upgrade.

B. COST SAVINGS FOR DIFFERENT SHARING STRATEGIES

From Table 2, 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 cost reduces compared to the baseline scenario as the physical site locations and other passive components are shared among all the operators, whereas the radios, spectrum, hardware, and core are not shared. Furthermore, in a “Active Sharing” deployment, the operators deploy a lower number of radios and hardware components compared to “Passive Sharing” that brings the cost further lower. Finally in the “5G NHN” deployment, the overall 5G network upgrade cost reduces further as end-to-end components are shared by all operators in the entire study area. In the last strategy, all the MNOs would lease slices from the incumbent MNOs and ideally provide services at all sites.

Note that a NHN has higher equipment capabilities which need to be satisfied, due to 5G security and dynamic slicing aspects, as multiple MNOs are on the network infrastructure simultaneously [64]. Hence, the single site cost for upgrading to the “5G NHN” strategy is the most expensive.

TABLE 2: Number of physical cellular sites per sharing strategy

Strategy	Macro cells	Small cells
“No Sharing”	16	40
“Passive Sharing”	4	10
“Active Sharing”	4	10
“5G NHN”	4	10

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. The MNOs prefer different sharing strategies depending on the existing demand and resource utilization. Technically, 5G is expected to support 1 million connected devices per km^2 [13], although this is a high-level target. In this evaluation, x is a 40% take-up rate [97], and the rural region of interest is treated as having between 1,000 to 25,000 mobile subscribers, along with thousands of devices for private networks and IoT applications. The upgraded 5G network would predominantly help to provide eMBB in rural areas while supporting other 5G rural applications relating to vertical sectors, such as health and transportation.

Figure 3 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 around

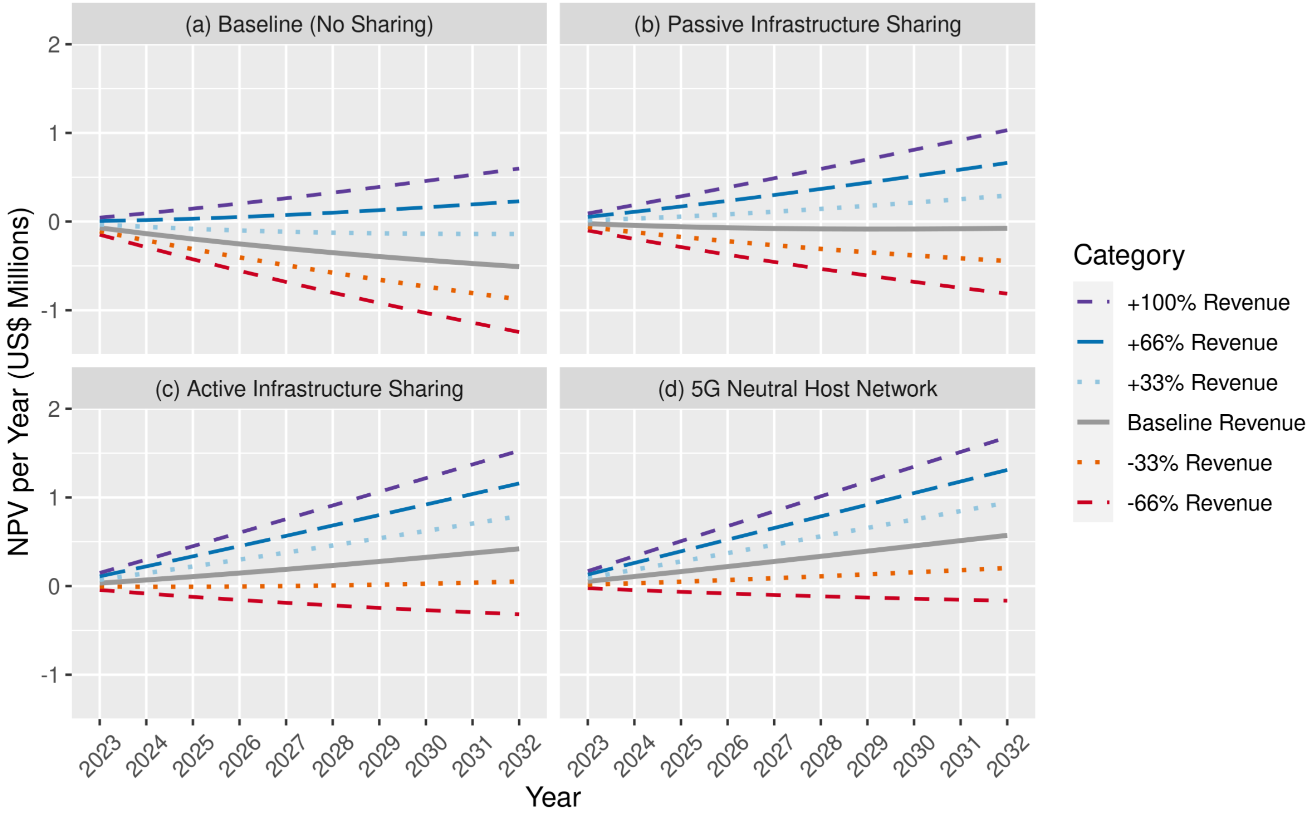


FIGURE 4: 5G SC + MC upgrade using various strategies in the region of interest with varying revenue sensitivities compared to a base scenario ARPU $30

$1,996,791, for “Passive Sharing” around $1,459,224, for “Active Sharing” around $994,446 and for “5G NHN” around $659,864. Figure 3 and Table 2 show that for an incumbent MNO, the cost of upgrading to a rural “5G 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 3 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 “5G NHN” provides impressive cost savings of around 35-50% against the baseline scenario.

Additionally, Figure 3 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 a “5G NHN”, respectively. Also, Figure 3 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.

C. BUSINESS CASE ANALYSIS USING NPV AND SENSITIVITY ANALYSIS

Figure 4 shows the sensitivity of the NPV by varying the revenue from -66% to +100% of the baseline value, with a customer 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 4 illustrate that the “5G NHN” business case is better 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 customer base needs to be very high per cellular site, say above 3300 subscribers in the study area. As the ARPU increases, say at $60, the required number of subscribers could reduce to as low as 550 in the “5G NHN” strategy for rural areas. The base scenario is calculated with a monthly APRU of $30 per subscriber. All sharing strategies’ business models are feasible when the ARPU is higher than $40.

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 required to upgrade. The estimates also demonstrate the difference in the return on investment (ROI)

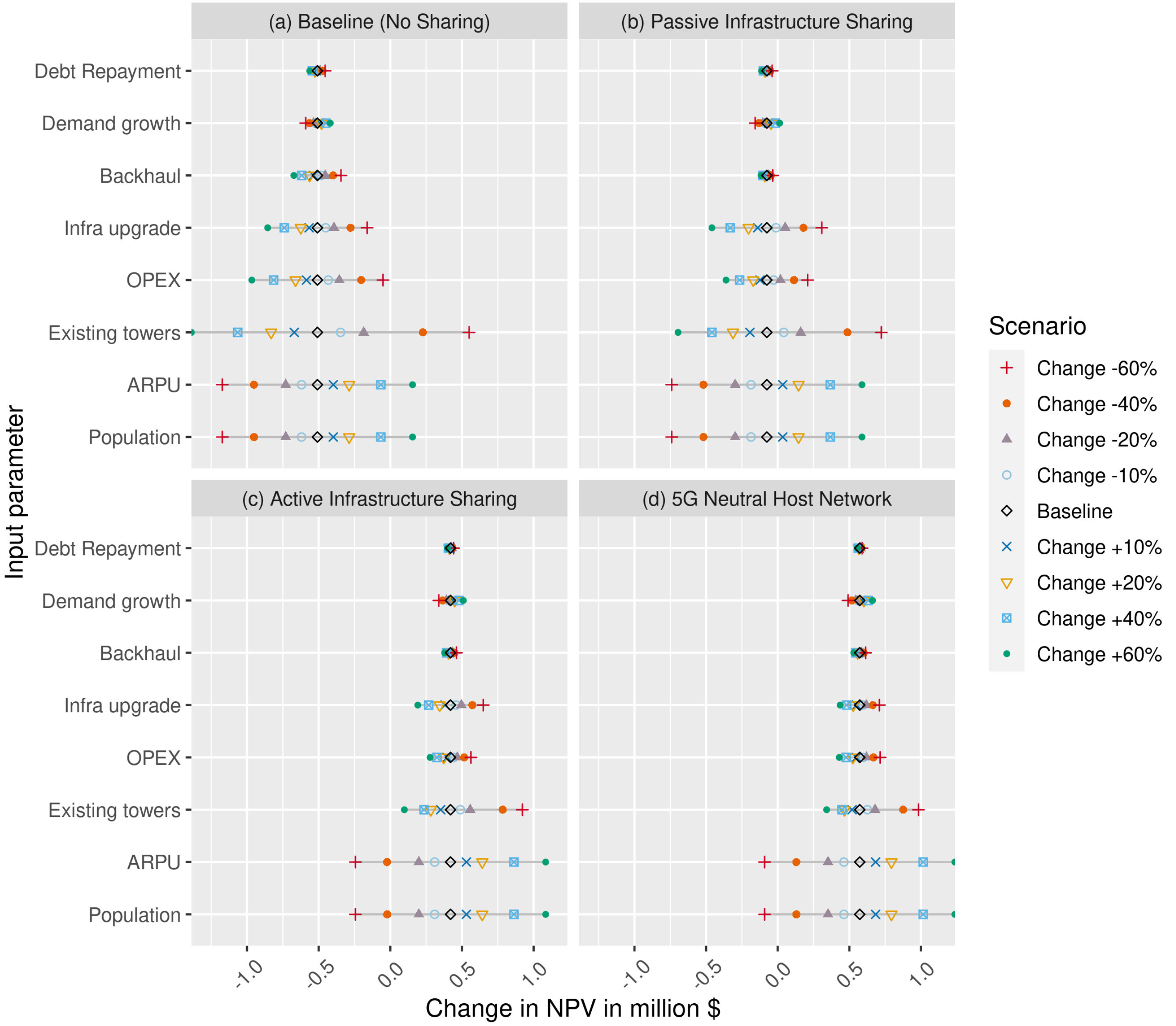


FIGURE 5: Sensitivity analysis of sharing strategies

for each 5G sharing strategy. Figure 4 shows that at $30, the ROI is negative for "No Sharing" and "Passive Sharing", whereas the ROI is positive for "Active Sharing" and "5G NHN". Figure 5 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 by 2 times in "Passive Sharing", 4 times in "Active Sharing", and 5 times in "5G NHN" compared to the NPV of the baseline scenario ("No Sharing"). Similarly, when the existing infrastructure increases by 10%, the NPV increases by 2 times in "Passive Sharing", 3 times in "Active Sharing" and 3 times in "5G NHN" 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.

V. DISCUSSION

The investment cost of the 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. 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 of the four strategies:

- **No Sharing** is suitable when there is high revenue potential for incumbent MNO services in a rural area. The

MNO would want to retain the monopoly of being the 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 demand for services is moderate, but there is healthy competition among a few operators. 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 cost while hopefully also improving business case feasibility.
- **Active Sharing** is an appropriate option when the demand for digital connectivity is low to moderate, and operators would like to complement each other's services. One example may include the provision of 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 in this instance.
- A **5G NHN** is the most advanced network sharing configuration and is suitable if multiple operators have a degree of trust in each other. Though it is the most cost-effective strategy, the operators leasing resources from the incumbent MNO need to be able to rent these resources at a fair price, along with having confidence in longer-term price expectations. This solution is the most viable for areas with low subscriber counts and, it could also cater to the full range of 5G applications. Equally, this could also be a sensible option in very high-traffic areas where a single neutrally hosted network may provide a more optimal engineering design, thanks to reduced interference and improved cell coordination [41], [84].

Given the interest by MNOs in 5G infrastructure sharing, the proposed business model strategies for rural areas could prove to be attractive options in areas of very low or very high data traffic. 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 via simple access agreements or bespoke special purpose vehicles. These models may differ considerably by context, in extremely high-density places (such as stadia, campuses, seaports, etc.) or rural areas with very low viability.

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 the industry moves towards 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 towards 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.

VI. 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 "5G NHN"). The evaluation considered the total cost of ownership over ten years for a generic rural area. In contrast to many other 5G techno-economic studies, the assessment accounted for the existing basic infrastructure and the level of operator indebtedness.

The results indicate that the "5G 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 9c 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 digital connectivity, the aim to deliver affordable universal mobile broadband to all by 2030 will be more challenging.

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