



HAL
open science

Infrastructure Sharing Strategies for Wireless Broadband

Shruthi Koratagere Anantha Kumar, Edward J Oughton

► **To cite this version:**

Shruthi Koratagere Anantha Kumar, Edward J Oughton. Infrastructure Sharing Strategies for Wireless Broadband. 2022. <hal-03840278>

HAL Id: hal-03840278

<https://hal.science/hal-03840278v1>

Preprint submitted on 5 Nov 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Infrastructure Sharing Strategies for Wireless Broadband

Shruthi Koratagere Anantha Kumar, *University of Strathclyde*, Edward J Oughton, *George Mason University*

Abstract—There is a growing need to provide high-speed wireless broadband to deliver mobility for an increasing number of global Internet users. However, there are a variety of engineering-economic challenges associated with this endeavor. Therefore, an emerging zeitgeist of the modern telecommunications era is the concept of *infrastructure sharing*. While this approach has existed for many decades, there has recently been growing interest by both network operators and governments, who share the joint aspiration of reducing costs and increasing broadband coverage. In this article we firstly explore *where* infrastructure sharing can take place, *how* these strategies can be implemented in practice, and *who* are the key enablers. Secondly, we report on a techno-economic viability assessment of rural 5G infrastructure sharing strategies, for four major approaches, which include Business-as-Usual (No Sharing), Passive Sharing, Active Sharing, and a Neutral Host Network (NHN). The findings suggest that any network sharing strategy has a higher Net Present Value (NPV) of between 20-90% compared the baseline strategy (*No Sharing*). In particular, a NHN approach can help reduce deployment costs by 10-50% compared with other strategies for providing rural wireless broadband.

Index Terms—Infrastructure sharing, broadband, wireless broadband, 5G, neutral host.

I. INTRODUCTION

INTERNET connectivity has become a pervasive need across society and the economy, driving demand for reliable, high-speed wireless broadband services. For example, it is now commonplace for many consumers to use wireless broadband to access a wide range of online services, from finance and virtual education to video calling and remote work activities.

The traditional approach for wireless broadband infrastructure deployment involves each network operator deploying and managing their own independent networks to provide broadband connectivity in a region. For example, Mobile Network Operators (MNOs) and Internet Service Providers (ISPs) sell their services to retail customers, businesses and the wholesale market. However, this traditional deployment method is both capital and labor-intensive, especially to install, maintain and repair [1].

While there are many wireless broadband connectivity issues in rural and remote locations [2], there are also challenges in other settlement locations. For example, in dense urban and suburban areas, connectivity can often still be poor, especially when existing infrastructure is operating at (or near) maximum capacity constraints [3]. Indeed, as adoption rates and data consumption per user increase, existing wireless infrastructure assets become saturated. Such bottlenecks lead to a severely

reduced quality of service for broadband users as demand exceeds the capacity provided by the existing network assets.

Regardless of broadband being crucial for economic development, in many locations, it is unfortunately not always economically viable for operators to deploy the necessary infrastructure via market-based methods [4]. Although there are many factors that affect the 'digital divide', including demand-side adoption aspects, the lack of supply-side infrastructure is a major contributor to this phenomenon. Very often, disparities in broadband infrastructure are a result of low population density and/or weak adoption. Thus, these areas are a poor priority for economically rational network operators to target for new broadband infrastructure deployments or upgrades. These major factors can also be compounded by high deployment costs resulting from low fiber Point of Presence (PoP) availability, challenging terrain, and the ongoing operational cost of network maintenance in these environments.

The consequence of these market failures mean that some citizens and communities can be disproportionately affected by these infrastructure disparities [4]. Indeed, the United Nations' Sustainable Developmental Goals include Target 9c, which aims to ensure everyone has access to affordable universal broadband by 2030. If achieved, such a goal will be particularly beneficial to those in the hardest-to-serve areas (predominantly in rural and remote locations).

Major engineering-economic factors in the telecommunication industry are now calling into question the traditional infrastructure deployment model utilized in recent decades. Consequently, there is renewed interest in new cost reducing strategies, such as infrastructure sharing [5]. Currently, to overcome capacity constraints in wireless broadband networks, regardless of urban or rural locations, a network operator has to choose from three capacity-expansion upgrade strategies.

Firstly, additional spectrum can be added to sites to provide greater bandwidth for packet transfer. Secondly, the network technology in use can be upgraded to a more spectrally efficient option (e.g., from 4G to 5G, or from Wi-Fi 5 to Wi-Fi 6). Finally, as a last resort (due to the expense), an operator may decide to partition an existing cell area and build a new site. Thus, increasing the network site density, level of spectrum reuse, and the overall available capacity. However, if none of these options are economically viable, then operators may need to consider other business model approaches. One of these strategic approaches is *infrastructure sharing*.

In this paper, we first present a general overview of infrastructure sharing for communications engineers in Section 2, considering *where* this strategy can take place, *how* different approaches may be pragmatically implemented, and also *who*

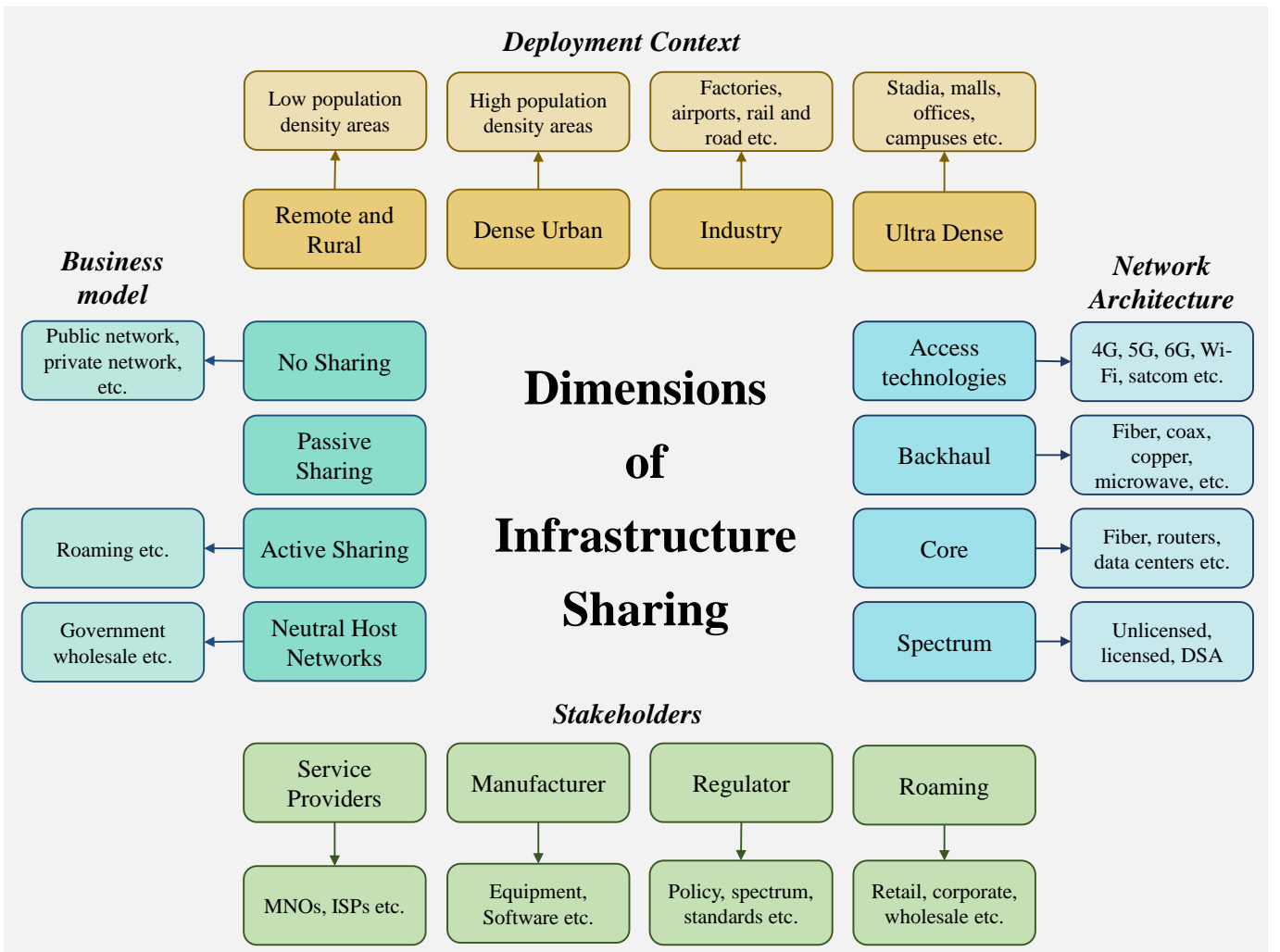


Fig. 1: Dimensions of infrastructure sharing strategies for wireless broadband

the stakeholders may be that are involved in such an endeavor. Secondly, in Section 3 we provide quantitative insights on the results generated from a techno-economic viability assessment of rural 5G infrastructure sharing strategies.

The content described is part of ongoing research studying the viability of infrastructure sharing strategies, exploring the impacts of various deployment scenarios, capacity targets, and realistic factors affecting investment (e.g., network operator debt levels) [6]. A large focus is placed on how different sharing strategies affect the economic viability of new 5G infrastructure upgrades in rural areas. Existing deployment models may perform poorly in these situations, highlighting the need for new technology and business model innovation.

II. DIMENSIONS OF INFRASTRUCTURE SHARING: WHERE, HOW AND WHO?

Wireless broadband infrastructure can be deployed and operated by a variety of entities, including MNOs, ISPs, companies in various industry verticals, third-party trusted companies, community network providers, or governments [7]. There is a wide range of motivating factors for these entities, from profit-seeking MNOs, ISPs, and other private companies,

to those with strong social objectives, such as community network providers and governments.

Private network operators usually take a rational infrastructure investment approach and deploy network assets based on the ratio of investment against potential profit, given the level of demand in the area. In contrast, those deploying wireless broadband assets to achieve social objectives may take an antithetical approach, instead targeting only those areas which are not economically viable via rational market-based infrastructure delivery. Figure 1 shows the many dimensions of infrastructure sharing strategies for wireless broadband delivery. These include the following four interrelated factors.

A. Deployment Context

There are numerous contexts where infrastructure sharing may be an attractive strategy. For example, this article covers in-depth the ability of network operators to enact various levels of sharing across heterogeneous electronic and non-electronic assets. Indeed, in a challenging rural deployment context, the ability to share costs helps network operators improve the economic viability of their investments. Moreover, cost sharing also helps in reducing network operator risk and exposure to

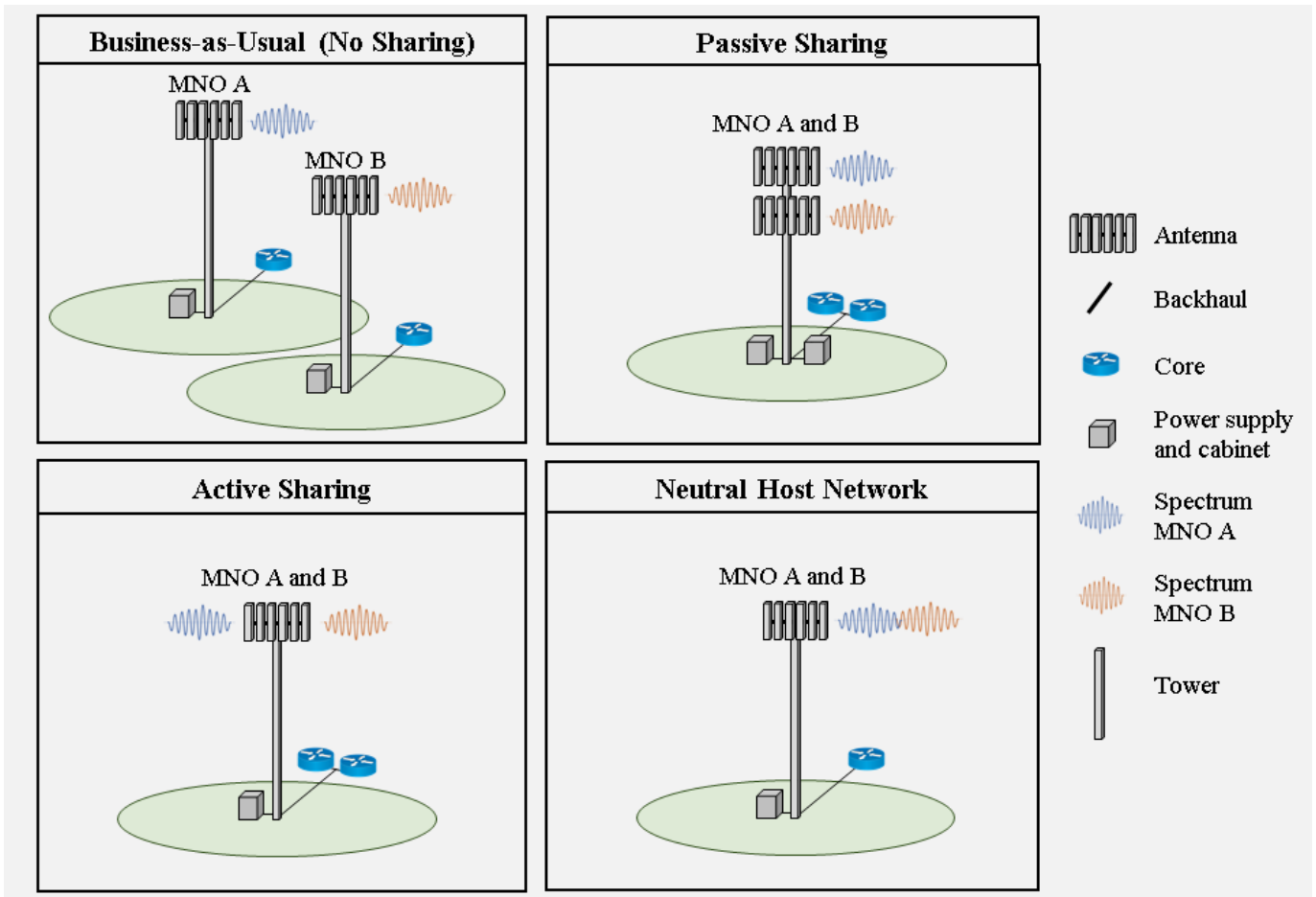


Fig. 2: Infrastructure Sharing strategies

demand uncertainty in situations where adoption and average revenue per user (ARPU) are weak.

However, sharing could still be a sensible option in many other contexts, even if there is a strong business case for deploying multiple independent networks. For example, in highly dense urban environments, shopping malls, and stadia, the benefits of a shared network include both improved interference control and more efficient management of the deployed civil engineering assets (as only a single infrastructure owner needs to coordinate with the city government or real estate management company). Another advantage of infrastructure sharing is increased resource utilization.

Moreover, in the case of transportation infrastructure, such as highways or railway lines, there is also a strong justification to be made for network sharing on safety management grounds. For example, this especially might be true in very high-risk situations, such as along high-speed railway lines. Indeed, broadband connectivity is essential for business commuters, but high-speed trains may be traveling at speeds of over 250 km/h. As a result, there are many advantages to sharing infrastructure in a variety of deployment contexts, beyond purely cost-related considerations.

B. Network Architecture

There is a wide range of wireless communication technologies and architectures that are amenable to infrastructure sharing. Indeed, we formally divide this area into four main groupings, which include access networks, backhaul connectivity, core networks, and spectrum resources.

Cellular, Wi-Fi, and satellite technologies broadly comprise wireless broadband access networks. Currently, infrastructure sharing is growing in both the cellular and Wi-Fi network domains. For example, in cellular networks, infrastructure sharing can range from roaming agreements between operators to a fully NHN architecture for providing wide-area coverage to users. In contrast, Wi-Fi access networks are often subcontracted to third parties when deployed to in-building environments (e.g., offices). This provides a single designed and managed connectivity platform for all building users to connect to, offering both Internet access and Wi-Fi calling when cellular coverage is poor.

However, the access network is only one of the main components of the network architecture. Frequently, backhaul connectivity may be shared to enable packet transport to and from a shared access location, to another infrastructure location, such as a fiber Point of Presence (PoP). Indeed, a variety of wireless and fixed backhaul technologies are in use, and thus, available for sharing strategies.

For example, in high-income countries, backhaul for cellular sites is most commonly a fiber optic link or a legacy copper/coaxial cable. Meanwhile, in low- and middle-income countries, a wireless microwave backhaul link (point-to-point or point-to-multipoint) is the most commonly used site backhaul option available for sharing.

In less common cases, network operators may decide to share a core network or even their licensed spectrum resources. Unlicensed spectrum resources are already widely shared by network operators, but this is usually for highly localized delivery (e.g., Wi-Fi) or by niche wireless ISPs operating in rural and remote areas (where the quality of service is delivered on a best-effort basis).

To summarize, the degree to which components in these four network segments are shared (or not), differentiates how the main infrastructure sharing strategies are implemented in practice.

C. Business model approaches

As highlighted in the introduction, the various economic challenges in the telecommunications industry are forcing network operators to explore new business models. Here, we summarize and highlight the main approaches for infrastructure sharing, as visualized in Figure 1. Moreover, Figure 2 provides a detailed architectural example of the differences in sharing strategies, in the case of cellular technologies (e.g., for 5G).

In a *Business-as-Usual (No Sharing)* approach, each operator deploys either a public or private independent network that is operated and owned by this entity. In many markets, such an approach represents the status quo and is popular with network operators in high demand locations because it provides 100% control over any built assets. Moreover, operators have the opportunity to retain all of the generated revenue and profit obtained. In contrast, governments may favor this approach for public broadband networks, when infrastructure asset construction is necessary to expand coverage and achieve infrastructure-based competition.

In a *Passive Sharing* approach, at least two operators share the passive (non-electronic) components, including the site compound and tower. Typically, a joint venture company is created to legally manage the operation, with each operator having a proportional shareholding. This infrastructure sharing strategy is already prevalent in many telecommunication markets and is a proven way for operators to collaboratively reduce costs.

In an *Active Sharing* approach, at least two operators share both passive and electronic components, such as antennas, radios, and baseband units (BBU). Available spectrum resources and the network core are not usually shared. Similarly, a joint venture company may be employed to manage the operation of the assets. To maintain infrastructure-based market competition, regulators may sometimes limit the number of operators who can actively share infrastructure. Roaming agreements are a basic form of this strategy, where operators allow their national or international competitors' customers to roam on their network, extending service coverage.

In a *Neutral Host Network* approach, two or more operators agree on end-to-end network sharing for all passive and active components, and may also include sharing of any spectrum resources and a core network. Increasingly, this type of sharing is gaining popularity, especially for certain environments, such as dense 5G small-cell deployments in urban centers. The infrastructure provider deploys and maintains the NHN infrastructure while other operators become virtual tenants on the incumbent network [8]. Similarly, the network operators can be managed by a NHN management company [3].

This method is being tested and trialed for a wide variety of contexts, including hospitals, densely populated city centers, rural and remote areas, indoor spaces, seaports, airports, and university campuses, as well as many others. Finally, a national wholesale network is also a well-established NHN form, with many examples in fixed and mobile broadband. Often governments take a strong position in directing such a wholesale strategy, either by playing an active role in deploying new broadband infrastructure, or regulating an incumbent operator to provide services based on set prices.

D. Stakeholders

Anyone involved in the telecommunications network is a relevant stakeholder, including network operators, manufacturers (hardware, and software), telecommunication regulators, and the final end-users of any provided broadband services. This section discusses each of these entities, with relevance to their role in infrastructure sharing strategies.

Firstly, service providers include any entities which operate network assets to deliver broadband service, and who may desire to enact network sharing strategies. It could be an MNO, ISP, or other service provider with the key business of transporting user traffic to and from global Internet networks, in return for revenue.

Secondly, manufacturers consist of any entity which builds hardware or software network components to enable network functions. This stakeholder is essential for ensuring that any assets produced are secure, stable, reliable, and provide high-speed services. Manufacturers have an important role in network sharing as they are responsible for ensuring their components can be loosely coupled to support easy interfacing between different vendor devices.

Thirdly, national telecommunications regulators have a key role in formulating and delivering industrial policies that balance economic efficiency and equity considerations. Therefore, they have a key leadership position in encouraging and enabling infrastructure sharing strategies. Moreover, regulators are also responsible for spectrum policy and ensuring efficient allocation of this scarce resource (including designating licensed and unlicensed bands). There is also a key role for regulators in international spectrum and standardization bodies to design and develop technical standards that support infrastructure sharing.

Finally, end-users are the final paying consumers of the provided broadband services, including retail customers, businesses, hospitals, utilities, schools, and local and national governments. Generally, end-users are agnostic to how operators provide broadband services, providing they receive their

desired quality of service. Thus, the average end-user is rarely concerned with which technologies or sharing strategies are implemented unless they feel an operator has failed to provide the service promised at the time of purchase.

III. TECHNO ECONOMIC ASSESSMENT FOR INFRASTRUCTURE SHARING STRATEGIES

Techno-economic assessment (TEA) is a key tool to help network operators and other telecommunication market stakeholders assess the suitability of proposed new technologies, business models, and policies [9]. The success of infrastructure sharing in practice is dependent on operators having adequate market incentives, therefore the techno-economic viability of any strategy is essential to understand. This includes the potential expected return on investment. Here we report the findings of a techno-economic model which evaluates various infrastructure sharing strategies [6]. The input-output structure of the TEA model used in this study is illustrated for reference in Figure 3.

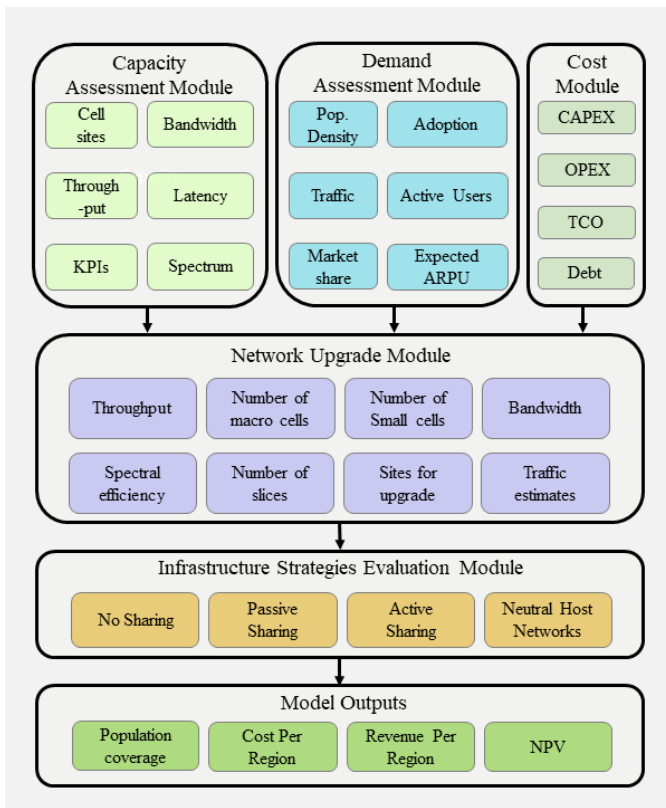


Fig. 3: Modeling methodology

The evaluation focuses on upgrading existing rural cellular infrastructure to target a number of 5G key performance indicators (KPIs). These KPIs include a 10-100x improvement in data rates, with a minimum busy hour download rate of >30 Mbps per user, an increase of 100x devices, 10x lower energy consumption, <50 ms overall latency and support for multiple operators [10]. This is achieved by implementing many of the main technological requirements for a 5G Standalone network based on 3GPP Release 18, including dynamic, secure slice creation capabilities to enable independent and isolated usage

by multiple operators [11]. Additionally, this architecture provides spectrum aggregation and dynamic spectrum sharing among the slicing tenants [12], [13].

Consider a rural area of approximately 500 km² with a low population density. Existing 2G and 3G infrastructure is present but provides poor coverage to sparsely interspersed villages. This is not an uncommon situation in low- and middle-income countries across the globe. For an assessment period of 10 years (2023-2032), the brownfield small- and macro-cells present are both upgraded to 5G to serve end-users with a mean monthly data usage of 50 GB. The model aims to estimate the number of cells needed for each upgrade strategy, which varies depending on the degree of infrastructure sharing, thus altering the supply-side deployment cost.

The main assessment metric used here, the Net Present Value (NPV), represents the present value of all necessary investment and potential future revenue, over the study period. Moreover, a value exceeding zero represents a positive return on investment, whereas a negative value indicates a loss. In Figure 4, the NPV is illustrated for the four 5G network sharing strategies explored, along with a set of revenue scenarios which are relative to the baseline estimate of future generated income. Future revenue is one of the most uncertain parameters, justifying exploration of the sensitivity of this parameter.

The results from the NPV analysis quantitatively demonstrate how the economic viability varies for each infrastructure sharing strategy. Indeed, in Figure 4 for a baseline ARPU of \$30, the NPV is still negative for both the *No Sharing* and *Passive Sharing* strategies, indicating a negative return on investment. In contrast, the NPV is marginally positive in the case of *Active Sharing*, and then substantially positive when implementing a *NHN* strategy.

Thus, infrastructure deployment approaches in challenging rural areas are well suited to using a neutral host. While this strategy provides the best business case based on these quantitative estimates, operators may also find this sharing option reduces their vulnerability to demand uncertainty in weak adoption and/or low ARPU locations. Equally, telecommunication regulators may favor that this strategy enables smaller, local operators to also provide broadband services, lowering the barriers to entry for entities with fewer capital resources.

Additionally, the results in Figure 4 illustrate that the business case for *Passive Sharing*, *Active Sharing* and a *NHN* approach, exhibit a higher NPV of between 10-20%, 20-35% and 35-50%, respectively, against the Business-as-Usual (*No Sharing*) strategy. Indeed, the findings suggest that sharing strategies outperform other non-sharing models by least 15% when matched to comparative revenue and demand conditions.

Furthermore, a sensitivity analysis of future revenue is present in Figure 4, achieved by generating different scenarios relative to the estimated baseline future revenue. Based on the adopted model parameters, the results indicate that increasing ARPU by 33% results in a corresponding NPV increase of 2x when using *Passive Sharing*, 3.5x when using *Active Sharing*, and 4x when using a *NHN* strategy, versus the Business-as-Usual model (*No Sharing*). The wider ramifications of these

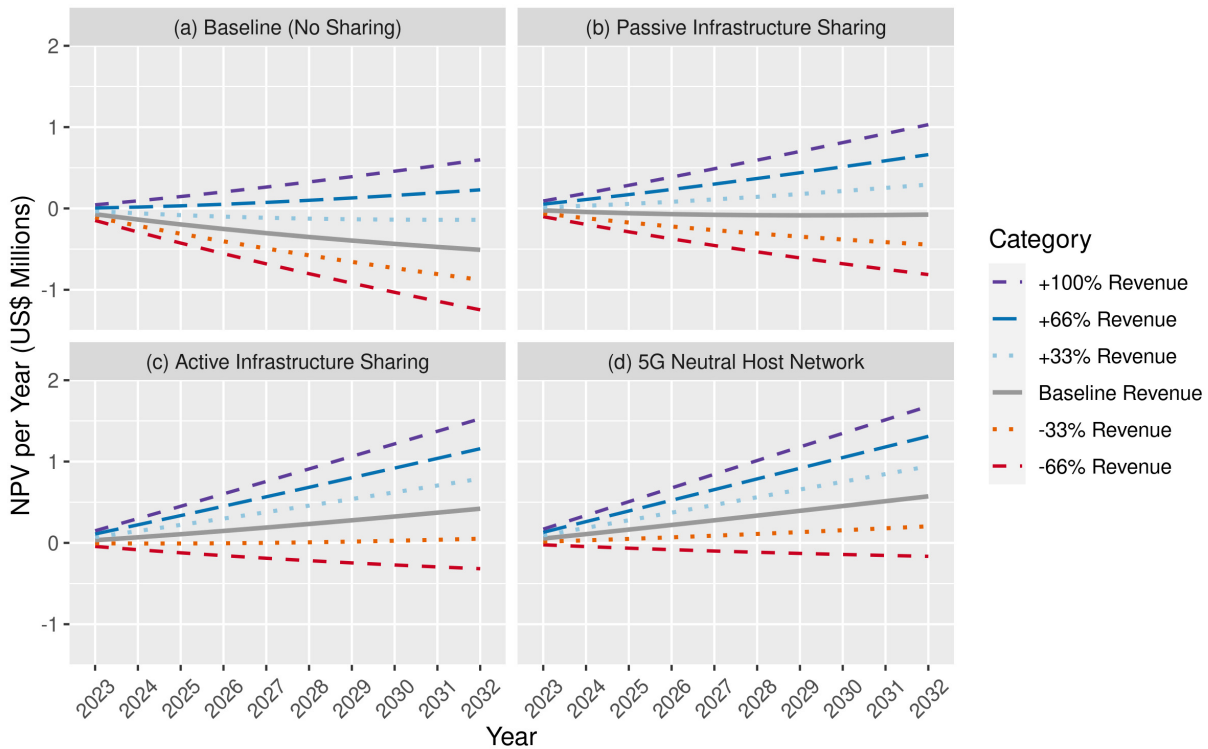


Fig. 4: NPV analysis for the various sharing strategies in rural scenario

results will now be discussed.

IV. DISCUSSION OF INFRASTRUCTURE SHARING STRATEGY PERFORMANCE

It is well established that the supply and demand dynamics involved in upgrading an existing network to a new technology (e.g., 5G) can be challenging in both urban and rural areas. Therefore, the following evaluation explores different aspects of the four main network sharing strategies, and discusses the deployment contexts in which they would be most suitable.

Business-As-Usual (No Sharing): When a rural area has high revenue potential, then a Business-as-Usual strategy may well be the best option for an operator to pursue. For example, an incumbent would ideally like to maintain any existing position as the lead service provider for applications and use cases in a target area. Indeed, if an operator does select this option then this may not necessarily lead to a detrimental effect on wider society. For example, in areas of high data demand, this may still support multiple networks being built or upgraded. There are also many established benefits from infrastructure competition among operators. However, there may be high barriers to entry for smaller local operators to enter the market and successfully compete.

Passive Sharing: Such a sharing model is preferred when there is healthy competition among operators, but only moderate demand for services present. Indeed, this moderate demand may generate insufficient revenue for independent operators to choose a Business-as-Usual strategy, forcing the exploration of other infrastructure sharing options. Typically, operators will negotiate how to carry this out in practice, but it may involve

reciprocal site access agreements on a site-by-site basis, or establishing a joint venture with equal ownership among the different participating companies. The network management of site assets over time may undergo significant changes, as less desirable site locations are decommissioned.

Active Sharing: In low-demand, difficult-to-serve places, the expense of infrastructure deployment may force operators to look at more extreme cost reducing measures, making an actively shared approach more desirable. However, a key challenge with this strategy lies in reaching agreement in the arrangements for network sharing with other incumbent operators (who are also usually competitors). In these challenging deployment contexts, operators may want to complement each other’s coverage areas via an active approach by enabling user roaming. In such a circumstance, operators work together to provide complementary coverage in each other’s service areas. Unless the potential operator is a national-level operator, there are high barriers to entry for local operators.

NHN: The most advanced network sharing option available that supports multi-tenancy among operators and other potential slice tenants. This option is the most practical for areas with low or ultra-high user densities [14], [15]. The network should aim to be capable of supporting all 5G KPIs and applications. Indeed, a 5G NHN strategy offers superior engineering capabilities, for example including cell coordination (e.g. for interference management), resource utilization and ad-hoc resource expansion. A high degree of flexibility can also be provided to operators, for example, with slice leasing periods as short as a matter of days, or even hours. Despite being the most economical method, operators who

lease resources from the incumbent MNO must be able to do so at a fair price and have confidence in longer-term price projections. Moreover, there are also many issues which could arise in the legal governance of each site, especially in how quality of service agreements are maintained and enforced between end-users, slice tenants, and other operators.

Finally, one key caveat that requires careful consideration is the impact of network sharing on market competition. The level of infrastructure consolidation over the next decade could be significant and requires careful scrutiny by telecommunication regulators to ensure competitive markets are maintained. Certainly operators (as rational market actors) will preference the selection of network sharing models based on the most attractive techno-economic feasibility, reflecting both the cost and revenue streams of any infrastructure upgrades. However, there may not always be mutually aligned interests between operators and regulators. Therefore, it is important for public policy to consider the wider ramifications of increased infrastructure sharing, along with any potential negative impacts on infrastructure-based competition.

V. CONCLUSION

In this article, a general introduction to infrastructure sharing strategies was first presented for engineers. This covered *where* infrastructure sharing may take place, *how* infrastructure sharing may take place, and *who* may enable infrastructure sharing to take place. Secondly, techno-economic results were presented on the quantitative performance of four main strategies for rural 5G upgrades, which included Business-as-Usual (No Sharing), Passive Sharing, Active Sharing, and a NHN approach.

Indeed, the findings indicated that any network sharing strategy has a higher NPV of between 20-90% compared the baseline strategy (No Sharing), which translates to a stronger business case for investment, and potentially higher profit margins. A neutrally hosted network may also have a variety of benefits for operators, governments, and end-users, beyond purely viability benefits. These include the ability for (i) operators to share risk in situations of uncertain demand, (ii) governments to lower the barriers to entry for small local operators, and (iii) for end-users to enjoy enhanced coverage from broadband providers.

However, future research is needed to explore both the positive and negative impacts of increased infrastructure consolidation over the next decade on infrastructure competition, in the many telecommunication markets around the world.

ACKNOWLEDGMENT

REFERENCES

- [1] A. Chaoub, M. Giordani *et al.*, “6G for bridging the digital divide: Wireless connectivity to remote areas,” *IEEE Wireless Communications*, vol. 29, no. 1, pp. 160–168, 2022.
- [2] E. Yaacoub and M.-S. Alouini, “A key 6G challenge and opportunity—connecting the base of the pyramid: A survey on rural connectivity,” *Proceedings of the IEEE*, vol. 108, no. 4, pp. 533–582, 2020.
- [3] J. Lähentmäki, “The evolution paths of neutral host businesses: Antecedents, strategies, and business models,” *Telecommunications Policy*, vol. 45, no. 10, p. 102201, 2021.

- [4] E. J. Oughton, N. Comini, V. Foster, and J. W. Hall, “Policy choices can help keep 4G and 5G universal broadband affordable,” *Technological Forecasting and Social Change*, vol. 176, p. 121409, 2022.
- [5] L. Abrardi and C. Cambini, “Ultra-fast broadband investment and adoption: A survey,” *Telecommunications Policy*, vol. 43, no. 3, pp. 183–198, 2019.
- [6] S. K. A. Kumar and E. Oughton, “Techno-Economic Assessment of 5G Infrastructure Sharing Business Models in Rural Areas,” *preprint*, 10 2022. [Online]. Available: https://www.techrxiv.org/articles/preprint/Techno-Economic_Assessment_of_5G_Infrastructure_Sharing_Business_Models_in_Rural_Areas/21258531
- [7] K. Samdanis, X. Costa-Perez, and V. Sciancalepore, “From network sharing to multi-tenancy: The 5G network slice broker,” *IEEE Communications Magazine*, vol. 54, no. 7, pp. 32–39, 2016.
- [8] L. Cano, G. Carello *et al.*, “Modeling the techno-economic interactions of infrastructure and service providers in 5G networks with a multi-leader-follower game,” *IEEE Access*, vol. 7, pp. 162 913–162 940, 2019.
- [9] E. J. Oughton and W. Lehr, “Surveying 5G techno-economic research to inform the evaluation of 6G wireless technologies,” *IEEE Access*, vol. 10, pp. 25 237–25 257, 2022.
- [10] L. Banda, M. Mzyece, and F. Mekuria, “5G business models for mobile network operators – a survey,” *IEEE Access*, pp. 1–1, 2022.
- [11] X. Lin, “An overview of 5G advanced evolution in 3GPP release 18,” *IEEE Communications Standards Magazine*, vol. 6, no. 3, pp. 77–83, 2022.
- [12] Release 18. [Online]. Available: <https://www.3gpp.org/specifications-technologies/releases/release-18>
- [13] L. Zhang, M. Xiao *et al.*, “A survey of advanced techniques for spectrum sharing in 5G networks,” *IEEE Wireless Communications*, vol. 24, no. 5, pp. 44–51, 2017.
- [14] L. Chiaraviglio, N. Blefari-Melazzi *et al.*, “Bringing 5G into rural and low-income areas: Is it feasible?” *IEEE Communications Standards Magazine*, vol. 1, no. 3, pp. 50–57, 2017.
- [15] J. R. Schneir *et al.*, “A business case for 5G mobile broadband in a dense urban area,” *Telecommunications Policy*, vol. 43, no. 7, p. 101813, 2019.



Shruthi Koratagere Anantha Kumar, aka, Shruthi K A (Graduate Student Member, IEEE) received the B.Tech. degree from GITAM University, Hyderabad, in 2016. She is currently pursuing the Ph.D. degree with the University of Strathclyde, Glasgow, U.K. She is a Visiting Faculty with George Mason University, Fairfax, USA, Researcher with the StrathSDR lab, the Department of Electronic and Electrical Engineering, University of Strathclyde, and a Visiting Researcher with the International Institute of Information Technology, Hyderabad. She specializes

in rural telecommunications, business models, pricing strategies, game theory, cost-assessment, and business models for 5G networks, especially for rural areas and 5G verticals applications.



Edward J. Oughton received the M.Phil. and Ph.D. degrees from Clare College, at the University of Cambridge, U.K., in 2010 and 2015, respectively. He later held research positions at both Cambridge and Oxford. He is currently an Assistant Professor in the College of Science at George Mason University, Fairfax, VA, USA, developing open-source research software to analyze digital infrastructure deployment strategies. He received the Pacific Telecommunication Council Young Scholars Award in 2019, Best Paper Award 2019 from the Society of Risk Analysis, and the TPRC48 Charles Benton Early Career Scholar Award 2021.