5G NETWORK SLICING FOR RURAL CONNECTIVITY: MULTI-TENANCY IN WIRELESS NETWORKS

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Abstract

As the need for wireless broadband continues to grow around the world, there is an increasing focus to minimise the existing digital divide and ensuring that everyone receives high-quality internet services, especially the inhabitants of rural areas. As a result, different technological solutions are being studied and trialled for improving rural connectivity, such as 5G with dynamic spectrum access. One of the architectures of 5G is network slicing, which supports network virtualisation and consists of independent logical networks, called slices, on the 5G network. Network slicing supports the multi-tenancy of different operators on the same physical network, and this feature is known as neutral host networks (NHN). It allows multiple operators to co-exist on the same physical network but on different virtual networks to serve end users. Generally, the 5G NHN deployment is handled by an infrastructure provider (InP), who could be a mobile network operator (MNO), an Internet service provider, a third-party operator, etc. At the same time, potential tenants would lease slices from the InP. The NHN strategy would help reduce resource duplication and increase the utilisation of existing resources. The existing research into NHN for small cells, in-building connectivity solutions, and other deployment scenarios help to understand the technological and business requirements. End-to-end sharing across operators to provide services to their end users is another innovative application of 5G NHN that has been tested for dense areas. Meanwhile, the feasibility and policy impact of NHN is not studied extensively for the rural scenario.

The research in this thesis examines the use of NHN in macro- and small-cell networks for 5G communication systems to minimise the digital divide, with a special focus on rural areas. The study also presents and analyses the 5G multi-tenancy system design for the rural wireless scenario, focusing mainly on exploring suitable business cases through network economics, techno-economic study, and game theory analysis. The results obtained from the study, such as cost analysis, business models, sensitivity analysis, and pricing strategies, help in formulating the policy on infrastructure sharing to improve rural connectivity. The contributions of the thesis are useful for stakeholders and policymakers to assess the suitability of the rural 5G NHN by exploring state-of-the-art technologies, techno-economic analysis, sensitivity analysis, newer business models, investment assessment, cost allocation, and risk sharing. Initially, the research gap is highlighted through the extensive literature review and stakeholders' views on rural connectivity collected from discussions with them. First, the in-depth discussion on the network economics of the rural 5G NHN includes the study of potential future scenarios, value network configurations, spectrum access strategy models, and business models. Secondly, the techno-economic analysis studies the key performance indicators (KPI), cost analysis, return on investment, net present value, and sensitivity analysis, with the application for the rural parts of the UK and India. Finally, the game theory framework includes the study of strategic interaction among the two key stakeholders, InP and the MNO, using models such as investment games and pricing strategies during multi-tenancy. The research concludes by presenting the contribution towards the knowledge and future work.

Acknowledgements

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I would like to thank Prof. Sachin Chaudhari at the Signal Processing and Communications Research Center (SPCRC), International Institute of Information Technology, Hyderabad (IIIT H), India, for providing me with an opportunity for fieldwork to study rural connectivity in India. He taught me the skills required for writing successful research papers, which later helped me write my thesis. He took the time to answer all of my questions and walked me through the process of thinking about my research gaps. Furthermore, I would also like to thank my colleagues at IIIT H for their support.

I would like to thank Dr Edward J. Oughton who is an Assistant Professor at the Centre for Data-Driven Research, Geography & Geoinformation Science Department at George Mason University, USA, for allowing me to pursue research in techno-economic feasibility analysis for different infrastructure sharing strategies for rural areas and for offering me the position of Affiliate Faculty. He has been supervising my work to produce high-impact papers for IEEE publications such as special feature editions of Communication magazine. He taught me how to create high-quality papers and broadened my understanding of factors impacting policy decisions in the telecommunications domain. Also, he guided me to model the entire research using Python and R modules to generate sophisticated results. He spent time and effort answering my questions and teaching me to write high-impact research articles.

I would like to thank all of my friends and colleagues in the StrathSDR lab, the University of Strathclyde and the Center for Data-Driven Research at George Mason University. I am blessed to have such amazing people as my research colleagues and friends. A special thanks to Tawachi Nyasulu, Joshua Goldsmith, Dani Anderson, Animesh Gupta, Niharika Ammu, Sahya Jeevan, Chandana Reddy, Alex Dickson, Kenneth Barlee, and Douglas Allan, for all the times they helped me with everything. Next, I would like to thank the anonymous reviewers and publication editors for their time and feedback. I would like to thank everyone at 5G RuralFirst, 5G New Thinking, the conferences that I have attended, journal reviewers, and the Rural Broadband Standards Architecture (RBSA) India working group for providing me with insights to complete my thesis.

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Research Outputs/Activities of the Author

Journal papers

i **Journal** Shruthi K.A., R. W. Stewart, D. Crawford and S. Chaudhari, "*Techno-Economic Study of 5G Network Slicing to Improve Rural Connectivity in India*", in IEEE Open Journal of the Communications Society, vol. 2, pp. 2645-2659, 2021
doi: 10.1109/OJCOMS.2021.3131370.

ii **Magazine** Shruthi K.A. and E. J. Oughton, "*Infrastructure Sharing Strategies for Wireless Broadband*", in IEEE Communications Magazine Feature topic: *The Evolution of Telecom Business, Economy, Policies and Regulations*, vol. 61, no. 7, pp. 46-52, July 2023
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iii **Magazine early access published** Shruthi K.A., D. Crawford, and R.W. Stewart "*Pricing Models for 5G Network Slicing using Game Theory*" - IEEE Communication Magazine Open Call - 5 June 2023.
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iv **Submitted to Frontiers** Shruthi K.A. and E. J, Oughton, "*Techno-Economic Assessment of 5G Infrastructure Sharing Business Models in Rural Areas*" - submission to Frontiers Special Edition on *Infrastructure Sharing in Broadband Networks: Impact on Telecommunications Operators and Consumers* - 31 May 2023.
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Conference papers

i **Published** Shruthi KA, Ihita GV, Chaudhari S, Arumugam P. "*A survey on rural Internet connectivity in India*". In 2022 14th International Conference on COMmunication Systems & NETworkS (COMSNETS) 2022 Jan 4 (pp. 911-916). IEEE.
doi: 10.1109/COMSNETS53615.2022.9668358

ii **Published** Shruthi KA, R. Stewart, D. Crawford and S. Chaudhari, "*Business model for rural connectivity using multi-tenancy 5G network slicing*", 2020 IEEE 17th International Conference on Smart Communities: Improving Quality of Life Using ICT, IoT and AI (HONET), 2020, pp. 182-188
doi: 10.1109/HONET50430.2020.9322837.

Chapters in a book

i **Published** Anderson, D., Shruthi K.A. and Stewart, R., 2019. "*Evolving spectrum sharing methods and standards: TVWS, CBRS, MulteFire and more*". In Spectrum Sharing: The Next Frontier in Wireless Network.
doi: 10.1002/9781119551539.ch4

White papers, posters, and oral presentation

i **Poster, published** KA, Shruthi, Stewart, R. and Crawford, D., 2021, June. "*Rural connectivity using 5G neutral host networks: game theory framework*". In Doctoral School Multidisciplinary Symposium.

ii **Oral Presentation** KA, Shruthi, 2021, November. "*Entering the rural market or not: 5G NHN using network slicing*" in 3^{rd} IEEE UK&I YP Postgrad STEM Research Symposium.

iii **Anchoring a Conference Workshop** Workshop 9 on Rural Connectivity at IEEE International Conference on Advanced Networks and Telecommunications Systems - 14^{th} December 2021. I helped in organising and anchoring the workshop.

iv **Presentation at SI-85 RBSA, C-DOT** Proposed a potential rural broadband architecture with business models to improve rural connectivity in India. Held at Centre for

Development of Telematics (C-DOT), Bangalore, India on 27th May 2022.

- v **Consultation of 5G spectrum policy - ICREIR**: Presented views on the 5G private networks policy using local areas spectrum licensing in India conducted by the Indian Council for Research on International Economic Relations (ICREIR). Held online - 15th June, 2022

Other activities

- i **Contribution to standards development, under review** TSDSI-SGSS-SWIC-732-V1.0.0, Rural Broadband Services & Architecture, Study Group and Services (SI-85) - Contributions towards a survey on existing Internet connectivity in India, 5G network slicing usage in India, KPIs requirements for Indian scenario, the study of emerging rural use-cases for the Indian scenario, rural broadband architecture supplementing existing infrastructure - Standardise service enabling layer for rural connectivity.
- ii **Visiting Faculty at George Mason University** - Working with Dr Edward Oughton to study the feasibility and strategies for 5G/6G deployments in rural areas, using 5G NHN. The research also includes a study on the suitability of infrastructure sharing strategies in the urban-rural scenario.
- iii **Magazine Reviewer** Participated as a reviewer for journals submitted in the IEEE Communication Magazine, Featured Edition, “Techno-Economic Analysis of Telecommunications Systems”.
- iv **Reviewer** for the “*Information Technologies And Intelligent Decision Making Systems*” (ITIDMS-23) (International Scientific And Practical Conference) and New Countryside (an open access international journal).
- v **Reviewer** for the “*Doctoral School Multidisciplinary Symposium (DSMS) 2023*”.
- vi **Upwork freelancing** on writing the literature review on MEC for energy-efficient computation offloading.

Contents

List of Figures

List of Tables

Acronyms

1G 1^{st} Generation.

2G 2^{nd} Generation.

3G 3^{rd} Generation.

3GPP 3^{rd} Generation Partnership Project.

4G 4^{th} Generation.

5GPP 5^{th} Generation Partnership Project.

AI Artificial Intelligence.

AMPS Advanced Mobile Phone Service.

APIs Application Programming Interface.

ARPU Average Revenue Per User.

ASA Authorised Shared Access.

ASIC Application-Specific integrated Circuit.

BBU Baseband Unit.

BCM Business Canvas Model.

BLER Block Error Rate.

BR Best Response.

BSs Base Stations.

CAPEX	Capital Expenditure.
CBRS	Citizens' Broadcast Radio Services.
CDMA	Code-Division Multiple Access.
CORD	Central Office Re-architected as a Datacenter.
CPE	Customer Premise Equipment.
CRAN	Cloud Radio Access Networks.
D2D	Device-to-Device.
DAS	Distributed Antenna Systems.
DCF	Discounted Cash Flow.
DFE	Digital Front-End.
DSA	Dynamic Spectrum Access.
EDGE	Enhanced Data Rates for GSM.
eMBB	Enhanced Mobile Broadband.
EMS	Element Management Systems.
ESC	Environmental Sensing Capability.
FPGA	Field Programmable Gate Array.
FTTH	Fibre to the Home.
FWA	Fixed Wireless Access.
Gbps	Gigabit per seconds.
GPRS	General Packet Radio Service.
GSM	Global System for Mobile communication.
GSMA	Global System for Mobile Communications Association.

HAPS	High Altitude Platform Stations.
HIBS	High Altitude IMT Base Stations.
HSPA	High Speed Packet Access.
IaaS	Infrastructure as a Service.
IC	Integrated Circuit.
IEEE	Institute of Electrical and Electronics Engineers.
IMT	International Mobile Telecommunications.
InP	Infrastructure Provider.
IoT	Internet of Things.
IP	Internet Protocol.
IPR	Intellectual Property Rights.
ISP	Internet Service Provider.
IT	Information Technology.
KPI	Key Performance Indicators.
LOS	Line of Sight.
LSA	Licensed Spectrum Access.
LTE	Long Term Evolution.
LTE-A	Long Term Evolution - Advanced.
M2M	Machine to Machine.
MEC	Multi-access Edge Computing.
MIMO	Multiple-In Multiple-Out.
mMTC	massive Machine Type Communications.
MNO	Mobile Network Operators.

MOCN	Multi-Operator Core Networks.
MORAN	Multi-MNO Radio Access Networks.
MoU	Memorandum of Understanding.
MSPs	Media Service Providers.
NaaS	Network as a Service.
NE	Nash Equilibrium.
NFV	Network Function Virtualisation.
NGMN	Next Generation Mobile Networks.
NHN	Neutral Host Networks.
NR	New Radio.
NS	Network Slice.
NSA	Non-Stand Alone.
NSI	Network Slice Instance.
NSIs	Network Slice Instances.
NSS	Network Slice Subnet.
NSSI	Network Slice Subnet Instance.
O-RAN	Open Radio Access Networks.
OFDM	Orthogonal Frequency-Division Multiplexing.
OPEX	Operational Expenditure.
OTT	Over-The-Top.
PDDCH	Physical Downlink Data Channel.
PoP	Point of Presence.
PRBs	Physical Resource Blocks.

PTMP Point-to-Multipoint.

PTP Point-to-Point.

PUs Primary Users.

QAM Quadrature Amplitude Modulation.

QoS Quality of Service.

QPSK Quadrature Phase Shift Keying.

RaaS Radio as a Service.

RAN Radio Access Network.

RATs Radio Access Technologies.

RMa Rural Macrocell.

ROI Return on Investment.

SA Stand Alone.

SAS Spectrum Access System.

SDN Software-Defined Networking.

SDR Software Defined Radios.

SINR Signal Interference to Noise Ratio.

SLA Service Level Agreement.

SoC System on Chip.

SON Self Organising Network.

SUs Secondary Users.

SWOT Strengths, Weaknesses, Opportunities and Threats.

TaaS Traffic as a Service.

TACS Total Access Communication System.

TCO Total Cost of Ownership.

TRAI Telecom Regulatory Authority of India.

TVWS Television White Space.

UAV Unmanned Aerial Vehicle.

UE User Equipment.

UMTS Universal Mobile Telecommunications System.

uRLLC Ultra Reliable Low Latency Communications.

V2X Vehicle to Everything.

VBaaS Virtual Backhaul as a Service.

VNC Value Network Configuration.

VoIP Voice over Internet Protocol.

VoLTE Voice over Long Term Evolution.

WCDMA Wideband Code Division Multiple Access.

Wi-Fi Wireless Fidelity.

WLAN Wireless Local Area Networks.

WSNs Wireless sensors networks.

Chapter 1

Introduction

1.1 Mobile Communication

Wireless communication is one of the essentials in today's world. The need for reliable high-speed wireless broadband connectivity has been increasing [1]. The advancement in telecommunication technology has led to broadband-speed Internet access on mobile devices. Digital applications and services such as e-health, e-governance, mobile banking, e-commerce, e-bookings, video-conferencing, broadcasting, online education, work-from-home, smart homes, smart buildings, and digital navigation have all benefited as a result of this [2–4]. Today, there have been many 5G deployments in urban areas around the world [5, 6].

With rapid development in the mobile communication system, the fifth generation (5G) is trialled, tested and rolled out [7–10]. There are three unique use cases of 5G technologies that set it different from the previous generations: enhanced mobile broadband (eMBB), massive machine-type communications (mMTCs), and ultra-reliable-low-latency (uRLLC) communication services. The 5G network provides data rates with gigabit per second (Gbps) per user equipment (UE), higher spectrum efficiency, higher mobility, energy-efficient, better coverage, and supports millions of devices simultaneously [10–12]. In addition, 5G networks are cost-effective, reliable and flexible to deploy, allow faster network expansion, and support remote monitoring and maintenance, self-organising networks (SON), software-defined networks (SDN) [13], and network function virtualisation (NFV) [14, 15]. There are ongoing studies to explore the use cases of 5G services for different applications [16, 17].

One of the architectures supported by 5G is network slicing [18–20] that allows a single physical infrastructure to be shared by a virtual instance known as a slice [21]. Furthermore, there will be multiple slices to support various applications for different tenants simultaneously. The tenants can also lease different slices from the same physical network, and co-exist on the same network, and this feature is known as neutral host networks (NHN) [22, 23]. The horizontal network slicing supports different use cases and, the vertical slicing supports tenants for a similar use case [24]. Most of the research on 5G and network slicing is focused on urban and industrial settings [25–29]. The research in [8] demonstrated that by using network virtualisation, capital expenditure (CAPEX) is reduced by at least 50% and operational expenditure (OPEX) by 50%. Since there is a spectrum crunch, sharing the spectrum among the tenants would improve the spectral efficiency and allow multiple users to access the under-utilised spectrum bands [30]. Additionally, the use of dynamic spectrum access (DSA) in conjunction with virtualisation further reduces the cost of the network [30–32].

5G and beyond technologies will support multiple radio access technologies (RATs) at different frequency bands [33], due to which millions of devices will connect to the same 5G base station (BSs). The network complexity increases further when 5G networks provide NHN capabilities [34]. Research on NHN for the small cell or inside the building, such as campus, offices, factor, etc., shows the benefits of using neutral hosts [35–37]. NHN shifts the focus towards the virtualisation of signal, and data processing along with the usage of virtual resources (software based rather than hardware-based), which helps reduce the physical hardware deployment. In [38], a third-party organisation known as an infrastructure provider (InP) deploys and operates the network. InP also selects the frequencies for operations based on the services to be supported. The InP network can be connected to the worldwide network using the Internet point of presence PoP and 3GPP gateway, such as the mobile network operators (MNOs) network [39, 40].

1.2 Motivation - Rural Connectivity Problem

As of today, only 64.4% of the world's population has a presence on the Internet, and most of the active Internet users reside in urban areas [41]. However, for the remaining 35.6% of the population, mobile Internet services are poor or do not exist, they mostly reside in rural areas. This situation led to rural and remote areas being deprived of the benefits offered by digital services, which otherwise would encourage rural development around the world; this scenario causes a digital divide [42, 43].

As the demand for high-speed Internet rural connectivity grows in rural areas, so does the question of how to tackle the problem, which has been investigated by scholars, academia, business, and the general public. The conventional or traditional method for broadband services deployment involves each MNO and Internet service provider (ISP) deploying and operating their independent or *No Sharing* network to provide connectivity in a region. This method is capital and manpower-intensive in rural areas, especially during installation, repairs, and maintenance [14]. Generally, rural areas generate low levels of network traffic and revenue compared to the urban scenario which leads to unprofitable network deployment in those areas for the MNOs and ISPs. Hence, these regions have low priority while deploying telecommunication infrastructure [44, 45]. And even if there is a network deployed in these regions using fibre plus Wi-Fi, a private network, or any other technologies, roaming issues exist when the rural customers move out of their home network or when visiting customers hop on the rural networks.

A study by Oughton shows that to tackle the digital divide in rural areas, many government and non-government schemes support and subsidise wireless broadband solutions [46]. Therefore, innovative technological solutions to improve mobile connectivity in rural and remote areas are currently being explored. Some of the initiatives are OneWeb, Technology Innovation Project (TIP) by Facebook, Airband by Microsoft, 5G RuralFirst by Scottish Government, 5G New Thinking in the UK, BharatNet in India and Digital India 2020 by Indian Government [47]. Each initiative or pilot trial focuses on addressing different use cases of the technologies, such as 5G, Wi-Fi, fibre, and open radio access networks (O-RAN), for solving existing challenges. A rural setting typically requires fewer equipment, towers, and network resources, and rarely reaches maximum capacity in comparison to an urban setting. If MNOs were to deploy their own independent 5G network, then it would lead to poor return on investment (ROI); an exorbitant cost for deployment per operator and the resource under-utilisation are stated as the key reasons for not deploying it [2, 48].

With such advancements in technology, the concept of 5G NHN could be extended to rural areas for minimising the digital divide. A survey on neutral host networks suggests that the 5G NHN model would be beneficial to maximise resource usage and lower the costs to provide 5G in rural areas [20]. Consequently, the system architecture and technologies require slight modification to bring 5G NHN in rural areas to support macro-cell networks. The network should provide services beyond personal communications, especially digital services in villages with low populations or remote areas. Also, there is a need for innovation to explore new network architecture, techno-economic study and business models to suit rural needs using the rural 5G

NHN and make the service sustainable. Furthermore, the network should be self-sustainable and lucrative for the MNOs and other stakeholders to invest in rural areas. One main advantage offered for rural connectivity using 5G NHN with MNOs as tenants on the network is to solve the roaming issues for customers and achieve data rates of at least 10 Mbps during peak hours.

1.3 Research Aims

This thesis proposes and discusses 5G network slicing supporting NHN, deployed by the InP for the rural mobile connectivity problem, to achieve the 30 Mbps per user target set by the ITU. 5G NHN would allow MNOs to exist on the same physical infrastructure but on different virtual networks. Furthermore, 5G NHN supports each slice to be customised independently by the application provider to suit their needs with the confidentiality of their business knowledge [49]. The relationship between the InP and MNO is like that of an airport and airlines. For example, the InP provides the telecommunication infrastructure to MNOs similar to the airport infrastructure provider, which builds the authorised infrastructure for airlines to operate from a particular location. Moreover, the MNO would lease slices from the InP to serve the end-users as airlines would pay for using runways at the airport to serve their passengers and their needs. Consequently, rural 5G NHN is evaluated and explored for coverage, cost, business opportunities, and pricing model.

The central questions for this research are as follows:

- Which technologies have the potential to boost rural connectivity whilst also supporting the ITU's 30 Mbps target yet being a cost-effective and self-sustaining alternative for large-scale deployment?
- What is the cost-effectiveness of the 5G NHN for deployment scenarios, for example, in a high ARPU market with low subscribers, and a subscriber market with low ARPU?
- What pricing strategies work best for 5G NHN deployment in rural areas?

In this PhD research work, rural 5G NHN is studied in detail to understand the potential impact and evaluate the suggested solution using different frameworks such as network architecture, network planning, microeconomics, techno-economic feasibility and game theory.

- The thesis' initial goal is to provide a system model and architecture for the rural 5G NHN using network slicing and shared spectrum. Next, the application of NHN in the rural context is explored.

- The important goal of the study is to summarise the views of the key stakeholders on the rural connectivity solution and 5G NHN.
- The rural 5G NHN architecture is explored to acquire a deeper knowledge of network economics by forecasting future scenarios, using a value network configuration (VNC), and business models using SWOT analysis and the business canvas model (BCM).
- The second goal is to perform the techno-economic analysis for the rural 5G NHN. An evaluation of the state-of-the-art in rural connectivity, KPI requirements, and techno-economic feasibility will determine if the solution is financially viable. To verify the trends in the output of the 5G rural NHN techno-economic feasibility study, in a high ARPU market with low subscribers, and a subscriber market with low ARPU, case studies from the UK and India are presented.
- The third important goal is to investigate the interactions among the two key stakeholders of the rural 5G NHN (InP and MNO). Investment games will aid in determining the feasibility of the suggested solution for both the InP and the MNO in the rural situation.
- The Shapley value and bargaining game are used to model possible pricing strategies for cost allocation. Finally, the study also explores the dynamic pricing model for rural 5G NHN and its usability in different scenarios.

1.4 Original Contribution

This work contains several contributions towards the use of 5G NHN with DSA for rural connectivity. These contributions provide initial evidence that the proposed rural 5G NHN can be a cost-effective solution and boost the rural telecommunications industry. NHN with shared spectrum is cost-effective compared to the conventional telecommunication network deployment - *No Sharing*. The NHN helps MNOs secure the rural mobile market and reduces the total cost of ownership (TCO) of their rural 5G network. Fig. 1.1 shows the flow of the different contributions of the research, and how the results could be used towards formulating policies for practical deployment in rural communities.

The main contribution to the knowledge towards rural connectivity presented in this thesis are:

- The gap for innovative rural solutions is addressed by proposing the new deployment strategy using rural 5G NHN, where the InP deploys the network and the MNO leases

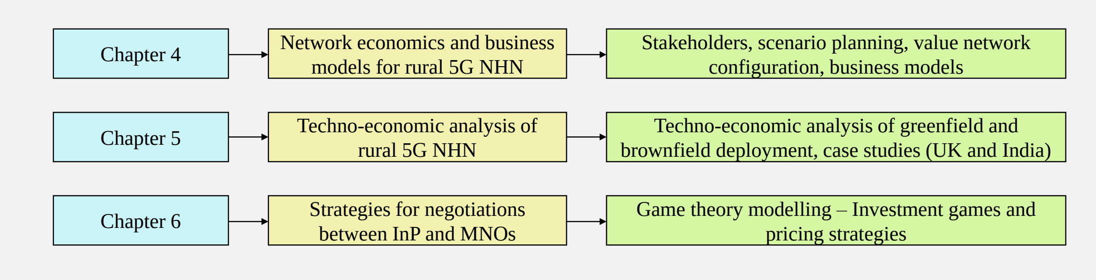


Figure 1.1: The contributions of this thesis

slices to provide services in those areas. Rural 5G NHN with shared spectrum is explored as a potential technological solution to address the digital divide challenge. The views of the stakeholders on the potential role of rural 5G NHN in addressing the digital divide are considered for focusing on the key gaps in terms of overall network feasibility.

- A novel 5G NHN architecture for rural areas which is driven by InP considering the potential future scenarios and the value network configuration helps to understand the value offered by the network and the various roles of the stakeholders. The potential business models offered by the rural 5G NHN are explored using the business canvas model. Results indicate that rural 5G NHN business models are an attractive investment for MNOs and industries, provided that the main weaknesses such as regulatory policies, slice customisation, and trust among the operators, of the NHN technology are minimised.

- Techno-economic analysis of the rural 5G NHN greenfield and brownfield deployments are explored to understand the sensitivity of the feasibility with respect to various input factors. The cost of rural 5G NHN varies depending on input factors such as country, location, population density, duration of investment, and average revenue per user (ARPU). The feasibility trends estimate the viability of 5G NHN for the UK and India scenario with case studies in both countries. The analysis of using 5G FR1 frequency bands to overcome the digital divide is studied using coverage simulations. The rural 5G NHN is a compelling option as it offers an average cost reduction of at least 50% compared to the traditional network deployment method of *No Sharing* for a 4-operator deployment scenario. One of the main benefits of using NHN is that the physical resources required are less than traditional deployment while still meeting the connectivity demand of a rural village.

- The strategic interactions of the key stakeholders, the InP and the MNO play a key role in driving the rural connectivity solutions. The case study helps to assess the pricing strategy that satisfies Nash Equilibrium at various ARPU and subscribers. The main areas are:
    - Whether to enter the rural market or not.
    - If yes, then what are the pricing strategies to fairly allocate cost-revenue among the InP and the MNO – Shapley value, bargaining games, and dynamic pricing ('per user' pricing with various over a period of time rather than instantaneously)?
- Policy recommendations on the technology and infrastructure sharing strategies for rural areas with the digital divide.

1.5 Thesis Organisation

Fig. 1.2 shows the conceptual map for each chapter and thesis organisation. The contributions of each chapter of the thesis are as given below:

- Chapter 1 introduces the rural wireless connectivity problem as the motivation for this work and provides an overview of the contributions and organisation of the thesis. This chapter also has a brief overview of the relevant background for the introduction of the work.
- Chapter 2 presents the literature review and the existing work on rural connectivity, technological capability of state-of-the-art equipment and technologies, 5G, network slicing, 5G NHN, spectrum sharing and DSA, infrastructure sharing, multi-MNOs end-to-end sharing, cloud RAN (CRAN, business models, techno-economic models and game-theoretical models in this chapter.
- Chapter 3 includes the views of the stakeholders on the potential of rural 5G NHN and the challenges that the technology would need to address. MNOs, standards organisations, equipment manufacturers, end users, and technology experts' viewpoints are summarised in the discussion. The research goals are strengthened by building on the stakeholder's viewpoints. Then, the research methodology and important assumptions are then presented to understand the background of the study.

- Chapter 4 evaluates the possible scenario, value network and business models of the proposed model. Future scenarios attempt to study various values for the business based on the VNC model for a rural village. Possible business models are explored for a rural area with 5G NHN using SWOT analysis and a business canvas model. Finally, multi-MNO spectrum sharing for rural 5G NHN macro- and small-cells utilising DSA is studied to maximise network throughput using shared spectrum technologies.
- Chapter 5 explores the techno-economic feasibility of the InP-driven VNC from Chapter 3. The key focus areas of the study are the state-of-the-art connectivity in the UK and India, the rural 5G NHN system model, formulation of various concepts for the analysis, techno-economic methodology, and sensitivity analysis. The proposed model estimates the number of subscribers, break-even time, and minimum ARPU along with sensitivity analysis for a sustainable rural wireless business. The study is extended by considering actual villages and verifying the trends calculated in the Indian and UK scenarios and studying the requirements for the feasibility of rural 5G NHN with a low number of subscribers.
- Chapter 6 uses game theory models for studying the strategic interactions between InP and MNO. First, the suitability of 5G NHN for the rural scenario using the investment games helps to decide whether the players want to enter rural 5G NHN. Next, cost allocation for the InP and the MNO in rural 5G NHN using either Shapley value, bargaining game or dynamic/mixed games are analysed. The suitability of each game is studied. The case study is performed using the data obtained from the UK rural 5G NHN scenario from Chapter 5.
- Finally, Chapter 7 summarises the main conclusions of the thesis and the potential direction of future work. This chapter also includes the ongoing research on one of the potential suggested future works.

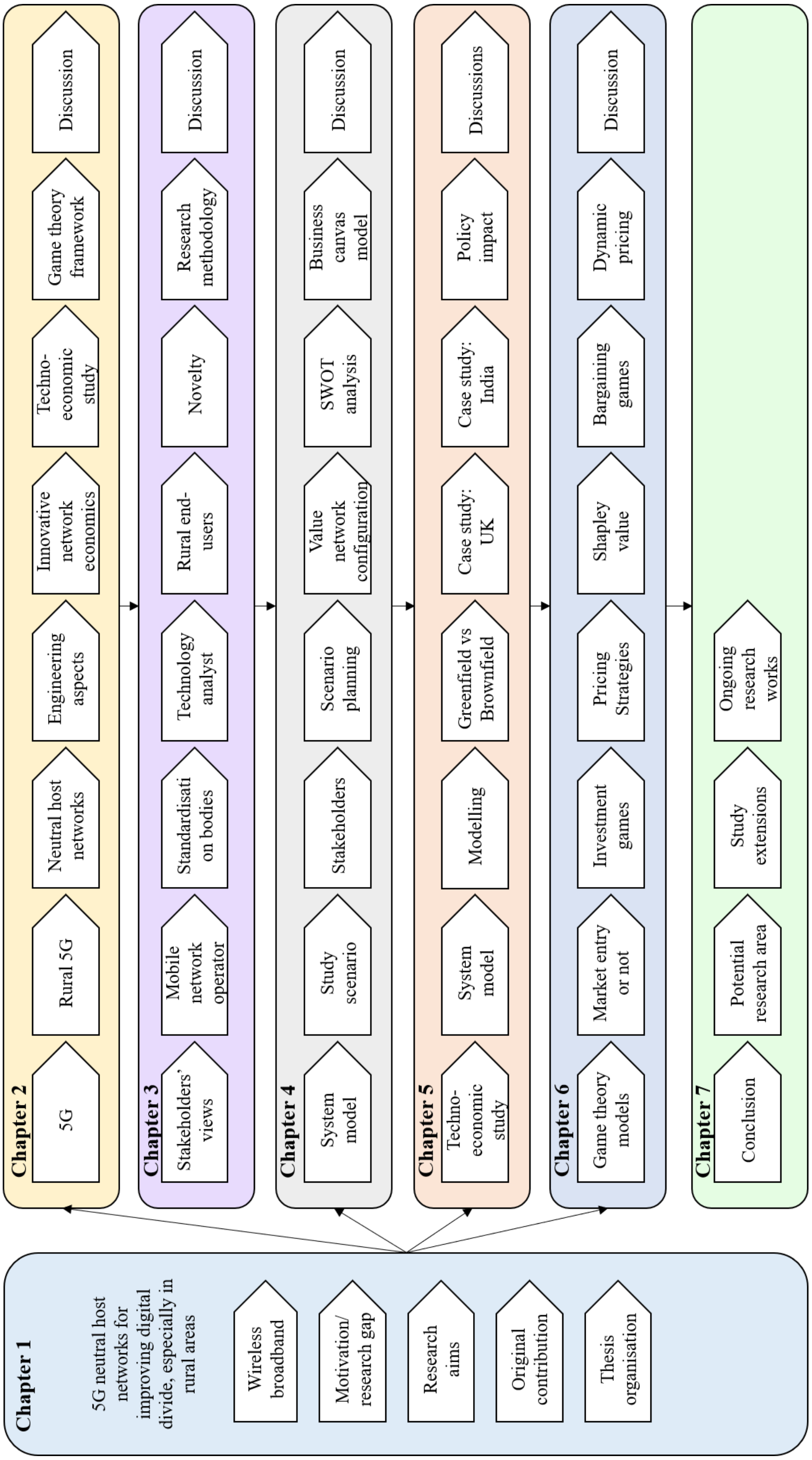


Figure 1.2: Conceptual map for each chapter of the thesis

Chapter 2

State-of-the-art for the Rural 5G NHN

The literature review in this chapter presents the overview of rural connectivity, potential technologies for the digital divide issue, and practical implementation of 5G networks in Section 2.1, 5G background in Section 2.2, 5G network slicing with NHN (radio resource as a service) in Section 2.3, rural 5G NHN shared spectrum in Section 2.4, and infrastructure sharing architectures for the rural scenario along with a network model of end-to-end network slicing among MNOs in Section 2.5. Furthermore, game theoretical models for MNO-InP interactions in the rural 5G NHN are described in Section 2.6. The review also presents game theory concepts, such as cooperative games, non-cooperative games, coalition games, Shapley value, bargaining games, investment games, oligopoly games and Nash equilibrium.

2.1 Rural Connectivity Background

Wireless broadband has changed the lives of people. The widespread usage of the internet on mobile has improved communication and the economy all over the world. The internet is erasing the challenges of physical distance using applications such as e-governance, e-banking, e-learning, digital health, e-payments, video conferencing, video streaming, communications, and virtual reality [50]. Despite the widespread acceptance of the role of the digital revolution, a digital divide exists between areas with high-speed digital connectivity and areas without it. While there are many wireless broadband connectivity issues in rural and remote locations as discussed by Yaacoub in [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 as presented by Lateenmaki in [34]. Indeed, as adoption rates and data consumption per user increase, existing wireless infrastructure assets become saturated. Whereas, prohibitively high roll-out costs and poor ROI lead to a lack of internet services in rural and sparsely populated areas as cited by Oughton in [51]. Currently, around 36% of the world's population is devoid of the benefits of Internet technology. Recently, during the COVID-19 pandemic, the world's population relied on the internet to perform activities remotely, such as work, study, socialise, surveillance, and shopping [52, 53]. People with poor or no internet connectivity were worst affected during the pandemic, as they could not work remotely or study from home and lack of personal communication. Most of these people live in rural or remote rural areas with poor or no coverage.

Rural connectivity objectives must overcome numerous obstacles, including innovation in technologies to suit the needs, business models, and ROIs. A survey on providing internet connectivity in rural areas, challenges, and possible solutions presented in [54, 55] shows that there is a need for overall innovations in every field.

2.1.1 Challenges

Though the government is encouraging initiatives and projects to improve rural connectivity while focusing on middle-mile connectivity, there still exist several challenges in improving last-mile connectivity and expanding the network by the operators. In [56–59], the authors describe different challenges related to rural internet connectivity around the world. Hence, the key challenges that need to be addressed by the operators are:

A. **Topography and population distribution**: Each country has diverse topography ranging from the plane, plateau, mountain, desserts, and extreme climatic conditions. The topography of the village and its population distribution plays a crucial role in internet connectivity. A sparsely populated village has the lowest priority while deploying networks because of low return on investment. An uneven terrain poses a challenge in providing digital connectivity [60]. A plane terrain with fewer obstructions is favourable for providing rural connectivity. Therefore, a unique solution is not possible for rural connectivity. Hence, the population distribution of the village along with its topography needs to be one of the main factors in demand estimations and network planning.

B. **Cost**: The main factor which makes rural connectivity challenging is the cost of providing internet solutions in rural areas [61]. The network deployment cost is high due to various factors such as the non-existence of either backhaul or point of presence (PoP), cost of equipment, repair and maintenance, and spectrum licensing in hard-to-reach locations. The scalability of the networks increases by lowering the cost of rural deployments. The techno-economic study of different technologies highlights the need for reduced deployment costs and operational costs in rural areas for improving rural connectivity [51, 62]. Furthermore, various studies have shown that unless the network's cost reduces further, and there is a need for policies to encourage rural deployments, provisioning 2G, 3G, 4G, and 5G [63, 64]. The economic cost models used in urban and industrial sectors are not appropriate for rural areas' scenarios.

C. **Per-capita income**: Generally, people living in rural areas have lower per-capita incomes compared to urban areas. The pricing should be attractive and affordable for people living in rural areas to spend on digital solutions and services [65]. The pricing of services could be different to attract rural subscribers. There is a need for the innovation of new revenue models to attract rural area subscribers.

D. **Business models**: The lack of innovative business models is the major challenge for rural connectivity as discussed by Juan in [66]. The traditional business models are not suitable for rural scenarios as the former focus on high ARPU, a high customer base, and a longer investment duration. In rural areas, the traditional deployment method is a loss-making business which fuels the need to find innovation in business models to make them a profitable opportunities. The new business model needs to focus on factors such as low ARPU, low to moderate customer base, and moderate investment duration [67].

E. **Funding and investment**: The MNOs and ISPs build a network with future profits in mind. Lehr mentioned that these SPs obtain funding and investment from big banks and government agencies [68]. As the rural telecommunication business is typically non-profitable for a new entrant or InP, the lack of funding allocated for rural last-mile connectivity and its development is another roadblock. There is a need for innovations in the possible funding model for local operators and InP in rural areas. The investment required for setting up a telecommunication service is significant, hence, making it sustainable is key for the scalability of any rural connectivity solutions.

F. **Technology**: Wireless communication technology needs to be specifically modified to meet rural communities' demand and use cases. The main focus of rural networks such as high coverage, high data rates per user, high energy efficiency, high spectral efficiency, support for all use cases using single network and soft roaming [69–71]. There is also a need for local spectrum licensing to encourage micro-operators or InP [72]. Open network technologies researched around the world, such as OpenRAN, and 5G open-source stack, could significantly reduce the cost of deployments [73, 74].

G. **Electricity**: The rural areas have irregular or unreliable power supply issues [44]. The rural telecommunication system stresses the need for renewable energy sources and a highly power-efficient system. The 5G systems compared to 4G are 10x times more power-efficient systems which is an advantage for rural areas as mentioned by Norp in [71].

H. **Digital awareness**: Another challenge is the lack of digital awareness and illiteracy among rural users. Rural communities need awareness regarding the benefits and convenience offered by digital technologies. When people understand the advantages of rural digital solutions and how they will improve their life, then people would demand better services. The content should be available in different languages to attract rural subscribers on the network [75, 76]. People living in rural areas would have access to new opportunities, especially in terms of economic growth, and employment for the younger generations [77, 78].

2.1.2 Technology and rural trials around the world

Wireless broadband technologies have revolutionised the world by connecting people around the world using mobile connectivity. Since 1980, the telecommunication industry has been advancing to improve various features such as maximising data rates, minimising latency, supporting multiple applications, maximising energy efficiency, maximising spectral efficiency and minimising network congestion. The different generations of mobile telecommunication are summarised in Table 2.1 [79–81].

Currently, the 5G standards-compliant devices are being developed and deployed for testing various use cases [82, 83]. The issues faced in the previous generations are addressed in the latest technology standards. The technology from 1G to 5G has evolved from supporting only voice calls to multiple applications such as voice, video, broadcasting, IoT, D2X, D2D, Machine to Machine (M2M) and others. 5G uses OFDM (Orthogonal frequency-division multiplexing), a method of modulating digital signals across multiple channels to reduce interference. It uses the 5G NR air interface as well as OFDM principles. 5G supports both narrow-

Table 2.1: 1G to 5G summary

Standard	Key features	Challenges
1G	AMPS, TACS, analog communication, 2 kpbs speed, voice only	Mobility and roaming issues
2G	GSM, CDMA, GPRS, EDGE, 64 - 135 kbps, digital communication, voice and text messaging, multimedia	Limited network capability and challenges in supporting internet services
3G	UMTS, WCDMA, HSPA, HSPA+, 0.144 - 168 Mbps, digital communication, voice calls, text, multimedia, data	Poor data performance, weak data rates, congestion issues
4G	LTE, LTE+ or LTE-A, 0.1 - 1 Gbps, digital communication, voice calls, text, multimedia, data, streaming video, VoLTE, VoIP, IP services, faster broadband services, low latency	Expensive hardware and equipment, high power consumption, no ad-hoc network sharing, lower data rates, low spectral efficiency, network drops
5G	NFV, SDN, network slicing, cognitive radios, dynamic spectrum access, mmwaves, device-to-device (D2D), vehicle-to-everything (V2X), AI, machine learning, cloud computing, 1 - 20 Gbps, high-speed broadband, no call drops, remote network management, Internet of Things (IoT), embedded system, ultra-low latency, M2M communication, suitable for various applications, supporting multiple frequency bands	Lack of research dedicated exclusively for rural connectivity using 5G, battery power consumption, high initial rollout costs

band and wideband applications. However, the research by Lai and Widmar in [84] shows that providing 2G, 3G, 4G, or 5G is going to be challenging in rural areas unless the cost of the network decreases. Similar conclusions were drawn in the study of William Webb's book "The 5G Myth", which suggests that 5G is mainly focusing on dense urban networks and is not suitable for other deployment scenarios in the traditional deployment scenarios [48]. The economic cost modelling adopted for urban and industrial areas is not suitable for rural settings, as discussed by Oughton in [7, 51]. Furthermore, passive sharing does not reduce the cost as significantly as active sharing supported by 5G and open networks [85].

Technologies shown in Fig. 2.1 such as 5G, hot air balloon base stations, drone base stations, satellite internet and backhaul, long-range Wi-Fi networks, unmanned aerial vehicle (UAV), and TVWS are being tested for suitability as rural solutions and analysed for their techno-economic feasibility. A brief discussion of their suitability for different rural scenarios is given below:

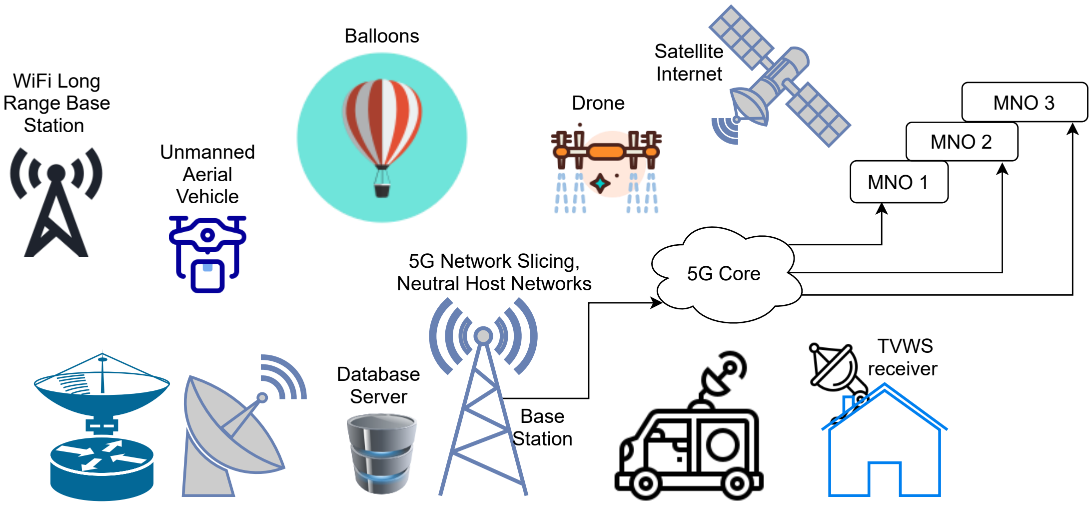


Figure 2.1: Different rural wireless broadband technologies

- **5G**: To address the issue of rural internet connectivity, researchers began testing the suitability of the design of a 5G communication infrastructure to address the needs of rural use cases. The research by Oughton in [8,46,86] investigated the costs of deploying and operating a nationwide 5G network with a duration of 10 years. The conclusion was that policy, technological advancement, and innovations in rural telecommunication business models will drive connectivity. Also, a key observation is that MNOs take a long time to deploy 100% coverage because the provisioning of telecommunication services is a costly procedure with a low or negative return on investment in rural or remote rural areas. Rural connectivity research projects by IIT Bombay [87, 88] present a potential solution, Frugal networks, that is low-cost and scalable for solving the digital divide using 5G NHN without network slicing and Wi-Fi. The proposed solution uses IEEE P2061 5G standards, architecture designed to support rural broadband communication. The network has two testbeds in Palghar, Maharashtra, India. The macro-cells support 5G access technologies while the village backhaul connectivity uses the TVWS link, and the last-mile uses wireless local area networks (WLAN) and Wi-Fi [88]. In another report by GSMA, the authors encourage sharing to reduce the digital divide to reduce overall costs in rural deployments [60]. It can be inferred from these studies that the main factor in minimising the coverage gap and connecting these places at affordable prices, is to reduce network deployment and operational costs and to find newer business models. Therefore, there is an emphasis on the need for a local service provider to deploy 5G networks. The risk of 5G adoption and technological and economic viability are also to be considered. The use of spectrum sharing in local 5G networks deployed by the InP is explored in [89, 90]. The studies highlight the benefits and ease of spectrum sharing in 5G bands, especially in higher frequency bands. In [42], the authors demonstrate the usage of the 3.5 GHz band for long-range coverage to provide broadband services.

- **Network slicing:** One of the 5G architectures that are being investigated extensively for rural solutions is network slicing. It encompasses applications ranging from slicing in the radio access network (RAN) to end-to-end network sharing. The network slicing for broadband-related applications is explored in [39] to improve rural broadband services, which are backed by eMBB services of 5G systems. The research shows the discussions on bridging the digital divide issues and focusing on multi-tenancy sharing of infrastructure to make rural connectivity sustainable. In [54], the authors' Noll and Dixit advocated using a single slice to give basic but free internet connectivity to people who cannot afford it in the Democratic Republic of Congo (DRC), while the rest slices are utilised for commercial operations. The solution educates rural residents about the advantages of access to the Internet. The idea of employing 5G NHN for industry verticals is being tested in a pilot study on the Orkney Islands, United Kingdom, where one of the slices will be utilised for BBC's [91] broadcasting applications and the remaining for the other rural industrial applications. The learning from the trial shows that 5G network slicing is an innovative option to encourage rural connectivity. The business models and value network configuration for 5G NHN in rural areas are explored by Shruthi in [19]. The research shows that the integration of the business ecosystem with rural connectivity solutions is crucial to improve the digital divide. Furthermore, the techno-economic feasibility of using 5G NHN in rural parts of India is studied by Shruthi in [18]. The results show that it has the potential to be considered for rural connectivity in India.

- **Satellite internet**: Satellite communication increasingly makes use of low earth orbit (LEO) satellites to provide internet connectivity to hard-to-reach rural areas which lack coverage using terrestrial telecommunication systems around the world [92–94]. Today, various satellite telecommunication companies such as OneWeb, SpaceX, Eutelsat, and Blue Origin are launching satellites to provide 5G and internet services for different applications [95–97]. The pricing would vary depending upon the application served, for example, affordable pricing for rural connectivity and high pricing plans for airlines and ships. OneWeb and SpaceX aim to remove the dependency of rural areas on fibre backhaul by providing excellent coverage and data rates using satellite internet [98].

- **HIBS/ HAPS**: High Altitude Platform Stations (HAPS) as IMT base stations (HIBS) is a non-terrestrial network that uses ground IMT-based frequency bands in their base stations at an altitude of 20 km in the stratosphere region of the atmosphere [99]. HAPS is mainly used for carrying aircraft communication payload, while HIBS is especially for communications platforms. Unlike satellites, they offer very low latency and provide coverage for an area up to 200 km in diameter [100]. The key use cases of HIBS are network expansion, disaster resiliency, IoT devices, and drones. However, there are many challenges that HIBS needs to address in terms of power requirements, operation conditions, operational requirements, interference, frequency of operations, link budget, and cost-efficiency [101].

- **Hot air balloon/UAV/Drone**: These technologies use flying antenna systems that work as a base station in the air between the backhaul network and the access network. The research in [102, 103] shows the application of hot air balloons/UAV/Drone for digital connectivity in hard-to-reach areas due to topographical challenges and for emergency services. The cost of the network is highly dependent on the number of drones required to support the use cases. The trials were performed for the drone to act as temporary base stations during network disruption in [104]. The results were satisfactory in the test trials. However, the feasibility of drones for a longer duration of usage is yet to be studied. Companies such as Google, NASA, Amazon, Taara, and Walmart are researching the use of these technologies for 5G service provisioning [105, 106].

- **TVWS**: Television WhiteSpace (TVWS) is a telecommunication technology in which information is transmitted using the TV frequency bands. After the digitisation of TV channels, a swathe of frequency became available around the world. In [107–109], the authors study and design the network by using TVWS technology to provide very long distance wireless backhaul capacity. TVWS acts as midhaul or backhaul technology. To offer services to end-user, the devices require last-mile connectivity via technologies such as 2G, 3G, 4G, 5G, and Wi-Fi. The frequency bands available for usage vary in different countries around the world. The application of TVWS in combination with Wi-Fi trials was performed in India by researchers of IEEE rural 5G broadband standards group [88]. The study in [90] highlights the different use cases of the shared spectrum and other test trials of TVWS in the UK. The results show the benefits of using shared spectrum bands for providing connectivity around the world.

- **Wi-Fi long range**: Long-range Wi-Fi is the technology for long-distance wide-area communication. This technology is being trailed as well as tested by different researchers and is easier to set up [42, 110]. The key advantages of long-range Wi-Fi are the usage of unlicensed spectrum, low cost and easier deployment, but the challenges lie in the maximum permissible operational power levels as it is operating in unlicensed spectrum bands [111]. This technology also uses MIMO systems to provide long-range coverage in rural areas and adhere to the usage policy of unlicensed spectrum bands. The recent study in IEEE 802.11ah shows that it has a potential for long-range backhaul and long outdoor networks [112] with power restrictions. The paper discusses the strengths and weaknesses of the technology and provides a survey of research from 2002 - 2014. This concept is extended further and researched to the networks in 2021 for topics such as fair allocation of resources, co-existence with other networks and use-case suitability.Frugal network uses a combination of fibre, and Wi-Fi to provide 5G connectivity in rural areas [88]. This combination of connectivity has also been explored in many African projects as mentioned by GSMA rural connectivity reports [60].

2.1.3 Comparison of possible technologies for rural connectivity

In Table 2.2, various potential rural technologies and their strengths, as well as weaknesses, are summarised. The challenges of 5G networks for rural solutions, such as local spectrum licensing, ease of new entrants into local markets, service subscription, and network slicing performance, must be addressed. Furthermore, Authors such as Georgakopoulos and Hamid in [128, 129] respectively, highlight the importance of renewable energy for rural connectivity was investigated, with the issue of connection to an alternate energy source in the absence of renewable sources. Similarly, though TVWS communication has a long-range, parameter limits exist for deployment in terms of factors such as power levels, maximum allowable interference levels and spectrum licensing. The price and reliability issues associated with solutions such as hot air balloon base stations, drone base stations, satellite backhaul, HIBS, HAPS, long-range Wi-Fi, and UAVs must be solved for these solutions to become scalable, according to the rural connectivity study. These solutions are not yet totally appropriate for use in rural areas at the current stage for a wide-area network. The study by Khalil in [59] summarises different rural technologies and their viability in terms of network architecture, performance,

Table 2.2: Comparison of different rural connectivity solutions

Technology	References	Strengths	Weaknesses
5G	[7,45,46,50, 51,86,88]	Very high speed, versatile applications, reasonable pricing, remote maintenance, software-defined networking, shared spectrum, supports multiple frequencies, works well up to 500 kmph, energy efficient	High TCO for independent deployment, difficulty obtaining spectrum licence, requires legal approvals and network planning, revenue depends on the subscription rates and existing infrastructure usage
Network slicing	[11, 18–20, 25, 38, 83, 113–123]	Easily scalable, cost-effective, supports neutral hosts and spectrum sharing, resource allocation as per demand, isolation of slices, 5G features, easy setup	Technology implementation, legal and government approvals, spectrum regulations, policies about sharing the infrastructure
Satellite internet	[2,92,94,95, 97,98]	Provide coverage anywhere on the earth increasingly using LEO, high-speed data rates, easy setup, supports OTT, smooth handover for mobile devices, low latency	High subscription fees, customer premise equipment (CPE), higher cost, dependent on weather, no roaming for in-house antenna, lower data capacity limits compared to terrestrial networks
HIBS/ HAPS	[99–101]	Wireless, non-terrestrial, long-distance, low latency, higher coverage	Techno-economic feasibility is not fully studied, weather-related challenges, legal approvals, interference planning, fuel issues
Hot air balloon/ UAV/ Drone	[2,102,103, 106]	Wireless infrastructure, long-distance coverage, relatively easy to set up anywhere, short requirements for base station	Techno-economic feasibility is not fully studied, weather-related challenges, legal approvals, interference planning, fuel issues, roaming agreements, continuous service requirement is not feasible
TVWS	[43,90,107–109,124]	Very good coverage, supports LTE, 5G small cells and internet, long-distance transmission, wireless backhaul, long transmission ranges, lower cost	Spectrum licence, DSA technology, licence duration, middle-mile technology, user-devices do not operate on these bands, power restrictions, interference management, dynamic change in frequency of operation
Wi-Fi long range, Wi-Fi plus fibre	[88, 125–127]	Easy to set up, unlicensed bands, devices support Wi-Fi bands, plug and play devices, in-house or local areas networks, very high data rates	Limited power supply, interference prone, customised for rural requirements, handover for mobile networks

characteristics, and deployment concerns. The research by Oughton in [8] shows that using open-source technologies for deploying 5G in urban scenarios with multi-MNO radio access networks (MORAN) sharing reduces cost by at least 50%.

Challenges with traditional 5G deployment

To overcome the rural connectivity challenge, researchers started to develop solutions by modifying the 5G communication system design for rural standards. There are many research works that study the scenario of providing a nationwide 5G network [7, 46, 86]. These studies conclude that the time taken by the MNOs to deploy 100% coverage is a longer and more expensive process with a low or negative ROI and the risk assessment of 5G adoption along with the techno-economic feasibility. The 5G solutions are prohibitively expensive for rural areas, which could be non-profitable for the MNOs to roll out networks in these places. In light of recent auctions of the 5G spectrum that have become expensive, another concept called dynamic spectrum sharing is becoming popular. The 5G systems support different frequency bands ranging from sub 1 GHz (450 MHz) to 52.6 GHz. Thus, localised spectrum licensing has revolutionised 5G.

2.1.4 Technological advancements

The sharing of infrastructure using neutral hosting makes them more energy- and cost-efficient. With mobile networks becoming affordable, they become more accessible to everyone who wants connectivity - enterprises, businesses, public buildings, and individuals. The technological advancements which make neutral hosting possible are discussed below:

- **Software defined radios (SDR):** In SDR, the radio communication hardware components are replaced by the software counterparts such as software on a system on chip (SoC), field programmable gate array (FPGA) computer or embedded system. SDR has been researched for a while, and with the latest technological advancements, it is possible to benefit from its capabilities.

  The price of an SDR might vary depending on features such as frequency range, maximum bandwidth, receiver antenna, transmitter antenna, and sampling rate. Spectre, for example, costs \$10,000, whereas the Realtek RTL2832U DVB-T tuning is just \$8. The SDR software handles all demodulation, filtering (both radio and audio frequency), and signal augmentation. SDRs allow the tune to different shared spectrum bands using a single antenna for DSA applications [130].

- **Spectrum sharing:** Spectrum sharing is a method of optimising the utilisation of the wireless communication spectrum bands by allowing several users to co-exist on the same frequency bands [131]. DSA is a type of spectrum sharing technology that provides the capability to opportunistically share the spectrum with secondary users (SUs) along with licensed or incumbent or primary users (PUs). Companies such as Federated Wireless, Google, and Fairspectrum have explored rural and in-building connectivity using spectrum sharing technologies such as CBRS, licenced shared access (LSA), and TVWS [132]. Recently, Ofcom in the UK is exploring the shared spectrum framework, similar to the CBRS framework but in upper n77 bands [133].

∗ **Spectrum database:** The spectrum database enables real-time effective spectrum usage and maximises the advantages of spectrum use by enabling dynamic spectrum sharing. The spectrum databases allow registered SUs to browse a database to see what frequencies are available in a particular location for their usage while protecting the incumbents from the interference of the secondary users [30, 134].

∗ **Spectrum sensing:** This is a process of periodically monitoring the presence or absence of the users on different bands using the spectrum analyser (plots the amplitude of an input signal versus frequency). Spectrum sensing helps in finding underutilised bands to maximise spectral usage by potentially reallocating it to secondary users. Real-time spectrum sensing has the potential to help to inform future spectrum policy decisions and could also feature in future spectrum access mechanisms. This is becoming achievable in upcoming radio networks since the advent of SDR technologies.

∗ **Cloud core:** In cloud core, all hardware, software, baseband processing, switching, and other infrastructure capabilities, are hosted online rather than physical infrastructure. It is less expensive to set up, more scalable, faster, and easier to scale. Without any physical deployments, the cloud core can increase or decrease the network's resources to match the resource requirements. The cloud core supports network as a service (NaaS), radio as a service (RaaS), and infrastructure as a service (IaaS) [135]. This research also uses a cloud-based approach for rural 5G NHN networks.

∗ **Multi-access edge computing (MEC)**: "*MEC aims to unite the telecommunication and information technology (IT) cloud services to provide the cloud-computing capabilities within radio access networks in the close vicinity of mobile users*" [136]. MEC is agnostic to the underlying radio technology infrastructure and is the flexible element in communication networks which makes it easy to adapt to any deployment scenario. Therefore, the operators can deploy MEC on the existing 4G network without upgrading to a full 5G system in order to keep the capital investment low and offer cost-effective solutions for the potential users for different use cases. This allows the service providers to observe the potential returns from the deployment and scale up accordingly. Hence, the deployment from 4G MEC to 5G MEC is smooth as there is a minimal upgrade at each transition stage, and can be a potential revenue source even without the need to wait for advanced 5G deployments. The “edge cloud” would help the service provider to host applications and test features of virtual networks and assess the potential income from it, during the smooth transition from 4G to 5G. The benefits offered by MEC and its virtualisation include accurate pricing models based on resources required and utilised, dimensioning of the edge resources as required by the application, lower upfront investment, and improved network capabilities.

∗ **Network functions virtualisation (NFV):** It enables network operators to manage and enhance their network capabilities on demand by replacing physical network equipment with virtual, software-based applications. With the deployment of updates on a regular basis, operators can maintain their systems up to date without disrupting their subscribers [137]. NFV enables businesses to divide distinct virtual networks inside a single physical network or to link devices across physical networks to form a single virtual network, increase resource utilisation and offer network flexibility [138].

∗ **Software-Defined Networking (SDN):** This is a networking technology that uses software-based controllers or application programming interfaces to connect with underlying hardware infrastructure and guide traffic on a network’s application programming interface (APIs) unlike traditional networks which use hardware devices to control network traffic (such as routers and switches). SDN allows for increased flexibility, customised network architecture, and a secure network to protect the network from threats and hacking [138]. SDN could use a few hardware components but mostly uses software components. SDN and NFV together support network slicing functionality.

∗ **Open-source radio technologies:** It allows any programmer to view, edit and modify the source code. Programmers with access to software’s source code can improve it by adding new features or fixing areas that don’t always work correctly [139]. Robust interoperability is one of the key advantages of adopting open source and open standards in the telecommunications industry. Open-source software aims to improve a wide range of technologies while avoiding incompatibilities. Lime Microsystems, a pioneer in SDR in the United Kingdom, has developed a full 5G network in a box solution for private networks, for example. The LimeNET box is powered by an AMD processor and follows Open RAN guidelines. LimeNET uses an app called LimeSDR for bespoke cellular applications, ranging from 5G-SA (StandAlone) and narrowband IoT to Enterprise applications.

- **Open RAN, virtualised-RAN (v-RAN) and cloud-RAN (C-RAN):** Open RAN is an industry-wide open-source, vendor-independent standard for RAN interfaces that allows interoperability between telecommunication vendors' equipment while lowering network expenses. The main purpose of open RAN is to provide an interoperability standard for RAN components. It includes non-proprietary white box hardware and software from a variety of vendors. Traditional RAN elements with standard interfaces bind network operators to a single vendor's proprietary hardware and software. The fundamental components of V-RAN and C-RAN are cloudification, intelligence, automation, and open internal RAN interfaces [140,141]. Facebook is working on OpenRAN devices to define and build 2G, 3G, and 4G RAN solutions based on general-purpose, vendor-neutral hardware private networks to support plug-and-play BSs and wireless network services and software-defined technology. Similarly, OpenRAN 5G project group focuses on open 5G NR architecture to support NHN along with network slicing.
- **Radio Frequency System-on-Chip (RFSoCs):** SoC is an integrated circuit (IC) that combines a whole electrical or computer system onto a single substrate. The Zynq RF-SoC DFE combines hardened digital front-end (DFE) blocks with flexible logic to create high-performance, low-power, and cost-effective 5G NR radio solutions for a wide range of use cases in any spectrum band [142]. The Zynq RFSoC DFE provides the combination of technologies, combining the cost savings of an application-specific integrated circuit (ASIC) based on hardened blocks with the flexibility, scalability, and time-to-market advantages of a programmable and adaptable SoC [142].
- **Neutral Hosting:** The working definition of a neutral host is that it "*is a service provider that builds and operates an integrated technology platform that is solely for sharing purposes*" [34]. NHN allows a third party - InP, to invest in the infrastructure for a public mobile access network and offer connections to the private network [143]. Technologies such as 5G network slicing with open RAN, and citizen's broadband radio services

(CBRS) support the NHN. The neutral host approach can solve the urban densification and rural digital divide issues by allowing operators to reuse the infrastructure of the InP supporting NHN [144]. The operators can benefit from the services without having to invest the initial investment or carry much of the ongoing running expenditure [113].

2.1.5 Need for 5G network slicing supporting NHN

Network slicing supports multi-tenancy by creating virtual networks (end-to-end) to support different applications and slice tenants such as ISPs, MNOs, industry verticals and small-scale businesses. The slice tenants can operate their 5G services easily and at affordable prices. 5G network slicing supporting NHN is possible because of the above technological advancements with radios, Open RAN, NFV, SDN, spectrum sharing, mobile technologies, SDR and other technologies. The slices are independent and isolated with guaranteed 5G KPI levels.

There has been some literature on using 5G NHN to provide internet connectivity in rural and urban settings [145]. The survey on the evolution paths of NHN, its strategies and business models is presented in [20]. The research also presents the use of NHN to revolutionise the telecommunication business models, especially for rural and in-building connectivity. The study in [19] explores a community-industry-driven ecosystem for rural 5G NHN for a wide-area network using value network configurations and business models. This research explores the deployments of rural 5G NHN to reduce the digital divide and concludes the suitability of NHN in a rural setting. The investigation by Oughton and Jha in [7] highlights the need for supportive 5G policies by eliminating spectrum licensing costs to deliver 6G for rural connectivity with application to the Indian scenario. The research also presents the exorbitant cost of 5G networks in traditional deployment and concludes the need for encouraging policies in rural areas to reduce the digital divide. As per the research, the cost-effective way of connecting rural areas is through wireless technologies. The trials in [39] show that multi-tenancy within fibre broadband for Government and non-Government organisations in Tonga reduces the digital divide. The research also suggests that a study on the integration of technologies to address the digital divide should be compiled and discussed, for discussion with stakeholders. The pilot test in [54] uses a single network slice to provide basic but free internet connectivity in the Democratic Republic of Congo (DRC) for people who cannot afford it, while the remaining slices are for commercial operations. In [9], 5G NHN is tested in a pilot study for a densely populated urban city where the InP is Barcelona city. 5G NHN is shared by network operators. Similarly in [38], 5G NHN is studied for a campus-wide network where the university acts as an InP, and MNOs lease slices from the InP network. The research in [91] presents the 5G RuralFirst pilot study on the Orkney Islands, Scotland, UK, which uses rural 5G network slicing for different industry verticals, especially wired broadband services for each home as well as a broadcasting application. The research focuses on providing connectivity for remote rural areas as well. This research highlights the use of 5G NHN for different applications and its practical implementation of it. The trial concludes that private and public NHN is possible to deploy and implement. Some of this research focuses on roaming services for subscribers moving to the MNOs' wider network in a seamless handoff fashion. This is a critical issue that must be addressed because if the handoff is not smooth, end-users will lose connectivity abruptly.

There are several case studies and pilot trials to verify the network slicing functionalities, working and use cases. For example, a 5G NHN pilot trial between InP and media service providers (MSPs) is studied in [9]. The slicing facilitated media use cases such as virtual reality, holograms, gaming and broadcasting. The test trial studied the process of implementation and deployment of ultra-dense NHN and its benefit in the media context. This paper also states the KPI requirements to support the use cases in Briston, Lucca, and Barcelona deployment scenarios. Similarly, the state grid corporation of China (SGCC) has been testing the internet+ strategy for their smart grid applications [143]. The authors propose the use of 5G network slicing for their use cases related to a smart grid. Furthermore, the TCO and ROI are also calculated. A large-scale pilot trial test-bed in the Hamburg seaport area proves that basic features of network slicing such as multi-tenancy, slice isolation, and flexible slice customisation are feasible [115]. The slices supported vertical applications such as eMBB, uRLLC, and mMTC in the port to avoid congestion and reduce operational delays.

Governments, academic institutions, and corporations offer various funding opportunities to encourage researchers to work on this challenge. The use of localised spectrum access is examined to encourage rural local 5G networks. The research in this thesis includes several United Nations Sustainable Development Goals, such as 'reduced inequalities', 'sustainable cities and communities', and 'industry, innovation, and infrastructure'. This is mainly because the 5G NHN using a network slicing approach with MNOs as slice tenants have been considered a cost-effective option for solving rural connectivity issues which could encourage the growth of communities and reduce inequalities. The subscribers on the rural networks would be directly the tenants of the MNOs and operators. This leads to seamless roaming services when the subscriber is travelling outside their home network, and this would help achieve the key objective of the research. The quality of rural networks would inevitably improve if every stakeholder is profitable.

2.2 5G Background

5G is the fifth-generation communication technology being developed by various standardisation bodies such as 3GPP, IEEE and 5GPP; and various pilot tests are being deployed around the world for multiple applications [146]. Furthermore, a few cities have deployed LTE 4.5 deployment which almost provides the features of 5G networks, while several cities have operational 5G deployments [145, 147].

5G promises to deliver ultrafast data in the range of Gbps per user, as low as 1 ms, extremely high spectrum efficiency (3x), hyper-densification (100x), very high connection density (up to 1 billion devices), highly reliable and superior network efficiency (99.9%, 100x), and energy-efficient (10x), compared to the 4G technologies [16]. 5G can support a wide range of technologies such as SDN, NFV, multiple-input and multiple-output (MIMO), beam-forming, internet of things IoT, green communication (using renewable energy sources), ultra densification, big data, mobile computing and DSA. The use cases of 5G include smart cities, smart agriculture, industry 4.0, self-driven vehicles, the internet of things (IoT), smart homes, smart universities and smart healthcare. The three main application categories of 5G as described in Chapter 1 are:

- eMBB: This allows ultrafast broadband on mobile phones for multi-media content. It allows applications such as video streaming, augmented reality, cloud computing, enhanced gaming quality, live streaming of sports, and an ad-hoc network for event coverage.

- uRLLC: This supports extremely low latency requirement applications such as critical communications, network slicing, robotic controls, autonomous vehicles, remote medical surgery, emergency management, and remote network maintenance.

- mMTC: This supports applications that consist of large devices, up to 1 million devices per km^2, and low bandwidth requirement applications. For example, IoT applications require mMTC capabilities, such as smart lighting, health monitoring devices, smart homes, and smart grid.

There are different studies to analyse the feasibility of providing 5G networks for a nationwide network. For example, the requirements for deploying a nationwide 5G network in the UK [12]. The report assumes an urban setting with 2x2 sharing between the operators would be feasible. The policy needs to be inclusive to achieve 5G rural connectivity and allow 1x4 sharing between operators, i.e., the four national MNOs sharing common infrastructure and spectrum in rural areas. The report also suggested using alternative solutions for backhaul and shared spectrum bands for operations to reduce costs. Similarly, to bring 5G connectivity to India, the white paper by Telecom Regulatory Authority of India (TRAI) [56] discusses the challenges in terms of network specifications, architecture, spectrum, backhaul, small cell deployment, investment, regulatory policy, and use cases. As pointed out by the research, newer business models, higher investments and deployments are needed to make 5G feasible [56].

2.2.1 5G network architecture

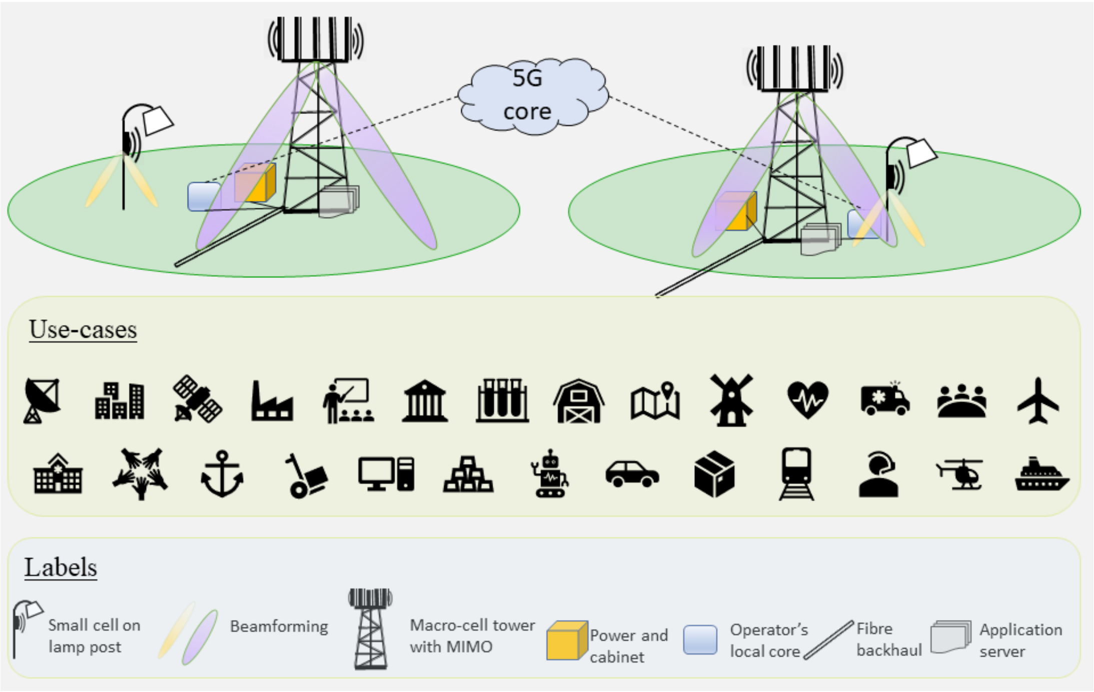


Figure 2.2: General 5G architecture along with the use cases

Fig. 2.2 shows the 5G architecture and the general use cases in different scenarios such as office buildings, seaports, airports, shopping malls, industry, schools, universities, virtual reality, hospitals, retail mobile users, transportation and logistics, and IoT applications. 5G enables remote monitoring and maintenance of networks. The backhaul could use technologies such as fibre, microwave, fixed wireless access (FWA), satellite, TVWS, and long-range Wi-

Fi. Similarly, the spectrum of operations could be varied depending on the coverage region, for example, macro-cells using sub 1 GHz, small cells using sub 6 GHz (FR1), femtocells using FR2 bands (24.25 GHz to 52.6 GHz) [10].

5G core supports C-RAN and virtualisation, service-based architecture, control and user plane separation, mobility and session management, key parameter indicator based SLA and QoS for new services. 5G also allows loose coupling to support easier interoperability between different devices and standards. Cloud services allow run-time expansion and reduction in the resources and network capacity that helps better resource utilisation to support multiple and additional applications as well [148].

2.3 5G Network Slicing and NHN

2.3.1 Sharing technologies

There are different levels of infrastructure sharing strategies available to select from for the InP and the operators. The main sharing strategies are *No Sharing*, *Passive Sharing* such as site or tower sharing, *Active Sharing* such as ACP, GWCN, MOCN, and MORAN and *Neutral Host Networks* as shown in Table 2.3 [149]. Table 2.4 shows there are different technologies supporting network sharing, and currently, network slicing is the most advanced among them. The key terms used in Table 2.4, are radio frequency (RF), evolved Node B (eNB), mobile management entity (MME), service gateway (SGW), and packet gateway (PGW). It can be observed that 4G technologies support some form of network sharing but not end-to-end network sharing as in 5G network slicing [150, 151].

Table 2.3: Infrastructure sharing strategies

Strategies	**Pros**	**Cons**	**Usage scenario**
No Sharing	Full control over the network infrastructure	High cost of deployment	Private network
Passive Sharing	Sharing of only passive components and reduced cost compared to *No Sharing*	No decision making power on the parameters of the passive components	Tower sharing
Active Sharing	Sharing of passive and active components, presence in a market where subscribers are low	Lower control on the network infrastructure	MORAN, MOCN, roaming
NHN	Sharing of all components, reduced cost, shared risk	Least control over the network competition, the risk to fair competition in the market	Wholesale, InP

Table 2.4: Network sharing technologies

Technologies	References	Features
Access point network (ACP)	[152]	RF, eNB, MME, and SGW are common, but PGW is different.
Gateway core network (GWCN)	[152]	RF, eNB and MME are common, but SGW and PGW are different.
Multiple operators core networks (MOCN)	[150, 152]	RF, and eNB are shared, and the core is dedicated to each operator and service.
Multiple operators radio access network (MORAN)	[150, 152]	Except for eNB, the rest of the components are shared. The traffic is routed to the corresponding operators using the eNB.
National roaming	[152, 153]	Roaming agreements in the national context, and the complexity lies in deciding when the network should prefer the home operator's network to another operator's network.
NHN using network slicing	[20, 151]	End-to-end components of the 5G system, including the spectrum, and each slice has virtual units on the radio, core, and transport levels, are shared.

2.3.2 Technology aspects of NHN

Network slicing allows the creation of virtual slices on the same physical resources to support a higher number of UEs, on-demand resource allocation, remote resource management for the UEs, higher spectral efficiency, lowering the cost, customised services, and isolated operations of the slice tenants [83]. The creation of network slicing is explained in [117]. As the hardware resources are shared among the slice tenants and resources allocated based on demand, network slicing increases resource utilisation. 5G network slicing supports cloud based-services for baseband processing and network upgradation. Furthermore, the independent operations of tenant's services on the slice are one of the most interesting features of 5G network slicing [154, 155].

The architecture of end-to-end 5G network slicing supporting NHN is as shown in Figure 2.3. Each slice tenant on the network would have their own virtual 5G RAN, virtual baseband processing unit and a connection to the InP's 5G core. The InP core connects to the slice tenant's network 5G core. The tenants on the network could be MNOs, ISPs, MSPs, industry verticals, event organisers, OTT and emergency services, to support 5G use cases. Depending on the legal and regulatory policies of the national regulator, the network could operate on one of the tenant's spectrum bands or shared spectrum bands.

In 5G network slicing, the slice can be created, connected, and terminated as per the demands of tenants. Ad-hoc service provisioning supported by network slicing is not possible in any other network-sharing technologies [136]. In 5G network slicing supporting NHN, multi-

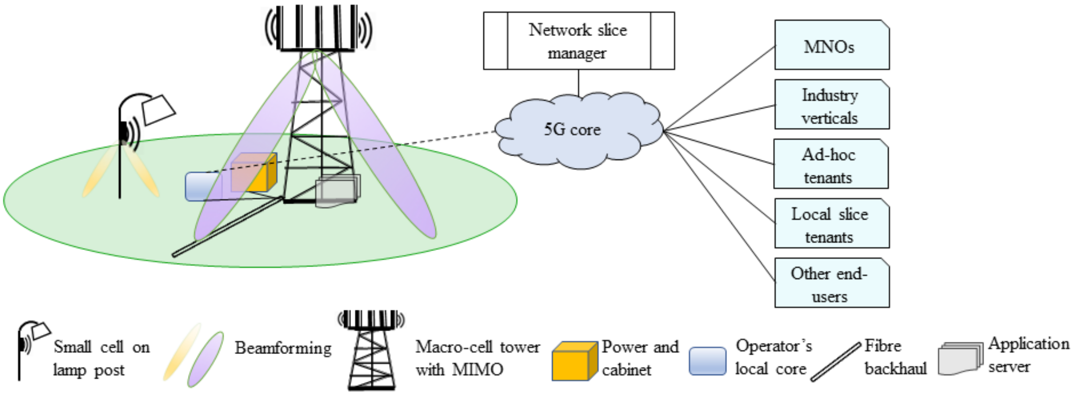


Figure 2.3: 5G network slicing architecture

ple operators can co-exist without a direct agreement with other slice tenants on the same InP network. The operators would need to have an agreement only with the InP [11, 83]. According to the service level agreement (SLA) between the InP and the slice tenant, the InP would allocate resources and provide minimum guaranteed resources to each one of them. Network slicing facilitates the co-existence of multiple slice tenants ranging from short to long-term duration on the same physical network [121, 156]. The concept of NHN has been explored for a few years but requires policies to encourage investments and deployments by new entrants [157]. 5G NHN using network slicing would play a crucial role in reducing rural internet connectivity costs as each operator could lease slices from a single physical infrastructure. Each operator can compete in terms of their service quality to end-users instead of infrastructure deployment-based competition [34, 113].

Fig. 2.4 refers to the system level layer of network slicing architecture defined by 3GPP, which includes network slice (NS), network slice instance (NSI), which is a set of physical and logical components that realise a NS, network slice subnet (NSS) is a sub-NS representing the logical network segment of NS, and network slice subnet instance (NSSI) is a combination of all NSI and can be shared by several NSIs. Fig. 2.4 shows the four phases introduced by 3GPP for the NS lifecycle management framework that include preparation (NSI environment preparation), commissioning (allocation and configuration of needed resources for NS requirements), operation (activation, supervision, reporting, modification, and deactivation of NSI resources), and decommissioning (removing and releasing NSI resources) [158, 159]. This architecture supports end-to-end network slicing, allowing multiple operators to co-exist on a single physical infrastructure.

An InP could be anyone, such as an MNO, third-party service provider, community, lo-

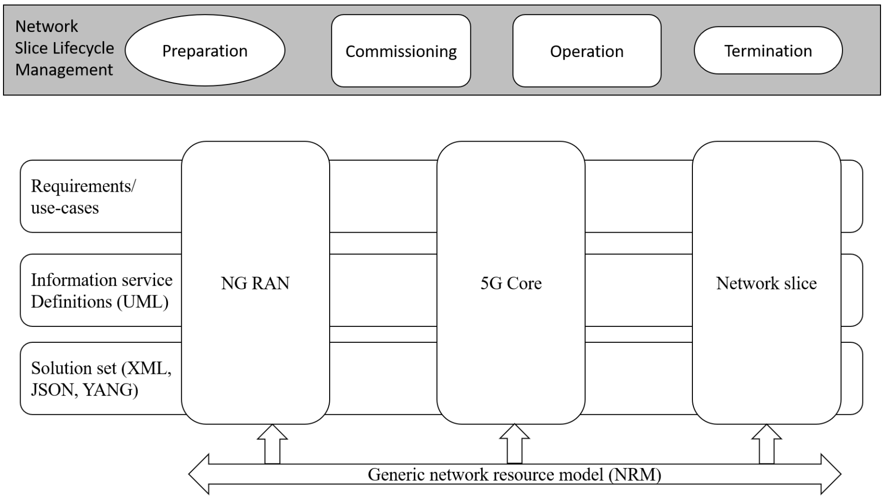


Figure 2.4: System level architecture of network slicing

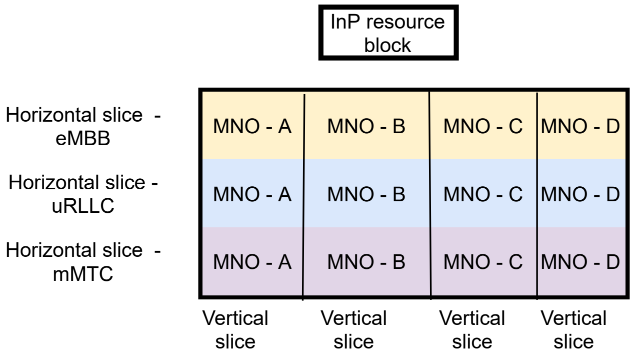
cal governing body, industry, university, or real estate owner, and earns revenue by leasing the slices. Network slicing includes a wide range of variations, such as end-to-end network sharing, core slicing, multi-tenancy, backhaul slicing, RAN slicing, and last-mile solution slicing [160–162]. The 5G network slicing architecture should be flexible to accommodate changes as required [163]. Based on the application, the slices could be created for a shorter or longer duration. One of the main advantages of network slicing is the confidentiality of resource allocation to end-users. 5G network slicing allows InP to modify its functionalities using virtual machines as per the demand of tenants on the slices to provide services to the end-users of the tenants with the support of NFV and SDN. This, in turn, helps in the realisation of the MEC applications. This represents the concepts of NaaS [164] and RaaS [165].

The concept of micro-operators deploying 5G network slicing for MNOs and their instances using micro-cells are studied in [166]. The paper proposed different approaches for the configuration of network slice instances (NSIs) while considering different deployment scenarios. Some of the research on 5G network slicing proposes NHN in small cells for urban, industrial, and university networks. The comparison between using distributed antenna systems (DAS) and third-party solutions such as NHN for indoor spaces is discussed in [40]. The author argues that DAS allows MNOs to control the technology, whereas third-party solutions allow scalability for indoor coverage solutions and also provide MNOs with the potential to grow in the sector of indoor coverage through NHN. The slice tenant controls the resource allocation to their end-users [167, 168]. Slice tenants have autonomy over the resources allocated to their end-users based on their business strategy, unlike in roaming agreements [11].

Resource allocation is the key to the adoption of this architecture, especially when the network is congested. The multi-resource allocation for network slicing should focus on fairness and system efficiency, as discussed in [169]. The paper describes the difference between resource allocations in earlier generations and 5G network slicing and later different optimisation algorithms proposed to implement fair and efficient resource allocation using game theory frameworks and algorithms. Similarly, in [170, 171], the authors discuss the different types of network admission algorithms and the possible monetising opportunities when a tenant leases the slice. The 5G network should be smart enough to decide the slice tenants based on whether service level agreements (SLAs) are achieved. The algorithm also uses the knapsack model of game theory to select the tenants on the network such that revenue is maximised and the network capacity is efficiently utilised. The study in [165] solves the resource allocation issue using an optimisation technique for maximising the system capacity with constraints on transmitted power and allocated bandwidth. In [172, 173], the authors focus on the resource allocations for the tenants and the end-users using admission control algorithms or resource maximisation optimisation with power and bandwidth constraints.

The research in [174] shows the traffic prediction model for the slices to help the InP decide on network capacity and resource requirements to meet the demand. To understand the impact of the slices on macro-cells and microcells, a recent study by Meneses explores the challenges, architecture, and concept of slice instantiation in [175]. Furthermore, the author stated the benefits and challenges of micro- and macro-cell slicing. The research is verified using OpenAirInterface and FlexRAN frameworks to evaluate the impact of several slices on the network. As the number of slices and users increases, the system throughput increases before reaching a saturation state. In this paper, the author uses a game theory model - the Stackelberg algorithm, with a leader and follower idea to study the required system throughput. The authors in [72, 176, 177] studied the concept of vertical and horizontal slicing along with the architecture and technology to support network slicing. The virtualisation of resources has been beneficial in implementing the neutral host concept.

Fig. 2.5 shows the 5G framework for end-to-end network slicing supporting NHN using horizontal and vertical slices. The horizontal slicing support different use cases, and the vertical slicing allow multiple MNOs who require a particular use-case from the horizontal slicing [178]. The InP deploys the 5G NHN in rural areas, and MNOs lease slices from the InP. Each MNO could provide services for multiple use cases in the same village using the same physical infrastructure. The InP deploys and manages the rural 5G NHN for its entire life cycle. Existing research has estimated that 5G network slicing with multi-tenancy reduces the CAPEX by at



	Vertical slice	Vertical slice	Vertical slice	Vertical slice
Horizontal slice - eMBB	MNO - A	MNO - B	MNO - C	MNO - D
Horizontal slice - uRLLC	MNO - A	MNO - B	MNO - C	MNO - D
Horizontal slice - mMTC	MNO - A	MNO - B	MNO - C	MNO - D

Figure 2.5: Rural 5G NHN with horizontal and vertical network slicing

least 30% and OPEX by at least 20% over traditional 4G deployment [179].

2.3.3 Rural 5G NHN use cases

Typically, 5G NHN infrastructure deployed by a single InP could potentially cater to the demand requirements of rural villages. The possible slice tenants on the InP network are as shown in Fig. 2.6 and the use cases that could be supported at different SLAs are described below:

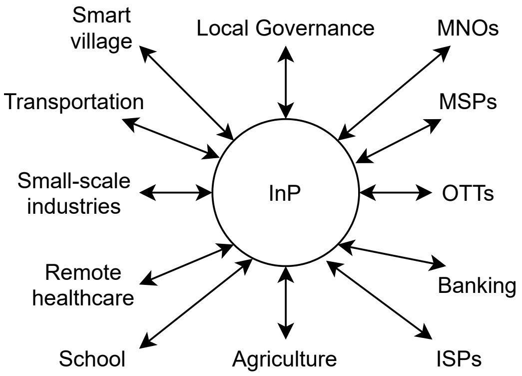


Figure 2.6: Network slicing application areas and the 5G use cases

- eMBB: The eMBB will benefit in meeting the requirements for higher data speeds and capacity volumes. Some examples of eMBB use cases would be video/voice calling, network slicing with multi-tenancy, remote monitoring, video monitoring of farms, remote health-care, industrial automation, soil assessment, video streaming, e-governance, e-commerce, and online learning. To support these applications, 5G should provide both coverage and capacity at a lower cost in rural areas compared to the existing network solutions to improve rural connectivity.
- mMTC: As discussed earlier, the mMTC refers to services for sensors and IoT devices

with limited power and bandwidth requirements. They would generally be present in rural use cases such as agricultural farms, small and large-scale industries, seaports, electrical grids, wind farms, fishery, poultry, and transport of farm produce.

- uRLLC: The uRLLC will help in mission-critical applications. For example, disaster management and response, control of critical services, machine-to-machine communication (M2M), industrial operations, remote health diagnosis, and remote maintenance of the 5G network. The data volume requirement may not be high for these applications, but the latency constraints are critical.

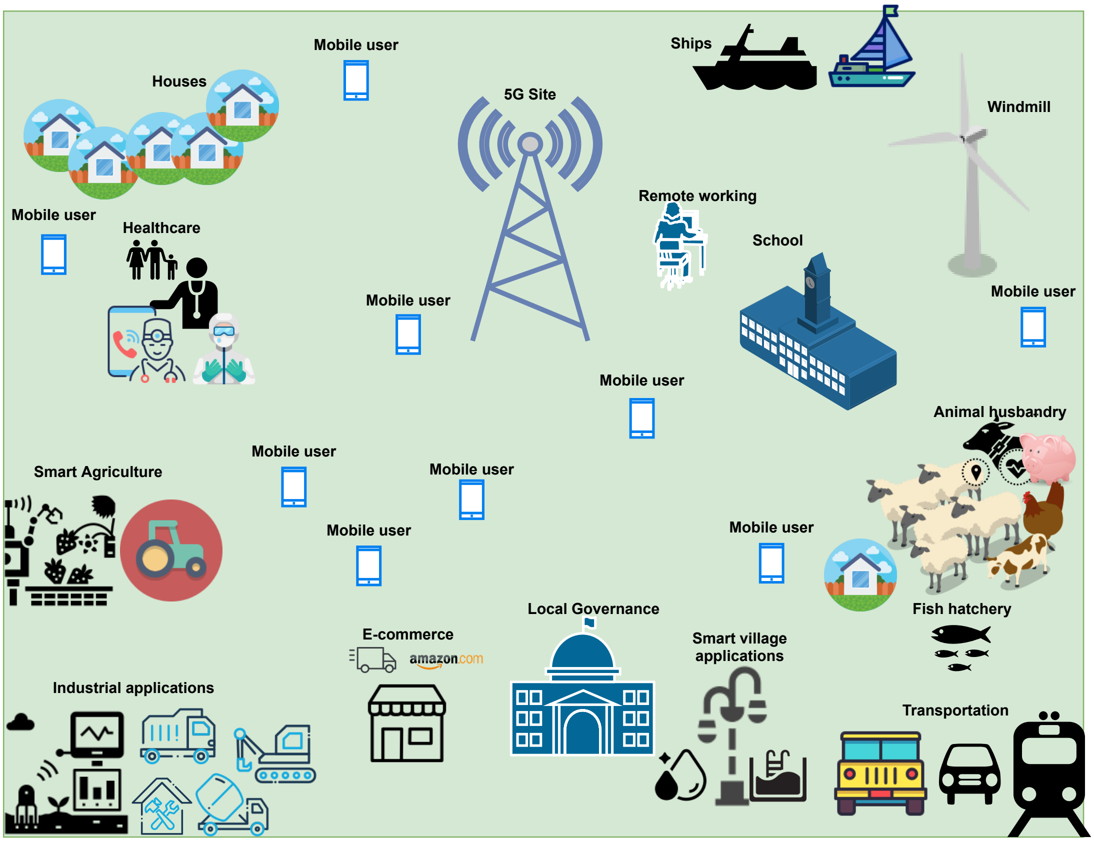


Figure 2.7: 5G use cases rural scenario

Fig. 2.7 shows the 5G NHN architecture and the possible use cases specific to rural areas and; each MNO could have more than one slice. The use case applications which justify the need for 5G NHN in rural areas are:

- *Smart agriculture and farming*: 5G networks support millions of devices such as IoT devices, which would be useful for sensing applications such as water levels, soil quality assessment, cattle and crop health monitoring, energy monitoring, and wind-farm sensors.

- *Smart village*: 5G networks can support smart village applications such as smart lighting, e-banking, e-payments, e-governance, digital assistance for aged people, emergency support requests, and disaster management.
- *Health*: Remote health monitoring and surgery play an important role in rural health assistance. E-healthcare during the pandemic helped to avoid burdening the healthcare system.
- *Education*: 5G networks will allow online education and remote schooling for kids and adults. People can access the knowledge available using the internet and apply it to solve rural challenges.
- *Remote work*: People could work remotely and continue living in rural areas. Working from home in rural areas would help the migration of people to over-populated urban areas.
- *Business*: Local businesses can build their online presence via good internet access, which helps them compete globally. Similarly, large businesses would get access to the local market, otherwise not be possible without internet connectivity. Also, local businesses could use the internet to support their production and manufacturing units using Industry 4.0 applications. 5G applications of local industries such as industry, water boards, and electrical grids would also encourage rural connectivity.
- *Rural tourism*: Some rural areas a quite popular as tourist spots and could monetise from tourism plus enhance the experience of tourists by having an online presence. Tourists could remotely work from rural areas and share experiences online with excellent internet connectivity. This would boost tourism in that area.
- *Personal communication*: Finally, personal communication is a crucial use case. Over-the-top (OTT) services, voice/video/text communication, private broadcasting, video surveillance, and internet services are all upcoming use cases in rural areas.

2.3.4 Current state-of-the-art

5G network slicing has been studied extensively as discussed. A key challenge in the telecommunication industry is that technology is highly dependent on the equipment vendors supplying equipment. Therefore, the concept of network slicing is being integrated along with Open radio access network (RAN) to encourage vendor-independent hardware and software in the telecommunication industry. The key technological challenge with NHN is the use of slicing and efficient resource allocation while maintaining agreed-upon performance for making it globally scalable [145]. Therefore, this concept is being further extended to 6G with network slicing as one of the key enablers [180]. The key benefits offered by NHN using network slicing, especially in rural areas, are maximisation of resource utilisation, efficient resource management, and reduction in terms of interference, cost, and power consumption [181]. The concept and implementation of the technology are quite complex and are being further explored to integrate it with open RAN in 6G.

2.4 5G NHN with Shared Spectrum

The dynamic spectrum management process based on network information theory is explored to improve the performance of communication networks as a whole. As a result, when the primary or incumbent user in a particular region is under-utilising their licensed spectrum, thus allowing secondary users to use it, but with restrictions such as power levels, bandwidth, interference tolerance, and frequency planning. DSA improves spectrum efficiency by increasing the number of users in the spectrum bands. To safeguard incumbent users, the band with secondary users supports DSA within a stringent interference level structure. Fig. 2.8 shows the generic architecture for spectrum sharing.

The key terminologies are:

- **Incumbent or primary user (PUs)**: They usually have the spectrum licences for the long term and coverage could be country-wide or state-wide depending on the spectrum policies of that country. Incumbents could be operators such as the military, MNOs, ISPs, TV broadcasters, and satellite users [40].

- **Secondary user (SUs)**: These are the licensed users who use the incumbent bands for a localised licence for cost savings. They should not interfere with the operations of incumbent users. Secondary users could be InP, micro-operators, private networks, mobile

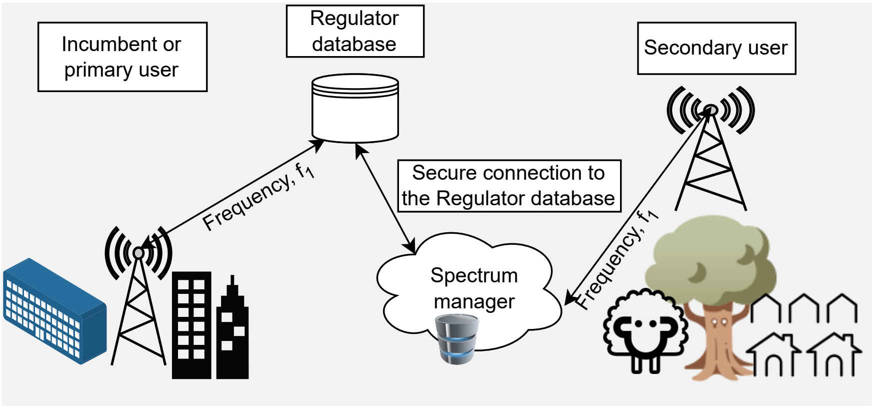


Figure 2.8: Generic spectrum sharing architecture

operators, drones, and local ISPs.

- **Geolocation database**: It approves spectrum usage, assigns frequencies to secondary users, monitors spectrum usage by all users, informs the national regulator about the usage, authenticates the users, stores usage details, and maintains records. The geolocation database monitors spectrum usage by different users.
- **Spectrum manager**: This allows registered devices to search a database and determine what frequencies can be used in a given area while protecting the signals of the incumbents from harm. It communicates with the PUs, SUs and databases. The time aspects of the shared spectrum licence are different for each sharing technology.

2.4.1 5G and spectrum sharing

The 5G spectrum bands are classified into two groups that include FR1 ($\leq$ 6 GHz) and FR2 ($\geq$ 6 GHz) spectrum bands. In Table 2.5, the frequency bands and their corresponding coverage and average data rates for a generic 5G network are summarised [182]. The main point is that data speeds are directly proportional to the spectrum band selected for transmission, and coverage is inversely proportional to the operating frequency. For example, the 700 MHz frequency bands have higher coverage areas and lower speeds, whereas the 3800 MHz band has lower coverage areas and higher speeds. Frequency bands in FR2 have ultra-high data speeds but smaller coverage areas. Hence, each operator would have to deploy multiple new radios (NR) to provide services.

Numerous studies have shown that spectrum and infrastructure reuse would significantly reduce the CAPEX and the OPEX [30, 131, 183]. Therefore, the next question arises regarding

Table 2.5: Frequency bands and its features

Frequency band	Range	Data rates
600 - 700 MHz	100s sq. mile	30 - 250 Mbps
3.2 - 4.2 GHz	several mile radius	100 - 900 Mbps
millimeter wave/ 24-39 GHz	one or lower mile radius	1 - 3 Gbps

the appropriate spectrum bands for the rural 5G NHN that can support higher coverage and data rate requirements.

2.4.2 Existing work

To encourage spectrum sharing of the underutilised spectrum of the MNOs and other incumbent operators, the authors in [184] propose using government reward models to encourage incumbents to share their unused spectrum band. It would encourage local 5G operators to invest by lowering existing spectrum licensing fees or subsidising their infrastructure. Spectrum sharing technologies such as licensed/authorised shared access (LSA/ASA), are analysed in [185]. The game theory framework helps to model the interactions between operators. Researchers evaluated the existing spectrum valuation and assessed the value of spectrum for the local 5G networks operated by micro-operators. The survey involves 5G bands spectrum valuation from each stakeholder's point of view. As studied in [186], the use of cognitive radio for spectrum sharing and the three business case scenarios for its use cases highlight its benefit. The business case indicates whether the value proposition is feasible. Currently, the n78 band ranging from 3.2 to 3.8 GHZ is becoming the 5G harmonised band around the world. Therefore, one of the recent initiatives, for example in the UK, is the upper n77 band (3.8 - 4.2 GHz) which allows shared spectrum access in the UK.

Matinmikko and Latva-Aho in the paper [187] introduces the concept of micro-operator for future mobile communication ecosystems. The authors propose the 3.5 GHz band for local operation and to avoid interference with a macro-cell. However, scalability is not investigated in the proposed method. The spectrum sharing technologies that are supported in the 5G network play a crucial role to maximise spectrum usage [188]. In [22], spectrum sharing for 5G NHN is discussed which shows that the micro-operator business case is beneficial to stakeholders such as InP (micro-operator), MNOs, and regulators. NHN is beneficial for the local operators to customise the slice to meet the needs of local requirements, maximise resource usage, and the MNO gains new streams of revenue. The potential of 5G NHN spectrum sharing is studied in [189]. The author uses a game theory framework to understand the financial gains achieved using NHN and spectrum sharing. Furthermore, the simulation results in [128] show that there is an improvement in the energy efficiency when common infrastructure and spectrum are used among four operators; which results in savings of around 50% when using 5G NHN, and gains by using spectrum sharing. The study in [183] concludes that the time and technology are right for introducing DSA in the 5G pioneer bands in the range of sub 6 GHz, especially citizens broadband radio service (CBRS) and LSA. The study also explores the cost models, potential revenue creation opportunities, legal policies, and challenges in NHN.

One of the crucial factors that decide the success of network slicing is a smooth handover from the InP network to the MNO network along with the interference of the InP spectrum bands over the incumbent spectrum bands [180]. The study also analyses the open challenges in 5G network slicing mobility management and provides several spectrum sharing techniques to reduce co-channel and cross-channel interference. Similarly, the concept of NHN for indoor spaces in [190, 191] demonstrates the usage of shared spectrum bands usage to avoid interference with the macro-cell operations. The paper also highlights the difference between roaming and slicing and also differentiates slicing from (MOCN) sharing, including the possible business models for this deployment scenario is discussed. The GSMA report in [192], presented a case study on using NHN in different spectrum bands and highlights the benefit of spectrum sharing.

2.4.3 Different spectrum sharing mechanisms for 5G NHN

Fig. 2.9 shows the bands available for spectrum sharing and the possible spectrum mechanisms on those bands. The major spectrum sharing technologies that can be operated with 5G, their benefits and their potential are:

- **TVWS** Due to the conversion of TV channels to digital, the frequency bands in the range of 470 MHz to 790 MHz are underutilised around the world. TVWS is a spectrum sharing technology in which the TV bands are used by secondary users for mobile communication, typically midhaul. The incumbent operators in this band allow usage by secondary devices, but with a maximum power level of 44 dBm, [193]. Fig. 2.10 shows the generic architecture of the TVWS network. The secondary users request frequency through the geolocation database, which provides information on the available frequencies and the network parameters for the secondary users.

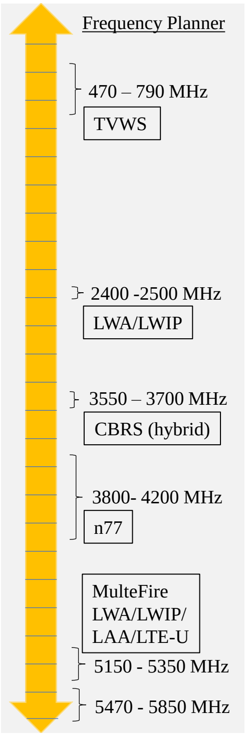


Figure 2.9: Spectrum bands and spectrum access methods for $\leq$ 6 GHz

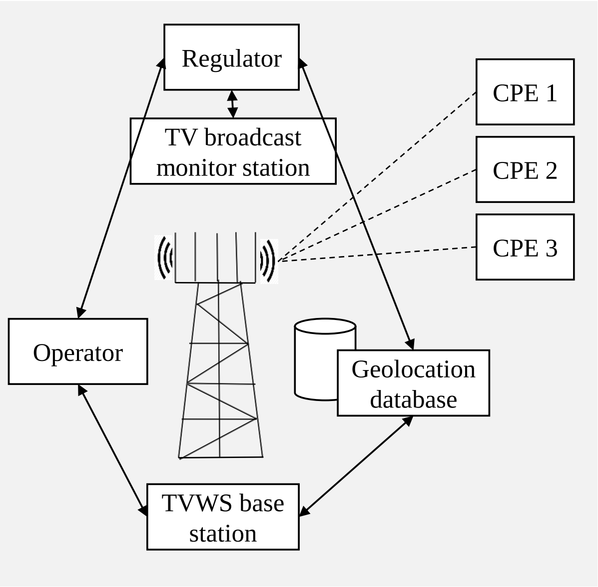


Figure 2.10: TVWS architecture

The researchers have explored using TVWS for improving rural connectivity in [194]. For example, in [195], the research shows the working of hopscotch networks using the TVWS band. The study used Pearl's algorithm with a Bayesian belief propagation implementation serving up to 100 households for the Isle of Tiree network trials. The research in [109] shows the feasibility of using TVWS in 5G networks for improving rural connectivity. The licence duration for the operation could be as short as 15 minutes.

- **CBRS** is a three-tier spectrum sharing technology approved by the FCC in the 3.6 GHz band. Fig. 2.11 shows the architecture of CBRS and its use cases. The environmental sensing capability (ESC) senses the spectrum available and their usage by secondary users using CBRS. The spectrum access system (SAS) allocates the secondary usage of the spectrum for a fixed duration of the investment. CBRS could support NHN as explained in [196]. The applications of CBRS such as industrial use cases, local rural community networks, seaports, and indoor connectivity have a positive scope [197].

  Fig. 2.12 shows the FCC-approved SAS architecture and its capabilities. The SAS is a smart and centralised manager that allows faster decisions and higher awareness for all users before selecting the desired frequency bands by the user. The research in [198]

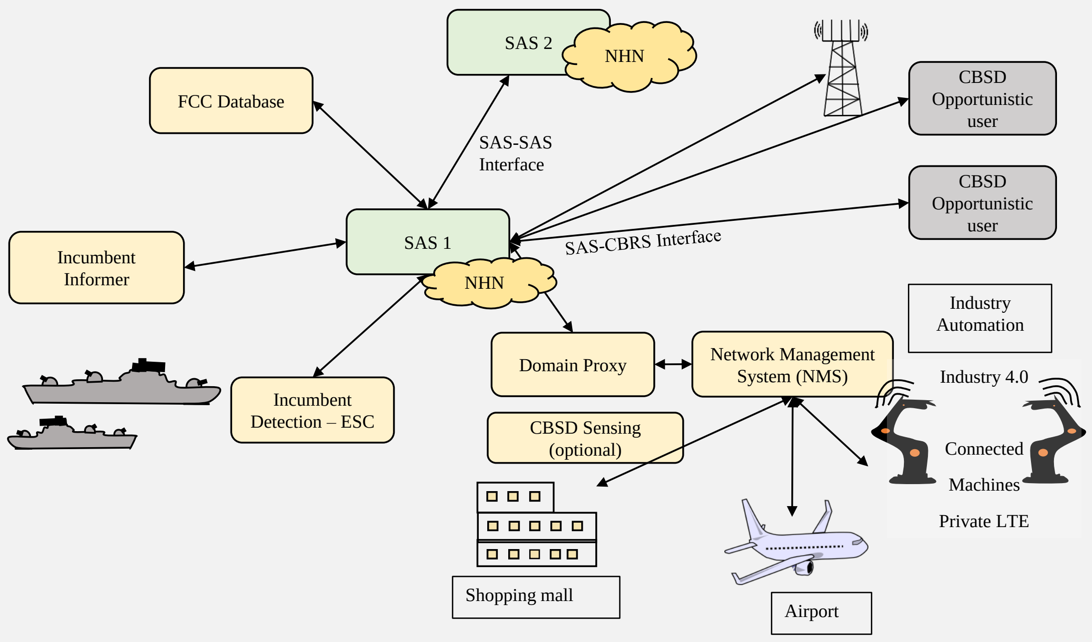


Figure 2.11: CBRS architecture

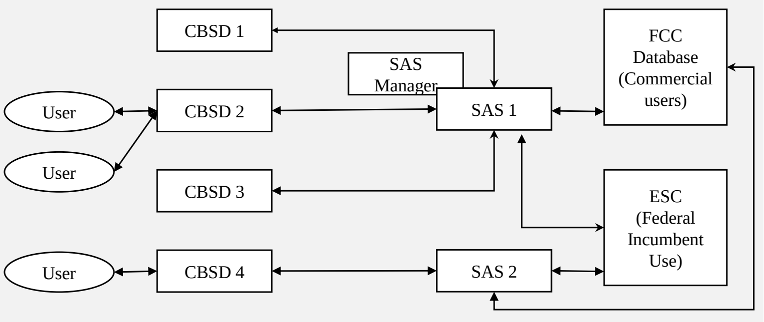


Figure 2.12: FCC SAS architecture

focuses on interference mitigation and user management. The licence duration could be ranging from 3 years to 10 years.

- **Shared access licence**: In the UK, Ofcom has approved the upper n77 band (3800 - 4200 MHz) as a shared access licence band. It has two possible types of licences - low-power and medium-power that determine the network operating parameters. The low-power licence allows a coverage radius of 50 m, while the medium-power coverage radius is determined using the possible network parameters in the region. The licences are valid as long as the operators are willing to pay the annual spectrum fees. The potential use cases include private networks, mobile rural, indoor coverage, and fixed wireless access.
- **LSA or ASA** is a spectrum sharing technology in which typical incumbent operators

are military bodies in Europe, operating in the 2.3 GHz spectrum band. Other underutilised bands could be available for spectrum sharing by SUs for 5G applications [199]. Fig. 2.13 shows the LSA architecture in which the LSA repository stores the details of frequency bands used by the SUs and the LSA controller authenticates the usage details against the licence certificate stored in its database. The licence duration could be ranging from 2 years to 10 years. In [200] explores the new business models for MNOs while using LSA, which would build a new ecosystem to support both MNOs and new entrants. Newer business models for LSA shift the competition towards providing better QoS rather than ownership of the infrastructure.

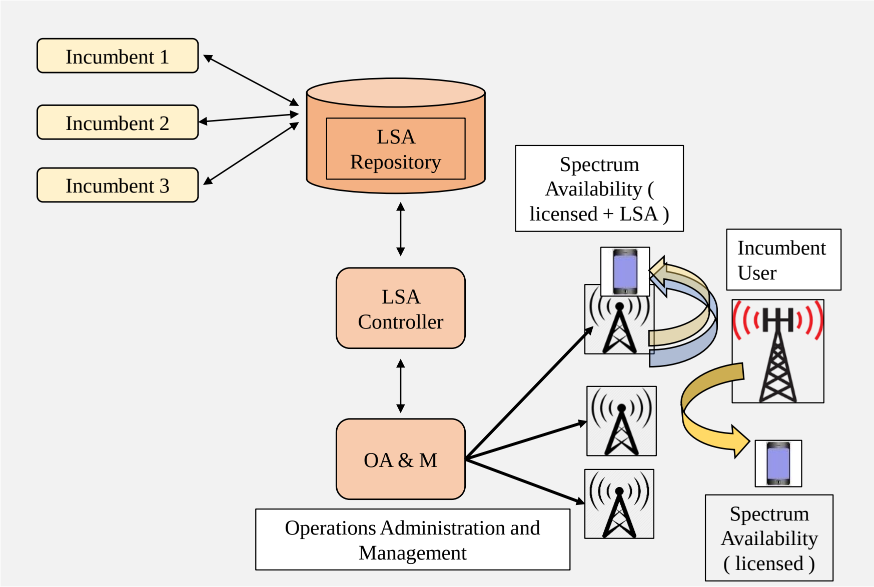


Figure 2.13: LSA architecture

2.4.4 Spectrum sharing in 5G NHN

The localised shared spectrum or unlicensed spectrum is a crucial deciding factor while calculating the viability of 5G NHN business. The ease of obtaining a localised shared spectrum band would encourage the InP to provide digital connectivity in rural and remote rural areas. When compared to the unlicensed band power threshold, the key benefits of the localised spectrum are lower spectrum licensing costs, guaranteed QoS, interference protection and higher power threshold [201]. It would encourage InP in using localised spectrum bands for 5G services and cater to MNOs' SLA.

Table 2.6 summarises the spectrum licensing duration of each technology. National telecommunication regulators have discussed policies to encourage the commercial use of shared spec-

Table 2.6: Shared spectrum licence duration

Spectrum sharing mechanism	**Minimum duration**	**Guarantee of obtaining the licence in the next auction**
TVWS	15 minutes to 24 hours	no
CBRS	3 years to 10 years	no
LSA	3 years	yes
Shared access licence	1 year	yes

trum and the entry of new providers into the 5G market. The national regulator consults the industry and academia every few years to amend the telecommunication policies of their country. In various instances, researchers and industry partners have highlighted the need for longer spectrum duration and guaranteed usage of spectrum bands to lower the barrier to investment in networks operating on shared spectrum bands [90, 156].

2.5 5G NHN Techno-Economics and Business Models

Generally, any new research solution needs different business models from each stakeholder's point of view to assess the opportunity and challenges, along with future scenarios, value network configuration, techno-economic and risk analysis [27, 62, 155, 157, 202–206]. Some researchers have been analysing new business models for 5G networks to ensure profitability. Table 2.7 summarises the key concepts from different network techno-economic and business model concepts.

2.5.1 Existing research

In [114,207], the author constructs the seven alternatives VNC models to understand the values offered by different network configurations possible for the wireless local area access. It helps in shaping the current and future technological regulations, advancements and policies. It also helps in understanding the roles of key stakeholders.

The study in [27] by Ahokangan and Matinmikko-Blue, explores the idea scenario planning of the micro operator in 5G and proposes the three generic 5G business models and their respective value ecosystems in terms of scalability, adaptability and sustainability. The difference between the proposed model and that of the traditional MNO business model for local services gives us the importance of understanding the future scenarios of the proposed solution.

In [209], the author analyses the spectrum spot market for mobile services and describes

Table 2.7: Network techno-economics and business model concepts

Model	Description	References
Value network configuration (VNC)	To analyse the interactions between different individuals or companies in a business	[29, 114, 207]
Scenario planning	To assess the factors that impact the future uptake of a solution	[23, 208]
SWOT analysis	Strengths, weaknesses, opportunities and threats analysis	[19, 209]
Business canvas model	To understand the different concepts of a business and the interactions between the stakeholders	[19, 209, 210]
(DCF) and net present value (NPV)	To evaluate the minimum cost per customer	[44, 46, 211]
Risk and sensitivity modelling	To understand the the most important factors impacting the business	[27, 46, 86, 116, 155, 202, 212]
TCO	The estimated overall cost involved in the business helps in understanding the profits	[7, 44, 46, 103, 148, 155, 179, 212, 213, 213, 214]
Mathematical modelling for minimising costs	TCO minimisation and resource maximisation model	[103, 215, 216]
Real options	To study the different options available in the life-cycle of the business	[217, 218]
Techno-economic analysis	TCO, sensitivity, feasibility, comparison of technologies, risk, stochastic modelling	[18, 62, 116, 149, 157, 206, 219]
Technical analysis	Coverage modelling, base station location, number of base stations and resource maximisation	[60, 103, 187, 220–223]

the newer revenue streams, pros and cons of the proposed solution, which helps stakeholders understand the main aspects of setting up and running the business using SWOT analysis and business canvas model. In [202], the authors highlight the new roles of the MNOs in the 5G ecosystem. The new technology is stimulating the need to innovate existing business models, their feasibility and social values in different scenarios. For the MNOs, the costs for upgrading to newer technology are increasing exponentially compared to the expected revenue streams from the solution offered. Therefore, a proper business model for 5G network slicing is required to increase technical acceptance and adoption.

Real options help in assessing the possibilities and mitigating risks in telecommunication projects. In [217] the research explores the use of real options in the telecommunication industry and includes no deployment, low-capacity deployment, medium-capacity deployment, and 100% deployment. In [120, 216] the study proposes a business model for IoT-based services for a platform that serves as an intermediary between human resources and wireless sensors networks (WSNs). Furthermore, in [216], the research shows the potential pricing strategies; one is the fixed payment method while another is the fixed plus variable payment method. The study analyses the users' take-up of the services by varying user cost ceilings, the number of WSNs, and user factors. In [224] the research analysed the potential of 5G services in IoT and the possible architecture, enablers and business models.

In [214], the paper studies the economic benefits of adding femtocell services as an add-on to existing macro-cell using the Stackelberg game resource allocation. The operator is the leader who decides the spectrum, and budget allocation for the femtocell and macro-cell services, and the end-users are the followers who choose between the two services and the resources to be requested. The research shows that spectrum reuse increases spectrum usage efficiency. In [119,225], results show the ROI from CAPEX is minimal but increasing CAPEX has a positive impact on the number of subscribers, profits and ROI because of improved quality of the service and user experience. Furthermore, research results show that a conglomerate performs better than individual telecommunication companies in terms of profits and ROI. Also, smaller telecommunication organisations spend more on OPEX compared to CAPEX. The regression analysis helps in understanding the relationship between different outputs.

The study in [152, 226] investigates the 4G technology, regulations and business aspects from the network sharing point of view and develops a model to estimate the savings and benefits from the network in different scenarios. The research in [227] calculates the profit-sharing between LTE and Wi-Fi by data offloading on Wi-Fi networks during congestion. The possible data bundles and TCO for each network are estimated using the coalition game and Shapley value and highlight the benefit of cooperation between LTE and Wi-Fi networks. Furthermore, [127] explores the pros and cons of 5G vs Wi-Fi 6 using techno-economic analysis.

In [228,229] the study considers the techno-economic feasibility of LTE FWA, and FTTH, respectively, for rural broadband. The population density, competition and regulation policies to analyse their impact on the network, especially on cash flow, standard financial indexes, sensitivity, risk, the ROI, profitability and subsidisation requirements for the network. In [223], the coverage, efficiency and deployment cost of the 4G LTE-A network is studied and it focuses on minimising coverage holes and interference at the cell edge. In [211], the author evaluates the techno-economic assessment of an LTE operator providing 30 Mbps fixed services in rural areas of Spain. Discounted cash flow (DCF) method is used to analyse the minimum ARPU for a sharing and non-sharing scenario. Furthermore, the sensitivity and risk analysis of the proposed solution.

In [230], the authors discuss the different investment strategies for 5G networks and conclude that the investment required for 5G networks is high for a few big MNOs, which would not be commercially feasible and further increase the digital divide. To overcome this challenge, the author believes that policymakers' decisions would make a difference by encouraging investments from InP. Also, investment from third-party operators will help in a faster rollout of 5G networks.

In [116], researchers propose a new model to allocate costs for slice tenants on a 5G network using a novel pay-as-you-go model. Its optimisation supports a planning tool considering TCO and RoI of the network that would allow virtual backhaul-as-a-service (VBaaS). As part of Central Office Re-architected as a Datacenter (CORD), it was determined that the project of VBaaS was three times more suitable than the traditional model. The TCO for 5G fronthauling is computed for a greenfield scenario [213]. The study shows how varying aggregated carriers impact the TCO, and change overall CAPEX and OPEX estimates. The research in [103] shows that TCO for providing emergency services using existing 4G, 5G fronthaul and backhaul services. The mathematical model optimises the number of parameters for emergency services to lower the TCO and provide maximum coverage to reap the highest benefit from the network. Subsequently, the sensitivity of the techno-economic analysis helps to understand the 5G capabilities to critical services while the gradient function plot helps to analyse the minimum points and explore the relationship between drone quantity required to maximise coverage and TCO minimisation. In [86], the research studies the integration of different spectrum bands to provide eMBB services in 5G networks and compares the traffic profile and capacity of 4G and 5G networks. The results show that the cost per user towards 5G network deployment is not uniform. In [148], the study discusses the need for optical-sliced networks for 5G backhaul and a new business model as pay-as-you-go for backhaul slicing to maximise resource utilisation. The network earns revenue by monetising traffic-as-a-service (TaaS).

In [13] the study performs the techno-economic analysis of the integration of SDN, NFV and cloud computing in 5G networks and calculates the CAPEX, OPEX, and TCO for the proposed architecture. It shows the significant cost reduction compared to the usage of traditional network architecture. In [212], the author performs 5G resource analysis for three different scenarios with varying geo-types and calculates the TCO by changing parameters and their impact on overall CAPEX and OPEX while considering the challenges present during the network deployment. The study in [46] explores the uncertainty related to 5G deployment in terms of technology, economics, and behavioural changes and highlights the required policy to support 5G deployment and the impact of 5G deployment in terms of cost, coverage and rollout. The research shows that 100% 5G connectivity would take time due to an exponential increase in cost, compared to the expected revenues from the network. The possible strategies and the corresponding cost model help understand the average CAPEX and OPEX and help predict the 5G deployment trends from 2020-2030 in Britain. In [155], the authors state the importance of innovation in the profit model for 5G network slicing. The model uses multi-objective optimisation problems to maximise profits and consider real-world challenges. Game theory helps in understanding the strategies involved while using 5G network slicing. In [215], the research models the demand estimation and consumer purchase delay to better understand the need of their consumers.

2.6 Game Theoretical Framework for Rural 5G NHN

In an everyday setting, people and firms interact with each other. Each firm takes a decision based on its assumption of what would be the best possible action for another firm to achieve its goal. This interdependence of people on each other involves a different combination of strategies [231, 232]. To achieve the best possible output collectively and/or individually, each firm strategically studies its belief in the decisions possible by competing firms to maximise their utility. This interaction uses game theory models to analyse the relationships.

According to [231], a game G is modelled mathematically consists of:

A. N players, where $n = 1,2,3,...,N$.

B. a list of possible strategies of all players, represented by $S = S_1 * S_2 * ... * S_N$, where $s_i \subset S_i$, $n = 1,...,N$.

C. The utility or payoff of each player is represented as $u_n(s_1,...,s_n)$, where $n = 1,...,N$.

The definition of game is as given in (2.1).

$$G = (s_1,...,s_N;u_1,...,u_N). \tag{2.1}$$

Game theory is an inter-disciplinary subject used in every field such as economics, mathematics, business location, sports, auctions, telecommunications, competition and day-to-day activities [233–235]. A game consists of more than one player who follows a set of rules and has more than one possible strategy. The different combinations of strategies result in outcomes used to calculate the utility or payoff of the players [231]. Game theory helps to calculate the following parameters:

- **Payoff or utility** is the incremental gain/loss in terms of a quantifiable output to a player by implementing a strategy.
- **Best response** (BR) for the player is the strategy which provides the maximum output for the player which is dependent on the strategies of other players.
- **Nash equilibrium** (NE) is a set of strategies for each player such that no player gets a higher payoff by deviating from their initial strategy.

Game theory investigates the choices available to each player and also the best response to maximise their payoffs. The best response in which no player would have an additional payoff by deviating from the expected behaviour is known as Nash equilibrium. The two main types of games are:

- **Cooperative game**: Players cooperate when there is value to them in terms of profits, knowledge, reputation, and trust, and an agreement among the players is crucial. The two main categories of games that are part of cooperative games - are the Core and the Shapley value. For players to form a cooperative game, each player should not have any incentive for a higher payoff. A coalition that involves all N players is called a grand coalition [236–238].
- **Non-cooperative game**: Generally, not all scenarios fit under cooperative game theory. There will be situations where the individual payoff has a higher preference than the cooperative game's payoff. The players focus on obtaining Nash equilibrium for their payoff rather than the grand coalition's output. The non-cooperative game theory involves games such as bargaining games, zero-sum games, rock-paper-scissors, and prisoner's dilemma [239, 240].

There are a few other forms of games based on the number of players (P1 and P2, or initial and child nodes), decision-making sequence, and symmetry of the game as described below:

- **Nominal and extensive form**: The nominal form of a game has payoffs for various combinations of strategy in the form of a matrix, shown in Fig. 2.14a. Extensive representation of a game presents strategies and the corresponding payoffs as a decision tree as shown in Fig. 2.14b.

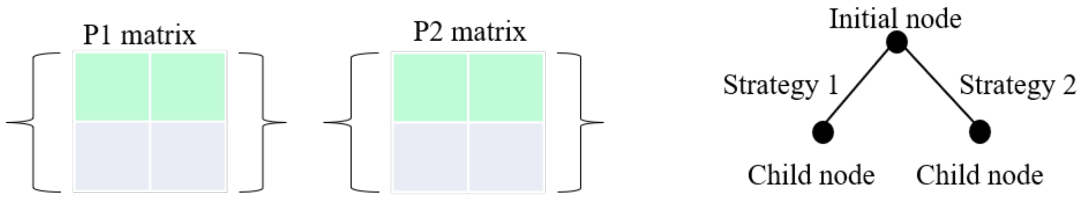


Figure 2.14: (a) Normal form; (b) Extensive form

- **Simultaneous Move Games and Sequential Move Games**: In a simultaneous game such as rock-paper-scissors, the players decide on the strategy to follow at the same time, i.e., the players decide on a strategy simultaneously. In this game, each player has no prior knowledge of the strategy taken by the other players. The player plays the game based on the belief in actions to be taken by other players. The player needs to understand the different possible strategies of other players to decide on their strategy [231, 241].

  In sequential games, one player, the leader, decides on a strategy while other players observe the action taken. The players observe the strategy of other players and choose their strategy in sequential move games such as chess. Based on the knowledge obtained from the leader, the other players, known as followers, decide on their strategy. An example of this concept is explained in [237, 242]

- **Constant Sum, Zero Sum and Non-Zero Sum Games**: Constant sum game is a game in which the payoffs of all players together remain the same irrespective of the individual payoffs. Zero-sum is a special type of constant sum game in which the payoff is 0. A typical example is gambling, where one loses, and another wins. Non-zero-sum games such as cooperative games are scenarios where the payoff is variable and is a win-win strategy for all players.

- **Symmetric and Asymmetric Games**: When players apply the same strategy then it is called symmetric games; for example in a prisoner's dilemma, the players can either confess or not confess. While in asymmetric games different strategies are used by the players. For example, the sports team decides to enter a game by adopting different strategies.

2.6.1 Why game theory?

After studying the techno-economic model, there is a need for understanding the interactions between the InP and MNOs. They both need to decide on the best possible investment for rural areas and the type of deployment. The InP and MNOs have different possible techniques for cost-revenue allocation among them.

Game theory has been widely used in the telecommunication industry to better understand the strategies among the stakeholders and maximise their payoffs. Telecommunication service provisioning involves interactions between the stakeholders which could be either cooperative or non-cooperative. One of the widely known applications of game theory is the spectrum auctions as researched by Milgrom in [243], which helped the US regulator FCC in modelling the auction for different spectrum bands and estimating the expected payoffs at different auction prices. Game theory is also used for modelling packet delivery and resource utilisation in various wireless broadband technologies [120, 172, 235, 237, 244, 245].

MNOs play an essential role in providing access to the global network and assisting InP installations in rural regions. End-users pay subscription fees for using MNO services, it generating revenue for the InP and indirectly impacting them. This stresses the need to understand the relationship between InP and MNOs and model their interactions. As a result, game theory is employed in this research to define and analyse interactions between InP and MNO(s) in terms of investment and pricing strategies for rural 5G NHN. In this case, the InP and MNOs must reach an agreement to deploy 5G NHN to improve rural connectivity and reduce the digital divide. Each player evaluates the optimal approach for maximising their payoffs.

Game theory algorithms facilitate the fair allocation of costs and revenues between the InP and MNOs. Monte-Carlo simulation estimates the uncertainty in terms of outputs for the game theory models by altering different parameters. Meanwhile, the Bayesian model aids in the modelling of the system's uncertainty in terms of input and output. Game theory models used in this thesis as discussed above are:

(i) **Investment game**: Investment game helps a firm in deciding whether or not to enter a new market, assess the major strategies and calculate their payoffs. The goal of this study is to discover the few main strategies that will have the greatest impact on the game's outcome and to help to make the optimal decision.

(ii) **Shapley value**: The Shapley value is a game theory concept that entails fairly allocating both gains and costs among several actors in a coalition. It is applied when two or more players are involved in a strategy to achieve the desired payoff where each actor's contributions are asymmetrical.

(iii) **Bargaining game**: When there is no standard pricing for the services or items supplied in the market, the bargaining dilemma develops. It aids in allocating the profits from a deal between two or more players. It is a non-cooperative game in which each player's goal is to maximise their benefits.

(iv) **Rubinstein game**: A Rubinstein game is an infinite negotiation series of a standard bargaining game. As the number of negotiation rounds increases, the profit share reduces.

(v) **Dynamic pricing**: A scenario where the pricing allocation among the players varies with market conditions and time.

The assessment of the business models for the services being offered and the demand requirement helps to create different pricing strategy models for each stakeholder. The relationship between InP and MNOs could be modelled as either a cooperative or a non-cooperative game. Shapley value is the most extensively used cooperative game theory model for cost allocation. In cooperative game theory, InPs and MNOs collaborate with the primary purpose of enhancing rural connectivity and the secondary goal of maximising their profits. The InP decides the total rent to charge the MNOs. Later, the MNOs collectively distribute the rent to be paid towards InP among themselves. Therefore, the goal of this model is to maximise resource allocation while minimising cost.

In non-cooperative game theory, InPs and MNOs collaborate with the primary aim of increasing their profits rather than improving rural connectivity. It uses a non-cooperative game theory model with a positive approach such as bargaining and Rubinstein games. The players negotiate about how the cost-revenue should divide among them, with each player declaring the overall cost invested towards the rural 5G NHN, and each player would prefer to maximise their financial gains. The possible outcome of this scenario is whether negotiation is achieved or not in a given duration of time.

Another way of modelling cost allocation is referred to as dynamic pricing, a combination of cooperative and non-cooperative games. Dynamic pricing is a means of revising a product's or service's price in response to changing market conditions. Dynamic pricing involves a fixed cost and a variable cost which the MNOs would pay to the InP. The goal is to minimise the risk per player and fairly allocate the cost revenue among the players. Real-life applications of dynamic pricing are in rental scenarios such as shopping malls, airports, and railway stations.

However, to ensure that each participant reveals the true cost of the investment, the players' 'truthfulness' must be reflected [246]. It is usually evident within some time if a player is declaring the real cost or not. To encourage players to report real cost, a parameter that punishes a player who lies about the true cost is included in the model, referred to as a pricing mechanism [246]. It assumes that players have complete information about others' strategies.

2.6.2 Existing research

The Shapley value defines a solution for cost allocation to maximise overall profits. Shapley's value is applied to the airport runway problem, an example of a cooperative game. The airlines contribute towards the cost involved in building runways for their aircraft [247, 248]. The airport's contractor builds a runway based on the airlines' requirements and allocates the corresponding cost to the airlines. Littlechild in [238] presents a simple and easily constructed expression for the Shapley algorithm for calculating the airport landing charges precisely for each airline. The unique characteristic of this game is that the maximum cost of any subset is equal to the cost of the ”largest” player in the subset.

The Shapley value concept is widely used in other industries such as cost-sharing among passengers in rideshare, cost-sharing among tenants in a shopping mall, and cost-sharing among a group of friends during a party. The concept of Shapley value extends to different fields such as telecommunication and related applications in the textbook [232]. Another example of Shapley value application is the cost allocation of a power plant among stakeholders such as electricity companies, tourism, government, and company [249].

The Shapley value has also been studied in the telecommunication domain. In [236] the authors ponder over the cost allocations model for 4G co-construction among the MNOs using the Shapley value algorithm along with a risk factor to make results close to a real-world scenario. The MNOs pay according to their requirements from the common infrastructure. The research in [20] explores network sharing in different countries. The challenges come in analysing the impact on existing businesses and protecting existing investments. In [237], the author proposes using Shapley value for MNOs to share the cost of services required for edge caching and network virtualisation applications. On a slightly different note, in [248] the authors explore ISP peering settlements in the context of sharing revenue among eyeball and content ISPs based on the Shapley value concept which results in fairness and incentives for the ISPs.

The authors in [250] explore the different applications of matching theory in wireless telecommunications. The research in [251] presents an overview of resource allocation and spectrum sharing in cognitive radio. The study uses the matching game to allocate resources to cognitive radios. The authors argue that the spectrum is allocated among the cognitive radios to maximise utility and payoff for each. In [252], the authors use matching game theory for the allocation of frequency bands to 5G small cells operated by micro-operators using shared spectrum technologies. The algorithm focuses on maximising both the utility of the micro-operator and spectrum usage. The study in [237] models the resource allocation in the 5G local operator deployed network using the Stackelberg game theoretical framework. The InP would rent the RAN and cache storage to multiple MNOs and agrees to provide guaranteed minimum SLAs to the MNOs. Here, the InP acts as the leader and MNOs act as the followers. The MNOs cooperate to maximise their output and the cost-sharing of rent among MNOs using the Shapley value. The rent is allocated based on the number of servers required for their applications. The research in [246] uses the game theory framework to model the interactions between stakeholders of 5G technologies. Cloud service providers and providers of health monitoring services use a bargaining game to share their revenue. The price paid by users is divided between service providers according to their investment and truthfulness. In [253], the authors discuss how game theory strategies are useful for negotiation for admission and resource control along with maximising the throughput in network slicing, especially for the slice tenants. Game theory is quite useful in strategies planning of the stakeholders.

2.7 Discussion

In this chapter, the literature review related to the rural digital divide, 5G, network slicing, neutral host networks, shared spectrum, techno-economic feasibility, and game theory framework was discussed. These studies helped in understanding the research gap, and the subsequent chapters present potential solutions to address those gaps.

Therefore, in this research work, the idea of NHN using 5G network slicing is explored to address the challenge of the digital divide, especially in rural areas. The literature review in this chapter highlights the need to explore factors beyond technological capabilities to minimise the digital divide. The technological aspects of solutions for the digital divide are explored in the existing literature review, the research presented in this work explores the cost-efficient solution using 5G NHN and their viability and pricing strategies for the InP and the MNOs.

Chapter 3

Research Aims and Methodologies

This Chapter aims to summarise the research aims, methodologies, and assumptions to justify the research carried out. In Section 3.1, the viewpoints of the stakeholders will help in streamlining the focus of the research gaps which would be useful for the industry as well. Next, in Section 3.2, the key research gaps, novelty to the contribution, and importance of the contributions are presented. Finally, in Section 3.3, the research methodology for this study and the key assumptions are presented.

3.1 Stakeholders' View on Rural 5G NHN

The opportunistic snapshot set of the stakeholders' views on the potential solution for the digital divide is collected using the 'interview' type of data collection to streamline the focus of the study further. The data collected This section presents the snapshot of the "real" barriers to adopting a technocratic-led NHN solution for addressing the digital divide.

3.1.1 'Interview' methodology

The 'interview' type data collection method was used for the qualitative study [254]. Typically, semi-structured research interviews consist of a few key questions to help focus on an area of interest so that policymakers can use more informed decisions, and the remaining questions can be determined during the interview, by the interviewer and interviewee to help cover other areas of the same topic in depth. The purpose is to learn the perspectives and experiences of rural connectivity stakeholders to use 5G NHN along with network slicing as a solution to improve broadband connectivity. A semi-structured 'interview style' is most appropriate as we are exploring the digital divide using 5G NHN and gaining detailed insights to obtain data on sensitive topics.

15 influential stakeholders were approached who are currently actively involved in 5G research and commercial activities in different countries. Twelve stakeholders among them responded to the survey and shared their opinions on NHN, including some well-known experts in the telecommunications field, directors of wireless broadband providers, independent technology analysts, technology evangelists, and entrepreneurs seeking solutions for the digital divide. The interviewees were contacted via LinkedIn or email, and the 'interview' was typically a one-on-one Zoom meeting that lasted 30 to 90 minutes. The research questions revolved around the generic view of stakeholders towards the use of 5G NHN, especially the role of MNOs in remote and rural areas with low populations, a general overview of the acceptance of rural 5G NHN by different stakeholders, the possible challenges, and their view of neutral hosting.

Furthermore, before the interview, the respondents were informed about the study components and ethical principles such as anonymity and confidentiality. The initial sample questions represent the stakeholders' generic perspectives on using 5G NHN in remote and rural areas with sparse inhabitants, especially the MNOs. A general overview of the acceptability of rural 5G NHN by various stakeholders, potential issues that need to be resolved, and the stakeholders' opinions on neutral hosting are then provided.

Topics covered in the research questions

The interviews were performed using a semi-structured 'interview' methodology, which resulted in several question formulations and the subjects covered in each interview as follows:

- The generic view of stakeholders towards using 5G NHN, in remote and rural areas with low populations.
- A general overview of the acceptance of rural 5G NHN by different stakeholders.
- The possible challenges and gaps that need to be addressed.
- The stakeholder view on neutral hosting, that is, end-to-end infrastructure sharing.
- A brief overview of the potential opportunities.
- Future research areas from the stakeholder point of view.

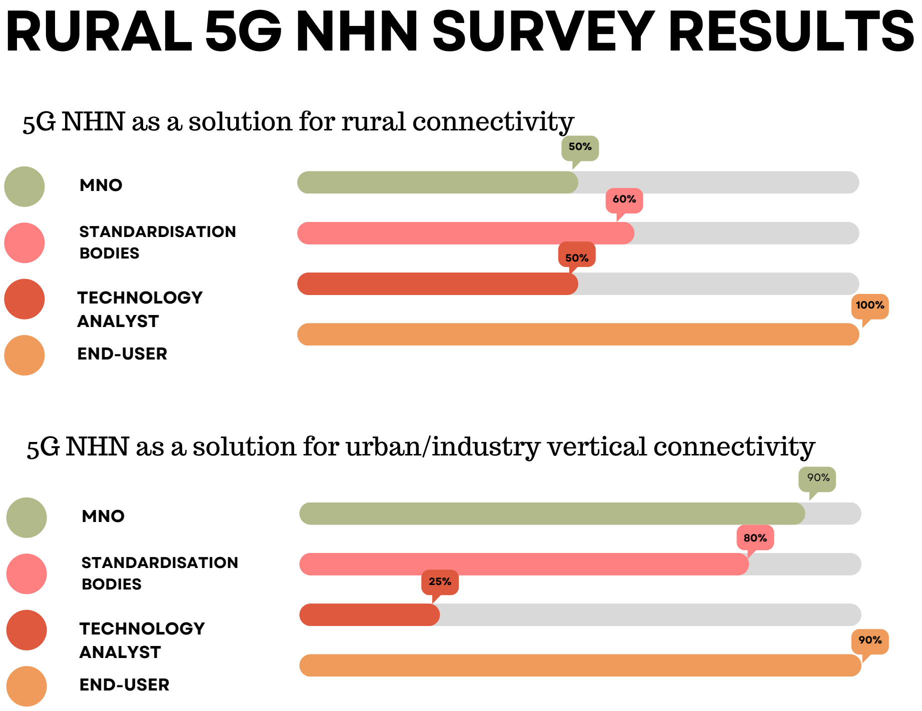


Figure 3.1: 5G NHN semi-structured interview responses

3.1.2 Findings

This study summarises the responses of stakeholders that includes 3 respondents who are MNOs, 4 respondents who are working with standardisation bodies, 2 respondents who are technology analysts, and 3 respondents who are end-users (rural communities inhabitants, local businesses, and council). The main findings are summarised in Fig. 3.1. The key observations and findings from the ‘interview’ with the stakeholders are as described below:

MNOs

This section presents the key feedback obtained from the MNOs on rural 5G NHN as a potential solution:

- In general, rural 5G NHN with MNOs on board was considered an exciting research topic with good potential. The network can act as either a stand-alone (SA) or non-standalone (NSA) 5G network depending on the use cases to be served in rural areas. A Memorandum of understanding (MoU) between MNOs is crucial for the successful implementation of rural 5G NHN. Rural 5G NHN could be a suitable choice if no single operator wants to deploy in that rural area. Currently, there has been no end-to-end slicing deployment to encourage co-existence among operators as any technologies before 5G cannot guarantee minimum resources during network congestion [181]. The next crucial factor is the ‘trust’ among operators in service provisioning, as they are very competitive. In the previous trials of LTE MOCN and MORAN, the resource allocation ratio was 30:30:20:20 for sharing between the MNOs, but these trials were not successful due to a lack of trust among the MNOs.

- Realistically, on a typical day in urban areas, only 10% of the LTE resources are used at any time. Therefore, 5G NHN is a good approach and highly suitable for urban areas with mmWave deployments. Except during busy hours, most subscribers are connected to indoor networks, such as Wi-Fi and femto cells, and various studies have supported this claim [16].
- The success of the 5G NHN lies in the profit-sharing agreement between the InP and MNO. The proposed game theory models work well with more MNOs that have a similar pricing strategy. In areas with a low to very low subscriber base, this solution is viable and innovative from the MNOs’ point of view.
- Another key deciding factor is the network slice manager and the cost of implementing that functionality at the operator side, such as core connection, SON, and element management systems (EMS) that allow remote monitoring and maintenance of the network to manage unexpected breakdowns. The problem lies in the interface of the equipment with different vendors that offer similar technological solutions. Hence, operators are shifting their focus towards open technologies such as O-RAN.
- Typically, the Government offers considerably lower subsidies than the retail prices of parts, making network deployment challenging in rural areas. Alternatively, MNOs consider satellite technology has the potential to serve as a rural connectivity solution for very remote areas with a population density of less than 5 people per km^2. Satellite communication is currently used for coverage purposes rather than capacity-based applications such as ships, in-flight connectivity, and remote areas. However, satellite communication is highly dependent on the line of sight with the receiver antenna and various losses caused by weather parameters such as rain, fog, and condensation.
- MNOs believe that the key challenges that need to be addressed as part of future work

are:

- This research assumes that the pricing plan is almost similar for different MNOs, but what happens if they have different pricing plans for the same services? Would all customers choose the one with the lowest price or the best service?
- The telecommunication regulators need to ensure that MNOs are on the InP network for a certain number of years to avoid burdening InP financially.
- When you have two operators in the telecommunications market instead of four, how does the model work?
- What happens to the rural 5G NHN when the demand for one MNO service is sufficient for monopoly over the InP network?

Standardisation bodies

The standardisation bodies present a different view on rural 5G NHN from the MNOs' viewpoint. They believe that technology has always been available. The question is how network slicing evolves to support NHN for rural connectivity. The belief is that rural 5G NHN is an innovative idea that can promote competition and can be cost-efficient for operators. NHN deployment encourages research of other upcoming technologies such as shared spectrum, and open source technologies, and supports new entrants into the market such as micro-operators, or tier 2 operators. Furthermore, the use cases, technical applications of the slices, and cost allocation models are very useful. However, the success of the solution lies in the technological advancement of topics such as challenges in slicing deployment, NaaS, slice isolation, mobility handover, security of slices and connections, multiple users loading on the network, dynamic resource allocation, and slice creation, remote monitoring, and maintenance of the network.

This discussion highlights the need for standardisation in different technological applications to ease the interfaces to achieve consistent, standardised interfaces with interoperability among the equipment from different vendors.

Technology analysts

According to industry technology analysts, rural 5G NHN can improve the digital divide and solve mobility issues. They have been analysing 15 different types of neutral host networks, one of them being the use of 5G network slicing. According to the technical analyst, the key challenges with any typical NHN that need to be addressed are whether it would be FWA or mobile networks, and if carrier aggregation is done, then at which spectrum bands? The potential future work must include mobile mobility during handover, maximum load per slice, price per NHN site, ease of business setup and legal paperwork, assured SLA and KPIs, slices, coverage vs speed decisions, Governmental policies towards NHN, payment methodology, cell edge cases, a regional or universal pricing plan, an end-user fault reporting system, and whether a single company would be setting up the network for all villages.

Rural end users

The end-users find the idea of 5G NHN innovative and would participate in community-led initiatives to improve rural internet connectivity and contribute to network deployment. A significant part of people's lives is impacted by the internet and IoT systems. As a result, rural end-users will support rural telecommunications deployment, such as rural 5G NHN, to meet their needs. They would be interested in learning about the steps involved in building a rural 5G NHN and helping the InP network deployment.

3.1.3 Summary

In this section, the views of different stakeholders towards end-to-end infrastructure sharing were explored. The data obtained in this study are similar to the results documented in the 5G New Thinking project report [255], which helps validate the analysis. For example, based on the discussion with key stakeholders on their standpoint on rural connectivity using 5G network slicing, it seems clear that policies supporting the NHN should consider the following three aspects:

- Although there has been a subsidy scheme in place for many years, the digital divide still exists. To minimise the digital divide, there is a need to shift to sustainable business practices. There is a need to consider alternative types of infrastructure sharing strategies to reduce the cost of wireless broadband deployment in rural areas while promoting competition between operators. Unless the business model becomes sustainable, the solution might not be scalable.
- There is a need to study locations where there is poor or no telecommunication infrastructure and formulate policies to support the improvement of digital infrastructure in these regions, such as open networks, spectrum sharing and low taxes. If the NHN strategy is applied, there is a need to ensure that MNOs are on the InP network for a certain

number of years to avoid burdening the InP financially.

- Infrastructure sharing policies should promote fairness and trust among the stakeholders. Typically, firms prefer monopoly-style business competition. NHN policies should allow easier entry for new entrants in rural areas while also preserving competition among the operators.

In summary, the findings of this study show that, although neutral host network technologies could be considered a potential solution, there is a need to study other non-technological challenges that are currently acting as a barrier.

3.2 Novelty of the work and Research Aims

Based on the literature review presented in Chapter 2 and the discussion with the rural connectivity stakeholders presented in Section 3.1, the research aims to explore how 5G neutral host networks using network slicing technology could help to bridge the digital divide, identifying cost-effective solutions that would increase the connectivity of the remaining 36% of the world's unconnected people in general

The key areas where this research would contribute to the knowledge and help to address some of the challenges raised by the stakeholders, are:

- Application of the 5G NHN concept to the rural areas that help explores the option of telecommunication as a service.
- Exploring the role of InP and MNOs to minimise the digital divide using 5G NHN along with the alternative business models to increase revenue in rural markets.
- Modelling and analysing the techno-economic feasibility of the proposed NHN model in greenfield and brownfield deployments.
- Investigation of the network feasibility without subsidies in a high ARPU marker (UK) against a high subscriber market (India), and studying the difference in the two markets.
- Assessment of the pricing strategies that would encourage investment by the InP and MNOs in rural areas using the game theory framework - Nash Equilibrium scenario. Further, the study assesses the scenarios where the MNOs would be willing to enter the NHN scenario.

- Policy recommendations on the technology and infrastructure sharing strategies for rural areas with the digital divide.

These results would assist the stakeholders in determining whether rural 5G NHN is an appropriate option available for their scenarios, and assist with creating a sustainable rural connectivity business. The results of this thesis could potentially assist in formulating rational policies for infrastructure sharing, particularly in rural areas.

3.3 Research Methodology and Assumptions

The study uses a business model framework, techno-economic assessment framework, and game theory framework to analyse the potential scope of using rural 5G NHN as a solution for the digital divide. The outline of the research methodology carried out is discussed as follows:

3GPP releases considered in the work are Releases 15, 16, 17, and 18. These releases describe the design and challenges of implementing network slicing, which was taken into account in the work described in this thesis. For *simulating NHN Slicing scenarios*, software such as MATLAB, Excel, and Python was used. The outputs were simulated using MATLAB, Python, and R. To realistically model the coverage plots and observe the line of sight (LOS) for each village that was studied, CloudRF was used. The diagrams were modelled using PowerPoint, Draw.io, and Canva, while the thesis was written using Overleaf. For NPV analysis, optimisation packages of software such as MATLAB, Excel, and Python were selected. MNO coverage plots were obtained from open-source network coverage tools such as CellMapper, Opensignal, and more.

For *carrying out detailed techno-economic modelling*, the research presented in 3GPP releases, Oughton, Lehr, Juan, Julie and many more researchers were used. The data for the study is obtained from the reference papers, and compared against the results obtained in different projects are described in Chapter 5. The data obtained were verified from the discussions with wholesale telecommunication deployment companies and MNOs. The stochastic modelling helped in assessing the number of sites required for rural deployment and modelling the interference from the neighbouring cells using a 19-cell configuration of extended Hata model for Rural Macrocell (RMa) planning as described in 3GPP documents, for example, [11, 150, 256].These documents have a detailed description for designing an appropriate technological model to suit the requirements using Python. The references papers guided me to model the techno-economic analysis using Excel and Python.

The fundamental inputs for how to gather and analyse data for game theory framework were gained from Prof. Alex Dickson, for *modelling the realistic strategies that rational stakeholders (i.e. InP, MNOs, etc.) would carry out*. The costing models and values were obtained from the research presented in Chapter 5 and the pricing sharing percentages were averaged for different demand factors. The often-referenced game theory textbooks and academic articles made modelling and data analysis easier to comprehend.

3.3.1 Assumptions

The study's key assumptions are critical in determining the applicability of the findings presented. InP deploys in rural locations with low to very low population density with poor or no prior coverage. InP deploys the network to mainly serve the MNOs who focus on providing mainly eMBB services to the end-users. Therefore, this study considers the revenue obtained from the retail end-users. Rational MNOs are considered in this modelling scenario, who would want to increase their coverage and quality of experience of users, in order to increase their revenues and profits. To assess the application of the model developed, it is applied for two countries: the UK, which has a higher ARPU and a lower number of subscribers; and India, which has a lower ARPU and a higher number of subscribers. The key network parameters and demand factors for the study in the Indian and the UK scenario are as given in Table 3.1. By keeping the technical assumptions common, it is easier to compare the two scenarios and the

Table 3.1: 5G simulation network parameters for the UK and the Indian scenario

5G KPI	**Value**
Downlink mean throughput per user	50 Mbps
Frequency band	700 MHz and 3800 MHz
Carrier Bandwidth	10 MHz and 20 MHz
Antenna Technique	MIMO
Transmitter Power	< 46 dBm
Modulation	256 QAM
Cellular Layout	120° sectorial antenna
Propagation Model	Okumura-Hata, Longley-Rice
Scenario	rural
Sectors	3
Tx Antenna Height	10 m and 30 m
BS Antenna Height	1.5 m
Network Slicing with Multi-Tenancy	Yes
Number of National level MNOs	4
ARPU UK	£15.31
ARPU India	INR178 (£1.72)

market it serves.

3.4 Discussion

In this Chapter, the research gap is explored and supported using the stakeholders' viewpoints. Based on the key research questions to be investigated, the next few chapters will explore the questions raised and discuss the findings obtained from the work.

Chapter 4

Network Economics and Business Models for Rural 5G NHN

The research in internet access in rural regions examines ways of evaluating the prospects of adopting 5G NHN. Network economics aids in the identification of cost-effective technology solutions for mobile network innovation. The research in [38] and [29] studies the techno-economic feasibility of 5G network slicing in the university and factory setting with possible expansion of MNOs on the network. The study in [114] uses a value network of 5G NHN in the factory. These studies demonstrate the potential of 5G NHN for commercial use cases. However, none of these studies explores rural connectivity applications in the context of the NHN for the MNO ecosystem.

This chapter analyses future scenarios, value network configurations, and business models for the rural 5G NHN examined in Chapters 1, 2, and 3. Firstly, the future scenarios possible using existing concepts are studied. The plan for the 5G NHN in rural regions next examines the maximum value that the network can provide in various circumstances such as InP-driven, MNO-driven, community-driven, and industry-driven. VNC is used to analyse the big picture and the business models from the stakeholder's point of view to study the feasibility. Later, using SWOT analysis and the business canvas model, 5G NHN business models are explored.

The major contributions of the chapter can be summarised as follows:

- Exploring 5G NHN system model with multiple buyer MNOs and a single seller InP.
- Understanding future scenarios, future trends and expectations for rural 5G NHN, and analysing the main factors impacting deployment.

- Studying the values offered by a different configuration of the network using the VNC model.
- Examining the SWOT analysis which helps in studying the trade-offs of 5G NHN in the rural scenario and the business canvas model (BCM) which helps to study the factors such as key activities, costs, customer relationship revenue streams and interactions of stakeholders for 5G NHN.

4.1 System Model

Consider a 5G NHN system with N tenants given by the set $N = [1, ..., N]$, who lease the slices from the InP present in the rural area, as shown in Fig. 4.1. Consider a village with a low population where only a single InP deploys the 5G NHN to cater to all the needs of the end users. According to conversations with MNOs, and informed by existing research, a single macro-cell may offer good coverage and high-speed data rates for practically all rural applications (detailed discussion and justification are presented in Chapter 5). As a result, the baseline scenario includes a single InP deploying network and all tenants leasing slices from the InP. As a result, network slicing becomes a single supplier - multiple buyers (InP - slice tenants) market.

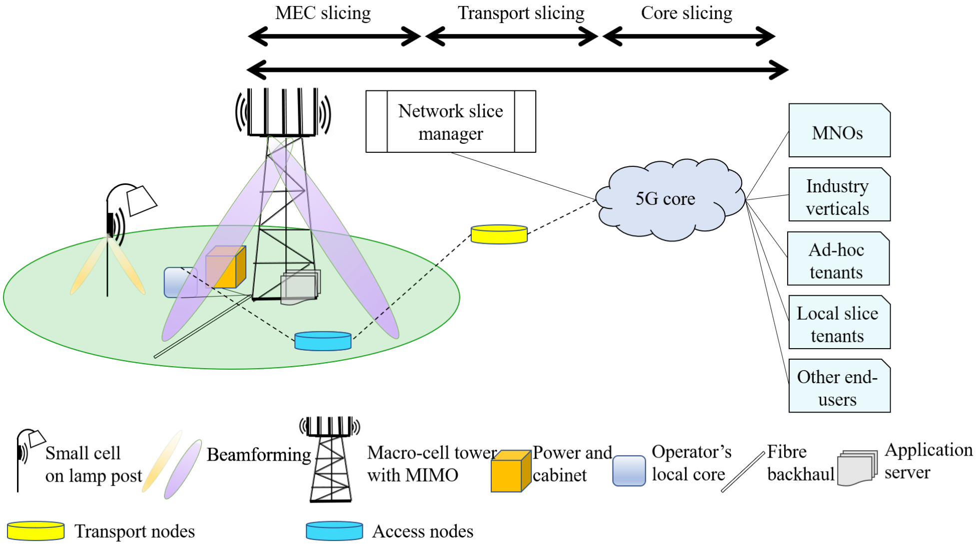


Figure 4.1: Network slicing high-level architecture

Assume that InP could be either a third-party company and the slice tenants could be anyone who wants to provide internet or mobile services and applications to their end-users. The frequency of the operation could be either a shared spectrum band or a locally licensed band. Additionally, the end-users would not differentiate between the service obtained from the 5G NHN network and the traditional network. The tenants compete in terms of QoS, resources available, congestion priority, SLAs and end-users. The regulatory body and the slice manager would be the decision-making bodies for the proposed solution. Their key role would be to monitor fair competition among the slice tenants.

This study focuses on tenants who are only MNOs and are interested in investing in the InP's network on a long-term basis to provide connectivity, mainly eMBB services to rural areas. The main motivation for the InP is profit maximisation and community welfare, and the MNO is entering into the untapped rural market and a new source of revenue. The MNOs and the InP, preferably, would have a cooperative dialogue to keep the demand and the supply matched. The MNOs and the InP would agree upon SLA and the pricing mechanism. Furthermore, by utilising 5G network slicing, MNOs would retain control over resource allocations to their clients. But assuming that the network performs as per the technology forecast, business aspects of the network are analysed. The terms customers, end-users and industry are used interchangeably.

4.2 Stakeholders

The key stakeholders who could impact or be influenced by a business are customers, investors, the government, suppliers and vendors, communities, and standardisation bodies. The following are the major responsibilities of stakeholders for a rural 5G NHN:

(i) **Standardisation bodies**: The standards drafting bodies such as 3GPP, IEEE and next-generation mobile networks (NGMN) play a crucial role for rural 5G NHN using network slicing [11, 88, 181, 257]. The main expectation of standard-setting bodies is to create widely supported standards for the production of components, network interface, hardware as well as software performance, compliance with current generations, and compatibility with previous generations to achieve the same goal. Standardisation should encourage loose coupling between different end-to-end resources used for the network. This method allows different devices and technologies to communicate with others easily. The 5G NHN market will attract the industry to include intellectual property rights (IPR).

(ii) **National regulator**: In the proposed context, the national regulator plays a key role in monitoring the use of spectrum [32, 258–260], and the restriction of independence, and competition in the industry. Since InP could use spectrum bands either by local licensing or shared spectrum, they should comply with appropriate legal procedures formulated by the national regulator. Furthermore, the InP will deploy 5G NHN and operate on either the licensed or the unlicensed bands by obeying legal operating laws stated by the regulator for operating on those frequency bands. Also, the use of an automated controller by the national regulator would help in reducing the physical effort required to approve the licenses. The regulator will develop a new pricing system to monetise shared spectrum in this new business environment and earn revenue while ensuring that long-term MNO investments in spectrum band license auction are not impacted [261].

(iii) **Mobile network operator**: As discussed earlier, the MNO can expand their business in rural areas with lower investment using 5G NHN when compared to the traditional deployment *No Sharing* method. The presence of MNO in the rural market will help connect to the world wide web, smooth handover, international roaming, and support industry verticals' 5G applications. This model would attract new customers to join the MNO network. During network busy times, InP allocates the minimum resources as per the agreed SLA with the MNO. One of the main challenges is the security of MNO networks and their data, especially when InP will connect to their core [26, 35]. Also, from the technological point of view, the end-to-end resource allocation of the network slice to the MNO end-users should be addressed [172, 173]. When these issues are addressed, this situation would be favourable for MNOs.

(iv) **Telecommunication equipment vendors**: 5G NHN rural model will include telecommunications vendors who will be manufacturing network equipment. They will adhere to production standards developed by standards-enhancing organisations and improve the quality of products and practices to meet real needs. Currently, NHN is in the process of testing and deployment for in-building scenarios using CBRS technologies [22] and 5G NHN [38, 91, 115].

(v) **Infrastructure provider**: The InP will consult with the MNOs to understand the MNO service level required to match supply and demand. The InP and the MNO will negotiate over the spectrum, QoS, SLAs and cost of the network slices. Because of the necessity, deploying a network based on cooperation between InPs and MNOs could help in minimising any losses incurred in running a rural 5G network [35]. This open dialogue will allow the InP to determine the required number of network slices to meet the requirements [27, 35, 187].

(vi) **Network slice manager**: The network slice manager can be either an equipment vendor, MNOs, InP or a combination of a few stakeholders. The network slice manager will communicate between the various stakeholders to cater to their needs, and manage the installed service requests [262]. Additionally, it allows customisation of the slice according to the tenant's KPI requirement. It will act as a mediator who would monitor and maintain a log of the resources used by the tenants.

(vii) **End-user** In this proposal, the end-user will benefit from improved telecommunication services during this deployment. The end-user can be mobile users, broadband users, tourists, or other industry verticals in rural areas. As consumers appreciate the benefits of connectivity in rural areas, then the need for good internet connectivity will grow. They can enjoy services that are not possible without the Internet and at affordable prices, as discussed in [2, 54, 125].

4.3 Scenario Planning

Scenario planning assists in the development of a range of future likely scenarios by taking into account current trends and uncertainties. It would help reduce judgemental ambiguity in business choices by predicting the behaviour of different stakeholders in uncertain settings. This section looks at the future scenarios for rural 5G NHN shared spectrum market competition, considering the relevant stakeholders. In scenario planning, potential trends and uncertainties help create four future scenarios for rural 5G NHN.

Theoretical background

As Schoemaker [208] states, foreseeing the future requires the knowledge of:

- Things we know we know.
- Things we know we do not know.
- Things we do not know we do not know.

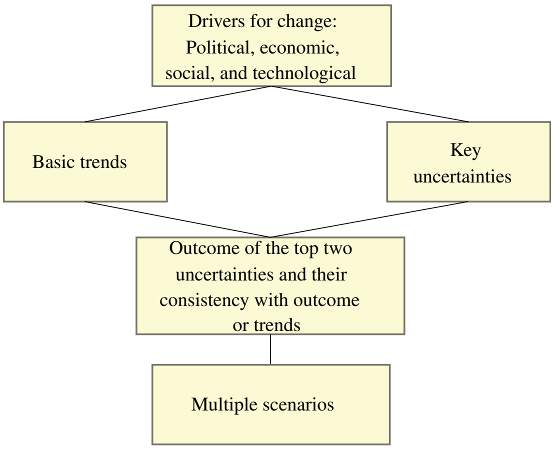


Figure 4.2: Scenario planning flow

It is important to think ahead of stakeholders' actions. In the 1950s, this approach evolved from military strategy planning to simulate war simulations by Schoemaker in [247]. Fig. 4.2 shows the flow chart for scenario planning. It considers changes in various factors such as basic trends, political trends, economic trends, and technological advancements that determine the possible outcome.

Scenario planning process

The generic process involved in scenario planning derived from [208] written by Schoemaker, is described below for rural 5G NHN:

Step 1: Define the time frame and scope of the analysis

The focus of this study is to find the future scenarios of 5G rural NHN communication. The scope is limited to 5G mobile connectivity and wireless broadband connection for applications, such as mobile internet, personal communication, IoT applications, smart village, M2M, healthcare applications, online education, and agriculture. The time frame is 10-20 years beyond 2023.

Step 2: Identify the major stakeholders

The stakeholders, as discussed in the previous section: are InP, MNOs, national regulators, telecommunication equipment providers, standardisation bodies, network slice managers, and end-users.

Step 3: Identify basic trends

The key trends in the telecommunication industry and other industries are influenced by technological, social, political, regulatory, economic, and research developments. The most important key trends affecting the future decision-making process are as follows:

- **Smart village and demand for internet services**: Recently, there is demand for smart villages applications which will help in the reduction of overall energy consumption by automating features such as farm services, water level monitoring, street lighting, fishery, mobile banking, e-wallets, healthcare monitoring and e-governance [56, 125].

- **Increasing number of IoT sensors and M2M connections**: These applications are driving the industry to use IoT sensors to support those applications. The machines communicate with each other using M2M protocols. Globally, the dependency on IoT devices and their application is increasing [224].

- **Increasing rural area traffic**: All the above use cases would generate traffic on the network that leads to an increase in the data traffic from the rural areas [220]. This fuels the need for 5G and MEC applications for the rural scenario as well.

- **Digitisation of banking services**: The digitisation of banking services encourages people to use e-wallets rather than cash and helps in online trading, loans, investments, and treasury services [263].

- **Spectrum allocation for NHN**: There is a spectrum bottleneck due to limited spectrum resources, however, in rural areas, the spectrum is underutilised. 5G has higher data rates even for shorter bandwidths, and there is a focus on spectrum sharing - ‘use it or reuse it’ [31, 199]. The national regulator policies encourage spectrum sharing and local licensing [124].

- **Standardisation of 5G NHN**: This technology is gaining popularity for applications such as indoor connectivity in offices and buildings, airport connectivity, autonomous vehicles, seaport, university and hospital connectivity [38, 115, 197]. Hence, the standards play a very important in the compatibility of different devices, technologies and vendors [22].

- **Energy and cost-efficient networks**: A single 5G network could consist of millions of connected devices. This leads to an increase in energy consumption, and it is another critical challenge in rural sites [136]. Hence, the devices and network should be both cost and energy-efficient [10, 11, 128].

Step 4: Identify key uncertainties

The key uncertainties shape the results and diverge to a different future, such as political, economic, technological, regulatory, and social reasons, as shown in Table 4.1.

Table 4.1: Key uncertainties for scenario planning - 5G NHN

Key uncertainties	Outcomes	Domain
NHN market competition	Monopoly or oligopoly	Economics
Spectrum access	Local licensing or unlicensed	Political, Regulatory
New entrants	Competition or disruption	Economics
Job scenario	Slight or significant impact	Social
Last mile connectivity	Public or private	Technology
Automation and regulations	Inhibition or supported	Regulatory

- **NHN market competition - Monopoly or oligopoly**: Because 5G NHN is such a novel technology, there are a variety of approaches to building the system. The NHN can be implemented by a single operator (monopoly) or several operators (oligopoly), depending on demand and the ease of doing NHN business in the target area. In general, an oligopoly market is competitive and welcomes new entrants. A monopoly market is closed to newcomers and has a high entry barrier. Furthermore, 3GPP, IEEE, NGMN, and CBRS wireless advancements are supporting the NHN market competitiveness.

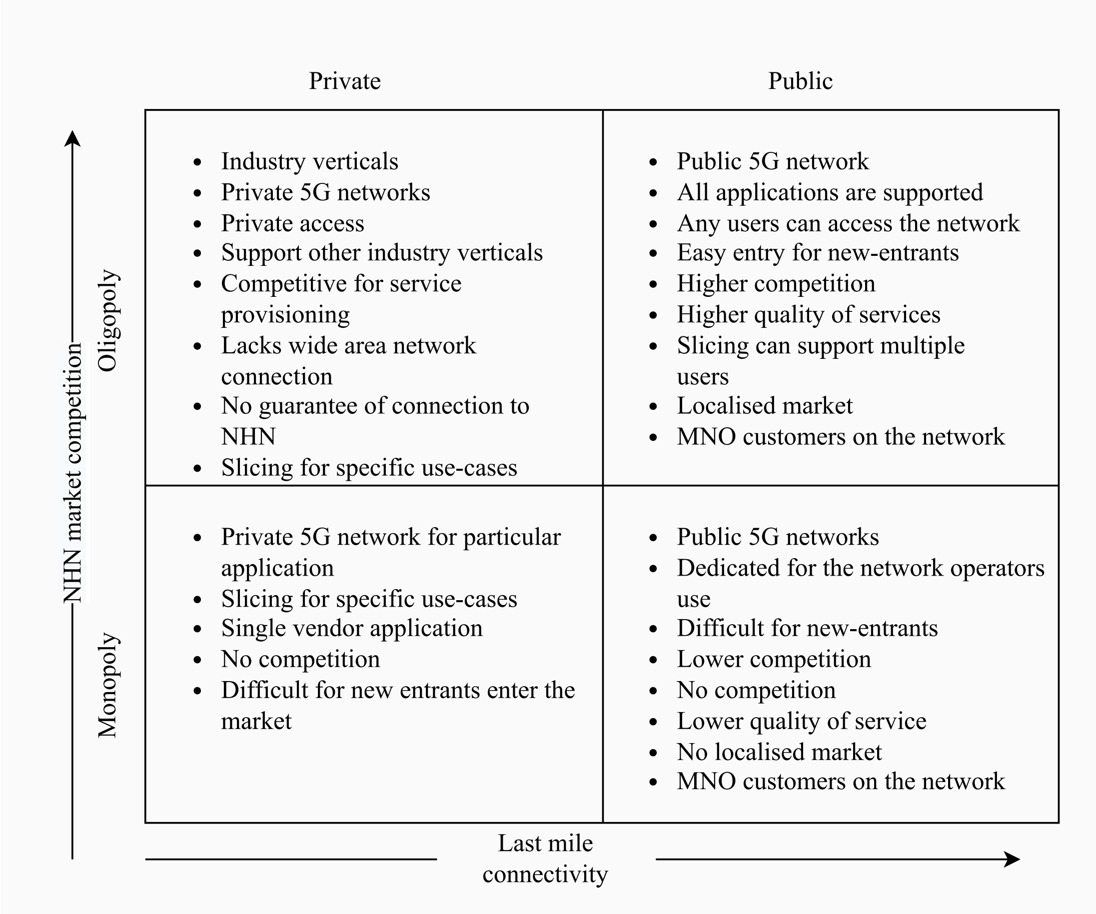
- **Spectrum for access- local licensing or unlicensed**: In the case of 5G NHN, the frequency of operations is yet unknown. Depending on the ease with which national regulators offer spectrum access and the associated cost; local licensing, unlicensed spectrum, or shared spectrum may start to become viable. It is important that local operators be encouraged, otherwise, they will not be able to compete.

- **New players entering the market - competition or disruption**: Rural 5G NHN or in-building NHN pose a threat to the current telecommunication business model. The newer use cases and applications require new business models that pose a threat to traditional telecommunication business models [202]. It is beneficial to encourage new players to drive innovations [36], which is only possible when there are more players.

- **Job scenario in a 5G world - slight impact or significant impact**: There would be a great impact on jobs with an increase in automation as well as artificial intelligence (AI) and dependency would shift from regular skilled to highly skilled employees. A newer job scenario is also an opportunity for the market to expand in a new way, but some people's employment would end owing to increased reliance on machines [264], which would force individuals to change careers or otherwise lose jobs.

- **Last mile connectivity - public or private**: Last-mile connection is critical for the growth of the 5G NHN. If a network is technologically and commercially viable, it can be extensively adapted. There are two types of networks: private networks with restricted access and public network to which anyone can connect [17]. They both utilise the same hardware and software, encoding techniques, and spectrum. However, the main distinction is that the public 5G network is for public usage, with tens of millions of users on a single countrywide network. A private 5G network is for the use of a single company or organisation for a highly secure connection, and in many cases, a single location. However, the term "location" can refer to anything from a building to a port [38, 115].
- **Automation/ regulations - inhibiting or supporting**: When technology relies heavily on automation, such as 5G, laws and regulations need to be in place to enable the proper use of automation and spectrum. The legislation should allow for industrial wireless broadband expansion while also ensuring the data safety and security of enterprises and individuals. The process of leasing slices should be easy, simple, and inexpensive to promote investment in 5G NHN. The policies should take efforts to avoid corporate monopolies and create appropriate pricing structures to encourage new entrants in the market. If the policies and the legal paperwork procedure between InP and MNO are time-consuming and inhibiting, then the stakeholders would not be keen on using rural 5G NHN.

Step 5 to 8: Scenario construction and assessment Based on the above considerations, the most critical uncertainties for rural 5G NHN are *NHN market competition - monopoly or oligopoly* and *last mile connectivity - public or private*. Fig. 4.3 shows the scenario matrix in which the x-axis represents the last-mile connectivity type, and the y-axis represents the NHN market competition type. In a monopolistic market, there are few major companies and little competition; but in an oligopolistic market, there are many participants and suppliers. An InP in a private 5G network is responsible for operations and maintenance, which costs more than a public network due to factors such as the need for in-house expertise. InP operators could support public networks to keep operational costs at a minimum.



	Private	Public
Oligopoly	• Industry verticals • Private 5G networks • Private access • Support other industry verticals • Competitive for service provisioning • Lacks wide area network connection • No guarantee of connection to NHN • Slicing for specific use-cases	• Public 5G network • All applications are supported • Any users can access the network • Easy entry for new-entrants • Higher competition • Higher quality of services • Slicing can support multiple users • Localised market • MNO customers on the network
Monopoly	• Private 5G network for particular application • Slicing for specific use-cases • Single vendor application • No competition • Difficult for new entrants enter the market	• Public 5G networks • Dedicated for the network operators use • Difficult for new-entrants • Lower competition • No competition • Lower quality of service • No localised market • MNO customers on the network

Figure 4.3: Scenario matrix for 5G NHN

A. **Oligopoly and private network dominates**

In this scenario, the industry and the InP would deploy the 5G network mainly for industry solutions. It is a private network with many competitors that provide this solution. MNO may not participate or play a minimal role in this scenario. In this case, InP can deploy different 5G technologies to meet the industry's requirements, following equipment standards. This scenario occurs when the InP and industry need to control access to the network, either due to the cost of joining the MNO network or because the industry's needs can be satisfied with a private network. Slicing can be used for different internal applications [29].

B. **Oligopoly and public network dominates**

In this scenario, the MNO and InP would build 5G primarily for public access, although private access is possible. The use cases of the industrial verticals might be supported on the same network by allocating a dedicated slice to each application. The network's primary goal is to enable both local and wide-area network applications. There would be end-to-end network slicing, and end-users could enjoy the benefits of improved performance and affordable tariffs in rural areas. This network is cost-effective when the deployment estimates the overall requirements of slice tenants and future possibilities [215]. This scenario occurs when InP deploys the network and MNOs and other partners lease slices from the InP network.

C. **Monopoly and private network dominates**

In this scenario, the InP deploys a private 5G network to meet the needs of a particular use case for a private network or an industry vertical. The market's competition would be monopolistic in nature; supporting, for example, other use cases in the region. An industry or community does not need to invest in a network if its needs are met by a private network.

D. **Monopoly and Public network dominates**

In this scenario, the InP deploys the 5G network solely for the MNO to meet the needs of the region of interest. The network is beneficial for MNOs' direct investment in 5G rural networks. The market competition is minimal for the MNO, and the entry barrier is high for new entrants. The MNO has a monopoly on the network, and end-users have to accept the QoS provided by the MNO due to a lack of competition. This scenario occurs when the network cost is high, and the demand is reasonably sufficient to reach a positive ROI. Vertical industries can lease InP network slices for serving users and applications from the MNOs.

Table 4.2 describes some factors which have a positive (+) or negative (-) impact on future scenarios. Existing solutions, for example, are a positive factor in an oligopoly-public situation since network upgrades are easy, while considerable evolution to existing infrastructure has a negative impact. However, in the monopoly-public scenario, the low cost of 5G installations promotes MNOs to invest in 5G deployments, but in the same situation, the ease of network setup, NHN, and local spectrum licensing have a negative influence.

Table 4.2: Underlying factors behind different future scenarios

Factors	**Oligopoly, private network dominates**	**Oligopoly, public network dominates**	**Monopoly, private network dominates**	**Monopoly, public network dominates**
Existing solutions	-	+	-	+
Evolution of technology	+	-	+	-
Low costs for 5G	+	+	+	+
Ease of provisioning 5G	+	+	+	-
Network slicing with NHN	+	+	-	-
Local spectrum licensing	+	+	+	-

4.4 Value Network Configuration for 5G NHN in Rural Areas

Value network models analyse services where an organisation acts as a middle-man for creating value that earns revenue for them rather than analysing traditional business concepts [265,266]. VNC consists of interlinked business actors and technical components [23,69,114,267], allowing a thorough examination of several scenarios to comprehend the most profitable network design. Business leads to value development in terms of money, knowledge, reputation, and loyalty for the outputs [29, 114]. Business strategies are interconnected to create value and lead to uncertainty in the business roles to be played by the actors which are interchangeable at times. Value networks help in understanding the roles played by actors in different businesses [267]. This section describes the VNC for rural 5G NHN businesses. The colour coding for different drivers is given in Fig. 4.4.

Figure 4.4: Colour labels for the four future scenario planning options

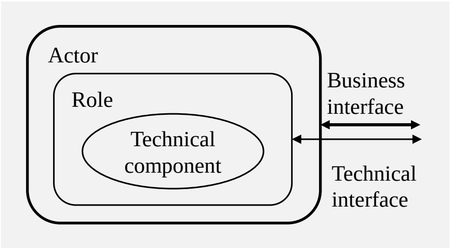


Figure 4.5: VNC block diagram

4.4.1 Technical architecture, technical components and roles

Table 4.3 shows the relations between technical stakeholders and their roles, allowing the study of actors. Fig. 4.5 shows the block diagram for VNC analysis for rural 5G NHN, an extension from VNC for 5G NHN in the smart factory in [29]. Technical components make technological functionality possible, and technical architecture leads to value creation [29, 114]. The actors play the roles related to their technical components [19]. Each actor has a business role and interconnects by business interface.

Table 4.3: Technical components of rural 5G NHN and their role

Technical component	Role description
Device (mobile/ stationary)	End consumers of 5G devices, apps, and IoT devices. Devices should work with a variety of technologies and applications.
Network (access and core Network)	The component that connects the device, the gateway, and the network application server. It also implements network slicing and C-RAN.
Authentication, authorisation and accounting (AAA)	Access to policies, regulations, billing, auditing, provisioning management, user authentication, and service monitoring.
Network slice Manager	The component that hosts slicing capabilities and enables use by multi-operator. It can also manage resource allocations to maximise the overall benefits of the slice tenants.
Cloud Service Provisioning	Includes security, local caching, data management, cloud services, edge computing and connection to slice tenants' core.
Network Equipment Provisioning	Hardware and Software for enabling network slicing and 5G networks.
Spectrum regulator	Spectrum allocation for the InP to provide 5G NHN using technologies such as shared spectrum, MNO's licensed or unlicensed spectrum band usage.

Table 4.4: 5G NHN Business roles, their description and examples

Business role	Description	Business actor examples
Slice provisioning	Includes slicing module, technologies, provisioning of slicing network, delivering data to the application server and end-users	Slicing service provider
Application service provisioning	Includes application level functionality	MEC application service provider
Network operation	Includes operation of the radio spectrum, access network, core network, slice management, buying radio connectivity to MNO core, and industry core	MNO, industry, small-scale business, rural applications
Account operations	Includes providing AAA services	InP, MNO, industry
Cloud service provisioning	Includes data management, data analytics, security, baseband processing, and application integration to end-user application core	Cloud service provider - eg. AWS
5G Access Gateway Function (AGF)	Connection to the external network. It manages advanced subscriber management, dynamic routing functionalities, manage wireline functionalities on the broadband network, policy management, bandwidth management	Gateway provider
Network slice management	Creation, planning, resource allocation and management, usage monitor	slicing service provider

The technical architecture for rural 5G NHN from Fig. 2.3 is combined with the VNC

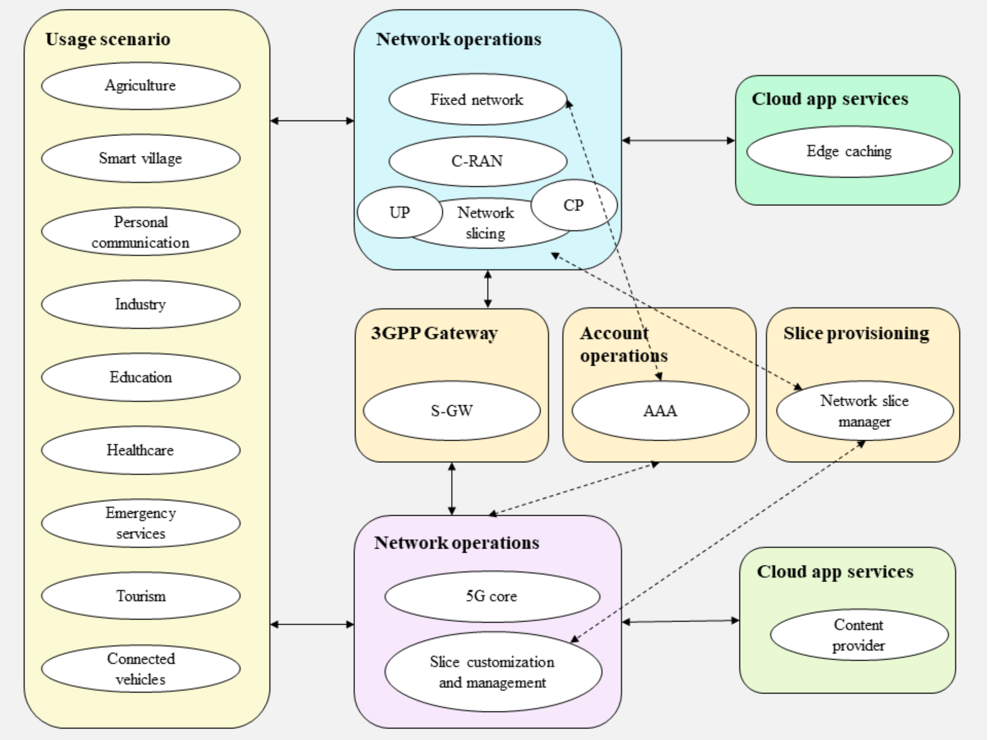


Figure 4.6: VNC rural network slicing architecture

block diagram from Fig. 4.5, and modified to obtain a VNC architecture for rural 5G NHN as shown in Fig. 4.6. The values are created across different domains spread across the device, network, and application. The key functionalities and roles of different technical components described in Table 4.4 are the most important features but do not encompass all of the features necessary for the deployment module.

4.4.2 VNC and analysis

For the scenarios discussed in Section 4.3, different future scenarios are possible depending on which actor is dominating/driving the business. Similarly, the roles of all actors will shift based on the driving actor. For this analysis, assume that MNO is interested in providing connections to end-users via the InP network. In each future scenario, the driving player has more influence on the network's VNC than other actors. For example, depending on the driving factor for the future scenario, the authentication, authorisation and accounting (AAA) operations could be performed by different actors. Hence, four alternate VNC architectures are possible for rural 5G NHN based on the four future scenario planning options.

InP driven VNC

The VNC in Fig. 4.7 is formed by end-users, industry verticals, InP, and MNO who are functioning over the device, network and application domain. The InP could be an organisation such as local governing bodies, small businesses, and third-party companies established by a conglomerate of operators. The industry verticals and MNOs would lease slices from the InP. End-users will be reliant on the MNOs for wide-area network access. The InP will connect to the MNO network via the 5G AGF and 5G core for a wide-area network. For the needs of the local region, the InP can install, operate, and deploy end-to-end 5G networks, account operations, setup, and slice provisioning. For enhanced user experience delivery and edge caching, the InP will own cloud resources and/or collaborate with cloud service providers. The cloud resource located locally would minimise latency and facilitate ultra-low-latency applications. As described in Section 2.4, the operating spectrum might be the LSA band or any other shared spectrum bands, locally licensed or unlicensed. The end-users would benefit from the high-quality network. The InP might establish a network based on off-the-shelf technology to reduce costs while shifting the focus away from network reliability. Also, efficient handovers between InP's and MNO's networks are critical for users to avoid disruption when users are roaming from one cell to another.

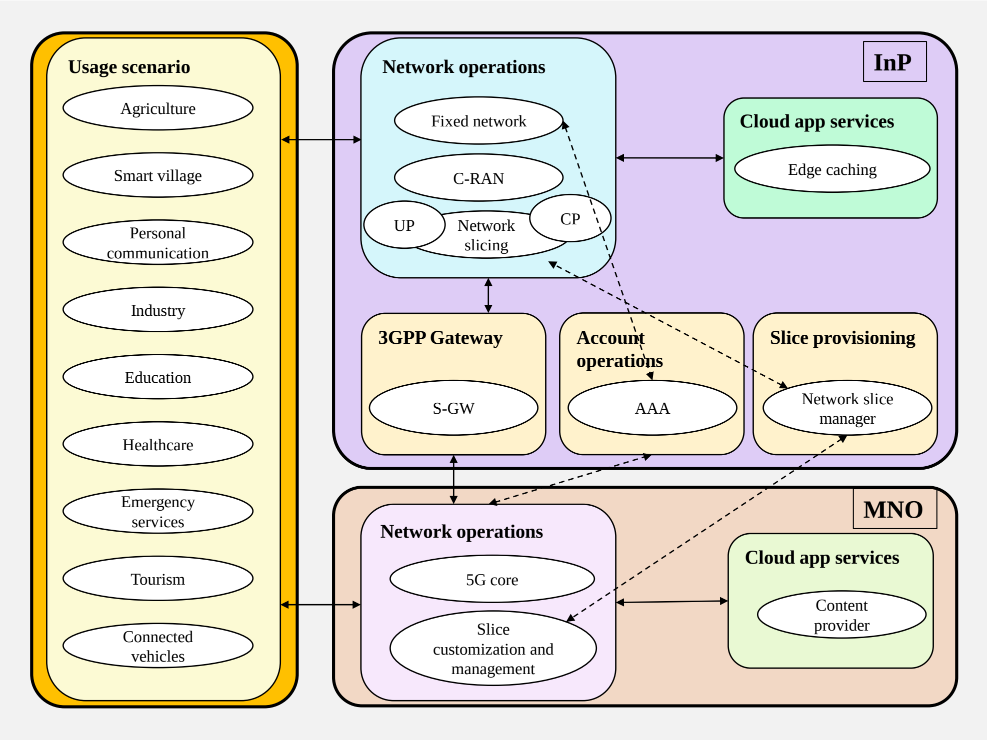


Figure 4.7: InP driven VNC

MNO driven VNC

Fig. 4.8 shows the VNC formed by end-users, industry verticals, InP, and MNO functioning over the device, network, and application domains. In this scenario, the industry verticals and MNOs would rent slices from the leading MNO, the InP. For both the public and private networks, end-users will be reliant on the lead MNO who would construct, operate, and provide end-to-end 5G networks. Leader MNO will also handle account operations, setup, slice provisioning, own cloud resources and/or collaborate with cloud service providers to improve user experience and edge-caching. A cloud resource for MEC applications would be located locally to reduce latency and support ultra-low-latency applications. The operating spectrum would be the licensed spectrum of the leading MNO. The end-users will benefit from the network's increased QoS. When users roam on this network, seamless handover is possible. The need for wireless broadband must, however, have a strong demand with high returns to draw in investment, and only then the MNO would be interested to establish and run their network. Direct MNO investments are typically challenging to obtain in rural locations because of their deployment requirements and challenges.

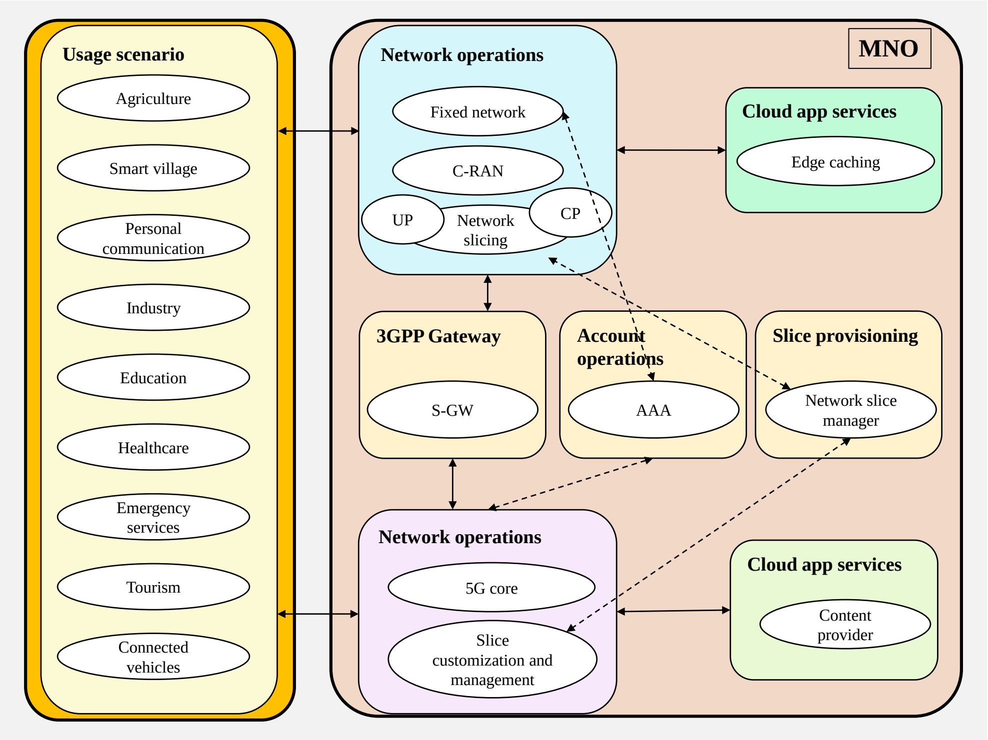


Figure 4.8: MNO driven VNC

Industry driven VNC

The VNC shown in Fig. 4.9, is formed by end-users, InP, industry and MNOs functioning respectively over the device, network and application domain. The InP, a third-party telecommunication company, will build a network dedicated to industry use cases but could be extended to cater to the use cases of MNOs and end-users. The MNOs would lease slices from the InP. The industry would have maximum resources allocated for itself and private networks. The MNO will be responsible for the wide-area network, while the industry-InP collaboration will be responsible for the private network and developing, managing, and provisioning end-to-end 5G networks that match local demands. For a better user experience, Industry-InP will also manage account management, setup, slice provisioning, edge caching, and own cloud resources or collaborate with cloud service providers for ultra-low-latency applications in Industry 4.0. As mentioned in Section 2.4, the operating spectrum might be LSA or any other shared spectrum bands, locally licensed or unlicensed spectrum. End-users will benefit from a network with enhanced QoS as a result of the industry-InP alliance. Also, while the industry focuses on their applications, smooth handover and minimal interruption are not a priority for this network, which depends on 5G AGFs and collaboration with MNOs. However, for an industry-InP partnership to install its network, the industry must be willing to upgrade the in-

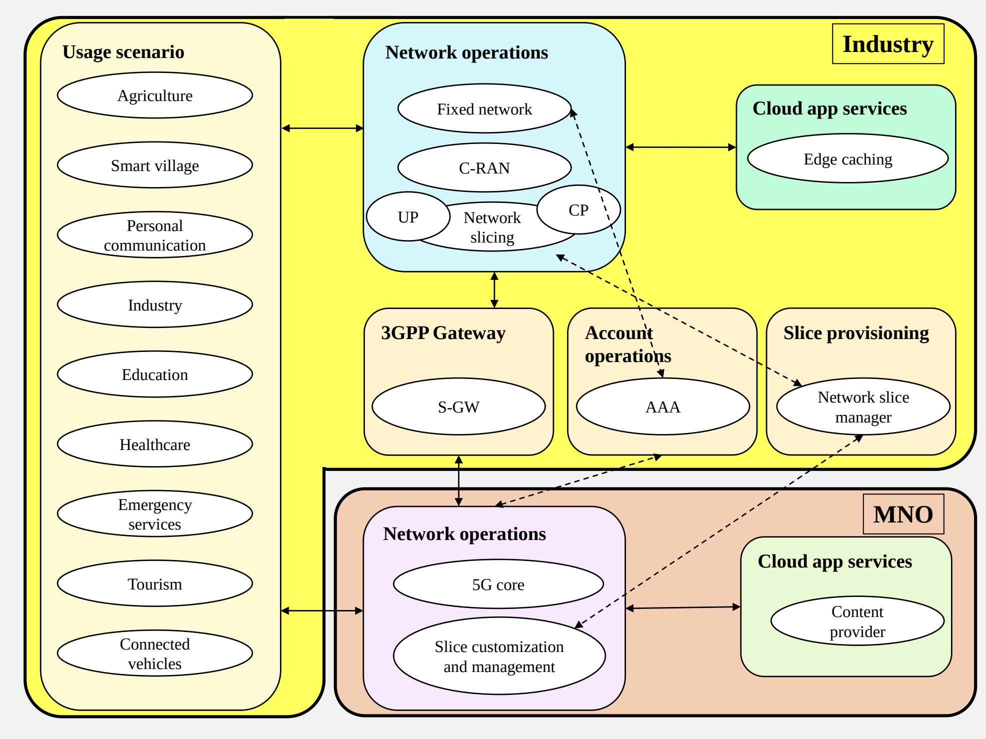


Figure 4.9: Industry driven VNC

frastructure and equipment that supports 5G services. Generally, industries located away from urban areas would offer scope for development around the industrial area and surrounding rural areas. The industry-InP partnership could deploy small or macro-cells in nearby rural areas by partnering with the MNOs.

End-users or community-driven VNC

The VNC shown in Fig. 4.10, is formed by end-users, InP and MNO functioning over the device, network and application domain respectively. The InP will create a network devoted to end-user use cases, which will result in a community benefit. The InP who deploys the

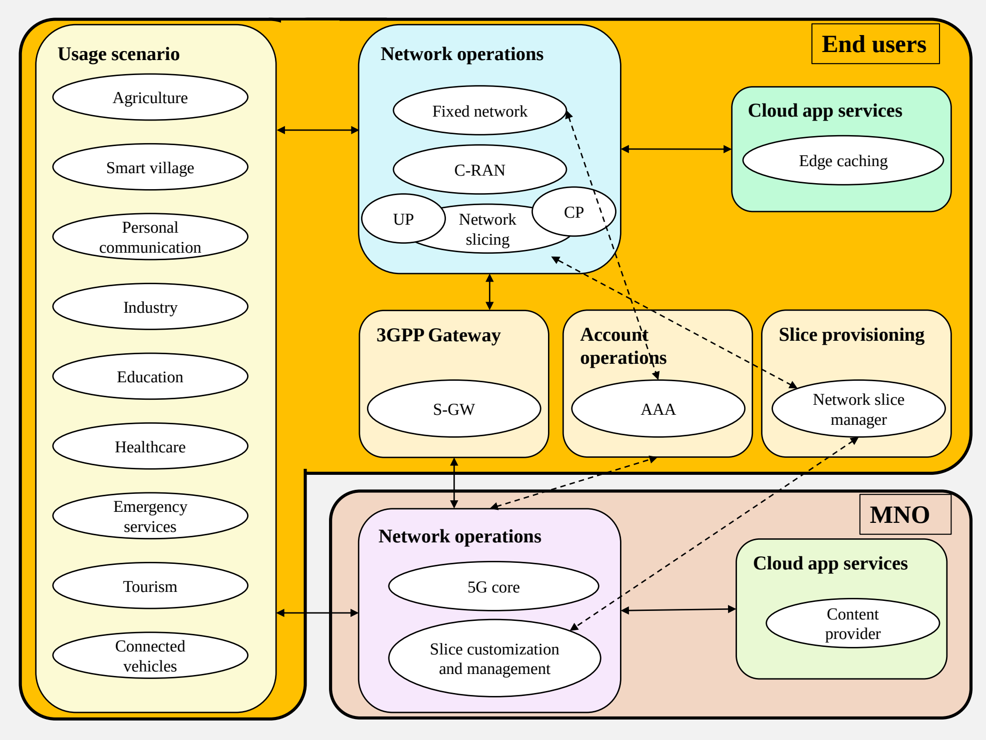


Figure 4.10: End-users driven VNC

network would lease slices to industry verticals and MNOs. The MNO will be responsible for the wide-area network, while the community-InP partnership will be responsible for the local area network. The community-InP collaboration would be provisioning end-to-end networks for 5G-enabled networks to meet the demands of the end-users. In addition, the community-InP partnership will handle account management, setup, slice provisioning, and own cloud resources or collaborate with cloud service providers and located locally to reduce latency and support ultra-low latency applications. The spectrum of operation could be either LSA or any other shared spectrum bands, locally licensed spectrum or unlicensed spectrum as discussed in

Section 2.4. The end-users will enjoy the benefits of the network at higher QoS provided by the community-driven InP. Smooth handoffs and minimal interruption are strongly dependent on the 5G AGF and MNO collaboration in this situation. However, for a community-InP partnership to install its network, the community must be ready to participate in 5G deployment for the community's benefit and cover the necessary costs. Because the community is working together, this circumstance would allow for a reduced-cost rollout. For 5G services, the InP might use commercial-grade or off-the-shelf equipment for lowering their TCO.

4.5 Business Models

The business model helps in understanding the various aspects of the viability of commercial success in terms of services offered, target customers, pricing model, infrastructure, organisation matters, trading, operations and pricing [268]. This section examines the SWOT Analysis and the business canvas model to define the model for the solution and estimate the market traction, earnings streams, the solution's competitive strength, and the significant obstacles. This aids in comprehending the rural 5G NHN business's potential.

4.5.1 SWOT analysis

SWOT analysis aids in the understanding of a company's strengths, weaknesses, opportunities, and threats. It helps in the strategic decision-making process to examine the internal possibilities and the external difficulties. It aids in determining the benefits and drawbacks of an option, as well as the likelihood of success. Table 4.5 discusses the SWOT analysis of 5G NHN in a rural setting.

5G NHN business's power resides in lowering network costs and raising profitability in low-income rural areas that attract 5G network deployments. The rural area with 5G deployment with no fallback to older technologies is a driving point for 5G NHN as the network QoS will not fallback to legacy technologies during congestion. This is an attractive feature since virtual networks help in handling the network traffic better by using MEC technologies. As per the SWOT analysis of rural 5G NHN, the inherent weakness is its feasibility to allow network sharing by the InP and adherence to the agreed-upon KPIs and SLAs. If these issues are addressed, then there will be opportunities in terms of connectivity, digital services, revenue, and job creation. However, owing to regulatory or legal policies, there is a threat of failure in this business approach.

Table 4.5: SWOT Analysis for 5G NHN in rural scenario

Strength	Weakness
- Faster deployments [11]. - Lower TCO [69]. - C-RAN allows expansion as per demand, and for a shorter duration as well [269]. - Localised spectrum ownership leading to relatively lower cost for spectrum access [22]. - Guaranteed KPIs as per SLA during network congestion [14]. - Improved resource utilisation due to network sharing [14]. - Remote network monitoring, and controlling [38]. - End-users will not realise the difference. - Independent usage of slices [69]. - Supports 5G applications for industry verticals, and private networks [69].	- Increased complexity in the network design [69]. - Getting approvals from the regulator for deployments and spectrum access [11]. - Pricing should be attractive for rural use cases and their per-capita income [27]. - Connection to the MNOs' network is required for wide-area connection [50]. - Slice tenants can not customise the InP network unless they explicitly bear the extra cost for customisation. - Security considerations while connecting to the core of the MNO [26]. - Feasibility of network in remote rural areas [50].
Opportunities	**Threats**
- Internet access in not-spots or poor coverage regions [50]. - Profits generated from rural networks. - Opportunity to expand businesses into rural market [50]. - Additional income to the regulator from spectrum sharing [32]. - Better quality of life and increase in opportunity for the inhabitants in rural areas [69]. - Creations of jobs. - Potential for spectrum sharing [32]. - Boost for local industry [50]. - Economic growth for rural areas.	- Hard-handoffs while roaming. - NHN can be considered as a threat to the existing telecommunication market [27]. - Non-cooperation between InP and MNOs would increase TCO for the 5G network. - Potential regulatory and legal limitations.

4.5.2 Business canvas model

The business canvas model is a strategic management template for identifying potential trade-offs in a business. The nine-block model was proposed by Alexander Osterwalder [270] and enables the business organisation to think in terms of business models rather than just products. The potential income streams, network costs, key partners, key resources, network value proposition, client groups, and channels are all examined for rural 5G NHN. Based on the subsequent discussion, Table 4.6 shows the summarised form of the business canvas model for rural 5G NHN [19]. The one-page BCM describes the fundamental concepts involved in the business, concisely grouping an idea.

Table 4.6: Business canvas model for 5G NHN

<table>
<tr><td rowspan="2">Key Partners
InP, MNO, regulator, local council, telecommunication equipment vendors, cloud service provider</td><td>Key Activities
Demand estimation, 5G NHN deployment, pricing strategy</td><td rowspan="2">Key Proposition
Rural connectivity, lower cost for rural 5G services, business expansion, digital services</td><td>Customer Relationship
AI support, customer service, network slice manager</td><td rowspan="2">Customer Segments
Rural market, industry verticals</td></tr>
<tr><td>Key Resources
Human resources, network slicing software</td><td>Channels
Web pages, technology forums, referral from customers</td></tr>
<tr><td colspan="3">Cost Structure
Network cost, spectrum cost, human resources, operational cost</td><td colspan="2">Revenue Streams
Slice rent, subscription fees, enterprise customers, local area network</td></tr>
</table>

- **Key Partners** This is a list of outside companies/suppliers that are needed to complete critical tasks and provide value to consumers.
  - *Partners*: InP, MNOs, national regulators, industry verticals, local government.
  - *Suppliers*: Equipment manufacturers, energy supplier.
  - *Motivations*: Additional revenue for the key stakeholders, business expansion, and IPR.

- **Key Activities** These are the actions that businesses need to understand for achieving the expected value proposition and involve decision-making on factors such as time, expertise, steps involved in the development of product/business, technical and non-technical aspects and strategy.
  - *Activities*: Technology development, creation of network slice manager, optimal pricing decision, usage predictions, network planning, coverage planning, demand prediction, network deployment.

- **Value Propositions** The primary value supplied by the business/product is the value proposition. It is traded for the amount of money that clients are willing to pay for the goods or services. As a result, it's critical to understand what major issues are, why they're significant, and why they're crucial to address.
  - *Value*: 5G mobile broadband, lower TCO, connectivity in not-spots, business expansion, globalisation for rural presence, access to digital applications such as e-healthcare,

online education, remote monitoring and managing of the network, e-governance, and online banking.
- *Needs*: Reliable, low latency, high-speed Internet, broadcasting, seamless connectivity.
- *Minimum value*: Innovative pricing strategies with break even estimations for ARPU.

- **Customer Relationship** This explains how the business/product interacts with customers, modes of communication and customer checkpoints.
  - *Customer growth*: Through negotiation and advertisement, the customer base would grow.
  - *Cooperation*: InP, MNOs and national regulator.
  - *Relationship*: User assistance, AI recommendation to improve network performance, self-organising networks, network slice manager.

- **Customer Segments** The strategy of segmenting clients into groups with comparable needs is known as customer segmentation. It assists in determining whom the solution aims at, who will appreciate the business/product given, their demographics, age group, and individual persons.
  - *Potential customers*: Consumers, retailers, slice managers, small-scale businesses, government, tourism and community.
  - *Most important customers*: MNOs, industry verticals, and government.
  - *Archetypes*: People with awareness of mobile connectivity benefits.

- **Key Resources** The practical resources necessary to complete the business's essential tasks.
  - *Resources*: 5G network, spectrum, tools to monitor and optimise the network, employees.
  - *Distribution channel*: Direct channel.
  - *Customer relationship*: Personal assistance.
  - *Revenue streams*: Network usage monetising by slice tenants.

- **Channels** Helps in understanding the route through which customers reach out for the business/products to become part of the seller's sales.
  - *Advertising*: Word of mouth, social media, websites, telecommunication support channels, and local governing bodies.
  - *Evaluation*: Surveys and network log analysis, desktop application.

  - *Purchases*: Online, and office.
  - *Delivery*: Online.
  - *Post-sales*: Customer assistance.

- **Cost Structure** Includes the monetary cost of operating the business. For example, the cost for key activities, value proposition, legal, insurance, depreciation, advertisement, CAPEX and OPEX.
  - *Inherent cost*: 5G NHN deployment cost, employees, operational cost, advertisement, insurance, and spectrum cost.
  - *Most expensive resource*: 5G NHN deployment and operation cost.
  - *Most expensive activities*: Network slice manager, legal costs and technical component, backhaul connections.

- **Revenue Streams** Defines how the value proposition offered by the business produces financial gains for the company.
  - *Revenue model*: A fixed monthly subscription, slice rent, enterprise usage, potential InP local area network, usage fees, roaming customers, data usage, industry vertical applications, private networks, and short-duration slice lease.

4.6 Discussions

The primary findings of the scenario planning process are that last mile connectivity and NHN ecosystem solutions, as well as the position of regulators, are the most important factors determining competitiveness: whether the last mile connection is provided by a public or private network, and the ease of market entry. The policies developed by the regulatory bodies to enhance digital connectivity in hard-to-reach areas and infrastructure would impact the technology. The uptake of technology, the cost of offering 5G services, the ease of spectrum ownership, and policies will contribute to future scenarios. As a result, four future possibilities emerge, each indicating how the future will unfold for 5G NHN.

Different players will drive the value supplied by the network based on needs, cost, connection solutions, ease of obtaining spectrum licence, backhaul connectivity, 3GPP connectivity, and expertise, according to the outcomes delivered from the VNC for rural 5G NHN. The actor driving the VNC has a direct impact on the type of network installed and its performance. VNC driven by InP and community-InP caters to local demands to provide services for rural needs with lesser stringent network quality requirements. In contrast, MNO-driven VNC and industry-InP-driven VNC are designed for high-processing applications that require a commercial-grade network.

The key findings of the business models for 5G NHN are that it has potential if the primary obstacles are addressed and mitigated. SWOT analysis and the business canvas model identify key actors and their responsibilities. The business canvas model depicts the main steps involved in firm formation visually. There is no such thing as a one-size-fits-all solution for all towns; instead, each community would receive a personalised solution depending on demand, requirements, budget, and legal laws.

The conclusions are based on a substantial literature review and expert interviews with various stakeholders in seminars (professors, researchers, MNOs, small-scale businesses, councils, industry, and project managers). Stakeholders can utilise the results of this chapter to choose the best course of action for their circumstances. The VNC and scenario matrix follow contemporary rural industry trends and uncertainties. The business models reflect the firm's advantages, drawbacks, and difficulties the problems have to overcome. It would also help them understand the influence of various stakeholders on the solution.

Chapter 5

Techno-Economic Analysis of Rural 5G NHN

Rural connectivity has been a key issue that governments around the world have yet to solve. There has been some literature on the use of 5G NHN to provide internet connectivity in rural and urban settings. This research mostly focuses on areas with absolutely no connectivity or poor coverage, where no MNO is generally motivated to provide services. Using rural 5G NHN, different MNOs could actively participate in providing 5G services to rural areas, especially those with low populations. The period during which a break-even financial model of the business venture is developed based on all costs associated with taking the product from idea to market and achieving sales sufficient to satisfy debt or investment requirements is known as the economic feasibility of business development.

A techno-economic model can help to comprehend the scale, profitability, and risk of the business. It involves an analysis of the technological, financial, market, and regulatory opportunities as well as risks. It is used in many research projects and considers almost all of the foreseeable factors that could have an impact on the business [7,8,25,38,44,47,271]. This chapter studies the techno-economic feasibility of the rural 5G NHN to understand the business case and also investigates the possibility of an InP-driven model delivering the rural 5G NHN with MNOs as slice tenants. The study sheds light on network requirements in terms of both technology and revenue generation. The major contributions of this chapter can be summarised as follows:

- A generic methodology model to perform techno-economic analysis, along with detailed mathematical calculations, for understanding the suitability of rural 5G NHN in both greenfield and brownfield development.

- An analysis of the technical requirements for rural 5G NHN and the stochastic modelling to understand the practical impact of nearby cells and other parameters on the achievable coverage.
- An overview of the state-of-the-art for Indian and UK telecommunications aids in understanding the network requirements for both. The application of the model developed in the UK and the Indian scenario to understand the suitability of the rural 5G NHN in different demand factors such as ARPU and the number of subscribers.
- A brief discussion on the policy impact on deploying rural 5G NHN.

5.1 System Model and Methodology

Fig. 5.1 shows 5G architecture for end-to-end network slicing that supports NHN. The 5G NHN deployed by InP consists of both macro-cells and micro-cells, which connect to the 5G core and later to the MNOs' core. Each slice consists of a virtual 5G RAN, a virtual baseband unit (BBU) and dedicated resources in the 5G core. Ideally, all operators would like to operate everywhere in the country. In the proposed solution, InP deploys and manages the network for its entire life cycle. Previous research has established that 5G network slicing with multi-tenancy reduces CAPEX by at least 30% and OPEX by at least 20% [13, 179]. In rural areas, service pricing could be reduced by lowering network costs to attract subscribers.

There are two types of possible deployments in rural areas:

- **Greenfield** deployment refers to a scenario where there is no form of existing broadband infrastructure. According to data, a little less than 3 billion people have not yet connected to the Internet even in 2022 [82]. Most of these users live in developing countries [272]. Therefore, stakeholders must select the most suitable and cost-effective technology to support their requirements.
- **Brownfield** deployment refers to a scenario in which some form of broadband technology is deployed. Therefore, stakeholders must upgrade the existing broadband infrastructure. According to data obtained by the ITU, there are hundreds of millions of users who are connected to the Internet but lack acceptable connection quality or use it through shared devices [272].

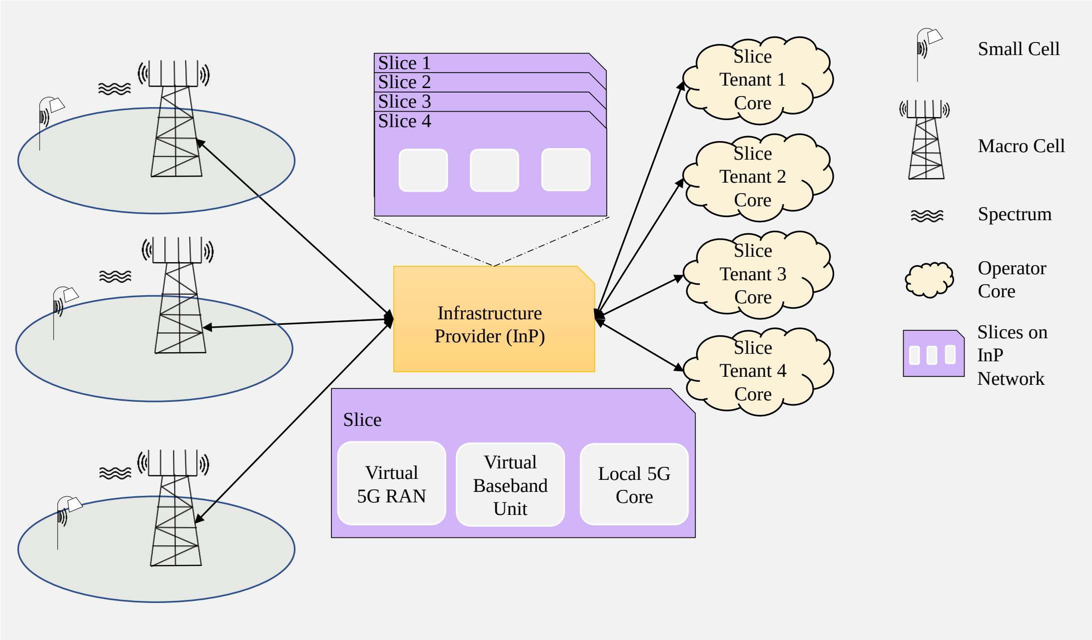


Figure 5.1: 5G multi-tenancy network slicing: A neutral host approach

In this chapter, the techno-economic assessment model is utilised to examine the viability of greenfield deployment of 5G network slicing supporting NHN in rural areas, especially in the UK and India. The detailed study of brownfield 5G NHN deployment is explored in the ongoing work [149].

5.1.1 Modelling methodology

Fig. 5.2 shows the modelling methodology used in this study to assess the viability of rural 5G NHN. To determine the network's viability for greenfield rural 5G NHN, various parameters are examined. The key inputs for the 5G NHN feasibility study are demand and capacity requirements along with capacity-expansion strategies. This model is derived from other techno-economic assessment models presented in [44, 46, 86, 116, 149, 179, 228].

This model shares similar features but differs from the models used in [7,8,44,66]. Techno-economic models, such as this one, are used for assessing the feasibility of rural 5G NHN with DSA for greenfield and brownfield deployment considering multiple input parameters. This model is derived in a way from [8, 66] which is for 5G MORAN and 5G NHN for the seaport but is modified to fit a rural site deployment that uses 5G network slicing with NHN and spectrum sharing focusing on eMBB use case. Therefore, this research does not explicitly focus on spectral efficiency but considers it in estimating network throughput as in (5.8), [7, 149]. Unlike in [44], the network congestion is already taken into account as InP provides a minimum guaranteed resource block to each slice tenant in case of congestion. The model considers analysis using network slicing in rural areas. The sensitivity analysis in this study considers various possible input scenarios and averages them across different values to account for the overall impact. In this study, the network design is such that the minimum average data rate per user is 30 Mbps, as per the ITU and UN requirements for addressing the digital divide [273].

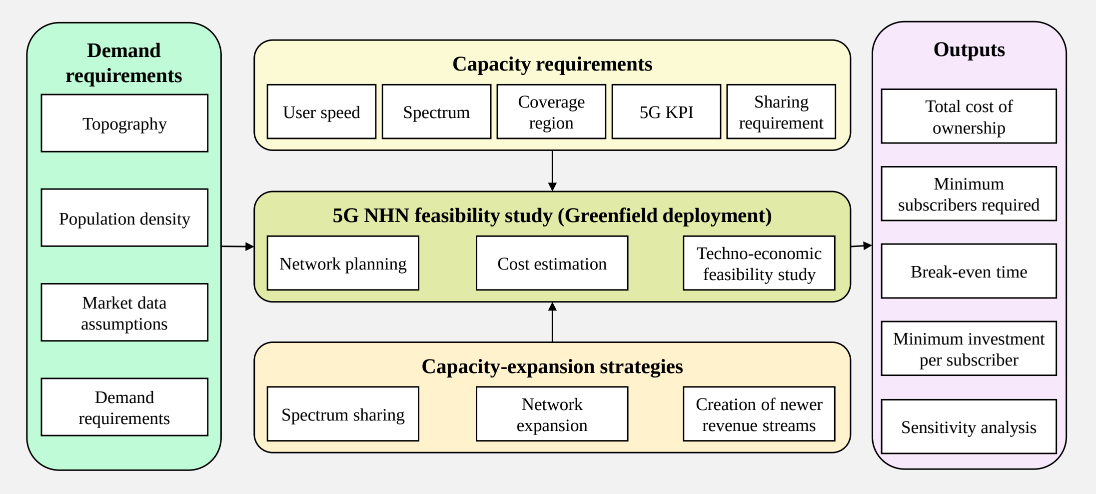


Figure 5.2: Modelling methodology

Demand assessment for the village must consider inputs such as topography, population density, use cases, market data assumptions, and user applications. Following that, equipment is chosen based on ***capacity requirements*** such as user speed, spectrum frequencies, intended coverage region, end-to-end sharing or not, KPI requirements and SLA, which determine the number of antennas required, its types and orientations, tower location, RAN, servers, processing units, power requirements, and backhaul capacity is also estimated. It is also crucial to minimise interference with incumbent users on the same band when using spectrum sharing technology.

Another module influencing the network's viability is the ***capacity-expansion*** that includes spectrum sharing, future network expansion strategies, and newer revenue streams. Typically these parameters depend on the upcoming use cases, network uptake, population, and predicted subscriber growth. The proposed ***5G NHN techno-economic assessment*** model for greenfield deployments takes input and analyses the best strategies for network planning estimates the cost of deployment, and calculates the feasibility. The ***outputs*** of this study includes the estimation of TCO, the CAPEX to OPEX ratio, minimum subscriber, break-even time, and minimum investment per user that help to determine if the network is viable in the evaluated region.

Coverage modelling helps with the visualisation of network design factors and engineering the network to meet requirements such as frequency planning, the ideal position for BSs, antenna directivity, route loss, cell-edge, clutter, topographical obstacles, signal to interference and noise ratio (SINR), KPIs, interference and detecting coverage blind spots. MATLAB antenna wave propagation toolbox, Radio Mobile, Python, R and CloudRF were used to simulate coverage plots for the hamlet of interest in this study. The FR1 frequency bands (less than 6 GHz) of 5G have coverage up to a few surrounding settlements. Research on network slicing suggests that 5G NHN will be able to support a higher number of users and that the network is scalable as per demand [9, 24, 150].

5.1.2 Stochastic and traffic modelling

Demand modelling

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 the amount of traffic per site [174, 274, 275]. Rural areas tend to have a small number of settlements, although there are a few outliers [2]. 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 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, $t \varepsilon T$. Then, the data consumed per day per user, $\delta_{t,day}$ MB/day [7, 46]. 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 hour with 3600 seconds [45], is calculated as:

$$\zeta = \frac{8}{3600}\frac{1}{30}\frac{1}{1000}\delta_t B_{HF} \tag{5.1}$$

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 [274],

$$\iota_{area} = x\zeta\frac{P}{A} \tag{5.2}$$

Capacity modelling

The detailed analysis of the parameters is presented in [18, 149, 276]. The theoretical data throughput for a 5G site is calculated using the equation given below [256]:

$$C_{5G} = \frac{\sum_{j=1}^{J}(\nu^{(j)}Q_m^i f^j R_{max}\frac{12N_{PRB}^{BW(j),\mu}}{T_s^{\mu}}(1-O_h^j)}{10^6} \tag{5.3}$$

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 5.1 - quadrature phase shift keying QPSK, and quadrature amplitude modulation QAM), 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 allocation of the resource block that is determined by the sub-carriers depending on the numerology and bandwidth of μ and BW, T_s is the symbol time, and O_h is overhead (typically ranges from 8% (FR1 uplink) to 18% (FR2 downlink)).

Table 5.1: 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

Next, to understand the practical implication of multiple 5G sites in the vicinity on the throughput, the new radio (NR) link budget needs to be calculated, considering the stochastic geometry modelling for capacity distribution and spectral efficiency, among the different UEs at varying distances from the gNodeB [256, 277]. The NR link budget estimations consider a standard deviation of 6 dB for a rural scenario and different propagation models for rural areas [7, 256], in line with the literature [219, 278]. The analysis also considers interference from the nearest 19 base stations configuration, since it is derived from the extended Hata model [277]. The NR link budget per UE (in dBm) is described in the 3GPP 38.901 standard

(5.4) [256]. In this study, since a greenfield 5G NHN in remote and hard-to-reach places is under evaluation, the impact of interference of neighbouring cells is minimal in the initial deployment stage.

$$\begin{aligned} LinkBudget_{Rx,dBm} &= TxPower_{TxBandwidth} + AntennaGain_{Tx} - CableLoss_{Tx} + \\ &\quad AntennaGain_{Rx} - CableLoss_{Rx} - PathLoss_{propagationModel} - \\ &\quad PenetrationLoss - FoliageLoss - BodyLoss - \\ &\quad InterferenceMargin - RainIceMargin - SlowFadeMarging - \\ &\quad PenetrationLoss_{indoor} - AttenutationLoss_{indoor} \end{aligned} \tag{5.4}$$

The 5G pathloss equations ($PathLoss_{propagationModel}$) 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

$$PL_{RMA_{LOS}} = \begin{cases} PL_1, & 10m \leq d_{2D} \leq d_{BP}. \\ PL_2, & d_{BP} \leq d_{2D} \leq 10km. \end{cases} \tag{5.5}$$

$$\begin{aligned} PL_1 &= 20log_{10}(40\pi d_{3D} f_c/3) + min(0.03h^{1.72}, 19)log_{10}(d_{3D}) - \\ &\quad min(0.044h^{1.72}, 14.77) + 0.002log_{10}(h)d_{3D} \\ PL_2 &= PL_1(d_{BP}) + 40log_{10}(d_{3D}/d_{BP}) \\ d_{BP} &= 2\pi h_{BS} h_{UT} f_c/c \\ d_{3D} &= \sqrt{(h_{BS} - h_{UT})^2 + d_{2D}^2} \end{aligned} \tag{5.6}$$

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 centre frequency in Hz. For PL_1 has a shadow fading, $\sigma_{SF} = 4$, $h_{BS} = 35m$, $h_{UT} = 1.5m$, while for PL_1 has a shadow fading, $\sigma_{SF} = 6$. These formulas are valid for $10m \leq h_{BS} \leq 150m$ and $1m \leq h_{UT} \leq 10m$. The SINR to modulation code conversion is as given in Table 5.2.

Table 5.2: SINR to modulation code relationship

Modulation code	SINR range
QPSK	4-14
4 QAM	14-20
16 QAM	20-26
64 QAM	26-32
256 QAM	32-34

The signal-to-noise ratio (SINR), $\gamma = 10^{LinkBudget_{Rx,dBm}}$, values are used in (5.8) 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 utilisation χ, SINR γ, targeted cell-edge data rates R_{data}, and spectral efficiency μ [279]. The cell radius is estimated as given below:

$$P_{UT_{sensitivity}} = -174 + 10log_{10}(B) + NF + Target_{SINR} \tag{5.7}$$

where, NF is the noise figure of the receiver, and $Target_{SINR}$ is the SINR sensitivity, which varies as per the equipment vendor. Generally, the realistic channel capacity C is lower than the theoretical channel capacity C_{5G}.

$$\begin{aligned} C &= Blog_2(1+\gamma) \\ &= B\mu\chi \\ \mu &= \frac{R_{data}}{B}\frac{1}{1-O_h} \\ \chi &= \frac{Application_{throughput}}{Device_{throughput}} \\ throughput_{one_user} &= \frac{C}{S}\Xi \end{aligned} \tag{5.8}$$

where S is the total number of subscribers and Ξ is the arbitrary constant based on the contention ratio.

The receiver sensitivity determines the cell-edge radius, that is, the distance at which $LinkBudget_{Rx,dBm} = P_{UT_{sensitivity}}$ decides the cell radius. The formula is as given below:

$$\begin{aligned} R_{cell} &= 10^{(P_{UT_{sensitivity}}-28-20log_{10}(f_c))/22} \\ coverage_{area} &= \pi R_{cell}^2 \\ Number_{Cells} &= \frac{Study_{area}}{coverage_{area}} \end{aligned} \tag{5.9}$$

Traffic modelling

The physical downlink data channel (PDDCH) in 5G NR is primarily used to carry the scheduling information to the UEs for resource allocation in the uplink and downlink. The block error rate (BLER), $BLER$, estimates the number of code blocks received erroneously for the total number of code blocks received [256]. Typically, there are three possible user behaviours, including short users (20 seconds), mid users (60 seconds), and long users (300 seconds); the scheduling demand varies with the number of active subscribers [280]. User scheduling helps operators assess whether the upgrade is sufficient to meet user demand at desired data rates.

As the number of active users on the network increases, there is a need to increase the number of gNodeB assets deployed to meet the minimum user data rate requirements [281, 282]. The number of sites required to be upgraded is estimated using link budget analysis, traffic management, and scheduling. The incumbent operator would select the outcome that provides the maximum number of towers for the upgrade, to account for the future demand from end-users and their applications [283, 284]. Typically, 20% of the network throughput is used to manage congestion. Therefore, the available data rate to serve user applications is $0.8C$ MBps. The throughput offered per site by a 3-sector antenna is $2.4C$. The traffic that the network needs to handle in the duration of investment, T years, considering a growth rate in subscribers $S_i = S(1+a)^i$, is estimated as Δ, that is shown (5.10). Typically, the contention ratio is Ξ, which determines the throughput per user for both macro and small cells, is given below:

$$\begin{aligned} \Delta &= \textstyle\sum_{i=1}^{T} \tau_{area} S_i \\ N_{cells} &= \tfrac{\Delta}{2.4C} \end{aligned} \tag{5.10}$$

5.1.3 Feasibility analysis parameters

Cost analysis

The cost per site is estimated by calculating the CAPEX, OPEX, and TCO for the investment duration of T (in years). The CAPEX C_c, includes installation of a new BS with a tower (C_{bs}), multi-carrier BS (C_{mbs}), fibre (C_f), backhaul (C_{bh}), 5G core (C_{co}), and other equipment such as batteries (C_{bt}) and backup generator support for power supply (C_{gt}), and technology licensing (C_{tech}), and is given:

$$\begin{aligned} C_c &= C_{bs} + C_{mbs} + C_f + C_{bh} + C_{co} + C_{bt} + \\ &\quad C_{gt} + C_{tech}. \end{aligned} \tag{5.11}$$

The OPEX C_o per year, includes day-to-day maintenance such as BS OPEX (C_{bso}), site lease (C_l), network maintenance (C_m), backhaul (C_{bho}), spectrum (C_s) and rentals (C_{rent}), is given:

$$C_o = C_m + C_{bho} + C_{rent} + C_{bso} + C_l + C_s. \tag{5.12}$$

In this study, TCO for the InP (C_{Ti}) is given as follows:

$$C_{Ti} = C_c + TC_o. \tag{5.13}$$

Let 5G network slicing supporting NHN deployed by InP have parameters as the total number of slices, $\beta = \sum_{n=1}^{N} \beta_n$, and the minimum required resource block per slice tenant be $\delta_{min} = [\delta_1, ..., \delta_N]$. Assume a 5G network has M KPI requirements, then KPI requirements of n^{th} MNO as $\rho_n = [k_1, ..., k_M]$. Therefore, the KPI of all MNOs in the rural 5G NHN is $K = [\rho_1, ..., \rho_N]$. The expenditure of InP will heavily depend upon the number of slices β, KPI requirements of the slice tenants K, the size of the slice γ, the type of virtualisation V, and the minimum guaranteed resource block δ_{min} [155]. There is a need to solve the complex dependency between various parameters to calculate the incremental cost C_{inc} for InP in provisioning services for the slice tenants, as,

$$C_{inc} = E(K, \beta, \delta_{min}, \gamma, V), \tag{5.14}$$

where $E(.)$ is the standard expenditure function, explored in more detail in [155]. The values of K, β, δ_{min}, γ and V will vary depending on each situation and MNOs' requirements [49]. Most of the overhead involved in slicing as well as the 5G infrastructure, is included as C_{Ti}. To simplify the analysis, we assume C_{inc} to be around 20% of C_{Ti} as most of the cost involved in slicing technology as well as 5G infrastructure deployment is estimated as part of C_{Ti}. Typically, C_{inc} can range from 0 to 20% depending on the additional KPI requirements of the MNOs. Therefore, the modified TCO, C_T for the network is,

$$C_T = C_{Ti} + C_{inc}. \tag{5.15}$$

This research assesses the TCO for a greenfield deployment in a region with no or very limited coverage. The lifetime of the equipment is generally around 10 years, but it can be functional for 20 years with minimal upgrades. InP can provide service in the village using localised spectrum bands. Generally, if shared spectrum bands are used for operational frequency for rural 5G NHN, then the duration of the spectrum licence could be 3, 5 or 10 years [89]. On the other hand, the spectrum band for commercial mobile communication for MNOs has a licence for 25 years tenure. If the spectrum is traded, then the duration of the spectrum depends on the agreement between the incumbent of the spectrum band and the secondary user.

Fig. 5.3 shows the cost and revenue relationship between InP, MNOs, and end users with their corresponding parameters. A cost model is a tool used by businesses to determine the best costs to produce a product to meet their requirements. It helps business owners assess how to price goods at the lowest possible cost and still make a profit. The cost and revenue streams for InPs and MNOs are as follows.

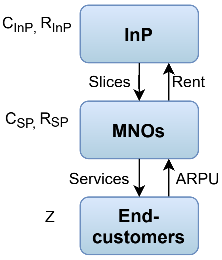


Figure 5.3: Cost and revenue relationship among InP, MNO, and end subscribers

InP: The cost for the InP C_{InP}, is the same as the TCO for the network inclusive of the incremental cost for slice provisioning, C_T.

$$C_{InP} = C_T. \tag{5.16}$$

Revenue R_{InP} is calculated as,

$$\begin{aligned} R_{InP} &= P + C_T, \\ &= xC_T, \\ &= \textstyle\sum_{n=1}^{N} r_n, \end{aligned} \tag{5.17}$$

where P is the InP's expected profit for the network, the InP's expected profit (in terms of percentage) is represented as $x \; \varepsilon \; (1,2]$, is a constant, N is the number of service providers on the InP network, and r_n is the rent paid by the n^{th} service provider on the network to the InP. The cost per tenant/service provider towards the slices depends on the individual KPIs required for their applications. However, the expected revenue of InP, R_{InP} is equal to the sum of all rents paid by the tenants towards the 5G NHN network.

MNOs: Similarly, the cost (C_{sp}^n) and revenue (R_{sp}^n) for the n^{th} service provider from greenfield deployment, is calculated,

$$\begin{aligned} C_{sp}^n &= r_n, \\ R_{sp}^n &= \textstyle\sum_{j=1}^{T} 12 Z_n^j S_n^j T, \end{aligned} \tag{5.18}$$

where S_n^j is the number of subscribers, and Z_n^j is the APRU per month for n^{th} slice tenant for j^{th} year. Similarly, for a brownfield deployment, the total revenue, R, over the period T for ARPU Z_{5G} for 5G services are calculated as:

$$R_{sp}^n = \sum_{i=1}^{T} 12\rho_{up_{sub},i}(Z_{5G,i} - Z_{old,i}) + 12\rho_{new5G,i}(Z_{5G,i}) \tag{5.19}$$

where i is the year of study, $Z_{old,i}$ shows the ARPU for existing infrastructure, $Z_{new5G,i}$ are the additional new subscribers joining the network who require 5G KPIs for their applications, and $\rho_{up_{sub},i}$ be the existing subscribers who would upgrade their services [149].

To streamline the analysis, the combined cost (C_{sp}), revenue (R_{sp}) and subscribers (S) of all service providers on the network in the village of interest are given by,

$$\begin{aligned} C_{sp} &= R_{InP}, \\ &= \textstyle\sum_{n=1}^{N} r_n, \\ R_{sp} &= \textstyle\sum_{n=1}^{N} R_{sp}^n, \\ S &= \textstyle\sum_{n=1}^{N} S_n. \end{aligned} \tag{5.20}$$

Outputs - Feasibility analysis

The techno-economic feasibility of 5G NHN is examined by varying the cost modelling parameters and obtaining the following output results:

- A *minimum number of subscribers* are required for the network to be feasible. Assume that the InP caters exclusively to MNOs, each with the same KPI criteria because they would be servicing end-users with identical demand to demonstrate the usage of 5G NHN in rural regions. As a result, the rent is shared evenly among the MNOs that only serve individual subscribers S with an ARPU per month of Z during the network's lifetime. Future studies may explore the network's potential subscribers from private 5G and other vertical businesses. Assume that the growth rate r_g for the number of individual subscribers in the life cycle of the network is zero to determine the minimum number of subscribers necessary for all MNOs in the network. Hence, the minimum subscribers, S_{min}, required to achieve the expected TCO at ARPU per month Z using

(5.18) and (5.20), is calculated as,

$$S_{min} = \frac{1}{12}\frac{C_{sp}}{ZT}. \tag{5.21}$$

- *Break-even time* (T_{be}, in years) is the time required for total profits to be zero with S subscribers at Z ARPU per month and is calculated as follows:

$$T_{be} = \frac{1}{12}\frac{C_{sp}}{SZ}. \tag{5.22}$$

- *Investment cost per user* helps to estimate the minimum ARPU that a subscriber would need to pay for the business to be feasible. The combined cost C^a_{sp} and revenue R^a_{sp} for all service providers together, considering the depreciation of CAPEX r_{dc} and the appreciation of OPEX r_{do}, the provisioning cost of service and a subscriber growth rate of r_g is given:

$$\begin{aligned} C^a_{sp} &= \textstyle\sum_{j=1}^{T}(C^j_{spc}(1+r_{dc})^j + C^j_{spo}(1+r_{do})^j \\ &\quad +C_{inc}) \\ R^a_{sp} &= \textstyle\sum_{j=1}^{T} 12S(1+r_g)^j ZT, \end{aligned} \tag{5.23}$$

where C^j_{spc} and C^j_{spo} is the overall combined CAPEX and OPEX cost for service providers in the j^{th} year, i.e., paid as rent to the InP.

The cash flow for the j^{th} year in InP-MNO business is calculated by $F_j = R^a_{sp,j} - C^a_{sp,j}$, i.e., revenue minus the cost for that year, and the overall cash flow, F, for the business is given by,

$$F = \sum_{j=1}^{T} F_j. \tag{5.24}$$

The net present value (NPV) (ζ) is used to estimate whether the business is lucrative ($\zeta > 0$) or not ($\zeta < 0$) by calculating the discounted present value at the targeted rate of returns r of future cash flows (5.24) during the duration of investment T. NPV takes into account the time value of money and can be used to compare similar investment options. The NPV is given as follows.

$$\zeta = \sum_{j=1}^{T} \frac{F_j}{(1+r)^j}. \tag{5.25}$$

Financial break-even occurs when the cash flows equal to the initial investments; this is only possible when the NPV is zero at the end of the study period [78, 86, 211, 218]. Hence, a firm attempts to determine the level of sales at which the NPVs are zero to achieve a break-even situation. Calculating the minimum investment cost per user (Z_{min}) (also known as minimal viable ARPU) such that the network is sustainable for a varying number of subscribers in the village is estimated using (5.26). This value would let the stakeholders decide whether the network would earn any profit at a price that people would be willing to pay. In this particular study, the analysis is for a 10 year investment period. The following optimisation equation with the constraints is solved to calculate the minimum viable ARPU per month using (5.23), (5.24) and (5.25).

$$\begin{aligned} \min_{S, r_g, C^a_{sp}, r} \quad & Z = \frac{C^a_{sp}}{\sum_{i=1}^{T} 12S(1+r_g)^i T} \\ \text{s.t.} \quad & \zeta = 0 \\ & Z > 0 \end{aligned} \tag{5.26}$$

- *Sensitivity Analysis* helps investigate the impact of dependent variables by changing the independent variables under the given set of assumptions. The study uses ‘Visyond’ as well as Python software for the estimations of factors impacting the NPV by varying each parameter at a time by ±10% variations from the base case, in which the input parameters result in NPV = 0 scenario and requires only wireless backhaul as discussed in Sections 5.2.2 and 5.3.2.

5.1.4 Key Parameter indicators (KPI) for rural scenario

Historically, network performance is determined by the equipment used by the network. Alternatively, KPIs define which characteristics of 5G networks are prioritised for the application of interest and what functionality of 5G networks is available. Depending on the application, load, demand, user density, virtualisation type, and other considerations, the KPIs can be changed [11, 28, 71].

Table 5.3 lists KPIs for 5G rural networks, with values 1, 2, and 3 representing high, medium, and low priority levels of KPI for every rural scenario deployment. KPIs aid the InP in determining the type of infrastructure required to satisfy the objectives of our proposed solution. For deployment in generic rural areas, the following issues should be considered:

Table 5.3: KPIs for 5G networks in a rural setting

5G KPI	**Category**	**Priority**
Peak data rates	eMBB	1
Peak spectral efficiency	eMBB	2
Data rate experienced by the user	eMBB	2
Area traffic capacity	eMBB	3
Latency (user plane)	eMBB, uRLLC	1
Latency (control plane)	eMBB, uRLLC	1
Connection density	mMTC	3
Energy efficiency	eMBB	1
Reliability	uRLLC	1
Mobility	eMBB	3
Mobility interruption Time	eMBB, uRLLC	3
Bandwidth (Max. aggregated bandwidth)	IMT-2020	$\geq$ 20 MHz

- *Peak data rates*: The network should have downlink data rates of approximately 50 Mbps and uplink data rates of approximately 25 Mbps [28, 71] for applications such as video calling, video streaming, surveillance, mobile health, online education, online consultation for farming-related queries and industrial automation. Applications such as IT education and services in rural areas help to improve rural area conditions [124, 285].

- *Peak spectral efficiency*: This parameter could be a moderate priority to accommodate a maximum number of users in limited spectrum bands. Generally, the number of devices on the network is low in rural areas [71].

- *Data rate experienced by the user*: Data rate experienced by the user should be moderate and satisfy the minimum 5G requirements. However, coverage should be high to focus more on providing connectivity to a larger area [71].

- *Area traffic capacity*: Data capacity per user in rural areas will increase by at least 10 - 20 Mbps compared to data capacity per urban user, due to reduced network congestion [46, 86].

- *Latency*: Typical delay is around 0.5 ms and 10 ms for the user and control plane, respectively, for 5G networks. The user plane allows commonly used user data to be cached at the edge to reduce delay for applications such as online education, virtual soil assessment, industrial automation, cattle health monitoring, and e-governance. The control plane helps to control the connection between the network and the user equipment [28, 91].

- *Connection density*: Usually, the network can support up to a million devices per km^2. The number of devices in rural areas is relatively low. Therefore, this factor has a lower priority during initial deployments [71].
- *Energy efficiency*: Rural areas have energy issues and frequently interrupted power supply. Hence, the network needs to consume less energy compared to a traditional telecommunication network. The network should be highly energy efficient [2, 126].
- *Reliability*: The network should be highly reliable to support network slicing and predict outages to avoid network breakdown [28, 91].
- *Mobility*: In general, roads in rural areas have lower speed limits. The number of vehicles that move at high speeds in rural areas is minimal.
- *Mobility interruption time*: This parameter can be of low priority for rural applications.
- *Bandwidth*: To support 5G performance criteria for applications such as retail, small business, and industry, a minimum bandwidth of 100 MHz. For retail subscribers, a 20 MHz bandwidth should be sufficient when network usage is low [71].

This definition of KPIs guides the adaptation of the network to the needs of rural regions. KPIs help estimate the cost of establishing a 5G network in rural areas. Compared to the needs of the system in urban areas, the requirements in rural areas are lower.

5.1.5 Simulation parameters and stochastic modelling

Table 5.4 summarises the non-cost-related parameter inputs used in this study. The stochastic modelling results at the cell edge with 95% confidence intervals are presented in Figure 5.4. Furthermore, based on discussions with the MNO, simulation of Python, and verification using cloudRF and MATLAB software, a single-site deployment at 700 MHz would be sufficient to meet all the capacity requirements of the applications in a representative village with coverage of up to 8 km and up to 3 km radius in an unobstructed environment and an environment with obstructions, respectively. Similarly, at 3800 MHz the coverage area is around 4 km and 1.5 km in an unobstructed environment and an environment with obstructions, respectively. In fact, there is a direct correlation between the UE's distance from the cell site and the declining SINR, which causes a decrease in spectral efficiency and, consequently, a reduction in channel capacity. Both small-cell and macro-cell techniques are taken into consideration for the 5G network upgrade. We consider:

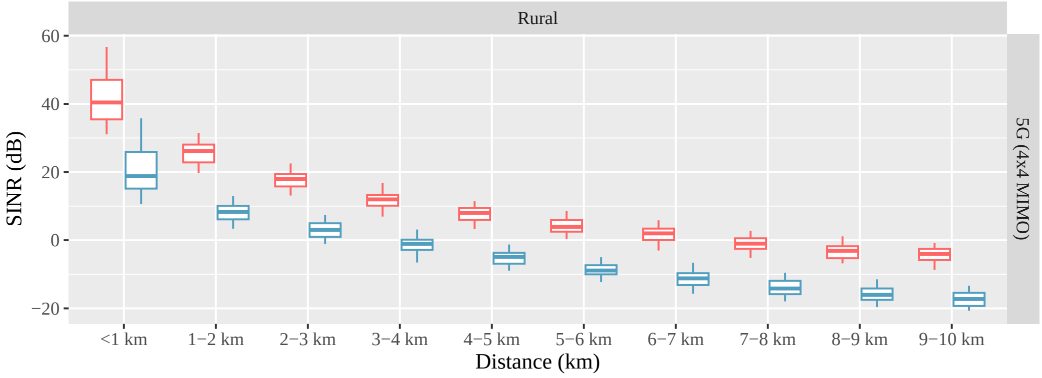
Table 5.4: Rural 5G RMa simulation parameters

Parameter	**Value**
Subscriber growth	4% per year
Number of MNOs	4
Busy hour factor	0.15
Expected average user traffic	50 GB/user/month
Minimum user rate	10 Mbps
Transmission methods	5G MU-MIMO
Propagation model	3GPP 5G NR RMa
Scaling factor	1
Sectors	3
Backhaul capacity	10 Gbps
Transmit power	40 dBm
Transmitter height (macro, small)	30m, 10m
Transmitter antenna gain	16 dBi
UE antenna gain	0 dBi
Modulation	TDD/ FDD
Number of aggregated component carriers	1
MIMO layers	4
MU-MIMO beamforming	8
Part of the slots allocated for DL in TDD mode	77%
Sub-carrier spacing	15 KHz, 30 KHz
Noise figure	5 dB
Target SINR	-6 dB
Cable loss	2 dB
Body loss (3.5 GHz)	3-5 dB
Slow fading margin	6 dB
Foliage loss	8 dB
Interference margin (3.5 GHz)	2 dB
Type of coverage	outdoor
Confidence interval	95%

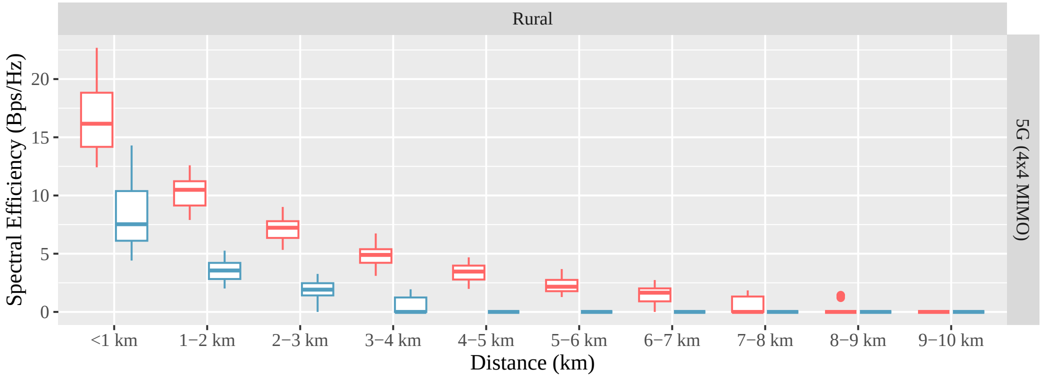
- large cells to have coverage up to 8 km,
- small cells to have coverage at a mid-band frequency of up to 4 km,
- and small cells to have coverage at a high mmwave frequency of up to 100 m.

Stochastic modelling of 5G networks helps in the estimation of the link budget along with the number of cells required at different frequencies to handle the network traffic. The results are obtained using the LOS models of 5G designed especially for rural macro-cell (RMa) type of deployments.

(a) SINR vs User Distance From the Cell Site



(b) Spectral Efficiency vs User Distance From the Cell Site



(c) Capacity (Mbps) vs User Distance From the Cell Site

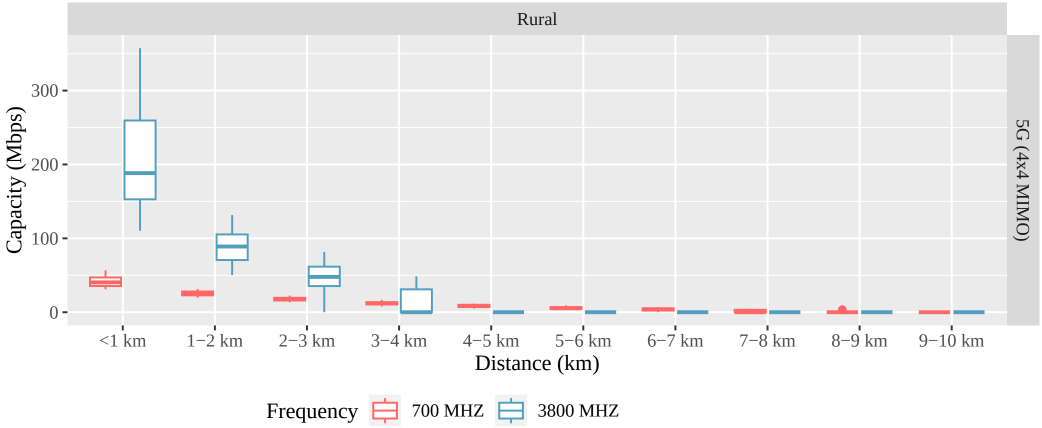


Figure 5.4: Stochastic modelling of users using LOS 5G RMa model at 700 MHz and 3800 MHz spectrum bands

5.2 Techno-Economic Modelling of Rural 5G NHN in the UK

This section presents the numerical results for the techno-economic model developed for 5G NHN by applying the concept in a UK scenario.

5.2.1 Existing infrastructure in the United Kingdom

Rural regions are home to around 17% (10,992,128) of the UK's population. Table 5.5 summarises the population distribution in villages across the United Kingdom. In rural parts of the United Kingdom, the average population growth rate is roughly 0.6% [286]. Some of these locations have limited or no internet connectivity.

Table 5.5: Population distribution in the United Kingdom - 2011 census

Population range	Number of towns
Less than 100	76
100 - 199	158
200 - 499	1,619
500 - 1,999	3,353
2,000 - 4,999	1,098
5,000 - 9,999	516

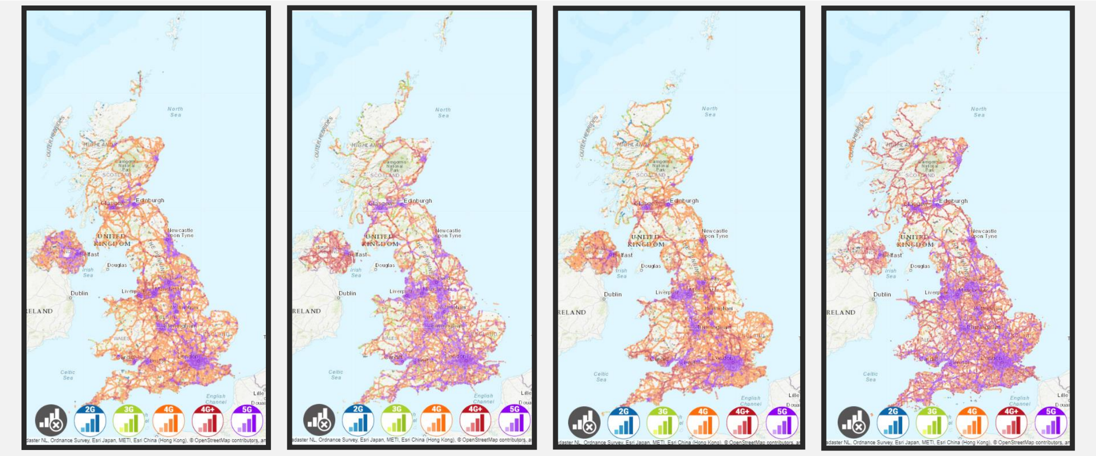


Figure 5.5: UK coverage maps of MNOs - (a) EE (b) O2 (c) Three (d) Vodafone

According to recent research, roughly 22% of the UK's population was without basic digital services during the COVID-19 epidemic [52]. Fig. 5.5 shows the UK mobile coverage of different operators. Table 5.5 summarises the population distribution in town/rural regions in the United Kingdom based on the 2011 census. Typically, localities with a population greater than 250 persons and strong population density have at least one MNO that provides 4G service. Studies have shown that rural locations with populations of less than 250 people and low population density, on the other hand, have low or no coverage. The Scotland government is actively working to provide 100% broadband connectivity to all as part of their R100 project [57].

According to [286] released in the year 2019, the ARPU per month for telecommunication services in urban and rural parts of the UK are £113 and £68 per month per household, respectively. In the United Kingdom, the ARPU per month for mobile and broadband services is £15 and £35 respectively [286–289]. Providing communications services in remote and rural locations is expensive. The number of subscribers in rural areas of the UK is low, so the potential ROI is modest because the ARPU per month for a bundle is high. In the UK, there is good competition among MNOs. However, the sector is significantly in debt, as every network improvement is exorbitant, and not every investment yields a return. Each telecommunications service provider in the UK has a spectrum licence that allows them to operate over the whole country. Ofcom has a strict policy to avoid a monopoly of service supply to manage the telecommunications industry and maintain fair competition. In the United Kingdom, the notion of a neutral host is being explored and studied to determine its influence on the existing spectrum market and market competitiveness.

According to numerous studies, rural locations in the UK are often hard to reach, necessitating a mix of backhaul options, including subsea cables, fibre, mmWave lines, and long-range Wi-Fi, to the nearest PoP. Connection to the PoP is one of the most expensive aspects of establishing a rural telecommunications network. Generally, rural areas do not upgrade their infrastructure for very long periods. The UK government is attempting to bridge the digital divide through several programmes and projects such as 5G RuralFirst, 5G New Thinking, Shared Rural Networks for 4G towers, and R100 [52, 91, 153]. In this analysis, the network take-up is around 40% for mobile services [124, 290]. For this study, the TCO and various costs required for 5G services for either brownfield or greenfield deployment, are from [12, 46, 91, 217], white papers and the annual report of different telecommunication companies. The statistics are from the UK census, Google Maps, research papers, case studies, discussions with the UK operators, and a few universities.

5.2.2 Cost estimations of the network - UK

Table 5.6, published in [46], shows the cost calculated using references from various journals, research data, and industry reports and when the network is deployed on a 2X2 MNO sharing basis and used in this analysis. As seen in Table 5.6, building a new greenfield 5G network will be more expensive than updating an existing LTE network to enable 5G networks. The cost of the core upgrade for any strategy is 10% of the cost of RAN implementation. Table 5.7 shows the system parameters used for the analysis: for a maximum of 400 subscribers and with a maximum ARPU per month of £80. In reality, an ARPU of £80 is very high for the UK scenario unless it is a bundle package. Practically, subscribers would be willing to pay around £30 to £40 per month towards wireless broadband and its bundles. However, the £80 ARPU analysis helps in understanding the feasibility of the network, if users are willing to pay higher for rural connectivity.

Table 5.6: Cost parameters for different 5G network requirements

Strategy	**LTE availability**	**Cost type**	**CAPEX**	**OPEX**
Integrating Spectrum into the macro-cellular network	Site with LTE	Additional carrier on current BS	£15,000	£1,800
	Greenfield site	Deploying a multicarrier BS	£40,900	£3,898
		Site lease		£5,000
		Civil works	£18,000	
		Fibre backhaul (per km)	£20,000	
Network densification through small cells		Small cell equipment	£2,500	£350
		Small cell civil works	£13,300	
		Small cell site rental		£5,000
		small cell backhaul		£1,000
Core upgrade cost on all strategies		10% markup on RAN deployment		

Table 5.7: Simulation parameters for the techno-economic analysis for the UK study

Parameter	**Value**
N	4
T	max 20
r_{dc}	-2%
r_{do}	2%
r_g	2%
S	max 400
Z	£10 - £80
r	5%
take-up	40%
Spectrum ($\leq$ than 1 GHz)	£0.5/Hz/person
Spectrum ($\geq$ 1 GHz)	£0.25/Hz/person
Transmission method	5G 4x4 MIMO

Depending on the period of spectrum and network operations licences, investment in 5G services in rural areas could last 3, 5, 10, or 20 years. The cost of a shared spectrum licence in the UK costs up to £900 per year, depending on the bandwidth required, when employing spectrum sharing. Assume that the deployment will continue for 10 years and that the nearest PoP will need an average of 10 km of fibre backhaul. In hard-to-reach places, the additional cost involved in the provisioning of wireless backhaul is part of $C_{backhaul}$. Therefore, estimating an accurate TCO for the deployment and operation of 5G networks with network slicing that enables multi-tenancy is essential to gauge the feasibility of the network. The following are the four situations that are explored for studying the application in a rural setting in the United Kingdom:

(a) Brownfield 5G MC - 5G macro cell (MC) deployment in existing 4G sites.
(b) Brownfield 5G MC and SC - 5G macro cell and small cell (SC) deployment in existing 4G sites.
(c) Greenfield 5G MC - 5G macro cell deployment.
(d) Greenfield 5G MC and SC - 5G macro cell and small cell deployment.

This study presents an analysis of these scenarios and compares the results of different situations.

Estimation of TCO for different 5G rural NHN scenarios

Fig. 5.6 shows the average TCO for rural 5G NHN for various strategies and the duration of the investment. Fig. 5.6 shows the benefits of using 5G NHN in rural areas with different deployment scenarios. The observation from the results is that the NHN reduces the cost by at least 60%. The spectrum of operations could be shared spectrum bands, LSA, MNO licenced bands, or other locally licenced bands, as discussed in Section 2.4. The TCO of the greenfield deployment of rural 5G NHN (Fig. 5.6c) is significantly higher than the TCO of the rural 5G deployment with existing LTE networks (Fig. 5.6a). Similarly, it can be observed in Fig. 5.6b and Fig. 5.6d that network expansion using small cells involves an additional cost but is not as high as the addition of macro cells.

When using 5G NHN in rural areas, the TCO for the entire network is lower than that of MNOs that deploy the 5G network in a 2X2 manner for any investment time. The results show that the advantage of delivering services in rural regions through slices outweighs the disadvantages of an MNO that does not own rural infrastructure. For each MNO, the risk involved in offering internet services in rural areas has decreased compared to any other form of infrastructure sharing [149]. In the rural area, end-users would not be aware of the various network designs.

It is worth noting that the cost per site for the InP network is estimated in this study using data from Table 5.6. In 5G NHN with four MNOs, each one will invest around £150,000 while a 2X2 sharing basis 5G network would require an expenditure of almost £375,000 per MNO (assuming all operators have similar network requirements). Unless the network's capacity reached its maximum level, expansion is not necessary.

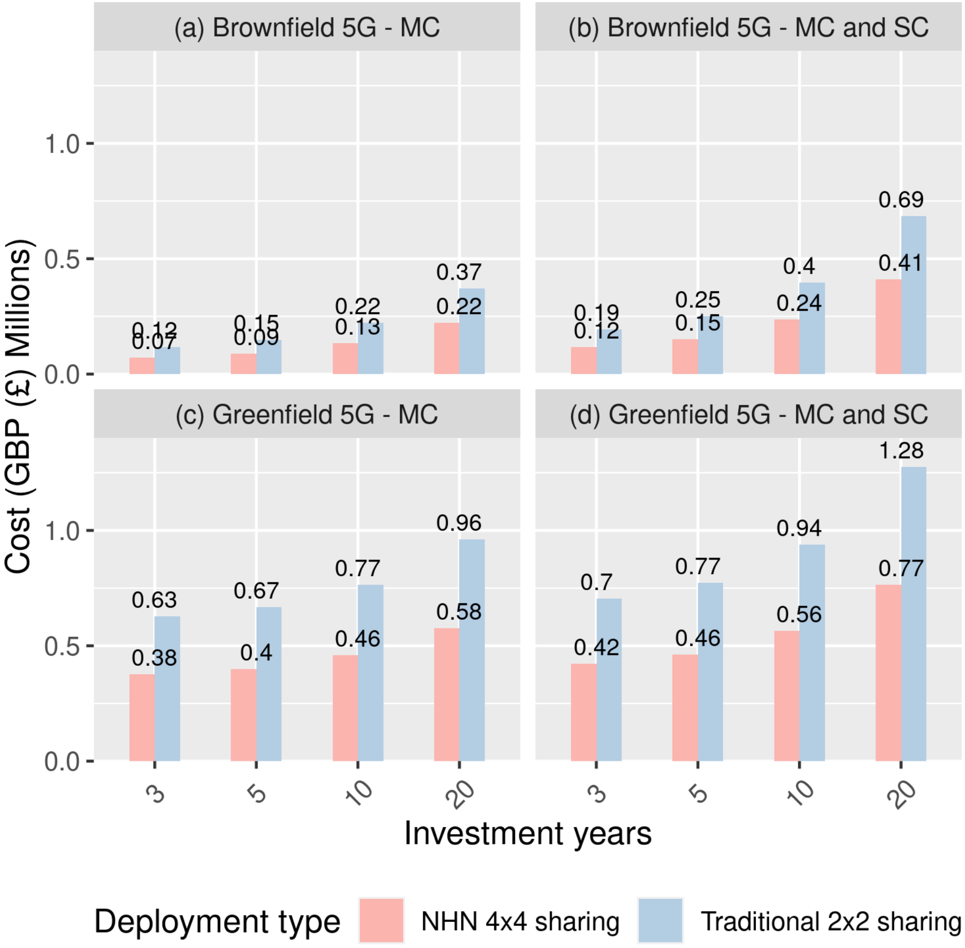


Figure 5.6: TCO of different deployment strategies

In the deployment scenarios presented in Fig. 5.6b and Fig. 5.6d, the cost varies due to the duration of the investment and the requirements of the small cell. On the other hand, the cost of the deployment scenarios depicted in Figs. 5.6a and Fig. 5.6c, on the other hand, vary depending on several factors, including distance from the nearest PoP, investment duration, backhaul capacity requirement charges, network expansion, legal and civil works, and site leases. The expenditure of an experienced telecommunication engineer to work in remote/rural places in the UK is prohibitively expensive. Strategies must be developed to address these issues. The above discussions present a snapshot of InP expenses and determine the slice of rent paid per MNO.

Minimum subscriber analysis for different 5G rural NHN scenarios

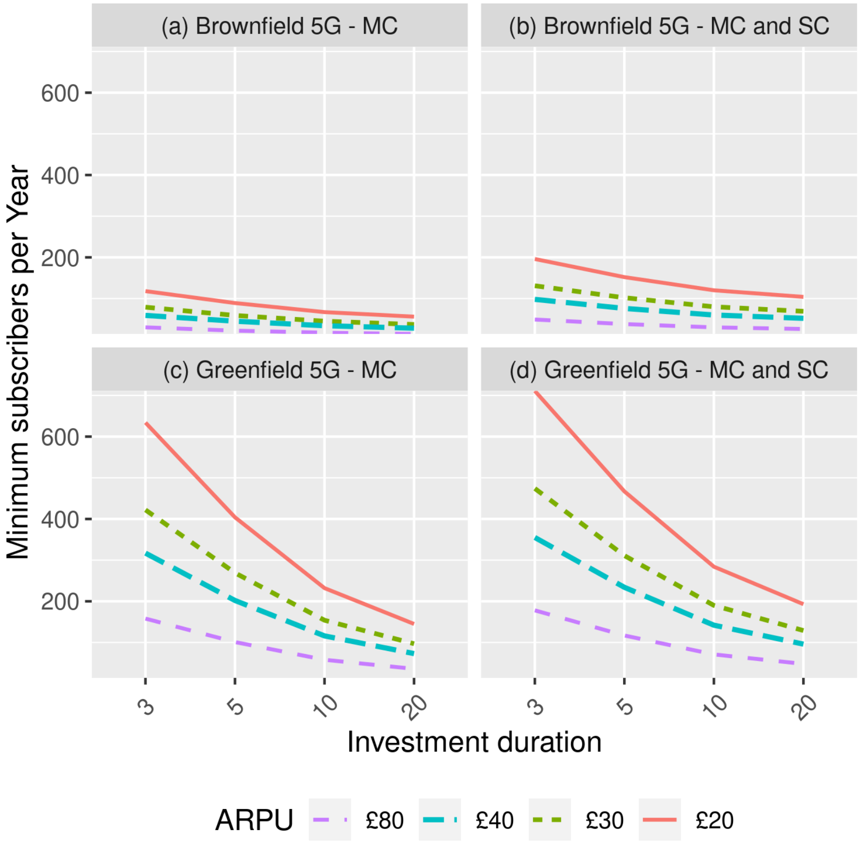


Figure 5.7: Minimum subscribers required in different deployment strategies

Fig. 5.7 shows the minimum number of subscribers required in a different deployment scenario. In Fig. 5.7a and Fig. 5.7b, the additional subscribers required in the brownfield deployments are less due to the lower TCO, as shown in Fig. 5.6a and Fig. 5.6b. Assume that the subscriber growth rate is zero at this point to simplify the calculation and minimal subscribers upgrade to the newer services. Consider multiple scenarios such that ARPU per month of £20, £30, £40, or £80; and the study period under consideration are over 3, 5, 10, and 20 years of investment duration to examine patterns. Fig. 5.7c and Fig. 5.7d shows that a greenfield rollout requires a higher number of new subscribers than a scenario for the 4G network that upgrades to 5G. The cost of backhaul and site leases is the most expensive investment. For a 3-year investment, all deployment scenarios need a larger number of subscribers, as shown in

Fig. 5.7. However, in a scenario with a deployment time of more than 10 years, the network becomes viable even with fewer than 350 and 100 users, for greenfield and 4G LTE to 5G network scenarios, respectively. As a result, it can be deduced that the rural network will be profitable if the investment period is longer.

The rural 5G network will be viable for a rural area with additional or new subscribers of 70, 150, 200, and 350 for deployment scenarios (a), (b), (c), and (d), respectively, with a 10 year investment and ARPU of £30. This is based on a 40% network take-up for greenfield deployment and the addition of 40% new subscribers compared to the existing subscribers in the brownfield deployment. Meanwhile, for deployment scenarios (a), (b), (c), and (d), the network is viable even with 30, 50, 90, and 160 new subscribers, respectively, assuming the ARPU per month is £80 for 10 years. In practice, subscribers join and leave the subscriber base; however, the general trend for the subscribers' growth rate is increasing [2]. In addition to retail consumers, the network would have other subscribers such as industry verticals, who would drive the network's feasibility.

Break-even time analysis for different 5G rural NHN scenarios

Fig. 5.8 shows the break-even time for various deployment scenarios to analyse trends using a varying number of subscribers and a 10 km average fibre backhaul. Due to a lower TCO, as demonstrated in Fig. 5.6a, the time to recover the investment in Fig. 5.8a is the shortest compared to any other instance for any ARPU per month value. The break-even time for a greenfield deployment is much longer than the break-even time for a 4G network upgraded to a 5G deployment, as seen in Fig. 5.8c and Fig. 5.8d. As shown in Fig. 5.8, when the ARPU per month reaches £80, all deployment scenarios result in a shorter break-even time. Additionally, with an ARPU per month of £80, the network becomes profitable even with 65 subscribers in a greenfield deployment without small cells while with 30 subscribers in a brownfield deployment without small cells. As a result, the rural network will be profitable when either ARPU per month, the volume of subscribers increases or both.

With 100 5G subscribers at a £40 ARPU per month, the rural network investment would be recovered in a minimum of 3, 6, 12, and 15 years for deployment scenarios (a), (b), (c), and (d), respectively. On the other hand, for a similar scenario but at an ARPU of £80 per month for deployment scenarios (a), (b), (c), and (d), the minimum time to recover the investment is 1, 3, 6, and 7 years. One noteworthy point to note from Fig. 5.8 is that £20 ARPU per month is only feasible for very low subscribers (≤ 100) when brownfield LTE networks are upgraded

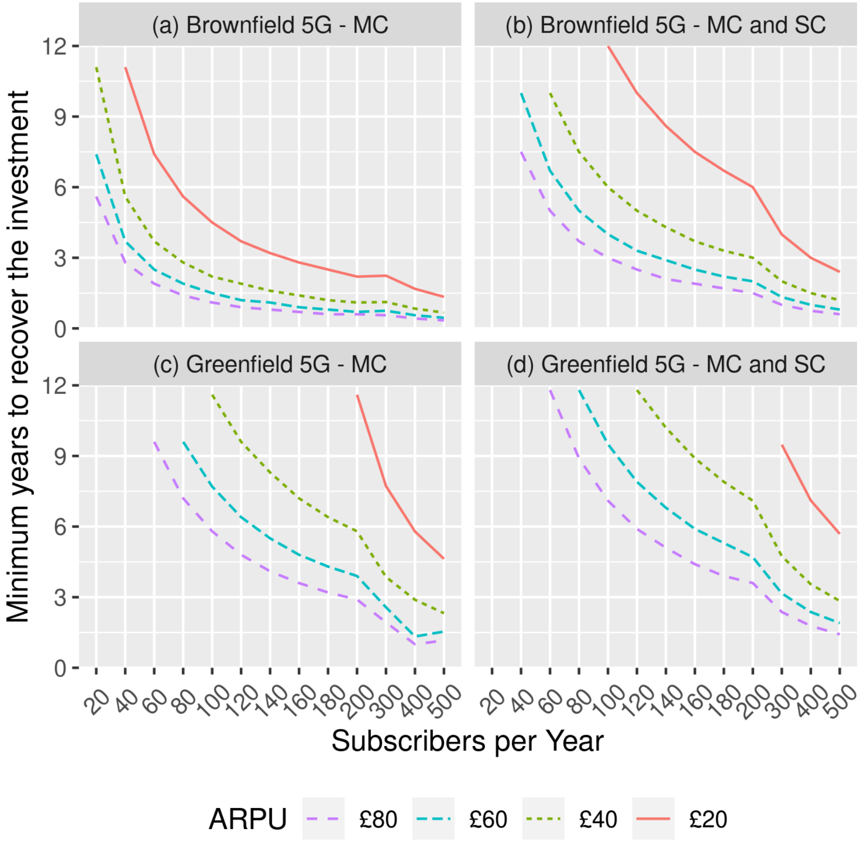


Figure 5.8: Break-even time in different deployment strategies

to 5G networks, but not in greenfield installations.

Investment per user analysis for different 5G rural NHN scenarios

Fig. 5.9 depicts the subscriber growth rate for this research, which is set at 2% each year, and the subscriber growth chart for an initial subscriber base of 100. The trend helps to understand the advantages of compounding.

The NPV is used to calculate the investment per user to achieve a no-profit, no-loss situation. Assuming that each subscriber must be active and have an ARPU per month of £20, £30, £40, or £80; The NPV analysis is carried out by altering the number of subscribers and assuming a growth rate (internal rate of return (IRR)) of 3% from the business to analyse trends over an investment duration of 10 years.

Fig. 5.10 shows the minimum necessary investment per user, or ARPU, for various deployment scenarios. In Figs. 5.10a and Fig. 5.10b, it can be observed that ARPU per month is the lowest compared to any other case for any number of subscribers and varying fibre backhaul

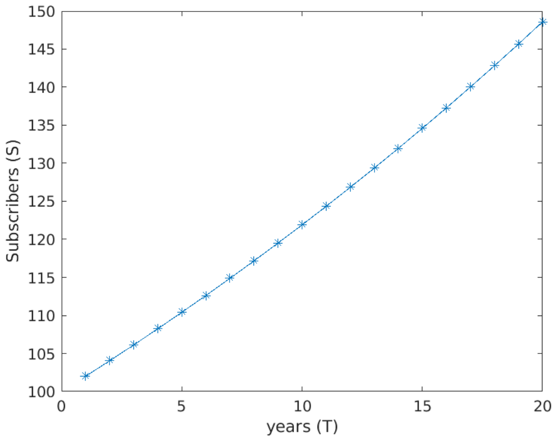


Figure 5.9: subscriber growth rate chart

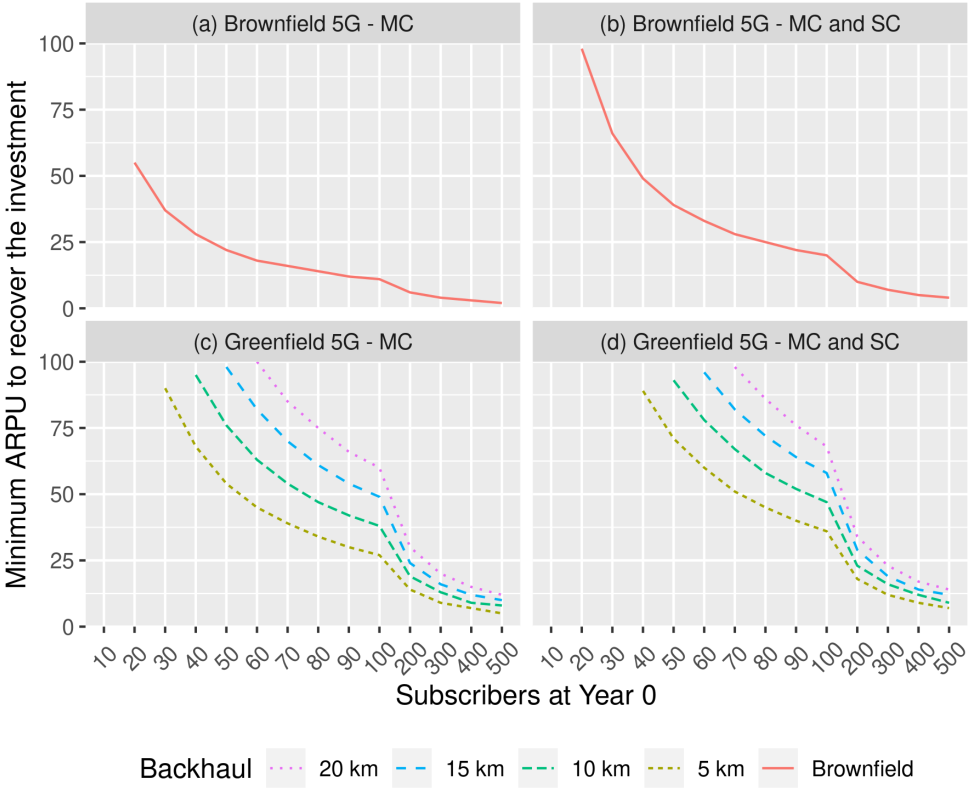


Figure 5.10: Investment per user in different deployment strategies

distances (5 km, 10 km, 15 km, and 20 km). The network is feasible for less than £10 when the number of subscribers is greater than 100 and 200 for scenarios (a) and (b), respectively. The ARPU per month needed for a greenfield deployment to be sustainable is much greater than the ARPU per month requirement for a 4G network upgraded to 5G, as shown in Fig. 5.10c and Fig. 5.10d. When the fibre backhaul is 5 km or fewer, all deployment scenarios become feasible for a smaller number of subscribers and a 10 year investment, as illustrated in Fig.

5.10. However, in a greenfield with macro and/or small cells and a 10 year investment and a 10 km fibre backhaul, the network becomes viable even when subscribers are more than 55 and 65 in greenfield and LTE to 5G network scenarios without small cells, respectively. The rural network will be profitable when the fibre backhaul distance is minimised and the number of users increases.

With a 40% network take-up, the rural network will be feasible for a village with a minimum new subscriber base of 30, 32, 63, and 84 for the deployment scenarios (a), (b), (c), and (d), respectively, with a 10 year investment and a 10 km fibre backhaul distance. On the other hand, with a fibre backhaul distance of roughly 20 km and a 10 year investment, the network can support a number of new subscribers 40, 44, 100, and 130, respectively, for deployment scenarios (a), (b), (c), and (d). One notable finding from Fig. 5.10, i.e., at £30 ARPU per month with a subscriber base ranging from 30 to 60, is profitable only in brownfield deployments, that is when the LTE network is upgraded to 5G networks (with and without small cells), but not in greenfield deployments.

5.2.3 Sensitivity analysis - UK

Table 5.14 shows the sensitivity analysis for rural 5G NHN in the UK scenario. Note that all data have been normalised to a total of 100%.

Table 5.8: Sensitivity analysis for rural 5G NHN

Input	**Input type**	**Influence on NPV variance**
Take-up	Demand	23.09%
ARPU per month	Demand	23.09%
Population	Demand	23.09%
Operations	Economic	12.71%
RANs, Tower and more	Economic	5.51%
Subscriber growth	Demand	3.97%
Backhaul	Economic	3.94%
Incremental cost (C_{inc})	Demand	3.82%
Spectrum	Economic	0.55%
Core	Economic	0.22%
Investment duration	Economic	0.11%

Demand parameters like ARPU, take-up percentage and population have each a 23.03% impact on the network sensitivity. Meanwhile, operations (including maintenance and failure) have a 12.71% influence on overall NPV. CAPEX, such as RANs, masts and towers, influence the overall sensitivity by 5.51%, whilst backhaul and subscriber growth affect the overall sensitivity on the feasibility by 3.94% and 3.97%, respectively. Other characteristics, such as incremental slice cost (C_{inc}) and spectrum, have a 3.82% and 0.55% influence on sensitivity, respectively, although the spectrum licence and core do not have a significant effect.

5.2.4 Case study UK

Table 3.1 shows the technical network parameters used for performing coverage analysis. The placement of a BS should ensure maximum coverage for all target use cases at frequencies less than 1 GHz. One of the main reasons for higher coverage areas in rural regions is the lack of tall barriers in the signal's path. The Okumura-Hata radio propagation model was used to explain signal to interference and noise ratio (SINR) values in the study area.

The data for Table 5.9 is obtained from different rural 5G projects in the UK and journals. Table 5.9 shows the case study on the suitability of network slicing for different villages, as described below:

- In **Westray**, the initial number of expected subscribers is around 140. If InP deploys a rural 5G NHN with a macro-cell, then coverage is uniformly present up to a radius of 6 km (254 km^2) at 700 MHz and 3 km (153 km^2) at 3800 MHz, from the tower location; and covers a few nearby islands as well. The terrain is almost plain, which leads to the coverage being present uniformly over the area. Woo is a tourist spot in Westray. The main potential end-users of the network are fisherman, local businesses, the council and their families. The location is also a tourist spot, generating additional revenue for the InP by serving roaming subscribers. In this scenario, with a subscriber growth rate of 4%, the network is feasible for any ARPU per month above £17.33. Network expansion depends on the demand for the services. The use cases would determine the operational frequency.

- In **Papa Westray**, the initial number of expected subscribers is 28. Unlike the previous case, it requires a higher ARPU per month or subscriber growth rate for the network to be feasible. One advantage for Papa Westray is tourists roaming on the 5G NHN network. The network, however, needs to minimise the blind spots created due to the topographical challenges, i.e., being surrounded by mountains. The site approximately covers the entire island. Due to the lower number of subscribers, the ARPU per month has to be higher than £51.54 to attract investment from the InP and MNOs. Another option would be a higher number of subscribers or local businesses as slice tenants, which would improve the feasibility at a lower ARPU.

- **Golan**, located in Wales, is expected to have 52 subscribers. It has mountains on one side and plain lands on the other three sides. The network is viable with a minimum ARPU per month of £45 and a 4% subscriber growth rate. The network can earn revenue by supporting agricultural and tourist applications as well. The village is close to a motorway, which attracts roaming subscribers, hotels in-house connectivity, and vehicles to everything (V2X) related use cases in the future.
- In **Colva and Drums**, the initial number of expected subscribers is around 400 in a stretch of 6 km of roadways. These locations around surrounded by mountain ranges and are popular tourist spots all around the year. Due to terrain challenges, it has poor connectivity. In this scenario, the network is viable for both InP and MNOs, as the minimum ARPU per month required for a feasible network is around £45. For more than 400 active subscribers, 5G NHN offers a viable option for rural connectivity.
- In **North Ronaldsay**, the initial number of expected subscribers is around 15 at a network take-up of 50%. The estimated cost for rural 5G NHN is £345,192, which requires a minimum ARPU per month of £161.77 or higher for the network to be feasible. The main issue is the relatively small subscriber base. It will not be feasible unless an industry paying high ARPU actively participates as a tenant on the sliced network. Currently, the assumed take-up rate and subscriber growth of 4% network are not viable because individual subscribers are typically unwilling to pay such high subscription fees.

Table 5.9: Case studies - UK

Location	**Westray, Woo**	**Papa Westray**	**Golan**	**Clova, Drums**	**North Ronald-say**
Population	400	80	150	400	30
Cost	£345,192	£205,314	£335,768	£450,968	£345,192
Subscribers	140	28	52	140	15
Minimum ARPU	£17.33	£51.54	£45.00	£17.00	£161.77

5.3 Techno-Economic Modelling of Rural 5G NHN in India

In this section, the techno-economic feasibility of 5G NHN in rural areas is presented, with application in the Indian scenario.

5.3.1 Existing infrastructure in the Indian scenario

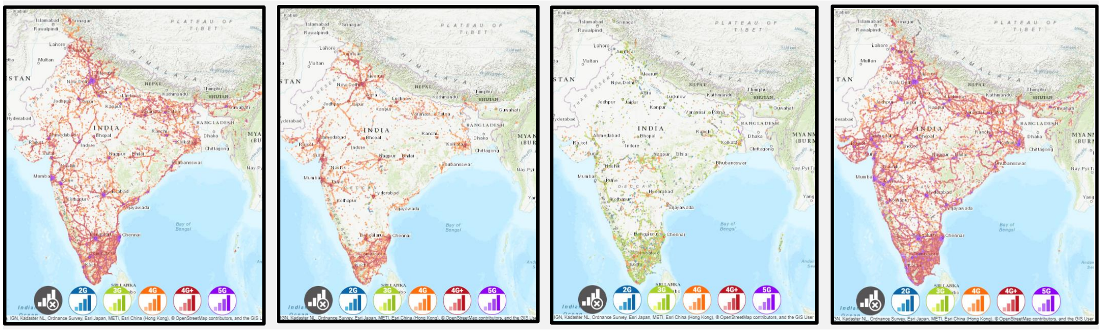


Figure 5.11: India coverage maps of 4 national level MNOs - (a) Airtel (b) VI (c) BSNL (d) Jio

Around 70% (898,024,053) of the Indian population live in rural areas. Most of these locations have little or no Internet access. Table 5.10 [291] shows the number of villages in India and their range of population distribution. In the Indian rural context, the 5G NHN has a variety of use cases, as shown in Fig. 2.6. People opted to live and work in isolated places during the COVID-19 pandemic. A reliable internet connection in rural regions will also aid the country's economic development [18]. Fig. 5.11 shows the coverage and services offered by the major MNOs in the country.

Table 5.10: Rural population distribution in India

Population range	Number of villages
Less than 100	45,276
100 - 199	46,276
200 - 499	127,511
500 - 1,999	129,977
2,000 - 4,999	80,413
5,000 - 9,999	14,799
10,000 +	3,961

Due to the high cost of building networks in rural areas of India, the competition among MNOs is minimal. In India, there are more than four national-level MNOs, but the telecommunication industry has a high level of debt [292]. As a result, MNOs are hesitant to offer telecommunications services in rural regions. In general, not all MNOs can obtain spectrum licences and authorisation to deliver services across the country utilising their infrastructure. As a result, MNOs have a roaming agreement and share infrastructure to provide service to each other's subscribers in different regions of the nation [271] and differs from NHN's using 5G network slicing, which minimises MNOs' dependency on one another and enables easier service expansion utilising the slices outlined in Table 2.4. To boost competition, attract new entrants, and improve network performance, MNOs in India should reduce the cost of telecommunications service provisioning, especially in rural areas [7]. Cost savings might come in the form of reduced costs incurred for spectrum, equipment, site lease, electricity, and licensing approvals.

In [4, 271], the current survey on rural connectivity in India is provided, with an analysis of emerging use cases, government initiatives, and rural connectivity projects, challenges, and prospective rural solutions to narrow the digital divide. Research reflects the need for a novel solution for last-mile connectivity that uses many technologies. According to research carried out by multiple survey companies based on information from the Telecom Regulatory Authority of India (TRAI), urban India has 93% broadband penetration, while rural India has just 29.3% [70, 293]. According to [294], the BharatNet plan would deliver 100 Mbps backhaul services to India's gram panchayats (GPs). According to [295], there are 165,082 GPs with optical fibre cable and other relevant equipment as of today. According to BharatNet case studies, communities are typically 2 to 10 km apart from GPs [4, 295]. In rural areas, a wireless backhaul link, either point-to-point (PTP), point-to-multipoint (PTMP), or relay networks to (PoP) located at the GP office, is preferable to minimise TCO per site.

Following a discussion with Indian MNOs, a commercial-grade BS can support just over 2000 and 20,000 active users simultaneously, at any one time, on LTE and 5G spectrum bands, respectively. The take-up of network services in India is approximately 43% in the year 2020 [41, 44, 296]. The average ARPU per month in India for mobile connectivity is INR 200, and the bundle that includes mobile, broadband, and TV services is INR 1,300 in urban areas [54–56, 293]. However, in rural parts of India, the ARPU per month for mobile connectivity is INR 68, and for the bundle inclusive of mobile, broadband, and TV services is INR 240 [70, 293]. MNOs offering a package are the latest trend.

5.3.2 Cost estimations of the network - India

Table 5.11 illustrates the varied prices of the components of the LTE/5G non-stand alone (NSA) network according to a study conducted by Oughton and Jha in [7, 47]. In general, telecommunication circles employ a cell threshold of 500 people per km^2 [7]. In this study, \$ 1 (USD) equals 75 rupees (INR).

There are four major national MNOs in India. All four operators want to be able to operate throughout the country. The number of prospective subscribers per village in rural India

Table 5.11: Unit cost of 5G components

Component	**Cost ($USD)**
Sector antenna	1,500
Remote radio unit	3,500
IO fronthaul	1,500
Processing	1,500
IO S1-X2	1,500
Control unit	2,000
Cooling fans	250
Power supply	250
Battery power system	10,000
Baseband unit cabinet	200
Tower	5,000
Civil materials	5,000
Transportation	5,000
Installation	5,000
Site rental (rural)	1,000
Router	2,000
Backhaul: Wireless link (small)	20,000
Backhaul: Wireless link (medium)	30,000
Spectrum (sub 1 GHz band)	$2.18/Hz/person [7]
Spectrum (over 1 GHz band)	$0.61/Hz/person [7]

is relatively significant. The TCO for single-cell site deployment using 5G network slicing with NHN is estimated using data from the Indian census, Google Maps, journal publications, research papers, conversations with the Indian operator, and a few institutions. According to Table 5.11 in the Indian scenario with assumptions given in the preceding section, the total cost of the 5G NHN network is approximate $ 66,000 per site. The added cost of slice provisioning is not considered in this analysis. Based on discussions with an Indian operator, the TCO for the rural 5G NHN having KPIs as described in Table 5.3, is shown in Table 5.12. The average CAPEX for the InP is approximately INR 3 million with r_{dc} depreciating at 2% per year, while the OPEX for the InP is around INR 0.15 million per year with r_{do} appreciating at 3% per year.

Table 5.13 lists the parameters used in the techno-economic analysis of the Indian rural 5G NHN. It is crucial to keep in mind that although the exact cost of spectrum using localised spectrum sharing technologies is not available for the Indian context, it should be less costly than the values in Table 5.11, which are for a national spectrum licence. The main reason for lower spectrum is that in most cases, the cost of acquiring a shared spectrum licence per location is lower compared to the cost of obtaining a licence for the entire country. InP would

Table 5.12: Deployment cost estimations

Greenfield Deployment	**Cost per BS (in INR millions)**	**Changes per year**
Installation of new BS with tower and other infrastructures such as batteries and backup generator support for supply + software (C_c)	3	-2%
Day-to-day maintenance per year (C_0)	0.15	3%
Core upgrade cost (included in the CAPEX)	10% on the markup of RAN deployment	
Incremental cost in provisioning of the slices as per the demands of the MNOs (C_{inc})	20% of the overall cost	

Table 5.13: Simulation parameters for the techno-economic analysis

Parameter	**Value**
N	4
T	max 20
CAPEX r_{dc}	-2%
OPEX r_{do}	3%
r_g	7%
S	max 1500
Z	max INR 1200
r	8%
take-up	35%

ideally seek a localised shared licence to provide services to the communities of their choice.

Fig. 5.12 shows the CAPEX to OPEX ratio per site for the InP as the network lifetime duration increases. CAPEX is initially relatively high in comparison to OPEX. Due to the wear and tear of the equipment, OPEX expenses increase dramatically above CAPEX prices over time. Depending on the duration of the licence granted for spectrum and network operations, the investment in 5G services in rural regions could last 3, 5, 10, or 20 years.

Using the data from Table 5.11, Table 5.12, and Table 5.13, the cost for different investment duration is estimated using (5.13), (5.14) and (5.15), assuming the network does not require any major upgrade during the lifetime of the investment. The results of the techno-economic study discussed in the previous section are presented below.

TCO for greenfield 5G rural NHN deployment

The cumulative TCO for all MNOs employing 5G with and without NHN for 3, 5, 10, and 20 years, respectively, is shown in Fig. 5.13. The TCO for InP is approximately INR 6 million ($ 81,600) for 10 years and INR 7 million ($ 95,200) for 20 years, respectively, including the

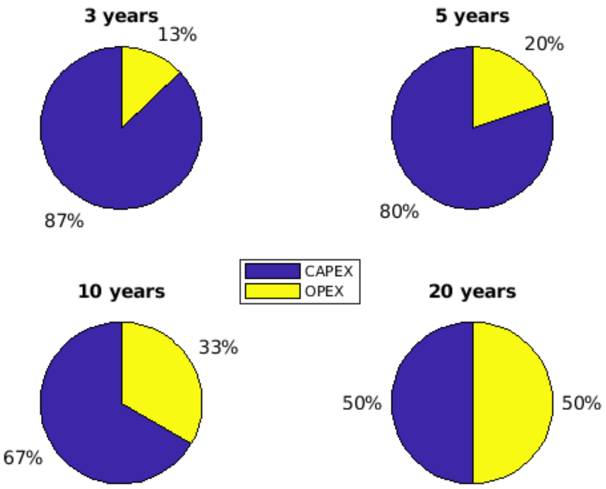


Figure 5.12: CAPEX to OPEX ratio with changing the investment years for a greenfield deployment

miscellaneous cost to support NHN.

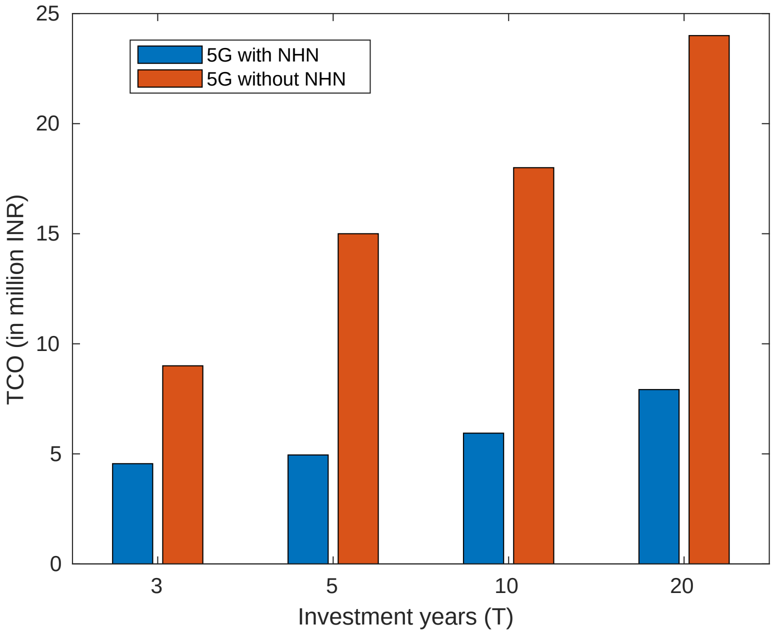


Figure 5.13: TCO for 5G networks with and without NHN

Figure 5.13 shows that the adoption of rural 5G NHN results in cost savings. Consider the following two possibilities for delivering 5G services in rural areas:

case 1: 5G NHN with spectrum sharing, and

case 2: 5G networks without NHN or any network sharing, i.e., each operator establishes their own 5G networks.

Further, consider the following scenarios with a 10 year network investment to provide services in a remote region with a single facility. The TCO per site for each MNO to deploy 5G without NHN is INR 4.75 million ($ 64,476), which adds up to INR 18.5 million ($ 254,452) for four MNOs. On the other hand, the cost of an InP that implements 5G NHN is INR 5.4 million ($ 73,960), with a TCO of INR 1.35 million ($ 18,320) per MNO, which equates to a 70% cost reduction per MNO. The 5G NHN decreases overall network costs per site by at least 65%, with much higher savings for MNOs.

Minimum subscribers for greenfield 5G rural NHN deployment

Fig. 5.14 shows the minimum number of subscribers required for the monthly ARPU ranging between INR 50 and INR 300 and an investment duration of 3 to 20 years. The cost of the provisioning service is equal to C_{sp}. When the investment period is 20 years, the network requires the lowest active subscribers compared to the other possible scenarios. Furthermore, even with a minimum of 100 subscribers and no subscriber growth rate, the network would be economically feasible with an ARPU per month of INR 300 for a 20-year investment, as illustrated in Fig. 5.14. With an ARPU per month of INR 50, INR 100, INR 150, INR 200, INR 250, and INR 300, the minimum subscribers required for a 10 year investment are about 1100, 575, 400, 300, 275, and 250.

As the ARPU per month increases, the number of subscribers necessary to achieve the break-even threshold decreases exponentially, more so when the ARPU per month exceeds INR 150. With a higher ARPU per month, the network becomes feasible for fewer than 500 subscribers for any investment duration. A three-year investment requires at least 500 subscribers with a subscription charge of INR 300 versus 2350 subscribers with a subscription price of INR 50.

Break-even time for greenfield 5G rural NHN deployment

Fig. 5.15 shows the time taken to reach the break-even point of the investment. The time to recover the investment depends on the TCO, network take-up, service demanded, ARPU, number of subscribers, and service quality.

For a rural site with a monthly ARPU of INR 50 having subscribers between 1200 and 700, the break-even time ranges from 12 to 20 years. Meanwhile, a 20-year investment becomes

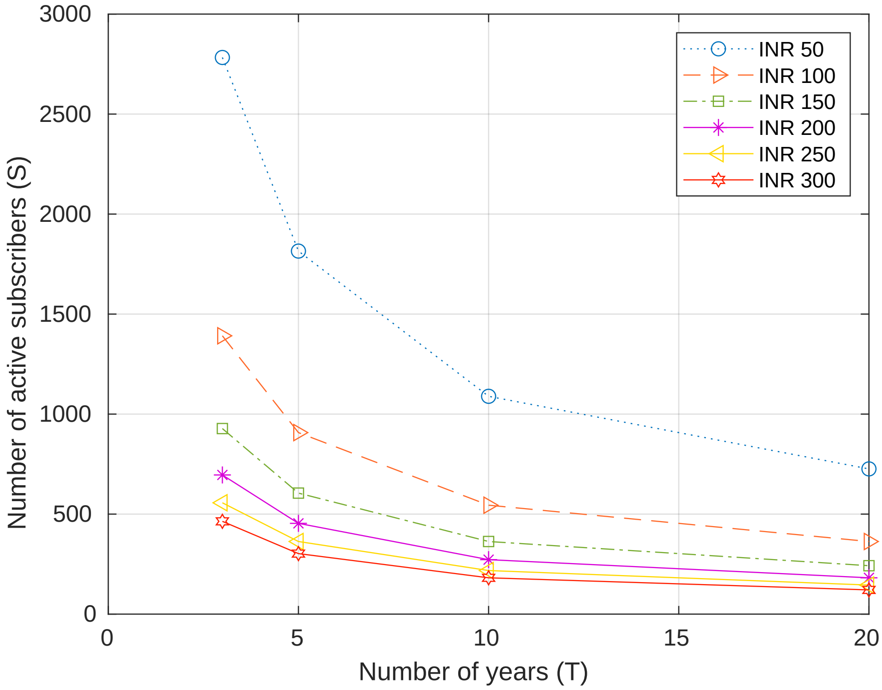


Figure 5.14: Minimum subscribers required on the network for break-even to be achieved

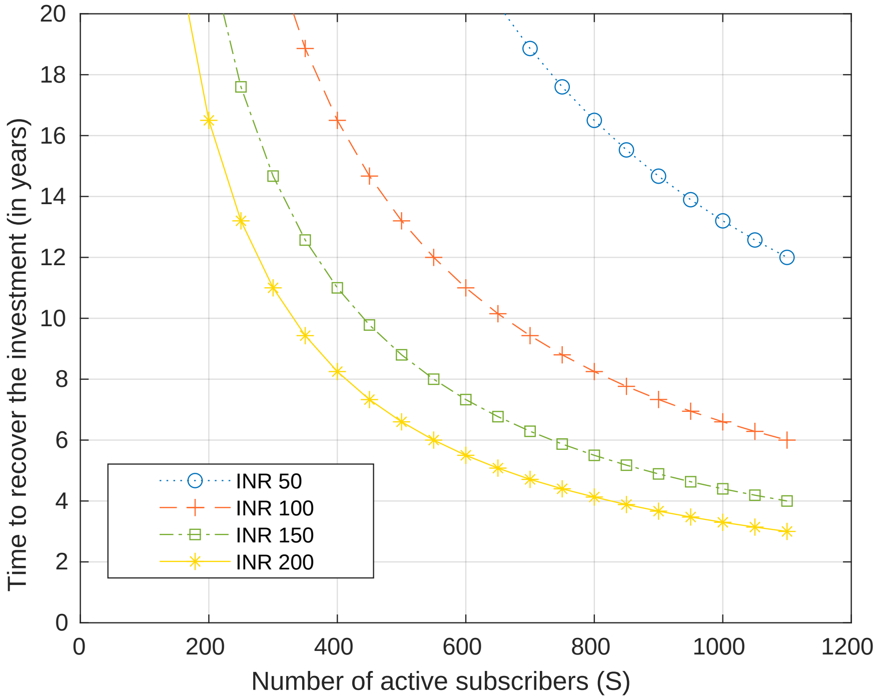


Figure 5.15: Time to reach the break-even point

feasible with fewer than 200 users on a network with a monthly ARPU of INR 200. Under the same conditions, the break-even point occurs in 3 years with 1100 subscribers. It gives us insight into the time frame the InP should invest based on the population, estimated ARPU per month, and network take-up rate of the rural community. A monthly ARPU of more than INR 100 makes the network viable for more than 1000 users.

Minimum investment per user for greenfield 5G rural NHN deployment

Fig. 5.16 shows the subscriber growth chart for a network having 100 subscribers in the first year with a subscriber growth rate, r_g of 7%.

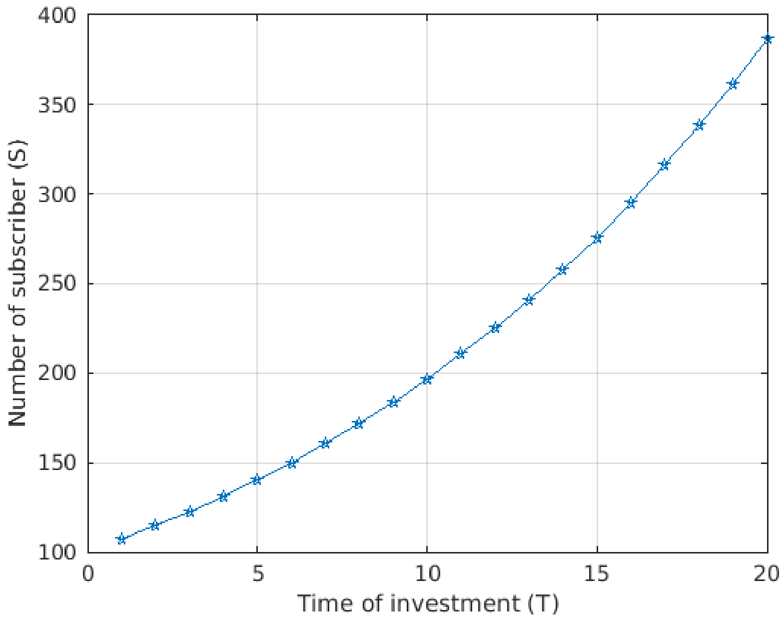


Figure 5.16: Subscriber growth chart over the number of investment years

Fig. 5.17 shows the minimum investment per user required to provide 5G NHN in a rural area to achieve zero NPV at the end of the investment period. A subscriber growth rate r_g is 7%, and the targeted rate of returns r is 8% (rate of returns of other alternative safe investments) is assumed. In rural areas where there are 100 active subscribers in year 0, the monthly ARPU per month should be INR 1,100, INR 600, INR 250, and INR 180 for an investment duration of 3, 5, 10 and 20 years, respectively. When the number of subscribers increases, the minimum ARPU per month reduces to less than INR 100 for any investment duration. Fig. 5.17 shows that 5G NHN is suitable for a village with a 3-year investment and also has less than 500 subscribers.

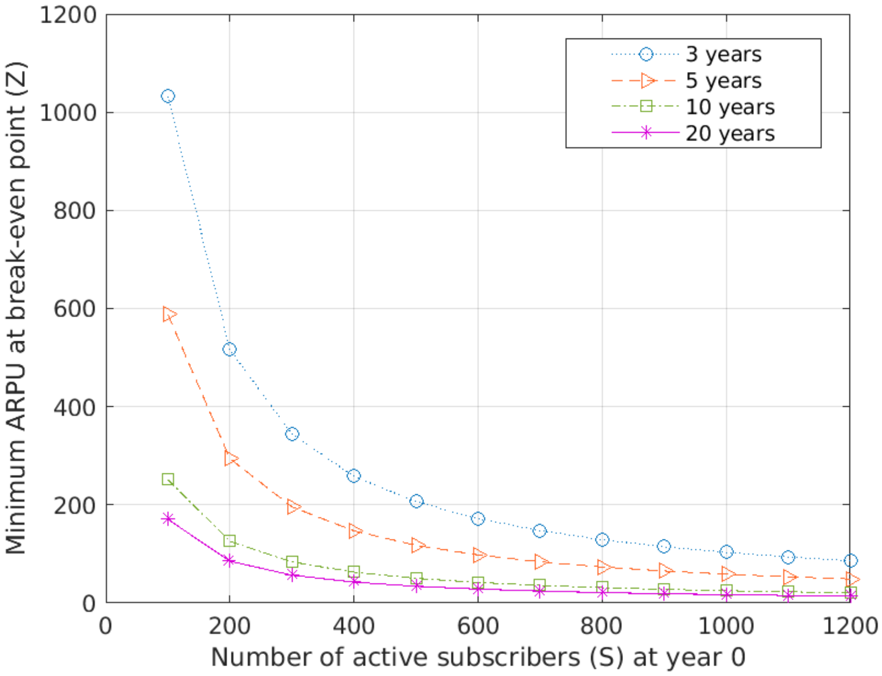


Figure 5.17: Minimum investment per subscriber towards the network to reach break-even point

Table 5.14: Sensitivity analysis for rural 5G NHN

Input	Input type	Influence on NPV
Take-up	Demand	22.34%
ARPU per month	Demand	22.34%
Population	Demand	22.34%
RANs, Tower and more	Economic	7.87%
Backhaul	Economic	7.16%
Operations	Economic	7.16%
Investment duration	Economic	6.93%
Incremental cost (C_{inc})	Demand	3.73%
Spectrum	Economic	0.02%
Core	Economic	0.01%

5.3.3 Sensitivity analysis - India

Table 5.14 shows the sensitivity analysis for rural 5G NHN in the Indian scenario. Note that all values are normalised to a sum of 100%. Demand factors such as ARPU, take-up percentage, and population have a 22.34% each, influencing the network's sensitivity. CAPEX, such as RANs, masts, towers, and more impact sensitivity by 7.87%, while backhaul, and operations impact by 7.16% each on the overall sensitivity. Other parameters such as the incremental slice cost (C_{inc}) and the duration of investment affect the sensitivity by 3.73% and 6.93%, respectively. Meanwhile, factors such as spectrum and core have negligible effects.

5.3.4 Case study - India

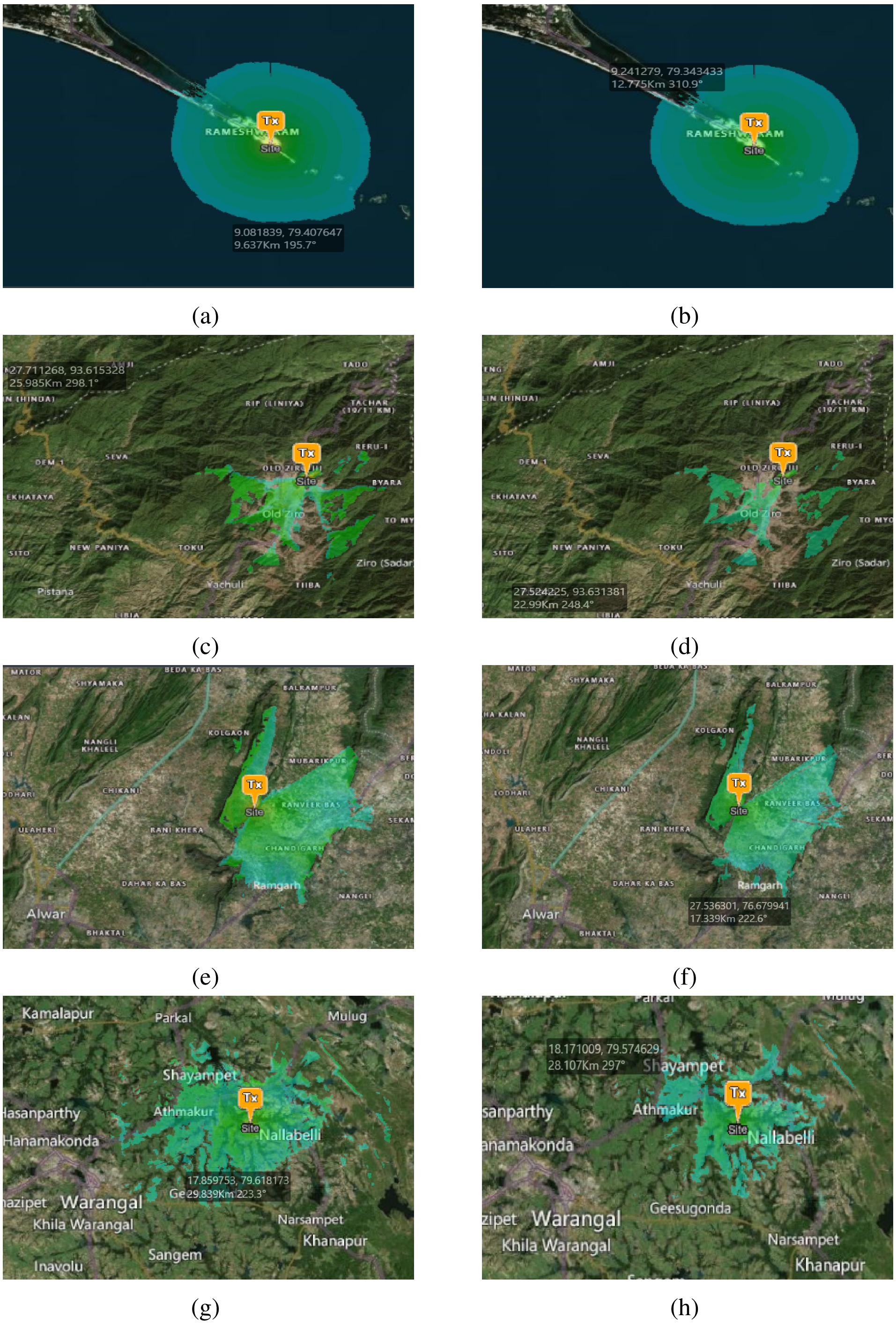
This section outlines a case study carried out for four Indian villages to verify the trends obtained. These villages have poor coverage or no coverage as per ‘OpenSignal’, making it suitable for studying the feasibility of the network. Consider a rural 5G greenfield NHN deployment with BS located in the centre of the village for coverage modelling.

Table 3.1 shows the case study performed for four Indian villages to verify the trends obtained. These villages have poor coverage or no coverage as per ‘OpenSignal’. The technical network parameters used to perform the coverage analysis for the Indian scenario. The simulations applied the Okumura-Hata radio propagation model to identify SINR values in the region of interest. According to calculations, the coverage radius in a rural area with a power level of 46 dBm can be as high as 4 km at 3.6 GHz and more than 10 km at 700 MHz. When employing a frequency less than 1 GHz, the BS location is such that 6 to 8 surrounding communities are covered per site. The low building heights are one of the key factors contributing to broad coverage in rural regions, making it appropriate for researching the viability of the network because there is minimal interference with the signal path.

According to the coverage plots of these rural regions, it is possible to offer adequate coverage and speed in the area using a 10 m antenna at a frequency of 700 MHz or 3800 MHz, as shown in Fig. 5.18. Cell coverage extends to adjacent farms and communities within an 8 km radius of the transmitter location. If necessary, power levels can be reduced to narrow cell coverage on the target village and its use cases. This research focuses on one specific location where the transmitter is located, to better understand the techno-economic feasibility of 5G NHN in low-subscriber areas.

The minimum investment is calculated for each village as shown in Table 5.15 using information from Fig. 5.17. The study used a 10 year investment plan with a 7% subscriber growth rate and a 35% initial subscriber take-up rate. Fig. 5.18 shows the coverage plots for different villages that use these frequency bands. At 700 MHz, the coverage is higher while the speed is reasonable (300 Mbps). However, at 3800 MHz, the coverage is slightly lower, but with very high data rates (700 Mbps). Therefore, the InP could select the frequency bands based on the ease of licensing the spectrum bands and their intended data rates for the subscribers.

In the coverage planning, an omni-directional antenna was used to support applications. From Table 5.15, it can be observed that for different villages the suitability of network slicing varies as described below:



(a) (b)

(c) (d)

(e) (f)

(g) (h)

Figure 5.18: Coverage plots with 10 m antenna height at I - 700 MHz with a bandwidth of 5 MHz and II - 3800 MHz with a bandwidth of 10 MHz: Dhanushkodi (I (a), II (b)), Lempia (I (c), II (d)), Bandholi (I (e), II (f)) and Muddunoor (I (g), II (h))

Table 5.15: Case studies - India

Location	**Dhanushkodi, TamilNadu**	**Lempia, Arunachal Pradesh**	**Bandholi, Rajasthan**	**Muddunoor, Telangana**
Topography	Sea-side	Mountain	Desert	Plain and rocky
Population	500	635	1357	3493
Subscribers	175	222	474	1222
Minimum ARPU	INR 185	INR 120	INR 70	INR 20

- In Dhanushkodi, the initial number of expected subscribers is 175. If InP deploys a rural 5G NHN on the shore, then coverage is uniformly present up to a radius of 9 km (254 km^2) at 700 MHz and 7 km (153 km^2) at 3800 MHz, from the tower location; and also covering a few nearby islands. The main potential end-users of the network are fishermen and their families. This location is also a tourist spot that generates additional revenue for the InP by serving roaming subscribers. The 5G NHN is not feasible in this scenario unless the ARPU per month is above INR 185, with subscriber growth of 7% or greater.

- In Lempia, the initial number of expected subscribers is 222. Similarly to the previous case, a higher ARPU (INR 120) per month or subscriber growth rate is required. One advantage for Lempia is the tourist subscribers, who will earn revenue for the network. The network, however, needs to minimise the blind spots created due to the topographic challenges, i.e., being surrounded by mountains. The site approximately covers a region of 100 km^2 at 700 MHz and around 40 km^2 at 3800 MHz from the transmission tower.

- In Bandholi, the initial number of expected subscribers is 474 making the network viable even with a zero-subscriber growth rate. At a 7% subscriber growth rate, the network is viable with a minimum ARPU per month of INR 70. The network can also earn revenue supporting agricultural applications. The site approximately covers a region of 120 km^2 at 700 MHz and around 50 km^2 at 3800 MHz around the transmission tower.

- In Muddunoor, the initial number of expected subscribers is 1222. In this scenario, the network is lucrative for both InP and MNOs, as the minimum ARPU per month required for a feasible network is around INR 20. Rural connectivity is an attractive option for more than 1000 active subscribers using 5G NHN. The site covers a region of 270 km^2 at 700 MHz and around 180 km^2 at 3800 MHz from the transmission tower.

From the above discussions, the feasibility of rural 5G NHN is sensitive to the deployment scenarios for different villages. The feasibility of the proposed solution depends on parameters such as topography, infrastructure requirements, demand, ARPU, expected end-users and duration of the investment. When the network is feasible for individual end-users, then the network would most likely be viable for additional business subscribers. Small- to large-scale business subscribers would generally pay higher ARPU per month compared to individual end-users. The impact of business subscribers in rural areas could be a possible extension of the study.

5.4 Policy Implications

Currently, though there is technology, the cost of provisioning wireless broadband is exorbitant and not affordable [2]. The most obvious finding to emerge from the analysis is the need for supportive policies to reduce the cost of infrastructure deployment and service provisioning in rural and remote rural areas around the world, which is similar to findings from papers written by Oughton, and Lehr [51,67,127]. The policies should encourage end-to-end sharing among the operators and ease the barriers for new entrants in rural and remote rural geographies. Telecommunications policies should also consider potential revenue streams and their impact on the lives of rural communities. The affordability of services for rural residents plays a key role in the take-up of 5G. Policymakers should regulate the prices of end-user devices, equipment, and spectrum in areas experiencing the digital divide [185]. Policies should encourage programmes that increase people's digital literacy. One of the key advantages of supporting policies that encourage sustainable rural wireless broadband solutions is lowering the dependency on government subsidies with time, the networks will increasingly become self-sustainable [149].

5.5 Discussions

The study explores 5G network slicing with NHN for tackling the digital divide. A generic techno-economic analysis framework for 5G NHN is developed, with a special focus on areas where no MNO is interested in providing services. The techno-economic study of system requirements and the corresponding KPIs for the 5G NHN helps in better understanding the use cases needed for rural areas. The methodology adopted is generic and can be applied to any country. The study explores the feasibility and costs involved to determine the viability of rural 5G NHN deployed by InP. The findings show that for rural scenarios, 5G NHN is considered a cost-effective solution compared to traditional network deployment of *No Sharing*. The sensitivity analysis summarises the inputs that have a significant influence on the feasibility of the proposed solution. Later, the proposed model was used in settings in the UK and India to investigate how well it might address the digital divide in circumstances with high ARPU and high subscriber bases, respectively. Additionally, the brief discussion highlights the state-of-the-art of telecommunication sector in both countries and the need for innovative solutions for the rural market. Results obtained from the TCO and NPV analysis show that the end-to-end slicing of the 5G network deployed by the InP with the required KPI and SLA can reduce the network cost by at least 50% compared to the traditional network deployment strategies in rural parts of the UK and India. The results also suggest that universal broadband could be both commercially viable and financially affordable by using neutral host models.

This chapter explored the challenges related to last-mile connectivity and the feasibility of the sensitivity of rural 5G NHN for the rural UK geographies. Findings indicate that it is possible to build a 5G network with 100 subscribers if either the ARPU per month or the investment duration is higher for the assessed area in the UK. Also, observations indicate that the cost of the network changes significantly depending on the distance of the fibre deployment required to achieve a high-speed connection. The most sensitive input parameters which determine viability are the demand parameters, such as take-up, ARPU and population. From the study, a higher subscription rate would drive rural connectivity. The network is feasible for a very low number of subscribers when the ARPU is higher. This is followed by the operational cost because of the high cost of hiring and sending a skilled person to perform repairs and maintenance on the rural site.

Similar findings are observed from the techno-economic analysis for the Indian scenario which indicates that 5G network slicing with NHN is a viable option in Indian settings. The proposed solution for rural connectivity is an attractive business option and would potentially solve the digital divide. In the Indian scenario, there is a decent subscriber number at any given location, as shown in Table 5.10. The challenge lies in providing 5G services in rural India at low ARPU. As discussed in Section 5.3.1, the InP would have to focus on the connectivity of the last mile to the villages from the nearest PoP to serve the end-users using low-cost backhaul solutions. 5G NHN encourages rural connectivity even for subscribers as low as 100 for a 10+ year investment. The Indian government has undertaken initiatives and projects to improve rural connectivity by providing fibre backhaul to every village panchayat [4]. The feasibility and sensitivity of using 5G NHN in rural last-mile connectivity were explored using the data obtained from the MNO and other stakeholders.

Chapter 6

Strategies for 5G NHN Negotiations Between InP and MNOs

Chapter 2 discusses the literature review highlighting the work done in the field of 5G communication systems using game theory. As shown in Chapter 5, observations indicate that techno-economic feasibility depends significantly on the possible returns earned from the network. As a result, it is critical to analyse the potential payoff for each player to enter the rural market and the cost-revenue sharing scenarios while keeping in mind the possibility of negotiation in terms of cost and KPIs for rural 5G NHN.

Consider the situation when the cost associated with KPI and SLA requirements, is a crucial decision element in a business feasibility study. A negotiating process allows the InP and the MNOs to achieve an agreement on their cost-revenue allocations. The data obtained from the UK scenario in Chapter 5 is taken as input to the game theory model developed in this chapter for a realistic scenario assessment of the investment and cost-sharing games.

The main contributions of the Chapter are as follows:

- Investment games help players understand the different strategies and suitability of InP-MNOs for rural connectivity. The study aims to understand the best possible strategy for InP and MNOs to cooperate to improve rural connectivity through deploying a 5G network with or without NHN in rural areas.
- The pricing strategy between InP and MNO using game theory models such as Shapely value and bargaining game helps to understand possible pricing strategies.
- A new pricing business model for rural connectivity using dynamic pricing is proposed.

An analysis of the combination of Shapley value and bargaining games for dynamic pricing allocation between InP and MNO is presented. The study also explores the impact of InP and MNOs declaring their true costs in 5G networks.

- A UK case study to understand the application of pricing strategies.

6.1 Pricing Strategy Models using Game Theory

The pricing strategy helps in distributing the cost of provisioning a service among the different stakeholders. It helps in understanding the range of services that can be provided and the corresponding costs per stakeholder.

6.1.1 Decision making flow chart

Fig. 6.1 shows a decision-making flow chart of the game theory algorithms related to cost-sharing for rural 5G NHN. It is appropriate to study the impact of the cost models on the

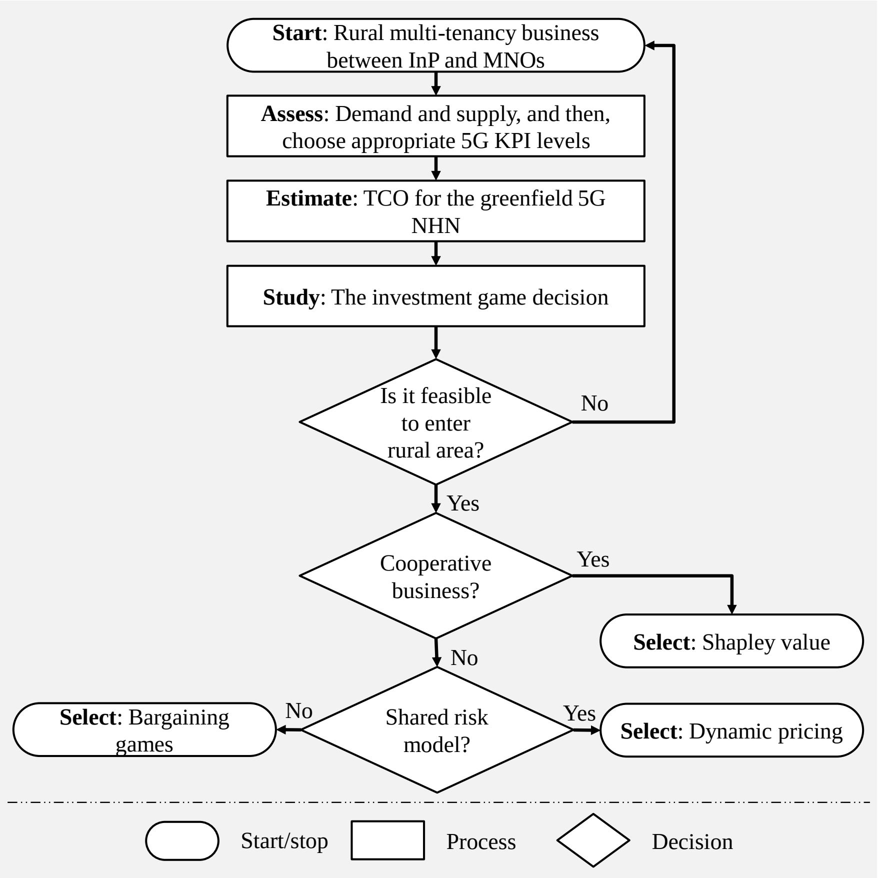


Figure 6.1: Decision-making using game theory framework

sustainable business models of rural 5G NHN. Fig. 6.2 shows the relationship between MNOs and InP. In the first step, the location, TCO and predicted returns for the site are estimated based on demand requirements. Further, MNOs estimate whether the network satisfies their techno-economic criteria. Then, the investment games for the InP and MNOs determine the viability of entering the rural connectivity market as discussed in Chapter 5. If feasible, the InP and MNO need to decide which type of business they would prefer: cooperation or non-cooperation with a positive approach, and who would bear the risk and by how much, as shown in Fig. 6.1. Next, depending on the risk-taking nature of players in the game, they would consider three possible models for this cost-revenue sharing model, shown in Fig. 6.1. The grand coalition of the MNOs and the InP can decide on which cost-revenue model to adopt. The MNOs and InP would negotiate over the possible revenue model till an agreement or disagreement was reached regarding the cost and technical specifications of the network.

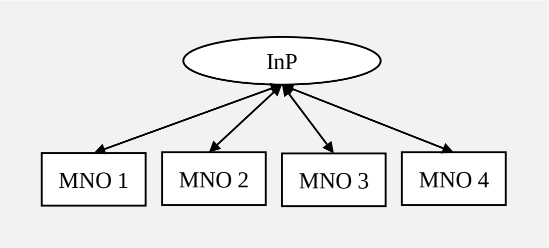


Figure 6.2: Hierarchical relationship between the MNOs and the InP

6.1.2 Investment games

Consider an industrial game in which InP and MNO are the players, and decide whether to enter the rural telecommunication market with 5G NHN or not. The InP-MNO relationship as a mathematical model explores an extensive form of game representation discussed in Chapter 2.6. The investment game for different approaches to rural connectivity using 5G NHN or not is studied by calculating their expected payoff. The results highlight the optimal decision for MNO and InP while entering the rural market using 5G NHN.

For each player (InP/MNO) in the investment games, there are three possible actions - not to enter the market (N_o), enter the market with an independent 5G network (I), and enter the market using 5G NHN supporting multi-tenancy (M), as shown in Fig. 6.3. The output for the analysis is compared in terms of the payoff, which depends on the expected profits. The profits

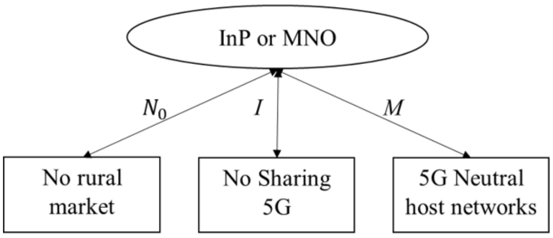


Figure 6.3: Investment game strategies for each player

(or loss), p, for the business are calculated by using the cost (c) and revenue (r) as shown,

$$p = r - c. \tag{6.1}$$

6.1.3 Shapley value

In this type of cost-revenue sharing model, the InP calculate the total rent to be charged to all the MNOs together, which is equal to the total revenue expected for the InP R_{InP}, as discussed in Chapter 5. Either the InP or MNOs divide the rent fairly based on the network requirements of each player using Shapley value. The Shapley value algorithm computes the additional cost of fulfilling the higher KPI criteria and distributes it equitably among the players who use the resources. The MNO provides services to the end-user on a subscription basis [237, 245, 253]. The InP guarantees that 5G services meet the agreed-upon standards, and protect user data that helps to maximise the output of the grand coalition formed by the InP and the MNOs. In this strategy, the InP receives a lump-sum payment for the service provided that covers the InP's expenses along with risk and earns a fixed return. If the subscribers for the services are fewer than planned, the MNOs will be at greater risk but InP has minimal risk in this model.

Mathematical modelling of cooperative game

Let v be the characteristics function that maps the 2^N combination of the coalition values to real numbers. The rent per MNO λ_n ($= r_n$ discussed in Chapter 5), $n \, \varepsilon \, N$ such that there is a fair allocation of the rent among the players that would reflect their requirements. Initially sort the MNOs based on ascending order of their slice requirements. The first step would be to divide the cost to cater for the slice with the lowest SLA and slice priority requirement equally among the number of MNOs. Next, divide the additional cost of provisioning for the second-lowest SLA and slice priority equally between the MNOs but the MNO with the lowest SLA and slice priority. Furthermore, carry forward this process until the incremental cost accounts for the

MNO with the highest SLA and slice priority. Note, an MNO could have more than one slice to meet its user demands.

The cost of providing rural 5G NHN by InP essentially depends upon the MNO with maximum SLA and slice priority as described in (5.14). The Shapley value function, λ_k, is a function that assigns to each possible characteristic function an N-MNO game, ν with a $N-$tuple, $\lambda(\nu) = (\lambda_1(\nu), \lambda_2(\nu), ..., \lambda_N(\nu))$ [237]. The function $\lambda_n(\nu)$ represents the value of MNO-n in the game with a characteristic function ν and is defined by the following axioms of fairness [231, 237, 238]:

A. Efficiency: $\sum_{n \subset N} \lambda_n(\nu)$.

B. Symmetry: if n and m are such that $\nu(\chi \cup n) = \nu(\chi \cup m)$ for every coalition χ not containing n and m, then $\lambda_n(\nu) = \lambda_m(\nu)$.

C. Dummy: If i is such that $\nu(\chi) = \nu(chi \cup i)$ for every coalition χ not containing i, then $\lambda_i(\nu) = 0$.

D. Additive: If u and ν are characteristic functions, then $\lambda(u + \nu) = \lambda(u) + \lambda(\nu)$.

There exists a unique function that satisfies all these fairness axioms, which is given by:

$$\lambda_n(\nu) = \sum_{\chi \subset N} \sum_{n \subset \chi} \frac{(|\chi| - 1)!(n - |\chi|)!}{n!} [\nu(\chi) - \nu(\chi - n)] \tag{6.2}$$

Algorithm 1: Cost sharing among MNOs - Shapley Value

```
Result: Cost per MNO is calculated
initialisation $\lambda_n(\emptyset) = 0$ for all $n \subset N$ ; Sort the MNOs in ascending order of their KPI
  requirements and cost: $\lambda^*_{\pi(1)} \leq ... \leq \lambda^*_{\pi(N)}$;
For n = 1 to N
$\delta = \lambda(n) - \lambda(n-1)$;
For i = n to N
$\lambda_\pi(i) = \lambda_\pi(i) + \frac{\delta}{(N-n+1)}$;
end For
end For
```

Equation (6.2) gives the average marginal contribution made by MNO-n when it joins the coalition χ. The direct computation of Equation (6.2) becomes computationally challenging when the number of MNOs increases. For simplifying Equation (6.2), the modified structure of Shapley value from [297] is used for the rent sharing among MNOs in the study. Littlechild and Owens use this to solve the airport runway cost-sharing problem [238], which states that the cost of any subset is equal to the cost of the largest player in the subset. Based on the Shapely value concept given by [238], Algorithm 1 used in this study describes the steps involved in pricing strategy among the MNOs using the Shapley value.

6.1.4 Bargaining games

The InP and MNOs in non-cooperative games strive to maximise their revenues and divide the user payment among them based on a pre-agreed-upon rate. The InP should provide 5G services to the agreed standards and user-security data protection standards. In real-life situations, tenants would rent slices for varying duration. For example, MNO could be a long-term tenant while a live telecast tenant could be an ad-hoc. It would be challenging to always obtain cooperation before setting up a network. In this scenario, the InP estimates the demand requirements and deploys a rural 5G NHN. MNOs and other tenants would lease slices as per their requirements. If there is a need for InP to expand the capacity to cater to a higher slice requirement, the InP would invest and charge accordingly from the MNOs who require that service. Due to the usage of a "per user" payment mechanism, this approach has a larger risk for the InP and a smaller risk for the MNO [216].

As both MNOs and InPs quantify their satisfaction in terms of monetary revenue gains from investments, both parties must collaborate to provide an agreed service to the same customers. Hence, the payment for the service should also be divided between them. As they work together, they will generate more revenue, which will benefit both parties and result in mutual gains. The ratio of the division of revenue is pre-negotiated between the InP and the MNO. It aids in determining the RoI.

Mathematical modelling of non-cooperative game

Let $q \ \varepsilon \ Q$ be the guaranteed SLA between the InP and the MNO negotiate. As discussed in [234,246], let the user-payment be denoted as Π and the cost for each player towards providing the user services for q SLA be c_i, $i \ \varepsilon \ [1,2]$. The total revenue for each player is represented as Π_i, $i \ \varepsilon \ [1,2]$ and the profits as ϕ_i, $i \ \varepsilon \ [1,2]$. The goal of the bargaining games is to maximise ϕ_i, i $\varepsilon \ [1,2]$ such that payment Π (a.k.a ARPU Z in Chapter 5) is split fairly among the players [246]. Let c_i be the cost of providing service to player i. Given the cost characteristics for player i, each player seeks a portion:

$$\pi_i = c_i + \phi_i, \tag{6.3}$$

where ϕ_i is the profits for player i, such that

$$\Pi = \pi_1 + \pi_2, \tag{6.4}$$

A game that reaches an agreement in the first round has the maximum payoff as discussed in A. Hence, the maximum payment to be divided among the player in the first round of negotiation is Π.

Payment-partition game

The disagreement leads to a payoff of 0 for each player. Let $s^* = (\pi_1^*, \pi_2^*)$ be an optimal payment-partition solution, then $\phi_i = \pi_i^* - ci$ is the optimal solution for the payment-partition scenario where $i \ \varepsilon \ [1,2]$ is known as Nash bargaining solution, which helps in computing the agreement strategy with the maximum possible payoff for each player with all the possible strategies taken by the other players. Hence, the agreement is a desirable output.

Payoff calculation

Each player has two possible actions: to declare real cost (C) or not declare (D). Depending on the belief of the player about the other player's action, they would decide their action. Let, c_i be the real cost for the player i whereas $c_i^{'}$ represents the false cost for the player i. The provider lies about the cost to earn higher profits. The optimal solution for each player in the payment partition game is shown in Table 6.1 and 6.2 [246].

Theorem 1. *There exists an optimal solution for the payment-partition game and given as follows:* $\Pi_1 = \frac{1}{2}(\Pi + c_1 - c_2)$ *and* $\Pi_2 = \frac{1}{2}(\Pi + c_2 - c_1)$.

Proof. The proof is included in the appendix. □

Table 6.1: Provider 1's payoff for different strategies of provider 2 in bargaining game

		Player 2	
		C	D
Player 1	C	$\frac{1}{2}(\Pi + c_1 - c_2)$	$\frac{1}{2}(\Pi + c_1 - c_2^{'})$
	D	$\frac{1}{2}(\Pi + c_1^{'} - c_2)$	$\frac{1}{2}(\Pi + c_1^{'} - c_2^{'})$

Table 6.2: Provider 2's payoff for different strategies of provider 1 in bargaining game

		Player 2	
		C	D
	C	$\frac{1}{2}(\Pi + c_2 - c_1)$	$\frac{1}{2}(\Pi + c_2^{'} - c_1)$
Player 1	D	$\frac{1}{2}(\Pi + c_2 - c_1^{'})$	$\frac{1}{2}(\Pi + c_2^{'} - c_1^{'}$

Pricing mechanism mathematical model

A Bayesian game [244] models a strategic type of game in which uncertainty about the players' strategies (input and output), is based on the beliefs about the other player's payoff. To encourage players to declare their true cost, a penalty system should be in place to punish cheating players, assuming that it is possible to determine whether a player has declared their true cost or not, and is known as the pricing mechanism [246, 298, 299]. Real costs may be approximated using a variety of sources such as annual accounts, profit and loss statements, audits, research papers, industry white papers, and certain cost information supplied by the supplier. According to the pricing mechanism, cheating has no effect on the current game, but it does have an impact on future games.

The pricing mechanism variable, $\alpha_i \; \varepsilon \; [0,1]$ and $i \; \varepsilon \; 1,2$ which represents the probability of provider i being truthful, and it modifies the players' payoff in the games. Assume that it is possible to reveal whether the InP-MNO game is being played truthfully. The value is adjusted using a punishment factor $\gamma \, \varepsilon \, [0,1]$, set by the centralised body monitor affecting the user payment in the future [246]. Thus, based on the previous value of α_i, that is $\alpha_i^{previous}$, for provider i, the current pricing mechanism variable is defined by,

$$\alpha_i = \begin{cases} \alpha_i^{previous} - (\alpha_i^{previous}\gamma), & \text{if provider i is caught lying.} \\ \alpha_i^{previous} - (\alpha_i^{previous}\gamma) + \gamma, & \text{if provider i is truthful.} \end{cases} \tag{6.5}$$

The player is penalised if they lie about their true cost but rewarded if they declare true costs (6.5) [231, 246]. The incentive steadily increases to urge the player to be honest, while the penalty curve quickly lowers to discourage cheating. The Bayesian form of the payment-partition game for InP and MNO cooperating to provide 5G services to end-users is computed. And further by including the pricing mechanism factor β_i, in order to motivate the player to declare the truth while cooperating is included, the payoff for player i is given by,

$$\pi_i = \frac{1}{2}(\Pi + \beta_i c_i - \beta_j c_j). \tag{6.6}$$

Bargaining game outputs

To understand the payment-partition game with a pricing mechanism, the strategies possible for the game are evaluated as described below:

A. Strategy 1: (C) The player always declares its real cost - β_i is 1 (no punishment game).

B. Strategy 2: (D) The player always lies about its real cost - β_i is 1 (no punishment game).

C. Strategy 3: (50% C/D) The player declares its real cost 50% of the time and lies about it the other times - β_i is 1 (no punishment game).

D. Strategy 4: β_i varies based on the previous action of the player (punishment game). The player monitors its β_i and lies only when its β_i is high, in order to minimise its cheating effects. The payment partition is done according to the payoff calculations given in Equation (6.6). In this case, the player lies when $\beta_i > 0.9$, else the player declares the real costs.

This strategy is effective when network take-up meets or exceeds expectations, i.e. when the number of subscribers is high. The disadvantage of this strategy is that when the population is low, i.e., when the predicted network take-up is low, the risk levels for the InP are relatively high.

6.1.5 Dynamic pricing: cost-plus pricing

Dynamic pricing is a means of revising a product's or service's price in response to changing market conditions. This strategy aids in increasing revenue from the sale of a product or service. For this study, to simplify the model, the price variation 'per user' happens over a long period of time rather than instantaneously, that follows, cost-plus pricing is considered. This game is a combination of Shapley value and bargaining games, used to share the costs, revenue and risk between the InP and MNO. In this type of revenue sharing, the MNO pays a fixed component and a variable component to the InP. The InP will receive higher revenues if the number of users increases and have a guaranteed fixed return even when the network take-up does not meet the estimation. Similarly, the MNO will pay a fixed amount to the InP for using their services and infrastructure and a 'per-user' charge to the InP. In this way, the MNOs reduce costs towards the network during poor take-up of the network.

6.1.6 Mathematical models for dynamic pricing

The possible business model for the 5G NHN in Dynamic pricing is represented in Equation (6.7), where C_{mix} is network slicing cost per MNO, b is the base price, m is the number of users per MNO, t is per customer usage time price, d is per customer data usage price, s_q is the QoS based on the SLA price, c_f is the convenience fees, s_f spectrum fees, s_p surge policy fees, and m_f is the miscellaneous fees. Table 6.3 shows the various fixed and variable costs involved in the dynamic pricing strategy.

$$\begin{aligned} c_{mix} &= c_{Shapley} + mc_{perUser}, \\ &= (b + s_q + c_f + s_f) + m(t + d + s_p + m_f), \end{aligned} \tag{6.7}$$

where $c_{Shapley}$ is the fixed cost for the MNO calculated using Shapley value, and $c_{perUser}$ is the variable cost for the MNO calculated using the payment-partition game.

Table 6.3: Fixed and variable costs

Fixed costs	**variable costs**
b	t
s_q	d
c_f	s_p
s_f	m_f

6.2 Investment Games - Results

Consider the **UK greenfield macro-cell scenario** discussed in Section 5.2 to design the investment tree for the InP-MNO game. The cost and revenue estimates help forecast the possible profits for each strategy. This model is generic and can be applied to any scenario. Let the game begin with InP selecting its strategy as either N_o or N, I, or M, followed by the MNO selecting its strategy as either N_o, I, or M. It is a sequential game where the InP plays the first move, and then MNO observes the strategy of the InP and decides on its strategy.

Typically, MNO's costs are often higher compared to the InP's costs for 5G networks, mainly owing to network specifications set out by the national regulator, civil works, security, interconnection and other legal certification expenditures. For example, the InP could be a community initiative with local landowners who would allow the fibre to run through their farm at minimal or zero cost and use grade 2 equipment in the network. According to estimations by Chapter 5 for the 5G NHN's greenfield macro-cell for the UK scenario, the cost of an MNO's

5G network deployment is roughly £450K, but the cost of an InP's 5G network deployment is around £400K. Furthermore, when MNOs lease slices, the cost of such slices is shared evenly among the MNOs on the InP networks. Assuming that all MNOs have the same criteria, the cost is evenly distributed among them, ranging between £150K and £200K.

Generally, the preferable strategy is one with larger profits as it helps in maximising the monetary gains. Assume that the UK greenfield macro-cell scenario and assume the village(s) to be covered has around 200 subscribers and the 5G NHN would be deployed by either InP or MNO, the ARPU of the network is £30, and the investment duration is 10-years. The customers are divided among the InP and MNO. The cost, revenue and profits calculations for the above game are as shown in Table 6.4. The sensitivity of the model is similar to the estimations presented in Section 5.2.3.

Table 6.4: InP-MNO game with the strategy of 10 years investment and 200 subscribers

(InP, MNO)	**Cost**	**Customers**	**Revenue**	**Profit/Loss**
(N_o,N_o)	(0, 0)	(0, 0)	(0, 0)	(0, 0)
(N_o,I)	(0, £450K)	(0, 200)	(0, £720K)	(0, £270K)
(N_o,M)	(0, £150K)	(0, 50)	(0, £180K)	(0, £30K)
(I,N_o)	(£400K, 0)	(200, 0)	(£720K, 0)	(£320K, 0)
(I,I)	(£400K, £450K)	(100, 100)	(£360K, £360K)	(-£40K, -£90K)
(I,M)	(£400K, £200K)	(50, 50)	(£180K, £180K)	(-£220K, -£20K)
(M,N_o)	(£400K, 0)	(industry, 0)	(£425K,0)	(£25K, 0)
(M,I)	(£400K, £200K)	(3 MNOs, 50)	(£425K, £180K)	(£25K, -£20K)
(M,M)	(£400K, £150K)	(4 MNOs, 50)	(£425K, £180K)	(£25K, £30K)

Fig. 6.4 shows the profits or losses for different possible combinations of the strategy. The payoffs are calculated based on the profits from different strategies. Fig. 6.4 shows that for any player with strategy *I*, the payoff is 0 because they are not participating in the competition by not entering the rural market.

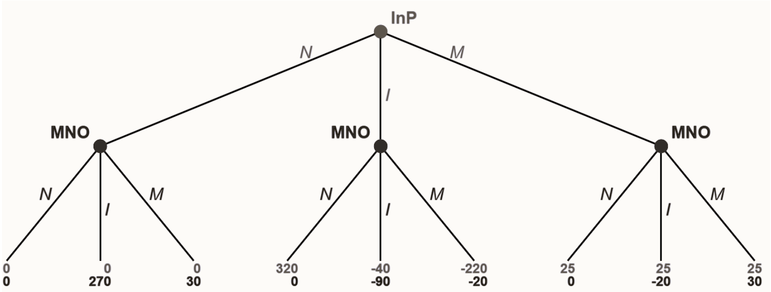


Figure 6.4: The extensive form of the 5G InP-MNO game: profits in £ Thousands

The different strategies possible for the InP-MNO game are described below:

A. **Case 1**: InP selects N_o

   (a) When MNO selects N_o, then rural connectivity is not possible.

   (b) When MNO chooses I, it becomes a monopoly for the consumers in the region, regardless of whether the service is excellent or poor because the customers have no other option. The scenario is beneficial for the MNO with profits of around £270K as shown in Fig. 6.4.

   (c) When MNO chooses M and selects 5G NHN, the profits reduce to £30K. The customers have a wide range of alternative network operators to switch.

B. **Case 2**: InP selects I

   (a) When MNO selects N_o, then the payoff for MNO is 0 and all the customers would be present on the InP network. The InP would have higher payoffs as their TCO towards the network is lower than the MNO's TCO. Customers have just one service provider choice, a monopolistic competition.

   (b) When MNO selects I, the customers have two service provider options, which would get equally split between the InP and the MNO. However, this is a loss scenario for both InP and MNO as their resources are under-utilised and duplication of parts of the network makes it an expensive option.

   (c) When MNO selects M, customers have a wide range of alternatives to select. Although an oligopoly competition, the InP would incur a significant loss as a result of increased competition. In this case, the MNO would suffer a reduced loss because users may select from a variety of service providers, and the InP network would be underutilised.

C. **Case 3**: When InP selects M

   (a) When MNO selects N_o, the MNO's payoff is 0. However, this causes a complication for the InP because their customers will have difficulty roaming outside of their own network. Customers would have access to a private and local area network without an option for a wider network. The InP will not supply commercial 5G services to retail consumers in this situation. If the network slices are leased to industry verticals and other MNOs, the InP profit would be around £25K, a 10% estimated profit margin overall.

(b) When MNO selects *I*, the MNO's payoff is in loss because customers have more alternative service providers. When compared to leasing network slices from the InP, the cost for MNOs to establish their network is greater. The InP would have a positive payout of roughly £25K if the network slices were solely leased by MNOs, an expected 10% profit margin overall.

(c) When MNO selects *M*, the InP and MNO would cooperate to reduce their cost and deploy the network to satisfy SLA and 5G standards. The InP would have a positive payout of roughly £25K if the network slices were solely leased by MNOs, an expected 10% profit margin overall. As illustrated in Table 6.4, the MNO would have a lesser investment and make reasonable profits from the network. This scenario appears to be the best fit for a rural setting, as both InP and MNO gain good returns. Because of greater competition among MNOs, customers benefit from better services and improved QoS. Because the subscribers are MNO direct customers, roaming and handoff are not a concern in this circumstance.

Observing the different payoffs in Fig. 6.4 helps in concluding that NHN is a suitable and viable business option for the given scenario. In the real world, the MNOs are not keen on deploying and maintaining their network in rural areas, unless profitable. In order to serve its client base, the MNO would probably like to offer services in rural areas by leasing out the network slices of the InP network. Similarly, investment games help in analysing every deployment location and sustainability in rural areas by adjusting multiple factors such as network take-up, subscribers base, ARPU, and investment length.

6.3 Pricing Strategies Evaluation Results

Consider the cost for the greenfield 5G deployment in a generic rural village that needs to deploy a fibre backhaul of 10 km to analyse the feasibility of the pricing model for rural areas. The simulation parameters for the greenfield deployment are as given in Table 6.5. The average TCO of the network in rural areas is estimated using the data from the research papers such as [2, 7, 18]. To understand the suitability of different pricing strategies, assume that the InP initially decides to deploy only a single macro cell, with a 3-sector antenna and MU-MIMO for a study area of 100 km^2 with up to 1,500 subscribers per MNO (assuming that each MNO has a 25% market share).

The three main pricing strategies are Shapley value, bargaining game, and dynamic pricing

Table 6.5: Simulation parameters for the pricing strategy

Parameter	**Range**
Subscribers	10 to 3000
ARPU	\$1 to \$80
Duration	10 years
TCO for the InP, rural 5G NHN	\$415,456
end-users growth rate	4%
Shapley value	InP charges are per the infrastructure requirements to support the customers and the MNOs share the price quotes by the InP
Bargaining game	70% of the revenue is taken by the MNO, while 30% of the revenue is given to the InP
Dynamic pricing	55% of the revenue earned is kept with the MNO, while 45% of the revenue earned from the end-users is given to the InP (fixed + variable)

model, which are suitable for evaluating the viability of different scenarios based on mainly the ARPU and number of subscribers. The ARPU and the number of subscribers are varied to observe the profits using pricing models in rural areas. The profit for both the InP and the MNO is heavily dependent on the pricing strategy, as shown in Figure 6.5, respectively. The findings demonstrate that the Shapley value is appropriate when both the InP and the MNO are experiencing losses and when ARPU and subscriber numbers are likewise declining. Dynamic pricing, however, is appropriate where there is no clear win-win situation between the InP and

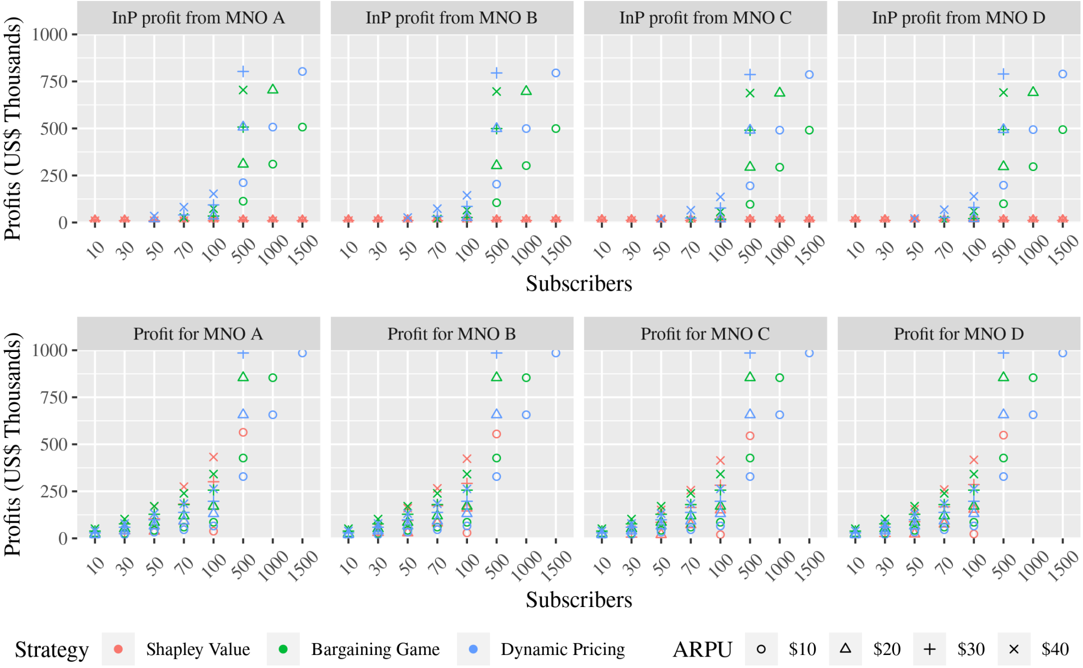


Figure 6.5: Profits using different strategies for InP and MNO

MNO, such as moderate subscriber numbers and ARPU. The bargaining game is more suitable when the number of subscribers and the ARPU are high.

Figure 6.5 show that the profits are exponentially increasing for the MNO when the InP selects the Shapley value as the risk is higher for the MNO. Meanwhile, the bargaining game is risky for the InP in the case of low subscriber take-up as they would invest a considerable amount upfront for the network. The dynamic pricing range falls between the overlap region of Figure 6.5. Because both the InP and the MNO share the risks associated with telecommunication deployments, dynamic pricing is appropriate for both parties during moderate ARPU and a moderate number of subscribers. The difference between dynamic pricing and bargaining games is minimal for an MNO. The InP and MNO can both earn maximum payoff by choosing dynamic pricing.

A few examples of the pricing strategy study results from Figure 6.5 is tabulated in Table 6.6. According to the result, the most appropriate pricing model changes with a given ARPU and the number of subscribers. The suitability of the pricing model for each operator varies according to the demand of the rural area. These scenarios show that the cooperation between the InP and the MNOs plays a crucial role in improving rural connectivity. The MNO and InP would negotiate to implement the optimum pricing strategy for each of them.

Table 6.6: Pricing evaluation - Average profits for each InP and MNO pair, at different ARPU and number of subscribers

Pricing model	**(InP, MNO)**	**(InP, MNO)**	**(InP, MNO)**
Subscribers, ARPU	**30, $40**	**500, $30**	**1500, $20**
Shapley value	($10,390, $53,768)	($10,391, $1,867,042)	($10,390, $3,837,992)
Dynamic Pricing	(-$22,563, $78,838)	($793,410, $985,475)	($1,680,338, $1,970,950)
Bargaining game	(-$46,214, $102,489)	($497,768, $1,281,117)	($1,089,0533, $2,562,235)

The Nash equilibrium (NE) is a set of strategies for each player such that no player derives a higher payoff by deviating from their initial strategy [239, 267, 300, 301]. For studying the NE for the game payoffs presented in Table 6.6, the online solver from [301] is used. The NE analysis shows that the most suitable pricing strategy is Shapley value for low ARPU and low subscribers; for the other scenarios, the most suitable pricing model is dynamic pricing.

6.4 Case Study - UK

As per statistics from [65], the average time a user spends on the internet is 4 hours 2 minutes per day and an average of 31 GB per month, which is slightly lesser than the predicted average of 45 GB per month [302] in the urban areas. To study the suitability of the pricing strategies in rural areas, consider a generic rural area in the UK that requires a greenfield deployment that a 10 km fibre macro-cell. Assume that the area to be covered has a maximum of 600 subscribers. Using the data from the [46] and methodology from Chapter 5, TCO for 5G network is estimated to be around £450K for a 2-by-2 sharing network among the MNOs, but the TCO of an InP's 5G network deployment is around £400K.

If all MNOs have the same KPIs and SLA requirements then the rent is evenly distributed among them. To better understand the usage of dynamic pricing, consider the three cases for the assumed scenario:

- Shapley value
- Bargaining games
- Dynamic pricing

Note: To understand the detailed analysis of the calculations presented in this section, kindly refer to Appendix B.

Therefore, the key inputs for the models are described below:

- **Shapley value**: For the estimation of the cost for the players in the Shapley value, the algorithm presented in Section 6.1.3 is used. For the revenue for the InP and MNOs at ARPU of £30 and £60, the Shapley values are estimated. The MNOs pay a fixed rent to the InP and keep any revenue earned to themselves.
- **Bargaining games**: By considering the truthful factor in the model described in [246] for the price sharing estimation, the optimal ratio between the MNO and InP for sharing of the revenue is 36.7%:63.3% of the ARPU paid by the end-users to the MNO. Hence, when the ARPU is £30, the InP receives £11 and the MNO receives £19. Similarly, when the ARPU is £60 the InP receives £20 and the MNO receives £40.
- **Dynamic games**: Assume that InP expects 50% of cost as fixed income and 50% as variable income, the yearly rent for the InP is at least £50,512. Hence, £25,216 as fixed income $c_{Shapley}$ and £25,216 as variable income $c_{perUser}$ should be received from the

combined rent of all the MNOs including all the costs discussed in Section 6.1.6. By considering the truthful model described in [246] for the price sharing estimation, the optimal ratio between the MNO and InP for splitting the revenue is 30%:70% of the ARPU paid by the end-users to the MNO. Hence, when the ARPU is £30, the InP receives £9 and the MNO receives £21. Similarly, when the ARPU is £60 the InP receives £18 and the MNO receives £42.

6.4.1 Observations

Figures 6.6, 6.7a and 6.7b show the profits earned by the InP and MNO for different ARPU and pricing strategies. From the figures, it can be observed that profits are minimal when the number of subscribers is low. The Shapley value is suitable for a scenario with less than 100 subscribers; dynamic pricing is suitable for more than 100 subscribers for the InP; whereas the bargaining game is suitable for more than 400 subscribers. However, bargaining games are always beneficial for MNOs since the risk associated with them is less in cases of low customer uptake. Meanwhile, dynamic pricing is beneficial for more than 100 subscribers. Inspecting Figures 6.6, 6.7a and 6.7b, indicates that the most profitable model for MNOs and InP with more than 300 subscribers is Shapley value and dynamic pricing. The application of the Nash equilibrium to this model infers that the most rational strategy is dynamic pricing.

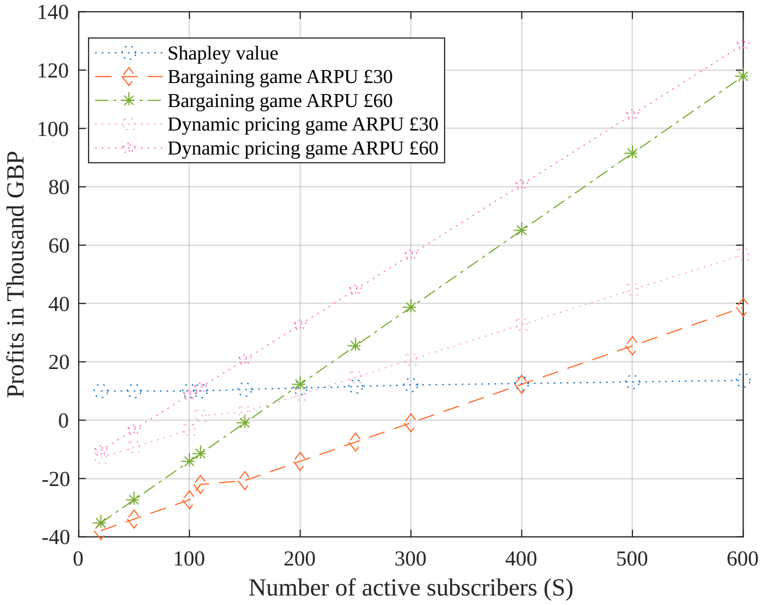


Figure 6.6: InP profits for different pricing models and ARPU

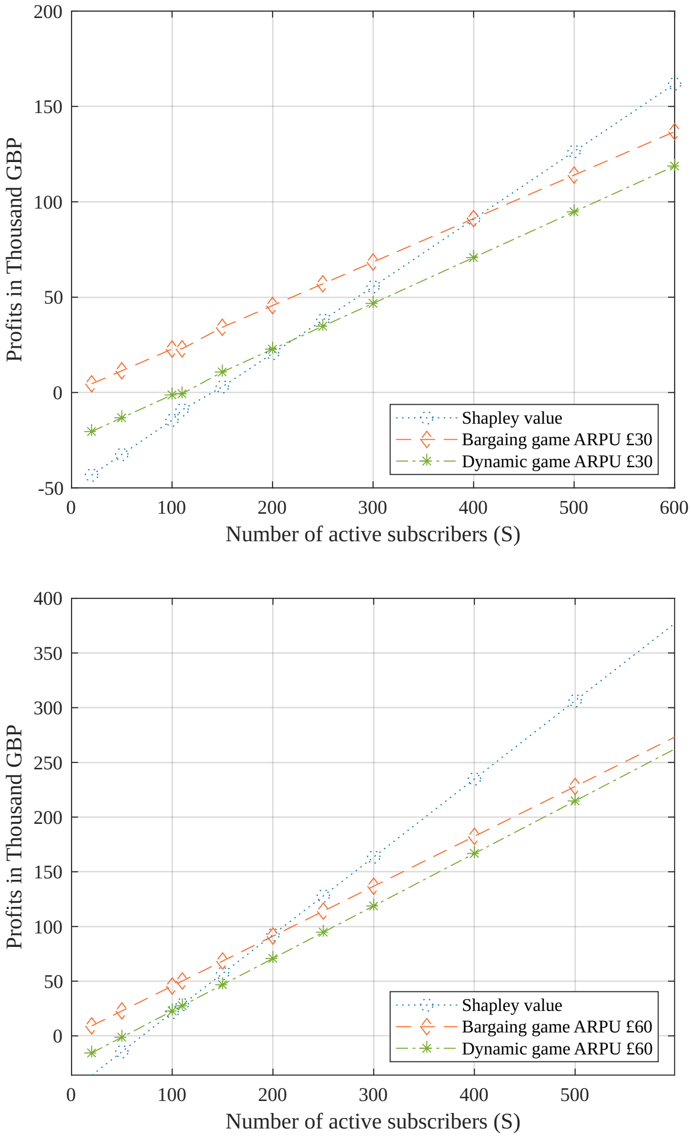


Figure 6.7: Profits for MNO player: (a) ARPU £30 (b) ARPU £60

6.5 Discussions

This chapter explores the need for game theory to better understand the various strategies that could be selected by the InP and the MNO when deciding whether to invest in rural 5G NHN and the potential cost allocation strategies. A generic decision-making game theory framework is proposed, used to study the InP-MNO interactions in any rural scenario with no existing or poor coverage. The best way to penetrate the rural market while bridging the digital gap and attracting businesses was then investigated using the InP-MNO investment games. The different pricing strategies using the game theory model have been analysed to determine the profits and risks associated with rural 5G NHN. The InP-MNO could consider either applying the Shapley value (fixed rent), bargaining games with pricing mechanism (variable rent with truthfulness and punishment) and dynamic pricing (a combination of the previous two techniques) to model the cost allocation between them, dependent on their expected revenue and risk appetite. On successful discussions, the InP and MNO agree on the cost allocation strategy and establish a business, enhancing connectivity in rural areas requiring fewer subsidies and becoming feasible for a low number of subscribers.

Results show that the dynamic pricing (with price variation over a period of time) for the rural 5G NHN business model makes rural connectivity an attractive option for stakeholders in these regions. These simulation tools allow stakeholders to analyse the suitability, feasibility and profitability of the rural 5G NHN business. The developed models are country agnostic. As the input parameters vary, the model allows the InP and the MNOs to assess the different investment options and cost allocation models to select the best strategy with the highest payoff. While 5G NHN has the characteristics to transform the feasibility of rural connectivity business into an affordable reality. The dynamic pricing model has a scope for the InP-MNOs to tap into a newer revenue stream in rural areas.

In reality, the practical usage of the pricing strategies is dependent on the policymakers. Both the InP and MNOs would ideally not want to disclose their detailed calculations for any deployment. However, the stakeholders can roughly estimate the overall cost as they could be an InP in a different location. Shapley would only be implemented in scenarios with ultra-low subscribers' scenario and the policymakers would ensure that there is fair competition with rational players. Furthermore, implementing real-time dynamic pricing is a major challenge that a regulator might not want the operations of 5G NHN to become highly dependent on the market scenarios. Hence, dynamic pricing with long-term variations is a better-suited solution with InP and MNOs handling the decision making regarding pricing strategies themselves.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

The goal of this research is to explore how 5G neutral host networks using network slicing technology could help to bridge the digital divide, identifying cost-effective solutions that would increase the connectivity of the remaining 36% of the world's unconnected people in general.

The central questions for this research were as follows:

- Which technologies have the potential to boost rural connectivity whilst also supporting the ITU's 30 Mbps target yet being a cost-effective and self-sustaining alternative for large-scale deployment?
- What is the cost-effectiveness of the 5G network sharing technologies for deployment scenarios, for example, in a high ARPU market with low subscribers, and in a subscriber market with low ARPU?
- What pricing strategies work best for network sharing in rural areas?

5G NHN is a potential solution for rural connectivity based on the literature review presented in Chapter 2 and stakeholders' view in Chapter 3. The viability of 5G, its KPIs, and the cost associated with it in rural areas are highly sensitive to the demand parameters such as the number of subscribers and ARPU. These factors range from low to moderate in rural and remote rural areas which encourages the need for innovative strategies such as infrastructure sharing to lower the overall cost of deployment. Based on a quantitative and qualitative analysis of rural 5G NHN, it can be concluded that the end-to-end sharing of the rural 5G using network slicing reduces the cost by at least 50% compared to the *No Sharing* scenario and improves the

QoS of the rural wireless broadband. The results indicate that co-existing of multiple operators as slice tenants on a single network improves the network viability as the cost per site per operator is now significantly lower. With the use of network sharing, this approach will support telecommunication as a service, a novel idea that is gaining popularity globally.

7.1.1 Main conclusions

Importantly, this research helps to address the weakness of network slicing that was discussed in Table 2.2 in Chapter 2. This research focuses on the technological implementation of 5G network slicing for rural scenarios, supporting policies to encourage infrastructure as well as spectrum sharing strategies such as NHN, and the potential feasibility offered by considering the adoption rates and realistic demand.

This study offered a broad overview of 5G network slicing supporting NHN: covering when NHN is applicable, how NHN is useful, and who may be able to facilitate NHN. The findings discuss various aspects of network slicing in rural areas such as neutral host networks, technological implementation, stakeholders' viewpoints, business models, KPIs, spectrum regulations, policies for infrastructure sharing, techno-economic feasibility, sensitivity models, case studies on the application of the proposed solutions, investment study, and pricing strategies. Next, techno-economic results on the quantitative analysis of the rural 5G NHN approach in rural parts of the UK and India were presented and compared against the traditional deployment strategies. The results obtained indicate that providing wireless broadband using rural 5G NHN is offering a cost savings of at least 50% compared to the traditional strategy of *No Sharing* in both countries, which helps in deploying a self-sustainable rural network and potentially high returns on investments.

Firstly, the technical components and business roles of the stakeholders are proposed that would utilise the functionalities of 5G NHN with network slicing and spectrum sharing for rural connectivity, which helped to model the network architecture of rural 5G NHN. The key benefit of the NHN model is to share risk with other operators and lower the investment in areas with uncertain demand and low traffic generation. Though the operators might have to share the profits, it is ultimately going to help in lowering their debt. Secondly, the lower cost per operator would encourage improving the overall QoS and quality of experience (QoE) of the end-users in rural areas as the competition now shifted towards a QoS/QoE based rather than infrastructure based. Thirdly, the proposed solution helps to minimise duplication of resources and carbon footprints as all operators co-exist on a single infrastructure which helps in achieving the UN's sustainable goals 8, 9, 10, and 11. Fourthly, the deployment of rural 5G NHN by the InP would alleviate the burden on the MNOs to establish a rural telecommunication network. Finally, investment games help the InP and MNOs in deciding whether rural 5G NHN in the target area is worth entering or not; while the pricing strategies help the InP and MNO select a suitable cost sharing model base on the demand estimations as well as expected techno-economic requirements. The suitability of the pricing strategies is subject to demand factors such as ARPU and the number of subscribers.

7.1.2 Other conclusions

Beyond these key conclusions, the following research results were attained:

- The perspectives of stakeholders on rural connectivity, reinforce the concept of leveraging rural 5G NHN to bridge the digital divide. They are eager to investigate this idea for solutions beyond rural areas as well.
- Rural 5G NHN is highly dependent on the stakeholder (InP, MNO, industry, and community), who would be driving the technological solution in rural areas as significant investment and expertise are required in establishing it. Each stakeholder has a unique role to play depending on who is driving the solution. The business models for the rural 5G NHN would have to consider factors such as use cases served, kind of slice tenants and their tenure on the network, revenue streams, deployment challenges, and other legal aspects.
- To realistically model the feasibility, the rural 5G NHN focuses on eMBB requirements, and network take up is expected to be 40% of the population. Since 5G NHN is likely to be deployed by an InP and shared among the slice tenants in that region of interest, the spectrum costs in the study use the estimated cost of localised spectrum sharing opportunities.
- In the sensitivity analysis for the *UK scenario*, the third most sensitive factor is OPEX because of high operational costs over an extended period, difficulty in getting skilled workers, minimum wage requirements, inflation, and additional factors. On a different note, as telecommunications equipment is typically imported, which raises the CAPEX cost, the similar sensitivity analysis in the *Indian situation* revealed that CAPEX is the third most significant component.

- Findings using the game theory models would help firms decide on policies governing network sharing in rural areas.
- To increase rural users' digital literacy, there is a need to create digital awareness and offer training. To increase digital literacy in rural areas, the model could use a slice to provide free basic connectivity similar to the work done by Noll and Dixit in [54]. However, rural 5G NHN should aim to attract users to buy the 5G services to drive and increase revenues with an initial goal to improve the feasibility.

Based on these conclusions, practitioners should consider using rural 5G NHN as a potential solution to tackle the digital divide, and appropriate policies should be formulated to support the deployment. The five main policy regulation drivers are consumers, market economics, industry, policy and regulations and technology. The research presented in the thesis represents one of the five levers - technology that can be pulled to change policy and influence outcomes for rural telecommunication policies and rural spectrum licensing. The work could be used to lobby/influence regulators to consider the adoption of new policies to advance rural connectivity.

7.2 Future Works

There is a wide range of possibilities for further research and development of the work presented in this thesis. It is worth noting that all research is performed assuming that MNOs are attracted to earn revenue from the untapped market. As part of future work, it is important to engage with MNOs and obtain their practical views on 5G NHN for each potential location. This would be part of an actual business plan for collaboration between InP and MNO.

To better understand the implications of these results, future studies could address:

- The practical deployment of rural 5G NHN would answer most of the questions proposed by stakeholders, such as slice isolation, slice security, dynamic resource allocation, MNO competition, government policies, spectrum sharing, o-RAN, and remote monitoring and maintenance of the network.
- The study can extend to explore the legal procedure (paperwork) to support rural 5G NHN, the impact of a third party on NHN deployments, the interface between InP and MNO core, the impact of private and public networks on a single physical infrastructure and pricing policy for different slice tenants.

- Chapter 4 research work can be extended to assess the business models for applications such as when the tenants are on the network for different duration, MNOs enter the InP network sequentially rather than simultaneously, ISPs use the InP network for providing broadband services, and private network deployments for industry verticals. Local enterprises in rural locations might be interested in business models that use industry verticals as an InP; this is something that might be investigated.

- The business model can also explore the scenario with multiple InPs to provide internet service in the same region. The impact of adding small cells, micro cells and femto cells can also be explored.

- Chapter 5 work could be extended to study the impact of rural 5G NHN in different countries. It would give a bigger picture regarding the feasibility of rural 5G NHN in generic settings.

- Future studies could explore the technological aspects of reliable network slicing, the impact of massive MIMO in rural areas, and MNOs' control on resource allocation and smooth handover for their end-users.

- The UK and India techno-economic study can also be extended to include other scenarios and study their impact such as government subsidies and community benefit schemes.

- Subsequently, an interesting area of study could be using different spectrum sharing technologies and their impact on the cost of the network. The risk analysis for spectrum sharing would provide information on various techno-economical challenges and frequency allocation of different rural 5G NHN cells could be a potential topic for research.

- Chapter 6 can extend to model different strategical interactions for each scenario model and VNC to evaluate the best possible strategy for InP-MNO games, pricing, and costing could be incorporated to influence the dynamic resource allocation that is useful to delve deeper into the cost allocation model. This could be potentially another PhD research topic as dynamic pricing allocation with dynamic resource allocation is a highly complex application and uses NP-hard optimisation.

- An additional extension of research could include the calculation of the resources deployed and their impact on profit maximisation on the InP, as well as resource allocation for end-users, and cost minimisation for MNOs. This would involve optimisation at different stages and the usage of Stackelberg games to model the InP-MNO resource allocation game.

7.2.1 Ongoing future work

The impact of existing infrastructure sharing in rural areas then need more study while considering the brownfield 5G deployments. As part of the summer internship and later research collaboration as a Visiting Faculty at George Mason University, I have been working with Prof. Edward J. Oughton on the above question by studying the suitability of rural 5G NHN in an infrastructure upgrade scenario. As part of this study, the existing rural infrastructure in various countries was explored in terms of macro and small cells. The four network sharing strategies in the upgrade of the 5G network are “No sharing”, “Passive sharing”, “Active sharing”, and “5G NHN”, as shown in Fig. 7.1. Several studies have highlighted the massive debt on the world’s telecommunications infrastructure [292, 303–306], and the existing infrastructure makes the techno-economic feasibility model highly complex. Therefore, the inputs for studying the techno-economic analysis are dependent on the existing infrastructure, debt, and potential future demand.

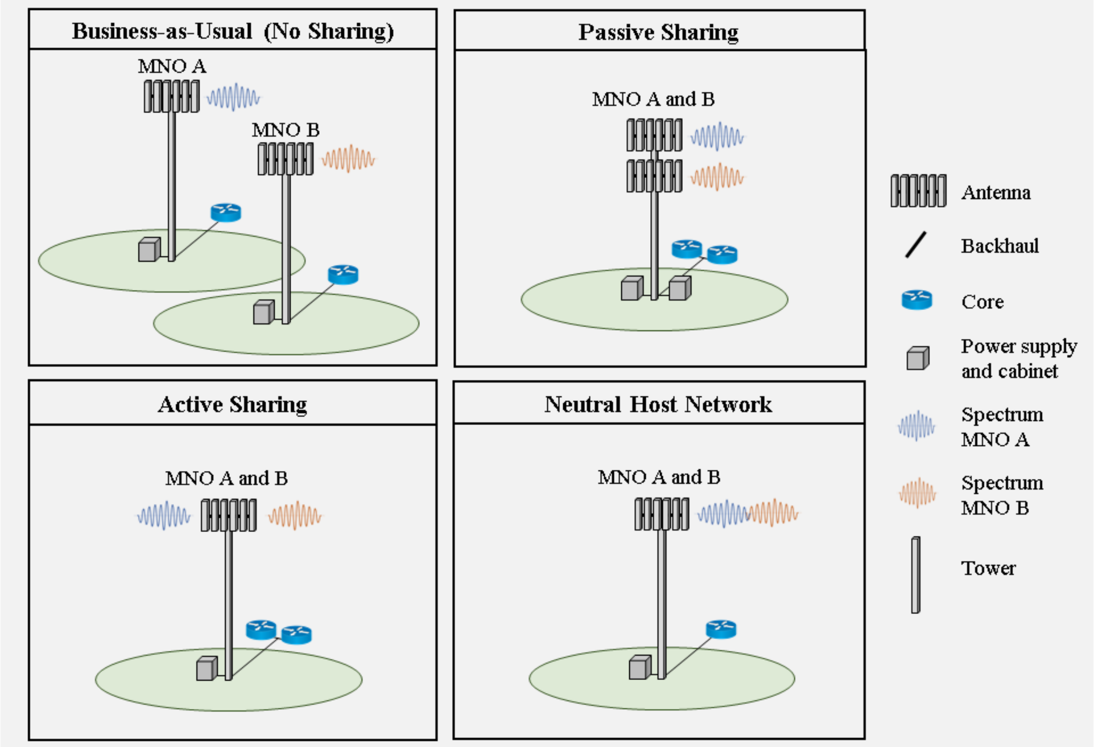


Figure 7.1: Network architecture of various sharing strategies of 5G upgrade: (a) No Sharing; (b) Passive Sharing; (c) Active Sharing; (d) 5G NHN

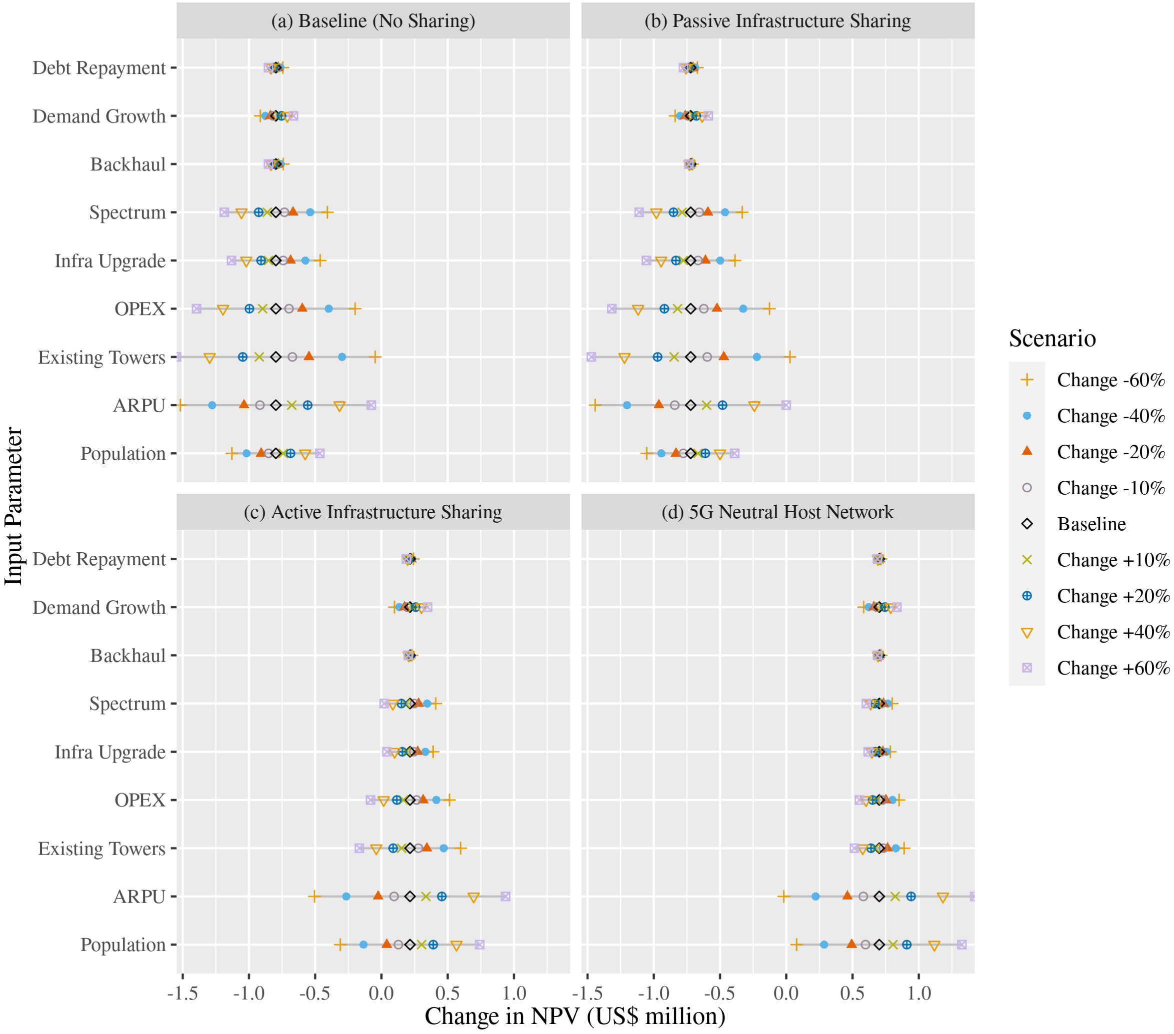


Figure 7.2: Sensitivity analysis of sharing strategies

The study estimated the potential sites that would need to be upgraded under different network sharing strategies and have an outstanding debt. The output of the study, Fig. 7.2, shows that the suitability of the model is highly dependent upon the ARPU, subscribers, competition among the operators, trust, and existing infrastructure that needs to be upgraded. Furthermore, this model is extended to the urban scenario as well. The journal written by Oughton and me [149] and [307] includes the study of the suitability of pricing strategies ranging from rural to urban scenarios.

7.3 Concluding View Points

Rural connectivity is a wide topic, as no one solution fits all the scenarios. Many technologies are being explored other than network slicing, such as satellites, drones, HAPS, ORAN, HIBS, FWA, and Wi-Fi. Besides technological advancement, the primary driving force for scalability is the stakeholders' ability to profit economically.

Appendices

Appendix A

Game Theory

A.1 Equivalence to a Rubinstein Bargaining Game

Assume a game of offers and counter-offers between two players, $\pi_i^r(t)$, where $i\varepsilon[1,2]$ and t indicates the time of the offer, for the partition of the cake, of the initial size of π^r. The bargaining offers continue till an agreement or disagreement of the offer is decided.

At the end of each bargaining period without an agreement, the cake is decreased by a factor δ_i. If the bargaining times out, each player's payoff is 0. offers can be made at time slot $t\varepsilon N_o$. If the two players reach an agreement at $t > 0$, each receives a share $\Pi_i^r(t)t\delta_i$, where $\delta_i\varepsilon[0,1]$ is a player's discount factor for each negotiation period that passes without an agreement being reached. The following equation gives the payment partitions of the two players:

$$\pi_1^r(t)t\delta_1 = \Pi^r - \pi_2^r(t)t\delta_2 \tag{A.1}$$

So, if an agreement is reached in the first negotiation period, then the payment partition is as follows:

$$\pi_1^r(t) = \Pi^r - \pi_2^r(t) \tag{A.2}$$

The payoff U_i^r of the player $i, j\varepsilon[2]$ if the agreement is reached in iterations t is

$$U_i^r(t) = \pi_i^r(t) = \Pi^r - \pi_i^r(t). \tag{A.3}$$

Such a game is called the Rubinstein game.

A.2 Payment Partition Games

For a fixed SLA guaranteed level $q \; \varepsilon \; Q$ such that a fixed payment, Π is received. The strategy set for the two players is all combinations of (π_1, π_2), where π_1, π_2, $\varepsilon \; \Pi$. All such possible pairs where there is an agreement are called S^a. Whereas all the possible pairs during a disagreement is called (s_1^d, s_2^d), when the negotiation fails. So, the strategy set is given by $H = S^a \cup (s_1^d, s_2^d)$. For any agreement $s \; \varepsilon \; ^a$, the payoff is defined as

$$U_i(s) = \pi_i - c_i. \tag{A.4}$$

Otherwise,

$$U_i(s_i^d) = 0. \tag{A.5}$$

This game is referred to as a payment-partition game.

A.3 Payment Partition

Proposition 1. Fix a specific quality q. The payment-partition game is equivalent to the Rubinstein bargaining game (discussed in Appendix A), when the agreement is reached in the first negotiation period.

Proof. Assuming that an agreement in the Rubinstein bargaining game is reached in the first negotiation period $t = 1$, then the game satisfies the following:

$$U_1^r(1) + U_2^r(1) = \Pi^r(1), \tag{A.6}$$

which is a constant. In the payment-partition game, assuming an agreement profile s, we have:

$$U_1(s) + U_2(s) = \pi_1 - c_1 + \pi_2 - c_2 = \Pi - c_1 - c_2. \tag{A.7}$$

Since $\Pi = \pi_1 + \pi_2$ and c_1, c_2 are constants for a fixed SLA guaranteed level. It follows that U_1, U_2 are also constant. it follows that the Rubinstein bargaining game and payment-partition game are equivalent.

The highest payoff is reached when bargaining agreement ends in the first negotiation period, that $\Pi^r = \Pi$, and that corresponds to the strategy profile s^* of the Rubinstein game as well as the payment-partition game. □

[246] states that even if the network has a probability of failure as p_f (either due to bad weather, network breakdown, or malicious attack), the optimal solution is the same (Theorem and proof in appendix). However, there is an effect on the payoffs of the individual player when p_f is non-zero.

A.4 Truthfulness

Lemma 2. *If provider i believes that the probability p^l_j, that is, that provider j declares the real cost than the probability p^h_j, then it is more motivated to lie, where i, j $i \neq j$*

Proof. In Table 6.1, provider 1 InP has a higher cost to provider 2 MNO, that is, $c_1 > c_2$. This is because InP will be deploying and maintaining the network whereas the MNO would lease the slices from the InP. When both of them declare their cost, the payoff for provider 1 is higher than provider 2. Hence a greater piece of the payment is assigned to the InP compared to the MNO. If provider 1 cheats, that is, lie about the cost involved and provider 2 declares the real cost, the provider 1 receives even greater piece of the payment compared to the previous scenario and $c_1^{'} > c_1 > c2$. □

Lemma 3. *If provider j believes that the probability p^l_i, that is, that provider i declares the real cost than the probability p^h_i, then it is more motivated to lie, where i, j $i \neq j$*

Proof. In Table 6.2, provider 2, MNO has a lower cost compared to provider 1, InP, thus $c_2 < c_1$. When both players declare their real cost, provider 2 receives a lower payment piece compared to provider 1. However, when provider 2 lies about its cost and shows a higher cost compared to the real cost then provider 2 receives a higher payment piece compared to previous scenario and $c_1 > c_2^{'} > c_2$. Hence, provider 2 is more motivated to lie. □

Appendix B

Calculation of an Individual Pricing scenario

In this section, we apply the concepts explored in this study for a UK greenfield deployment. First, we study the pricing strategies for the players (MNO and InP) by varying the subscribers and, then explore the three pricing strategies for the two players. Lastly, we apply Nash equilibrium to find the most rational output for the two players.

B.1 Pricing Strategy for the Players

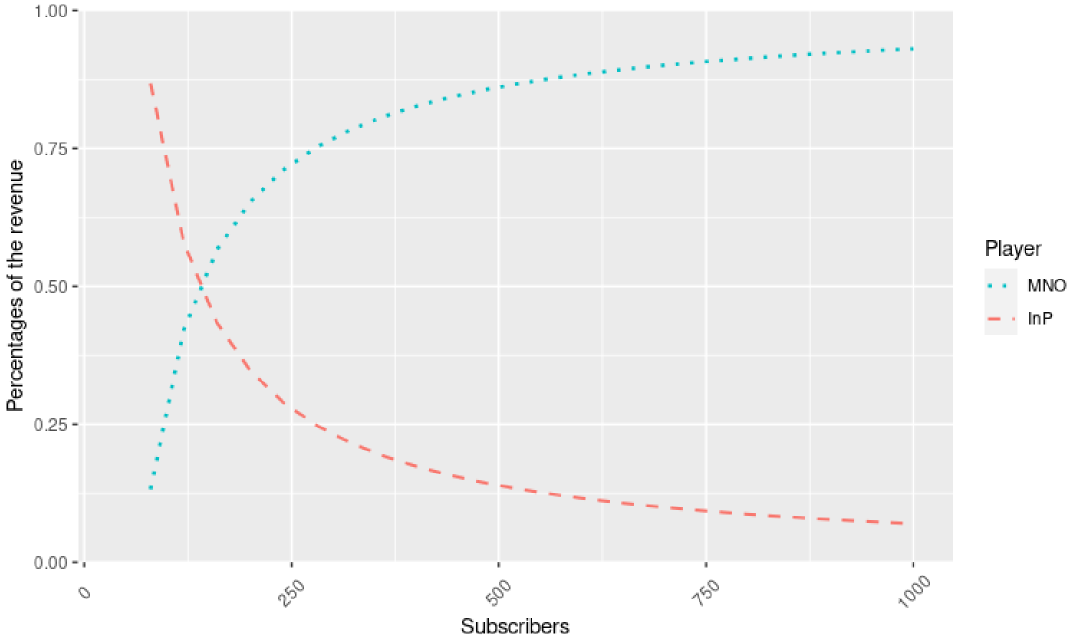


Figure B.1: Percentage of the revenue share calculator for the InP and MNO

For a greenfield deployment, Fig. B.1 shows the calculations for the InP and the MNO percentage calculations of the revenue share wrt to expected revenue from the end-users at ARPU £30. In this estimation, the subscribers are increases to understand the revenue distribution among the two players at a break-even scenario for the InP. When the subscribers are low, the percentage of the revenue would potentially be very high for the InP and minimal for the MNO. As the subscribers increase, the MNO would potentially take out most of the revenue earned from providing telecommunication services in rural areas.

Table B.1: Percentage cost allocation for the players

Player	**InP**	**MNO**	**InP risk**	**MNO risk**
Shapley value	Fixed value	$\geq$ fixed value	minimal	maximum
Bargaining games	40%-60%	40%-60%	maximum	minimal
Dynamic pricing	30%-40%	60%-70%	moderate	moderate

By assessing the possible demand and risks involved in the deployment of rural 5G NHN, providers select the best type of revenue sharing percentages among the players. Table B.1 shows a summary of different revenue sharing percentages between the InP and the MNO for the revenue generated by end-users between the InP and the MNO with the risk involved in each game theory method. In Shapley value, there is a fixed price that an MNO needs to pay the InP irrespective of the gains/loss. Whereas, in the other two cost allocation models, the percentage is negotiated based on the expected returns from the 5G NHN networks.

B.2 Shapley Value Output

As discussed in section 5.2 and 6.2, for a generic greenfield rural deployment the TCO for InP supporting 5G NHN inclusive of network slicing costs catering to the dedicated requirements of all slice tenants, is around £415,123 and the expected revenue could be around £505,122 for the InP. Table B.2 summarises the TCO for InP and MNO ranging from setting their networks and/or with some form of sharing to 5G NHN. The MNOs share the rent paid towards the InP, that is, the InP's expected revenue.

Table B.2 shows the cost of each MNO varies based on their network requirements. Assume four MNOs (A, B, C, and D) and one InP are part of the rural 5G NHN. The average cost for an independent network for an MNO as per data in [46, 50, 57, 62, 287] is around £500,000 for a village that requires a 5G network having 10 km fibre backhaul with 10-years of investment. Hence, the cost of an independent 5G network for MNOs is £450,123 for operator A, £500,687

Table B.2: Shapley value costs for single site 5G NHN in rural areas

MNOs participating	**InP Cost**
v(A)	£450,123
v(B)	£500,687
v(C)	£525,755
v(D)	£500,233
v(A,B)	£459,202
v(A,C)	£501,402
v(A,D)	£530,413
v(B,C)	£500,623
v(B,D)	£550,111
v(C,D)	£534,623
v(A,B,C)	0
v(A,B,D)	0
v(A,C,D)	0
v(B,C,D)	0
v(A,B,C,D)	£505,122

for operator B, £525,755 for operator C, and £500,233 for operator D. The operators can deploy their network by collaborating with another MNO. Network sharing with another operator is attractive because the network doesn't reach its full potential Hence, the cost of two sharing 5G networks, not multi-tenancy, is £459,202 - operators A and B, £501,402 - operators A and C, £530,413 - operators A and D, £500,623 - operators B and C, £550,111 - operators B and D, and £534,623 - operators C and D [46]. There is no data on three operators network sharing without multi-tenancy, therefore, consider it zero. The network deployed by the InP with service differentiation for MNO requirements and services for 5G NHN in rural regions costs £505,122. These data is given as input to the (6.2) and the outputs are as shown in Table B.3.

Table B.3: Shapley value output for 5G greenfield macro-cell NHN

MNO	**Cost**
v(A)	£103,730
v(B)	£123,730
v(C)	£136,541
v(D)	£141,117

From Table B.3 observations, cost per MNO in 5G NHN reduces exponentially to provide services in rural with savings of around 66% compared to a "No sharing" strategy of deployment. The cost for each operator in rural 5G NHN are - £103,730 for operator A, £123,730 for operator B, £136,541 for operator C and £141,117 for operator D. This pricing strategy is attractive when the overall revenue from the network is low and the MNOs are cooperating to reduce the digital divide.

B.3 Bargaining Game Output

Assume, the cost per month per subscriber for the MNO varies from £12 to £15 when truthful and £15 to £18 when lying. Similarly, the cost per month per subscriber for the InP varies from £6 to £9 when truthful and £9 to £12 when lying. When the provider lies, they claim 10% more than the actual cost. In this case, unlike in [246], the investigation is done when the players are declaring unequal costs while lying.

Table B.4: InP's and MNO's payoff payment for all strategies possible in the UK

	MNO			
	C	*D*	*C/D*	*Cheat-if-beta-high*
InP				
C	£11, £19	£19, £11	£15, £15	£11, £19
D	£7, £23	£15, £15	£11, £19	£8, £22
C/D	£9, £21	£17, £13	£13, £17	£10, £20
Cheat-if-beta-high	£10, £20	£18, £12	£14, £16	£11, £19

Table B.4 shows that the bargaining game with pricing mechanism helps the providers in determining the payment received by each of them. Also, by using a pricing mechanism, the players are motivated to declare the truth. The percentage share of the InP and the MNO is proportionate to their investment in the network and the network's corresponding demand. The cost per MNO is dependent totally on the number of subscribers served by the MNO and the traffic generated by these subscribers indirectly. At lower profits, the InP incurs a loss in this method.

B.4 Dynamic Pricing Output

The cost allocation in this type is slightly complicated as the risk needs to be shared between the InP and MNO to attract investments and provide digital services in rural areas. Assume, the cost per month per subscriber for the MNO varies from £12 to £15 when truthful and £15 to £18 when lying. Similarly, the cost per month per subscriber for the InP varies from £6 to £9 when truthful and £9 to £12 when lying. When the provider lies, they claim 10% more than the actual cost. In this case, unlike in [246], the investigation is done when the players are declaring unequal costs while lying.

Fixed cost per year - Shapley value

Suppose the fixed rent paid to the InP account was 50% of the TCO (i.e. £25,000) for the year *i* paid by all the MNOs. There are four MNOs providing service in that area for the UK scenario network. Assume that each MNO expects different QoS and SLAs from the InP network. The additional cost in providing the SLAs of the MNOs is as shown in Table B.5.

Table B.5: Fixed cost per year calculations using Shapley value

5G NHN	**add A**	**add B**	**add C**	**add D**	**Shapley value**
Marginal cost	£12,500	£2,000	£3,000	£7,500	
cost A	£3,125				£3,125
cost B	£3,125	£667			£3,792
cost C	£3,125	£667	£1,500		£5,417
cost D	£3,125	£667	£1,500	£7,500	£12,917
Total					£25,251

For calculations of fixed cost per MNO, use the Algorithm 1. The costs incurred per MNO A, B, C, and D are £3,125, £3,792, £5,417 and £12,917, respectively. It shows that the MNO having the highest requirements would be paying the highest rent for receiving services with the highest SLAs and catering to the maximum end-users. The overall fixed cost is generally shared among all the tenants on the network for that financial year. Furthermore, future works could consider the complex calculations of varying fixed costs per quarter or dynamically.

Variable cost per year - bargaining games

For dynamic pricing, the percentage allocation for the InP using bargaining games is as shown in Fig. B.2. The revenue sharing per end-user is lower for the InP in this scenario compared to the only bargaining scenario due to fixed payment. Let's consider the UK greenfield macro-cell scenario with an ARPU of £30 and an investment duration of 10 years.

Fig. B.2 shows that the InP would receive a share of around 10% of the revenue generated by the end-users. Furthermore, Table B.6 shows the results impact of the pricing mechanism for computing the variable cost and the cost allocations in dynamic pricing.

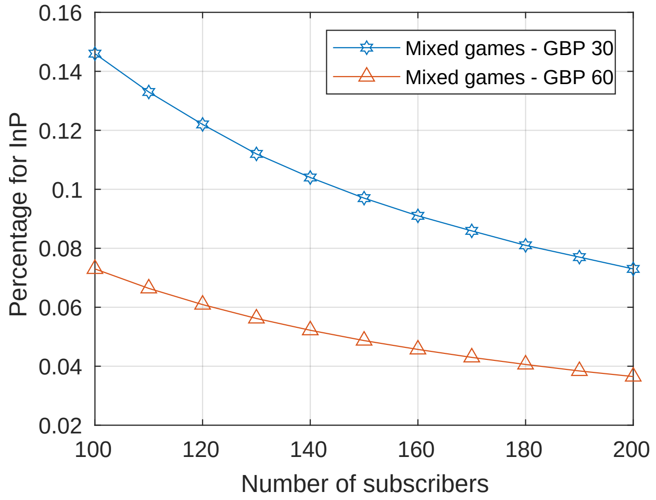


Figure B.2: Dynamic pricing percentage calculations

Table B.6: InP and MNO variable cost allocations in dynamic pricing

	InP			
MNO	*C*	*D*	*C*/*D*	*Cheat-if-beta-high*
C	£23, £7	£25, £5	£24, £6	£22, £8
D	£13, £17	£15, £15	£14, £16	£12, £18
C/*D*	£18, £12	£20, £10	£19, £11	£17, £13
Cheat-if-beta-high	£22, £8	£25, £6	£23, £7	£21, £9

Cost per MNO

In real-life situations, no player is 100% truthful or 100% telling lies. Therefore, consider the 'cheat-if-beta-high' scenario for this study. Assuming there are around 200 subscribers in a village when the InP and MNO follow the 'cheat-if-beta-high' strategy, then the cost per MNO is as shown in Table B.7. Assume that the number of subscribers per MNO is directly proportional to the fixed cost and the demand estimate of each MNO. This study considers retail customers only. Hence, based on the Shapley value obtained in Table B.5, the number of subscribers for MNO A, B, C and D are 25, 30, 43, and 102, respectively.

Table B.7 shows the total cost per MNO for the year *i* charged as rent by InP for using the slices to provide 5G services to their end-users. It also shows that each MNO only pays for the service used by them. This cost allocation technique significantly reduces the risk both for the InP and the MNO. For the scenario considered, the cost for MNO A, B, C and D is £7,122, £8,588, £12,131 and £29,223, respectively. The InP can earn higher revenues, when there are higher subscribers in dynamic pricing than the Shapley value scenario. InPs and MNOs alike

Table B.7: Total cost per MNO per year in the UK model scenario

Player	**Fixed cost**	**InP share per £30**	**Subscribers**	**Variable cost**	**Total cost**
MNO A	£3,125	£9	25	£3,997	£7,122
MNO B	£3,792	£9	30	£4,796	£8,588
MNO C	£5,417	£9	42	£6,714	£12,131
MNO D	£12,917	£9	102	£16,306	£29,223
Total	£25,251			£31,813	£57,064

will find dynamic Pricing attractive when the subscribers range from 100 to 400.

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