ICRIER AND VODAFONE IDEA CENTRE FOR TELECOM

RE-EVALUATING SPECTRUM REGULATION: 5G AND BEYOND

Report

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MARCH 2026

Re-Evaluating Spectrum Regulation: 5G and Beyond

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March 2026

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Glossary

Acronym	Explanation
3GPP	The **3rd Generation Partnership Project** is a collaborative project between a group of telecommunications associations, set up with the initial goal of developing globally applicable specifications for third- (3G) and future-generation mobile systems.
5G	**Fifth-generation network**. Fifth-generation wireless is the latest iteration of cellular technology, engineered to significantly increase the speed and responsiveness of wireless networks. The 3GPP standards committee migrated from 4G LTE to next-generation 5G in 3GPP Release 14 in 2016. The New Radio (5G NR) requirements for 5G communication networks were defined in 3GPP Release 15, which started in 2017 and concluded in 2018.
5G+	**5G and beyond networks** that include the currently deployed 5G networks and 6G networks and services to be standardized by 2030.
5G NR	**5G New Radio** is a radio access technology developed by 3GPP for the 5G mobile network and defines the global standard for the air interface of 5G networks.
5G NR-U	**5G New Radio – Unlicensed** is a 5G version of the 4G LTE License Assisted Access standards. NR-U is part of 3GPP Release 16, which supports 5G NR operating in unlicensed spectrum. NR-U allows 5G systems (existing carriers) to use unlicensed spectrums to offload non-critical traffic. This can help alleviate spectrum constraints and deliver better 5G experiences. NR-U is aimed at developing 5G private networks.
6G	**Sixth-generation cellular mobile technology**, standards for which will be finalized by 2030, augments the capabilities of the technology multi-fold in terms of performance and applications.
AGR	**Adjusted gross revenue**. The gross revenue accruing to telecom licensees by way of operations of the cellular mobile service as per their license conditions
API	**Application programming interface**. A set of functions and procedures allowing the creation of applications that access the features or data of an operating system, application, or other service.
ASA	**Authorized shared access**, where the spectrum assigned/earmarked for government/other users on a primary basis could be used by access service providers on a secondary basis.

CBRS **Citizens Broadband Radio Service**. A mobile service operating mainly in the US in the Federal Communications Commission authorized band of 3550–3650 MHz, currently used for military and satellite communication in shared-use mode.

CCA **Combinatorial clock auction**

CDN **Content delivery network**. A system of distributed servers (network) that delivers pages and other web content to a user based on the user's geographic location, the webpage's origin, and the content delivery server.

CNPN **Captive non-public networks** are deployed mainly for enterprise use, either by mobile network operators (MNOs) or non-MNOs, using spectrum that is exclusively allocated or otherwise. CNPNs, by definition, shall not be connected to the public switched telephone network/public land mobile network or the internet.

DoT **Department of Telecommunications**, a unit of the Ministry of Communications of the Government of India, with a vision to provide secure, reliable, affordable, and high-quality converged telecommunication services anytime, anywhere for accelerated inclusive socioeconomic development.

DSM **Dynamic spectrum management** dynamically allocates radio spectrum resources based on current demand and network conditions. Using machine learning and artificial intelligence techniques can enable the network to adapt to changing traffic patterns and dynamically adjust the allocation of spectrum resources.

FCC The **Federal Communications Commission** is an independent agency of the US federal government that regulates communications by radio, television, wire, satellite, and cable across the US.

FWA Telecom carriers use **fixed wireless access** to provide broadband access to homes using a fixed antenna connected to 5G networks using high frequencies. The carriers call these "air fibre" as they provide high bandwidth, similar to optical fibre cables, using wireless technologies.

GLDB **Geolocation database**, which stores spectrum usage details across space and time and is queried for possible sharing by secondary users.

GSM **Groupe Speciale Mobile (Global Systems for Mobile)**. A public all-digital cellular network standard using transmission bands around 900 MHz, 1800 MHz, and 1900 MHz, developed by the European Telecommunication Standards Institute. Besides telephony services, a GSM network can provide short messaging services and data communication in circuit and/or packet mode. The GSM Association represents the corresponding interest group.

IAB **Integrated access and backhaul** is a key 5G NR feature defined by 3GPP, primarily in Release 16 and enhanced in subsequent releases. It allows radio spectrum to be used simultaneously for wireless backhaul (connecting to the core network) and access (serving end users), enabling dense and cost-effective network deployments

IEEE — **Institute of Electrical and Electronics Engineers**. The world's largest professional association dedicated to advancing technological innovation and excellence for the benefit of humanity.

IoT — **Internet of Things** refers to the collective network of connected devices and the technology that facilitates communication between devices and the cloud.

ISP — **Internet service providers**, who have a licence or authorization to provide internet access services. However, they cannot provide traditional voice communication, much like Telecom and Internet Service Providers, due to licence restrictions.

ITU — The **International Telecommunication Union** is an agency of the United Nations that coordinates telecommunication operations and services worldwide.

LAA — **Licensed assisted access** was introduced in Release 13 of the 3GPP specification to enable the operation of an LTE system in an unlicensed band. LAA combines an LTE carrier in the unlicensed spectrum with an LTE carrier in the licensed band using carrier aggregation.

LBT — **Listen Before Talk** is a technique that listens to a channel before sending or receiving communication signals to avoid possible interference and is deployed in recent Wi-Fi systems and 5G NR-U as mandated by regulators in certain countries.

LSA — **Licensed Service Area.** There are 22 LSAs in India, divided across four categories: metro, Category A, Category B, and Category C. The licences are given for providing telecommunication (mobile/landline) and internet services for each LSA.

LSA — **Licence Shared Access**, widely deployed in Europe, providing secondary access to spectrums held by the government and other users. The technology approved by the European regulator uses a spectrum geolocation database to provide secondary access on a non-interference basis.

LTE — **Long-Term Evolution**. Next-generation 4G technology for GSM and CDMA cellular carriers. Approved in 2008 by 3GPP with download speeds up to 173 Mbps.

MeITy — **Ministry of Electronics and Information Technology, Government of India**

mm Wave — **Millimetre wave,** with frequencies in the range of 15–80 GHz, used for various purposes, such as backhaul, fixed wireless access, and satellite communication.

MNO **Mobile network operators,** who are licensed to provide cellular mobile communication services.

MNP **Mobile number portability**. The facility to keep the same mobile number while switching (porting) to a different operator/geography/service.

MTC **Mobile termination charges** are paid to the terminating mobile carrier for calls originating either domestically within a country or in a foreign country.

MVNO **Mobile virtual network operator.** A licensed mobile service provider typically leases/rents spectrum and other facilities from an MNO to provide mobile communications and internet services.

NFAP **National Frequency Allocation Plan** periodically prepared by the Wireless Planning and Coordination Wing of the Department of Telecommunications to designate different spectrum bands for different usages.

NPV **Net present value** is used to calculate the current value of a future stream of payments from a company, project, or investment. To calculate NPV, the timing and amount of future cash flows need to be calculated and a discount rate equal to the minimum acceptable rate of return selected.

NSO **Network service operator** that leases network services on a wholesale basis to virtual network operators.

NTN **Non-terrestrial networks** that include both geostationary and non-geostationary satellite systems that provide communication services to fixed or mobile terminals and ground stations and provide additional coverage, mostly supplementing terrestrial cellular mobile networks.

NTP **National Telecommunications Policy of India**, released by the Government of India, that provides broader policy goals and objectives for the telecom sector in the country. Versions of NTP were released in 1994, 1999, 2018, and most recently, draft NTP 2025.

PLMN **Public land mobile network.** The mobile telecommunication network that provides voice/data services.

PNSA **Private network service area** is a geographically granular area in which private networks can be developed to suit the specific needs of industries, such as in airports, ports, special economic zones, and industrial parks.

PSTN **Public switched telephone network.** A telecommunication network that typically has wireline access and provides voice/data services.

QoS **Quality of service.** Uses mechanisms or technologies that work on a network to control traffic and ensure the performance of critical applications with limited network capacity.

SAS	**Spectrum access system.** A cloud service that protects higher-priority users by controlling lower-priority devices' operating parameters (channels or transmission power). SAS is an entity authorized and certified by the FCC to coordinate and control the operation of devices using dynamic spectrum management.
SMRA	**Simultaneous multiple-round ascending auction** is a widely used auction methodology for allocating radio spectrum to mobile operators. This method allows simultaneous bidding for radio spectrum bands across licence service areas. The Government of India has been using SMRA since 2010.
THz	**Terahertz communication** is being standardized for 6G and includes very high frequencies in the terahertz range (0.1–10.THz).
TRAI	The **Telecom Regulatory Authority of India** is a regulatory body set up by the Government of India under Section 3 of the Telecom Regulatory Authority of India Act, 1997. It is the regulator of the telecommunications sector in India.
TSP	**Telecommunication service provider.** Typically, a licensed entity that provides telephony service.
VNO	**Virtual network operator.** A licensed telecom operator typically leases/rents spectrum and other facilities to provide telecommunications and internet services.
WANI	**Wireless access network interface** is a modular Wi-Fi network architecture that enables the provisioning of public Wi-Fi, including roaming and payment, promoted by the Telecom Regulatory Authority of India to improve Wi-Fi penetration in India.
Wi-Fi	**Wireless fidelity.** Local area wireless networks based on IEEE 802.11 b/g/n standards operating in the licence-free Industrial, Medical, and Scientific radio frequency bands of 2.4 and 5 GHz. ISPs usually provide internet services using this technology.
WiGig	**60 GHz wireless network protocols**. It includes the current IEEE 802.11ad standard and the upcoming IEEE 802.11ay standard. The WiGig specification allows devices to communicate without wires at multi-gigabit speeds. Also called 60GHz Wi-Fi.

Executive Summary

Radio spectrum is a scarce national resource, but it is critical for enabling next-generation connectivity, including 5G and beyond networks, as well as emerging applications such as the Internet of Things (IoT), Industry 4.0, and machine-to-machine communications. With digital infrastructure becoming central to economic growth, spectrum allocation has to be able to meet future requirements when 6G gets standardized by 2030.

India's spectrum allocation has evolved significantly since 1994, adopting various methodologies and culminating in the simultaneous multiple-round ascending auction mechanism in 2010. Nevertheless, legacy challenges persist, including high reserve prices, unsold spectrum, spectrum fragmentation, and limited flexibility in assigning spectrum for enterprises and non-telecom users. Technological and service advances simultaneously continue to reshape spectrum demand, introducing the possibility of spectrum co-existence across mobile access, backhaul, Wi-Fi, satellite communications, and private networks in certain bands.

Recognizing that recent developments require a more flexible and forward-looking regulatory approach, this report examines global practices and proposes regulatory guidelines for India's spectrum regime. It identifies key challenges in spectrum regulation, including high reserve prices, geographic licensing issues, spectrum for captive non-public networks, spectrum co-existence, competition, and market structure. Addressing these challenges is essential to improve spectrum efficiency, enhance competition, and support widespread deployment of advanced digital services.

This report also proposes a set of policy and regulatory recommendations, including revisiting reserve prices, particularly in sub-GHz bands, to improve spectrum uptake; establishing a five-year roadmap to provide regulatory certainty; introducing more flexible licensing models, such as micro-level service areas for enterprise and private use; enabling spectrum sharing and leasing frameworks; institutionalizing leasing markets; and establishing a nationwide geospatial spectrum database to support spectrum sharing.

Further, the report proposes dedicated spectrum provisions for private networks, including spectrum carve-outs and granular frameworks for enterprise use, such as in factories, ports, airports, and campuses. Complementary use of unlicensed spectrum is also recommended for increased indoor coverage via Wi-Fi. Periodic spectrum audits and methods to assess surrender mechanisms can ensure that underutilized spectrum can be re-allocated to productive uses.

These reforms have broad strategic implications. For the government, they highlight the need to balance revenue with digital inclusion and acknowledge the need to treat digital infrastructure as an enabler in itself rather than merely as a source of revenue. For telecom operators, greater flexibility in spectrum use can reduce costs and improve service quality.

Enterprises could unlock Industry 4.0 applications, IoT, automation, smart manufacturing, and smart cities. Cumulatively, these developments would benefit customers through more rapid 5G coverage, reduced tariffs through lower spectrum costs, more reliable and inclusive rural connectivity, and improved service quality.

India’s spectrum regime is at a critical inflexion point. As the country advances in 5G deployment and prepares for 6G technologies by 2030, spectrum policy must shift from a scarcity-driven model towards a dynamic, flexible, and inclusive framework. By adopting rational pricing, enabling shared access frameworks, empowering enterprises, and promoting efficient market structures, India can achieve superior digital connectivity and march steadily towards its 2030 vision.

Acknowledgements and Disclosure

The authors would like to thank ICRIER and Vodafone Idea Centre for Telecom for funding this project, titled "Re-evaluating Spectrum Regulation: 5G and Beyond". The authors would like to place on record the data analysis carried out by Lipika Dasgupta, Research Associate at MDI Gurgaon; Ankit Parwani, T Shantanu, and Revanth Puppala, students at IIIT-Bangalore; and Siddhanth Gupta, summer intern at IIIT-Bangalore. The authors would like to thank Payal Malik, Visiting Professor, InViCT and Saloni Dhadwal, Research Associate, InViCT for their support throughout this project. We would also like to thank Rajesh Chaudhary for his contributions to the report's design and Aswathy Gopinath for her editorial assistance.

An AI-enabled digital tool was used to assist with the production of this report.

Chapter 1: Spectrum Allocation and Assignment in a 5G+ World

1. Introduction

Radio spectrum is the invisible but indispensable foundation of all wireless communications. From voice calls and high-speed mobile broadband to satellite transmissions, TV broadcasting, Wi-Fi, and even connected factory machines, every modern digital service relies on the careful management of radio frequencies. As the digital economy expands and converges across sectors, spectrum policy has come under renewed scrutiny. Policymakers, regulators, and industry stakeholders are being forced to revisit foundational questions: How should spectrum be allocated across use cases? Who should get access to it, and on what terms? And how should spectrum be priced, if at all?

Historically, spectrum management evolved in a relatively compartmentalized world since its first allocation for mobile services in 1945 in the United States (US). Broadcasting was largely analogue and one-way, while mobile networks were engineered for voice, and satellite communications served niche needs. Spectrum allocation decisions—i.e., what frequency bands would be used for which services—were made primarily at the international level through the International Telecommunications Union (ITU) and translated into national policies. Spectrum assignment—deciding who gets to use those bands—was mostly handled through administrative mechanisms, particularly for public broadcasters, government agencies, or dominant incumbents.[1]

The 1990s marked a shift towards market-based spectrum assignment, triggered by growing mobile penetration and rapid technological progress. Economists like Ronald Coase had long argued that spectrum, like any scarce resource, should be allocated via markets.[2] The rise of mobile telephony and the emergence of competitive telecommunications markets provided the political and commercial impetus to translate these ideas into action. Many countries adopted auctions of one kind of another as the preferred method for assigning access spectrum to mobile operators. Of these auction formats, the simultaneous multiple round ascending (SMRA) auction became the preferred mechanism, allowing regulators to allocate spectrum transparently while raising significant public revenues.

While auctions have now become the norm for mobile access spectrum, much of the spectrum used for other functions, such as backhaul, Wi-Fi, or satellite, continues to be assigned through administrative licensing or offered as unlicensed spectrum. This split approach is beginning to become outdated. The 5G era, and the emerging shape of 6G, has blurred the lines between access, backhaul, Wi-Fi, and satellite. Mid-band spectrum, once considered too high for mobile access, is now the most valuable means of delivering both

1 Prasad, R., & V. Sridhar. (2015). The dynamics of spectrum management: legacy, technology, and economics. *Management, 40*(3). 388–391.

2 Hazlett, T. W., Porter, D., & Smith, V. (2011). Radio spectrum and the disruptive clarity of Ronald Coase. The Journal of Law and Economics, 54(S4), S125-S165.

urban capacity and rural connectivity. The same bands are also attractive for Wi-Fi expansion and satellite gateways. Therefore, continuing to treat each category of use as a separate silo, with different rules and pricing regimes, can create allocative inefficiencies and distort investment incentives.

Spectrum is not merely a technical parameter or a public asset; it is increasingly a general-purpose input in the digital economy. Like electricity or transport infrastructure, its availability and pricing have wide-ranging implications:

- Productivity gains in agriculture, health, education, and logistics depend on ubiquitous, reliable connectivity.
- Startups and small and medium enterprises (SMEs) require low-cost access (often via Wi-Fi or shared 5G networks) to participate in the digital economy.
- Public-service delivery (e.g., digital ID, remote learning, telemedicine) relies on both licensed and unlicensed spectrum.

Data from 285 Chinese prefecture-level cities between 2011 and 2019[3] indicated that the digital economy has an overall positive impact on urban total factor productivity (TFP), not only directly but also indirectly: the digital economy facilitates the advancement of industrial structure and promotes innovation and entrepreneurship, both of which contribute to improved urban productivity. In addition, the study revealed strong spatial spillover effects: digital economy development in one city significantly enhances TFP growth in neighbouring cities, indicating regional interdependencies in digital-driven productivity gains.

This foundational role justifies pro-competitive, inclusive, and future-proof spectrum policies, such as:

- Lower barriers to entry for rural internet service providers (ISPs) and community networks.
- Unlicensed access in appropriate bands for innovation and experimentation.
- Tiered access for balancing incumbents and new users.
- Administrative pricing for infrastructure spectrum.
- Low-price regime for licensed spectrum.

In short, spectrum policy must align with broader digital development goals, not merely fiscal or commercial objectives.

This chapter aims to unpack the evolution, design, and implications of spectrum allocation and assignment mechanisms in this new world. We begin by clarifying the conceptual

[3] Prasad, R., & V. Sridhar. (2015). The dynamics of spectrum management: legacy, technology, and economics. *Management, 40*(3). 388–391.

distinction between allocation (deciding use) and assignment (deciding users), then explore how spectrum has been assigned across different types of services (mobile access, backhaul, Wi-Fi, and satellite) using a mix of auctions, administrative pricing, and unlicensed regimes. We examine innovative mechanisms like the broadcast incentive auction in the US, which allowed market forces to re-allocate spectrum from broadcasting to mobile use. We also discuss the slow evolution of secondary markets in spectrum, including sharing, trading, and tiered access models like the citizen band radio service (CBRS) framework in the US.

The central thread running through this chapter is the growing convergence of spectrum needs and the inadequacy of legacy institutional divisions to respond to these shifts. Mid-band frequencies, particularly the 6 GHz band, are a case in point. These frequencies are simultaneously in demand by mobile operators, Wi-Fi providers, and satellite service firms, reflecting the broad range of applications and rising importance of this spectrum range in enabling next-generation connectivity.

What is striking is not only that these diverse actors are targeting the same spectrum bands but also that they are often using them in similar ways. For instance, mobile network operators intend to use 6 GHz spectrum primarily for indoor coverage, operating at low power levels. As a result, both cellular and Wi-Fi systems are converging in their deployment environment (indoor), power characteristics (low), and range (short-distance coverage). Further, there is a convergence of associated use cases. Yet, in many countries, half the 6 GHz band may be auctioned to mobile operators for billions of dollars while the other half is made available to Wi-Fi services free of charge, creating stark asymmetries in pricing and rights despite functionally equivalent use cases. In such contexts, identical end users may receive similar services from mobile or Wi-Fi networks operating in adjacent parts of the same band but under radically different regulatory and economic regimes.

Similar issues arise in the case of backhaul spectrum, which forms the connective tissue of mobile broadband networks. Despite its growing importance, it continues to be allocated and priced on the basis of administrative formulas that do not account for spectrum scarcity, usage density, or opportunity cost. These mismatches between evolving technological and economic realities on the one hand, and legacy spectrum management institutions on the other, highlight the urgency of revisiting spectrum assignment frameworks in light of the convergence of use cases, architectures, and deployment patterns across technologies and industries.

We argue that spectrum should increasingly be treated as a general-purpose input, akin to energy or transport infrastructure, in the digital economy. This perspective implies that spectrum should be made widely and affordably available across sectors and applications, even if that means lowering reserve prices in auctions or subsidizing spectrum access for targeted users. In a world where connectivity is critical for education, health, commerce, and innovation, the affordability and availability of spectrum become a broader public policy concern.

The chapter concludes by outlining policy recommendations for 5G and beyond, including auction design reforms, increased use of flexible and hybrid assignment models, expansion of secondary markets, and a more integrated approach to mid-band management across access, Wi-Fi, backhaul, and satellite. Ultimately, spectrum policy must move beyond a revenue-maximizing mindset towards one that promotes inclusive, innovation-friendly, and resilient digital infrastructure.

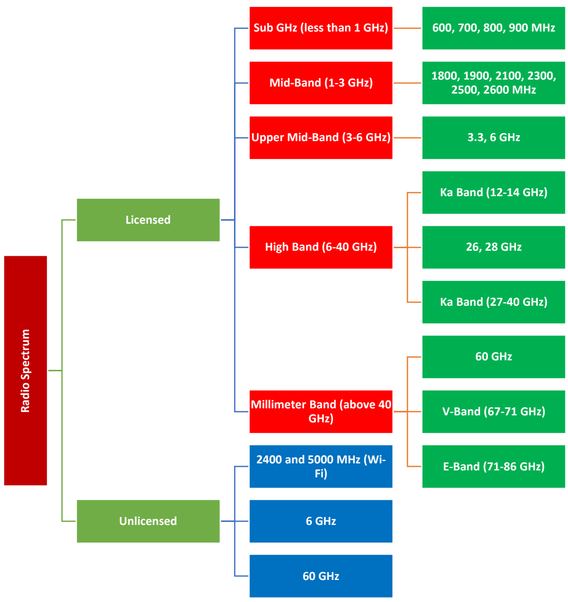
2. Spectrum Bands for Mobile Services

Radio spectrum refers to the part of the electromagnetic spectrum that can be used for communication and corresponds to frequencies from 3 KHz to around 300 GHz. Spectrum is managed at an international as well as national level for allocation and assignment. The central body coordinating at the international level is the ITU, which has jurisdiction over the spectrum from 9 kHz to 275 GHz. Under the ITU are organizations at the regional and national levels, such as the Confederation of European Post and Telegraph Agencies in the European Union (EU) that operates at a pan-European level, and various country jurisdictions within Europe that operate in individual regions.

In India, the allocation of different parts of the frequency spectrum for various purposes is outlined in the National Frequency Allocation Plan document. The plan is entrusted to the Wireless Planning & Co-ordination wing under the Department of Telecommunications, Government of India.

An overview of the radio spectrum for licensed and unlicensed use is provided in Figure 1.1. The various bands standardized by 3GPP for LTE and 5G New Radio (NR) are provided in Appendix 1-1.

Figure 1.1: Overview of Spectrum Bands in Licensed and Unlicensed Bands



A key consideration in the allocation of radio spectrum for mobile services is international harmonization. Harmonization refers to the coordination of frequency band usage across countries and regions so that equipment can be manufactured at scale and cross-border services like satellite communications or aircraft telemetry can function smoothly.

For mobile broadband, global harmonization of bands like 700 MHz, 1800 MHz, 2.1 GHz, and 3.5 GHz has enabled the development of global device ecosystems, reducing costs and improving interoperability. The ITU's World Radiocommunication Conferences (WRCs), held every three to four years, play a central role in identifying candidate bands for new services and updating global allocation tables.

However, harmonization is not always feasible or desirable. Countries vary in their legacy spectrum usage, defence needs, geography, and development priorities, and spectrum allocations often reflect a patchwork of global trends and national deviations. For example, while the 3.5 GHz band (also known as the C-band) is widely used for 5G in Europe and Asia, the US initially relied more heavily on millimetre wave bands (30–300 GHz) before repurposing portions of the C-band through a complex re-allocation process.

The 5G era has introduced new allocation challenges. Mid-band spectrum (1–7 GHz), especially around 3.5 GHz and 6 GHz, is now seen as the "sweet spot" for 5G, offering a balance between coverage and capacity. However, these bands are often already occupied by legacy users such as satellite downlinks, fixed microwave links, or military radars and are also in demand for Wi-Fi. The varied possibilities of use, combined with different national priorities in the context of great power competition, are straining harmonization.

3. Unlicensed Spectrum

Unlicensed spectrum has been one of the most successful spectrum policy innovations of the past three decades. Wi-Fi, which operates primarily in the 2.4 GHz and 5 GHz bands, has become a foundational part of broadband access, offloading mobile traffic, enabling home and enterprise connectivity, and supporting Internet of Things (IoT) devices.[4]

Spectrum for Wi-Fi is allocated on an unlicensed basis, which means that users do not need individual authorization or pay usage fees. Instead, they must comply with technical standards, particularly power limits and interference-avoidance mechanisms (like dynamic frequency selection or listen-before-talk).

The success of Wi-Fi has led regulators to expand the availability of unlicensed spectrum. For example, in 2020, the US Federal Communications Commission (FCC) opened up the entire 6 GHz band (5.925–7.125 GHz) for unlicensed use. The EU and the United Kingdom (UK) followed with allocations of 500–600 MHz of the same band. These developments enabled the deployment of Wi-Fi 6E and Wi-Fi 7, which promise multi-gigabit speeds and ultra-low latency.

[4] Britannica. (n.d.). Wi-Fi. In *Britannica.* https://www.britannica.com/technology/Wi-Fi

However, the unlicensed model has its limits. The lack of a spectrum price means there is no market signal to allocate spectrum to its highest-value use. Moreover, as more users pile into unlicensed bands, the risk of congestion and interference grows, especially in dense urban areas. This has triggered debates about whether mid-band spectrum like 6 GHz should be allocated entirely for unlicensed use or whether a hybrid or licensed approach might be more efficient.

4. Spectrum for Non-Terrestrial Satellite Networks

Satellite communications (satcom) play a vital role in the global communications ecosystem, offering wide-area coverage, connectivity to remote regions, and critical services such as television broadcasting, emergency communications, maritime and aeronautical connectivity, and increasingly, broadband internet. These functions make satellite systems indispensable, especially in geographies where terrestrial networks are sparse or economically unviable.

Most satellite systems operate at large altitudes. Geostationary satellites (GEO) orbit at 35,786 km, introducing high free-space path loss and ~500 ms round-trip latency. Low Earth orbit (LEO) systems, such as Starlink and OneWeb, operate at altitudes between 500 km and 2,000 km. They reduce latency (~30–50 ms) but require multiple satellites and seamless handover protocols.

From the perspective of spectrum policy, satellite communications operate across three principal service categories: fixed satellite services (FSS), broadcast satellite services (BSS), and mobile satellite services (MSS).[5] These classifications reflect both the nature of the user terminal and the type of application. FSS typically supports point-to-point links between fixed ground stations—common in enterprise data, backhaul, and gateway connectivity. BSS delivers content such as direct-to-home television to broad user bases using high-power geostationary satellites. MSS, in contrast, enables connectivity to mobile terminals such as ships, aircraft, or handheld satellite phones and is often used in remote or underserved areas.

While a variety of frequency bands can be used for providing satellite communication services, the widely used frequency bands are L-band (1–2 GHz), S-band (2–4 GHz), C-band (4–8 GHz), Ku-band (10–15 GHz), and Ka-band (17–31 GHz). New-generation satellite communication systems aim for deployment in higher bands, such as the lower part of the V-band (37.5–52.4 GHz) for user links as well as gateway links and E-band (71–76 GHz/81–86 GHz) for gateway links.

Each of these services relies on distinct uplink and downlink frequencies—the former used for transmitting signals from the Earth to the satellite and the latter for transmitting signals back from the satellite to the Earth. For instance, in FSS, uplinks are commonly in the 14 GHz band and downlinks in 11–12 GHz, whereas BSS typically uses downlink-only bands in 11.7–

[5] Pelton, Joseph N. (2011). *Satellite communications*. Springer Science & Business Media.

12.2 GHz, with minimal or no uplink. MSS bands vary more widely, often using L-band **or** S-band for both uplink and downlink, given the need to support smaller and mobile terminals with lower antenna gains. The division of satellite spectrum into service types and directional uses is crucial for managing interference, coordinating international satellite orbits, and designing co-existence rules with terrestrial networks, especially as emerging constellations (e.g., LEO satellites) blur traditional boundaries. Policy must therefore navigate not only service categories but also uplink–downlink symmetry, antenna characteristics, and dynamic spectrum sharing across altitudes and geographies.

Satcom systems span large geographic areas. Interference from terrestrial systems, particularly in adjacent or co-channel bands, can degrade service over wide regions. For this reason, satellite operations typically require:

- Exclusive spectrum assignments with strict coordination requirements.
- Protection zones around uplink Earth stations, often extending up to 10 kilometres.
- Emission masks and power limits on terrestrial users in nearby bands.

This physical architecture makes satellite systems both broad in coverage and vulnerable to interference, especially in congested mid-band frequencies that are now in demand by terrestrial 5G.

These satcom services are assigned spectrum in globally harmonized bands, often coordinated through the ITU. The main frequency bands include:

- L-Band (1–2 GHz): Used for MSS due to its favourable propagation.
- C-Band (3.6–4.2 GHz downlink, 5.925–6.425 GHz uplink): Historically important for FSS and BSS.
- Ku-Band (11–14 GHz) and Ka-Band (18–31 GHz): Offer higher bandwidth but face greater attenuation. Primarily used for FSS and BSS.
- V-Band and E-Band (above 40 GHz): Emerging bands for high-throughput satellite systems.

With LEO satellite systems being deployed, there is an increasing need for spectrum allocation for these systems. As an extension to terrestrial networks, satellites were first mentioned in a deployment scenario for 5G in 3GPP Release 14, aimed at providing 5G communication services in areas where terrestrial coverage was unavailable and supporting services that could be accessed more efficiently through satellite systems, such as broadcasting services and delay-tolerant services. In Releases 15, 16, 17, and 18, 3GPP launched several standardization activities to support the integration of satellite networks and 5G terrestrial networks. The spectrum bands used by various satellite service providers are provided in Table 1.1.[6]

[6] Prasad, Rohit., & Sridhar, V. *5G and beyond: Rewiring telecom regulation in India* [Unpublished]. Oxford University Press.

Table 1.1: Spectrum Bands Used in Satellite Systems

Satellite System	Deployment Frequency Bands	Planned Satellite Numbers
SpaceX	Ku/Ka (1st Generation)	4,408
	Ku/Ka/E (2nd Generation)	30,000
	V-Band	7,518
Kuiper (Amazon)	Ka Band	3,236
	Ku/V Bands	7,774
Boeing	V Band	5,921
Astra Space	V Band	13,620
OneWeb	Ku/Ka (Phase 1)	648
	V (Phase 2)	6,372
O3B	Ka-Band	70
	V Band	24
Telesat	Ka Band	300
	V Band	1,671
Vodafone and AST SpaceMobile	S Band (1980-2010, 2170-2200 MHz); Q/ V Band (33-50 GHz)	250

5. Backhaul Spectrum

As mobile networks become more data-intensive and densified, especially in the 5G era, robust and scalable backhaul becomes essential to ensure quality of service. Spectrum policy for backhaul is thus a crucial component of overall spectrum management. Unlike access spectrum, which is typically assigned through auctions, backhaul spectrum is largely administered through point-to-point licensing and administrative pricing owing to differences in usage patterns, economic rationale, and engineering requirements.

Backhaul refers to the links that connect radio access network elements—such as base stations, small cells, and distributed antenna systems—to the core network. It serves as the data-transport backbone of mobile communication systems.[7] As mobile networks evolve to support ultra-low latency, high throughput, and massive device densities under 5G and beyond, the demands placed on backhaul links have intensified.

Backhaul is typically structured in two hops:

[1] First Hop: From the radio access point (e.g., a macro base station or small cell) to an aggregation point. This hop may use microwave spectrum in the 6–23 GHz range and is often short-range, highly localized, and built on a point-to-point basis.

[7] TRAI. (n.d.). Consultation Paper on "Provision of Cellular backhaul connectivity via Satellite through VSAT under Commercial VSAT CUG Service Authorization". https://www.trai.gov.in/consultation-paper-provision-cellular-backhaul-connectivity-satellite-through-vsat-under-commercial

[2] Second Hop: From the aggregation point to the core network. This hop usually requires much higher capacity and may cover longer distances. Consequently, it tends to use higher frequency bands, including millimetre-wave spectrum such as the E-band (71–86 GHz) or V-band (57–71 GHz), or in some cases, fibre.

This hierarchical design allows mobile operators to efficiently manage traffic flow while balancing cost, scalability, and latency. Wireless backhaul, particularly for the first hop, is essential in both urban densification and rural coverage scenarios. It enables operators to rapidly scale coverage without waiting for fibre deployment. For the second hop, where capacity demands surge, millimetre-wave bands become critical enablers.

Unlike access spectrum—where interference risks, scarcity, and omnidirectionality justify the use of auctions and the assignment of specific geographies—backhaul spectrum is usually not auctioned and not assigned over a geography. Instead, it is licensed administratively and sold on a point-to-point basis. There are several interlinked reasons for this distinction:

- Backhaul spectrum is used as supporting infrastructure rather than for providing direct services to end-users. Its value is instrumental, i.e., it enables service delivery but is not monetized independently. Hence, regulators do not seek to extract economic rent through competitive bidding.
- Because backhaul links are typically narrow-beam and geographically localized, the same frequency band can be reused in different locations with appropriate coordination. This spatial reuse lowers the scarcity value of the spectrum, making auctions both unnecessary and inefficient.
- Mobile access spectrum users require exclusive, high-power, omnidirectional rights to operate without interference over wide areas. In contrast, backhaul users only need narrow, directional links and do not require exclusivity beyond their specific path. This makes administrative coordination feasible, often through link-by-link licensing based on interference analysis and geographic separation.

Given the critical role of backhaul in expanding mobile coverage and capacity, particularly in rural and underserved areas, regulators often maintain modest pricing to encourage deployment. Auctions would raise costs and potentially delay infrastructure rollouts.

Administrative pricing models vary by country but generally follow principles of:

- Charging on a per-link or per-hop basis
- Differentiating by frequency band, link distance, and bandwidth
- Applying nominal annual licence fees rather than upfront charges

These principles help promote predictability, ease of business, and operational scalability for mobile operators and internet service providers.

6. Spectrum Allocation: Principles and Controversies

Spectrum allocation refers to the process by which regulators designate specific frequency bands for particular categories of services or technologies. Unlike spectrum assignment, which determines *who* gets access to a given band, allocation addresses the more fundamental question of *what* the band should be used for.[8] For example, the 700 MHz band may be allocated for mobile broadband, while the 4.2–4.4 GHz band might be allocated for aeronautical radar systems.

Spectrum allocation decisions are typically made at two levels. At the international level, the ITU coordinates global harmonization of spectrum use, especially to avoid cross-border interference and enable economies of scale in device manufacturing. National governments then translate these international allocations into domestic policies, sometimes with adaptations to meet specific national needs.

Allocations can be exclusive or shared. In an exclusive allocation, a single type of service, such as licensed mobile access, has exclusive rights. In a shared allocation, different services (e.g., fixed wireless access and satellite earth stations) may co-exist under conditions that prevent harmful interference. In recent years, the idea of dynamic or tiered access has gained traction, especially in congested bands, where multiple classes of users can operate with prioritized rights.

6.1 Technology-Neutral vs. Service-Specific Allocation

One of the central policy questions in spectrum allocation is whether regulators should prescribe the type of technology or the type of service that a frequency band must support. Although these two dimensions—technology and service—are related, they are not the same and should be clearly distinguished in regulatory discourse.

Technology neutrality refers to the principle that spectrum users should be free to choose which wireless technology or protocol they deploy within an allocated band, i.e., the regulator does not mandate the use of a specific transmission technology such as GSM, LTE, 5G NR, or Wi-Fi. Instead, the band may be authorized for use with any technology that complies with general interference and emission standards. This approach gives operators the flexibility to adopt the most efficient, cost-effective, and innovative technologies as they evolve, without having to seek new approvals from the regulator each time a change is needed. For example, under a technology-neutral regime, a mobile operator that initially deployed LTE in a band can later upgrade to 5G NR or a future protocol without requiring regulatory reclassification of the band.

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[8] Prasad, R., & V. Sridhar. (2015). The dynamics of spectrum management: legacy, technology, and economics. *Management, 40*(3). 388–391.

Service neutrality, by contrast, refers to the principle that spectrum users should be free to offer any kind of electronic communication service—whether voice, data, broadband access, private network services, or IoT connectivity—within a given band. This means that the regulator does not designate the band exclusively for mobile access, satellite uplinks, broadcasting, or fixed wireless access but instead allows any of these services to be offered, provided they comply with technical rules and co-existence requirements. Thus, service neutrality focuses not on the technology being used but on the business model or end-use application of the spectrum.

While the two concepts are distinct, they do interact and are often implemented together under broader liberalization policies. For instance, a band designated for "terrestrial wireless broadband" might allow both LTE and Wi-Fi (technology neutrality) and both commercial mobile services and community broadband (service neutrality). In such cases, the user enjoys wide discretion over both how the spectrum is used technically and what services are provided economically.

However, one can exist without the other. A regulator might allow technology neutrality within a service-specific framework, such as by mandating that a band must be used for mobile services but allowing any radio access technology (e.g., LTE or 5G) to deliver that service. Conversely, a regulator could allow multiple services over a band while mandating the use of a particular technology for interference management or harmonization reasons. For instance, multiple services are allowed within the 3.5 GHz band (also known as the C-band), such as mobile broadband, fixed wireless access, and private networks. However, to ensure interference coordination and maintain global harmonization, the regulator might mandate the use of 5G NR as the only permitted technology in the band.

The EU has been a strong advocate of both technology neutrality and service neutrality, enshrining these principles in its 2009 regulatory framework and subsequent directives. The EU has aimed to enable more flexible, market-responsive spectrum use, where rights are defined as broadly as possible, and operators can respond dynamically to technological progress and consumer demand.

India, too, has signalled a commitment to these principles in its National Digital Communications Policy (NDCP) 2018, which encourages harmonized, flexible, and technology-neutral spectrum assignments. In practice, however, India, as with many other countries, continues to implement service-specific allocations. A notable instance is the allocation of the 26 GHz band, where India's Department of Telecommunications (DoT) has designated this band exclusively for International Mobile Telecommunications (IMT)/5G services, i.e., for use by mobile network operators. However, there may be provisions that allow operators to use a different technology after notifying the DoT licensor.

Technology and service neutrality can reduce regulatory burden, promote innovation, and lead to more economically efficient use of spectrum. They can also support emerging use cases, such as private 5G networks or dynamic spectrum sharing, that do not fit neatly into traditional service categories.

However, neutrality frameworks also present risks. Unconstrained entry of new services or technologies into a band may increase the risk of harmful interference, particularly in adjacent channels. There is also a concern that public interest services, such as broadcasting, emergency response, or scientific research, could be crowded out if commercial actors dominate access to flexible bands.

Moreover, neutrality does not mean the absence of regulation. On the contrary, it places greater responsibility on regulators to ensure that technical co-existence is well designed, spectrum rights are clearly defined, and enforcement mechanisms are effective.

7. Spectrum Assignment Mechanisms for Access

While spectrum allocation defines what frequency bands may be used for and by which *type* of services, spectrum assignment determines who gets the rights to use the spectrum and under what conditions. This section explores the main approaches to spectrum assignment, contrasting administrative and market-based mechanisms, analyzing the relative merits of auctions and beauty contests, and exploring the evolving role of hybrid and dynamic assignment frameworks.

7.1 Administrative Assignment: Centralized Control and Legacy Practices

Historically, most spectrum around the world was assigned through administrative licensing, where national regulators directly selected licensees based on policy priorities, technical qualifications, or perceived merit. This top-down model of spectrum management was dominant during the formative decades of radio and telecommunications, and it continues to play a role in several areas today. Administrative assignment remains prevalent for:

- Public-interest allocations such as defence, aviation, railways, or emergency services
- Point-to-point microwave backhaul links, particularly in rural or remote areas
- Satellite gateways and earth stations
- Community networks, campus deployments, and pilot or experimental use-cases
- Temporary licenses for events or trials

Within this administrative framework, comparative evaluations—also known as beauty contests—were often used when demand exceeded supply. Regulators would evaluate applicants on criteria such as service rollout plans, financial strength, technological capabilities, or proposed tariffs. Administrative and comparative assignments offered certain advantages:

- Policy alignment: Governments could steer spectrum towards national priorities or underserved regions.
- Interference management: Regulators retained close control over co-existence in congested bands.
- Predictability: Users gained long-term, stable access to spectrum for specialized needs.

However, these methods also exhibited significant limitations:

- Lack of price discovery: There was no mechanism to determine the spectrum's economic value.
- Inefficiency and hoarding: Spectrum could go unused or be allocated to entities with limited incentive to deploy quickly.
- Barriers to entry: New or more innovative players were often excluded in favour of incumbents or those with greater political influence.

While intended to ensure optimal societal outcomes, beauty contests were also criticized for non-transparent procedures, susceptibility to lobbying, and subjective decision-making. As the telecommunications sector liberalized and the commercial value of spectrum rose sharply, especially with the arrival of 3G, 4G, and 5G, regulators worldwide began to shift towards more market-driven approaches.

7.2 Market-Based Assignment: Auctions

Spectrum auctions have become the dominant mechanism for assigning high-demand commercial spectrum, especially for mobile broadband.[9] In an auction, interested parties bid for licences, and spectrum is awarded to the highest bidder(s) according to predefined rules.

Spectrum auctions are typically multi-unit auctions because spectrum must be sold in multiple blocks, often across different geographic service areas and frequency bands. Each licence represents a separate good, but there may be complementarities (e.g., adjacent blocks or adjacent areas) or substitutabilities (e.g., similar bands in overlapping regions). The challenge for regulators is to design auctions that allow bidders to express their preferences over these multiple items while ensuring transparency, efficiency, and competitive outcomes.

Over time, regulators have converged on three main multi-unit auction formats, each with its own advantages and limitations. These are discussed below.

[9] Bichler, M., & Goeree, J. K. (Eds.) (2017). *Handbook of spectrum auction design*. Cambridge University Press.

7.2.1 Sequential Auctions

In a sequential auction, spectrum blocks are auctioned one after another in a fixed order. Bidders place their bids on each item as it comes up, without knowing how much they will win later or how prices will evolve in subsequent rounds.

Pros:

- Simplicity of design and administration.
- Low overhead for both regulators and bidders.

Cons:

- Exposure risk: Bidders may win a licence in one round but fail to win complementary licences in later rounds, leaving them with suboptimal or unusable holdings.
- Strategic uncertainty: Later bidders can game the system by adapting their strategy based on earlier outcomes.
- Inefficiency: Because bidders cannot express package preferences, the final allocation may not maximize total value.

Sequential auctions are rarely used for spectrum sales today, except in very small or simple contexts.

7.2.2 SMRA Auctions

Pioneered by the US FCC, the SMRA auction is now a workhorse format for many countries. Here, all spectrum blocks are auctioned at the same time across multiple rounds. Bidders can bid on multiple items in each round and revise their strategies in response to price signals. The auction proceeds until no new bids are placed on any item.

Pros:

- Price discovery: Bidders learn about market demand and adjust accordingly.
- Flexibility: Bidders can shift bids across regions or frequency blocks as prices evolve.
- Transparency: Prices and standing high bidders are typically public, enabling informed decisions.

Cons:

- Still has exposure risk: While better than sequential auctions, SMRA does not allow package bidding, so bidders may still end up with incomplete or mismatched holdings.
- Collusion and signalling: The open nature of bidding can enable tacit coordination among incumbents.

- Complexity for large auctions: When many blocks are on offer, tracking and adjusting bids can become cumbersome.

Despite these limitations, SMRA has remained widely used, particularly when complementarities between licences are modest and bidder strategies are not too interdependent.

7.2.3 Combinatorial Clock Auctions

The combinatorial clock auction (CCA) was developed to address the exposure problem of the SMRA format. In an SMRA auction, bidders can bid on multiple licences simultaneously but cannot express package-level preferences, thus running the risk of winning only part of a desired set (e.g., one region but not the adjacent one), which may render the spectrum they do win commercially useless or less valuable.

To solve this, CCA allows bidders to submit bids for packages of licences rather than for individual licences alone. This enables all-or-nothing expressions of interest, so that bidders win either the whole package or nothing at all, thereby eliminating exposure risk.

However, the introduction of package bidding creates another challenge: the combinatorial explosion of possibilities. With *n* items up for auction, the total number of possible non-empty packages is $2^n - 1$. Even with just 10 spectrum blocks, that results in over 1,000 potential combinations. For 20 items, the number exceeds one million. Bidding over this vast space becomes cognitively and strategically complex for bidders and computationally challenging for regulators to process and evaluate.

To manage this complexity while still preserving the benefits of package bidding, the CCA is typically structured into two phases:

[1] The Clock Phase

The auction begins with a clock round, where the regulator sets initial prices for each licence category (e.g., 20 MHz in a specific band and region). These prices are incrementally increased in each round, and bidders state how many units of each item they are willing to purchase at those prices.

This phase does not permit package bidding in the strict sense; rather, it collects aggregate demand data and helps guide prices towards market-clearing levels. Bidders can adjust their quantity demands in response to rising prices. The clock phase ends when excess demand is eliminated for all items.

This phase serves three functions:

- It provides price discovery, helping bidders form valuations.
- It simplifies early-stage participation; therefore, bidders need not calculate and rank complex packages up front.
- It generates activity rules and eligibility constraints that govern bidding rights in the next phase.

[2] Supplementary (Package) Round

After the clock phase ends, the auction proceeds to a sealed-bid supplementary round, where bidders may submit one or more all-or-nothing package bids. These packages may include:

- The combination bid implied by their final clock round demand.
- Any additional packages of interest that were previously ineligible due to price or eligibility constraints.

Each bidder's bids must be consistent with their revealed preferences during the clock phase, as enforced by activity rules designed to deter strategic manipulation.

The auctioneer then applies an algorithm to select the combination of non-overlapping winning bids that maximizes total revenue (or, in some variants, total value based on predefined weights). Winners pay either:

- A second-price-style payment based on opportunity cost (what others would have paid if the winner were excluded), or
- Some other variant of value-based pricing to discourage overbidding or gaming

This two-phase spectrum assignment methodology has certain advantages and disadvantages:

Advantages:

- Eliminates exposure risk, enabling bidders to express true preferences for bundles.
- Improves allocative efficiency, especially when items are strong complements.
- Reduces collusion, since supplementary round bids are sealed and not publicly observable.

Disadvantages:

- High complexity for bidders, who must evaluate and prioritize potentially thousands of combinations.
- Opacity: Final outcomes can be difficult to interpret, and pricing rules may be hard to explain.
- Computational intensity: Winner determination and pricing can be resource-heavy, requiring specialized software and validation.

While package bidding in combinatorial auctions helps solve the exposure problem, it can also create a distinct and often underappreciated inefficiency: aggregation risk, sometimes referred to as the free rider problem in complementary bidding. This occurs when two or more separate bidders each want a subset of a package that a third bidder values only as a whole, and although the combined value of the separate bids exceeds the package bidder's value, they fail to coordinate, and the package bidder wins at a lower overall valuation.

If poorly designed, packaged auctions can lead to:

- Overpricing: Excessive bid amounts (so-called "winner's curse") that strain operators and delay network rollout.
- Exclusion: Smaller or newer players may be unable to compete.
- Underutilization: Firms may acquire spectrum speculatively and hoard it.
- Low uptake: When reserve prices are set too high or competition is weak, large swathes of spectrum may remain unsold or may be sold at the reserve price in a de facto bake sale. This not only signals market failure but also delays the productive use of valuable frequencies.

Regulators have developed various mechanisms to mitigate these risks, such as spectrum caps, bidding credits for new entrants, and rollout obligations.

India's experience with auctions reflects both the promise and pitfalls of the model. While auctions brought transparency and fiscal gains, aggressive bidding in 2010 and 2016 (e.g., 3G, 700 MHz) left some spectrum unsold or underutilized. More recently, pricing reforms and rationalized reserve prices have improved outcomes.

7.3 Assignment Conditions: Duration, Renewals, and Usage Obligations

An assignment is not just about who gets the spectrum but also under what terms and conditions. Key elements of a spectrum licence include:

- Duration: Typically 15–20 years for mobile spectrum, with optional renewals.
- Geographic scope: National, regional, or circle-based licensing.
- Bandwidth: Amount and duplexing arrangement (paired or unpaired).

- Technology usage: Whether the band is technology-neutral.
- Performance obligations: Rollout targets, quality of service (QoS) benchmarks, rural coverage.
- Spectrum fees: Upfront charges, annual usage fees, or revenue shares.

Well-designed licence conditions can promote efficient deployment and public benefit. However, excessive constraints may deter investment or constrain flexibility. The trend globally is toward greater flexibility, including:

- Allowing technology-neutral use.
- Permitting leasing and spectrum sharing (where appropriate).
- Establishing clear renewal guidelines to reduce policy uncertainty.

India's unified licence framework and the recent recommendations of the Telecom Regulatory Authority of India (TRAI) on spectrum sharing and leasing reflect this shift.

While auctions are designed to allocate spectrum efficiently, regulators must also ensure that the outcomes promote competition and avoid excessive market concentration. Two commonly used tools to achieve this are spectrum caps and reserve prices.

7.4 Spectrum Caps

Spectrum caps are limits on the amount of spectrum that any single operator can acquire in a given auction or hold overall. These caps may be defined:

- Per band (e.g., no more than 40 MHz in the 700 MHz band),
- Across band categories (e.g., low-, mid-, and high-band totals), or
- Geographically, to address local monopolies.

Caps help level the playing field by ensuring that large incumbents do not corner the market. They can also create space for new entrants or smaller players, enhancing long-term competition. The current spectrum caps in India are as follows:

Band-Wise Cap (Intra-Band Cap)

This limits how much spectrum a telco can hold **within a specific frequency band** in a telecom circle.

- **For Sub-GHz Bands (700 MHz, 800 MHz, 900 MHz):**
  - **Cap: 40%** of the total spectrum assigned in that band in a circle.
  - *Rationale:* These bands are excellent for wide-area coverage and building penetration (indoor coverage). Capping them prevents a single operator from having a massive coverage advantage.

- **For Other Bands (1800 MHz, 2100 MHz, 2300 MHz, 2500 MHz, 3300 MHz, 26 GHz, etc.):**
  - **Cap: 40%** of the total spectrum assigned in that band in a circle.
  - *Note:* The 2015 rules had a higher cap (50%) for bands above 1 GHz, but this was unified to 40% in subsequent orders.

Overall Cap (Inter-Band Cap)

This limits the **total amount of spectrum** a telco can hold **across all frequency bands** in a telecom circle.

  - **Cap: 35%** of the total spectrum assigned across all bands in that circle.
  - *Rationale:* This is the ultimate check to ensure no operator can become a "spectrum superpower", controlling a disproportionate share of all available airwaves in a region.

Spectrum Cap for Future Technologies

A very important recent introduction is a special cap for the spectrum suited for future technologies, particularly 5G.

- **Cap for 5G-Centric Spectrum (3300-3670 MHz + 26 GHz bands):** No telco can hold more than **40%** of the total spectrum assigned in this combined category in a service area.
  - *Rationale:* This specifically ensures that the incredibly valuable upper mid-band and high-band 5G spectrum is distributed fairly among operators to foster 5G competition.

7.5 Reserve Prices

Reserve prices are the minimum price at which a licence can be sold. They serve multiple purposes:

- Ensure public value is not undersold.
- Signal the government's estimate of the spectrum's economic worth.
- Deter speculative bidding.

However, setting reserve prices is a delicate balancing act. If set too high, it may discourage bidding or lead to unsold spectrum, particularly when market interest is limited or when auction conditions (such as licence obligations) are unattractive. This has occurred in several countries, including India's 700 MHz auction in 2016, where spectrum remained unsold despite its strategic importance due to high reserve prices. Conversely, very low reserve prices risk underpricing and speculative acquisition.

In a maturing telecom sector with uneven competition, striking the right reserve price based on demand forecasts, business viability, and international benchmarks is as much an art as a science.

7.6 Geographic Scope: Service Area Definitions

Regulators typically divide a country into predefined licence service areas. These can vary significantly in size:

- National licences (e.g., France)
- Regional or state-level licences (e.g., India's telecom circles)
- Smaller units like Partial Economic Area or Local Licensing Areas

Granularity allows flexibility; smaller operators or regional players can participate, while larger players can achieve national coverage. However, overly small units can fragment the market and complicate network planning. Hence, regulators have to choose the right level of aggregation for different purposes: for instance, large LSAs may be suitable for sub-GHz spectrum while smaller LSAs may be suitable for the millimetre wave spectrum.

8. Spectrum for Universal Access

Universal access to high-quality connectivity remains a central objective of telecom policy, particularly in countries like India, which have geographic, economic, and social divides. Spectrum policy plays a pivotal role in enabling this goal, not merely by increasing overall capacity but by ensuring that spectrum reaches underserved regions, supports affordable services, and accommodates diverse access architectures.

Universal access begins with coverage, and sub-GHz spectrum, especially the 700 MHz and 600 MHz bands, is critical to this coverage. These bands have superior propagation characteristics, allowing signals to travel longer distances and penetrate buildings more effectively. In rural and remote areas, fewer towers are needed to provide coverage, making network economics more viable for operators.

However, high reserve prices have historically deterred uptake of these bands in India. Future spectrum policy must rethink pricing and licensing frameworks for low-frequency bands to reflect their public utility role, not just their market value. Targeted subsidization or availability through Universal Service Obligation Fund–linked mechanisms can bridge the viability gap.

Universal access is also about democratizing network ownership and deployment. Unlicensed spectrum plays a vital role here, enabling community Wi-Fi, school and library networks, and local connectivity solutions in villages, tribal regions, and disaster-affected zones. The 2.4 GHz and 5 GHz bands have already supported grassroots innovation in India. The upcoming 6 GHz band shows further promise, with the WRC24 having identified half the band for unlicensed use. Policymakers must also try to make low-priced licence spectrum available to niche operators in underserved areas. One enabler is the creation of rural LSAs, where spectrum assignment can be implemented in innovative ways.

9. Rethinking Spectrum Assignment for the 5G Era

9.1 A Spectrum Policy Inflection Point

Satellite spectrum management today sits at the intersection of legacy infrastructure and emerging broadband demand. Traditional satellite systems require predictable, interference-free spectrum with generous geographic and technical protections. Meanwhile, 5G, Wi-Fi, and backhaul demand is pressuring regulators to liberalize spectrum use, repurpose mid-band spectrum, and enable sharing.

The collision is most pronounced in the mid-band, where all four major uses (access, Wi-Fi, backhaul, and satellite) converge. In this crowded arena, rigid exclusive-use models face growing limitations. Tiered access regimes, shared licensing frameworks, and intelligent coordination mechanisms (like SAS) offer a path forward, but only if they are implemented with rigorous safeguards for incumbents, especially satellite services.

As LEO constellations rise and new high-throughput satellites begin using Ka- and V-bands, there may be opportunities to relieve mid-band congestion by transitioning some satellite operations to higher frequencies. However, such transitions are capital-intensive and geopolitically complex.

Ultimately, a more integrated approach to spectrum policy that balances short-term economic efficiency with long-term infrastructure resilience is critical. Satellite services remain central to global digital inclusion, and their spectrum rights must be carefully woven into the broader tapestry of spectrum governance.

9.2 Arguments for Subsidization: Spectrum as Public Infrastructure

Another dimension of future-ready spectrum policy is to recognize spectrum as a form of public infrastructure, especially in bands critical to societal goals, such as education, health, MSME digitization, and public service delivery.

Mobile network operators and Wi-Fi-based service providers alike are central to these outcomes. But where operators are expected to extend access in underserved areas, deploy dense small cells in public buildings, or support free public Wi-Fi, spectrum access can become a barrier to socially beneficial investment.

In such contexts, the case for targeted subsidization or differential pricing is compelling. Governments might consider:

- Free or low-cost access to spectrum for not-for-profit digital initiatives.

- Credits or cost offsets on spectrum fees for operators meeting rural coverage or public Wi-Fi targets.
- Dedicated shared-use spectrum pools for public institutions, smart city networks, or community-run broadband.

Crucially, such subsidies should be linked not to the identity of the provider (e.g., telecom vs. tech firm) but to the nature of the service and public value it creates. In essence, spectrum can be treated as a public good, not only in the sense of non-rivalry but in terms of its role in enabling broader social and economic infrastructure.

9.3 Auction Design for Fair, Efficient, and Future-Ready Assignment

As convergence in use cases accelerates, auction design itself must evolve to accommodate more heterogeneous user groups, flexible access models, and dynamic valuations.

Historically, auctions have been structured to allocate large, contiguous blocks of spectrum to a handful of licensed operators, optimized for nationwide mobile coverage. But in today's landscape, a more diversified set of players—neutral hosts, enterprise networks, satellite operators, public agencies—are entering the field, many of whom do not need exclusive nationwide licences, operate at lower power and scale, and are targeting niche or localized use cases.

To meet this challenge, future auctions should incorporate:

- Tiered licensing: Including city-wide, campus-level, and regional licences alongside nationwide ones.
- Usage rights segmentation: Allowing multiple classes of users—licensed, lightly licensed, and unlicensed—to access the same band with defined co-existence protocols.
- Dynamic pricing mechanisms: Including usage-based pricing or tiered annual fees instead of large upfront payments.
- Set-asides for innovation or public benefit: Ensuring spectrum access for experimental technologies, community networks, or public-interest deployments.

Moreover, auction formats should internalize inter-user trade-offs and co-existence possibilities. For example, rather than assigning all of a mid-band spectrum block exclusively to mobile operators, regulators could reserve segments for shared or hybrid use, balancing revenue generation with ecosystem diversity and long-term innovation potential.

Auction design must shift from a binary, winner-take-all model to a more layered, inclusive, and flexible allocation architecture—one that reflects both the converging technical landscape and the plurality of players and business models shaping the wireless ecosystem.

Appendix 1.1: The 3GPP Spectrum Bands

LTE Operating Band	NR Operating Band	UL_Low	UL_High	DL_Low	DL_High	Duplex Mode	LTE Bandwidths	NR Bandwidths	Nickname(s)	Region(s) of Usage
1	n1	1920 MHz	1980 MHz	2110 MHz	2170 MHz	FDD	5, 10, 15, 20	5, 10, 15, 20, 25, 30, 40, 45, 50	UMTS IMT, 2100, IMT Core	EMEA, Asia, Japan
2	n2	1850 MHz	1910 MHz	1930 MHz	1990 MHz	FDD	1.4, 3, 5, 10, 15, 20	5, 10, 15, 20, 25, 30, 35, 40	PCS, 1900	North America, Canada, Latin America
3	n3	1710 MHz	1785 MHz	1805 MHz	1880 MHz	FDD	1.4, 3, 5, 10, 15, 20	5, 10, 15, 20, 25, 30, 35, 40	DCS, 1800	Europe
4		1710 MHz	1755 MHz	2110 MHz	2155 MHz	FDD	1.4, 3, 5, 10, 15, 20		AWS, 1.7/2.1	North America, Canada, Latin America
5	n5	824 MHz	849 MHz	869 MHz	894MHz	FDD	1.4, 3, 5, 10	5, 10, 15, 20, 25	GSM850, Cellular 850, UMTS850	North America, Canada, Latin America, Australia
7	n7	2500 MHz	2570 MHz	2620 MHz	2690 MHz	FDD	5, 10, 15, 20	5, 10, 15, 20, 25, 30, 35, 40, 50	IMT-Extension, 2.5 GHz	Europe
8	n8	880 MHz	915 MHz	925 MHz	960 MHz	FDD	1.4, 3, 5, 10	5, 10, 15, 20, 25, 35	GSM, EGSM, GSM900, EGSM900, UMTS900	Europe, Latin America
9		1749.9 MHz	1784.9 MHz	1844.9 MHz	1879.9 MHz	FDD	5, 10, 15, 20		UMTS1700	Japan
10		1710 MHz	1770 MHz	2110 MHz	2170 MHz	FDD	5, 10, 15, 20		UMTS, IMT2000, 3G Americas	-
11		1427.9 MHz	1447.9 MHz	1475.9 MHz	1495.9 MHz	FDD	5, 10		PDC; 1500 MHz lower	Japan
12	n12	699 MHz	716 MHz	729 MHz	746 MHz	FDD	1.4, 3, 5, 10	5, 10, 15		US
13	n13	777 MHz	787 MHz	746 MHz	756 MHz	FDD	5, 10	5, 10	700 MHz Block C	North America
14	n14	788 MHz	798 MHz	758 MHz	768 MHz	FDD	5, 10	5, 10	700 MHz Block D	North America
17		704 MHz	716 MHz	734 MHz	746 MHz	FDD	5, 10		700 MHz Block A	North America
18	n18	815 MHz	830 MHz	860 MHz	875 MHz	FDD	5, 10, 15	5, 10, 15		Japan
19		830 MHz	845 MHz	875 MHz	890 MHz	FDD	5, 10, 15			Japan
20	n20	832 MHz	862 MHz	791 MHz	821 MHz	FDD	5, 10, 15, 20	5, 10, 15, 20		Europe
21		1447.9 MHz	1462.9 MHz	1495.9 MHz	1510.9 MHz	FDD	5, 10, 15		1500 MHz upper	-
22		3410 MHz	3490 MHz	3510 MHz	3590 MHz	FDD	5, 10, 15, 20			-
24	n24	1626.5 MHz	1660.5 MHz	1525 MHz	1559 MHz	FDD	5, 10	5, 10	MSS spectrum	North America
25	n25	1850 MHz	1915 MHz	1930 MHz	1995 MHz	FDD	1.4, 3, 5, 10, 15, 20	5, 10, 15, 20, 25, 30, 35, 40, 45	PCS G block	North America

LTE Operating Band	NR Operating Band	UL_Low	UL_High	DL_Low	DL_High	Duplex Mode	LTE Bandwidths	NR Bandwidths	Nickname(s)	Region(s) of Usage
26	n26	814 MHz	849 MHz	859 MHz	894MHz	FDD	1.4, 3, 5, 10, 15	5, 10, 15, 20, 25, 30		
27		807 MHz	824 MHz	852 MHz	869 MHz	FDD	1.4, 3, 5, 10			
28	n28	703 MHz	748 MHz	758 MHz	803 MHz	FDD	3, 5, 10, 15, 20	5, 10, 15, 20, 25, 30	APAC700	APAC
29	n29	N/A	N/A	717 MHz	728 MHz	SDL	3, 5, 10	5,10		North America
30	n30	2305 MHz	2315 MHz	2350 MHz	2360 MHz	FDD	5, 10	5,10	WCS	North America ATT
31		452.5 MHz	457.5 MHz	462.5 MHz	467.5 MHz	FDD	1.4, 3, 5			Brazil
32		N/A	N/A	1452 MHz	1496 MHz	SDL	5, 10, 15, 20			
33		1900 MHz	1920 MHz	1900 MHz	1920 MHz	TDD	5, 10, 15, 20		TDD 1900	-
34	n34	2010 MHz	2025 MHz	2010 MHz	2025 MHz	TDD	5, 10, 15	5, 10, 15	TDD 2.1	China
35		1850 MHz	1910 MHz	1850 MHz	1910 MHz	TDD	1.4, 3, 5, 10, 15, 20			-
36		1930 MHz	1990 MHz	1930 MHz	1990 MHz	TDD	1.4, 3, 5, 10, 15, 20			-
37		1910 MHz	1930 MHz	1910 MHz	1930 MHz	TDD	5, 10, 15, 20		PCS Center Gap	-
38	n38	2570 MHz	2620 MHz	2570 MHz	2620 MHz	TDD	5, 10, 15, 20	5, 10, 15, 20, 25, 30, 40	IMT Extension	EMEA
39	n39	1880 MHz	1920 MHz	1880 MHz	1920 MHz	TDD	5, 10, 15, 20	5, 10, 15, 20, 25, 30, 40		China
40	n40	2300 MHz	2400 MHz	2300 MHz	2400 MHz	TDD	5, 10, 15, 20	5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100	IMT-2000	China, Others
41	n41	2496 MHz	2690 MHz	2496 MHz	2690 MHz	TDD	5, 10, 15, 20	5, 10, 15, 20, 25, 30, 40, 45, 50, 60, 70, 80, 90, 101	US 2600	North America, China
42		3400 MHz	3600 MHz	3400 MHz	3600 MHz	TDD	5, 10, 15, 20			Japan, EMEA
43		3600 MHz	3800 MHz	3600 MHz	3800 MHz	TDD	5, 10, 15, 20			APAC, EMEA
44		703 MHz	803 MHz	703 MHz	803 MHz	TDD	3, 5, 10, 15, 20		APAC700	APAC
45		1447 MHz	1467 MHz	1447 MHz	1467 MHz	TDD	5, 10, 15, 20			China
46	n46	5150 MHz	5925 MHz	5150 MHz	5925 MHz	TDD	10, 20	10, 20, 40, 60, 80, 100	5 GHz LAA	5 GHz NR-U
47	n47	5855 MHz	5925 MHz	5855 MHz	5925 MHz	TDD	10, 20	10, 20, 30, 40	V2X	
48	n48	3550 MHz	3700 MHz	3550 MHz	3700 MHz	TDD	5, 10, 15, 20	5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 100	US 3.5 GHz	North America
49		3550 MHz	3700 MHz	3550 MHz	3700 MHz	TDD	10, 20		US 3.5 GHz, LAA	North America
50	n50	1432 MHz	1517 MHz	1432 MHz	1517 MHz	TDD	3, 5, 10, 15, 20	5, 10, 15, 20, 30, 40, 50, 60, 80		
51	n51	1427 MHz	1432 MHz	1427 MHz	1432 MHz	TDD	3, 5	5		
52		3300 MHz	3400 MHz	3300 MHz	3400 MHz	TDD	5, 10, 15, 20			
53	n53	2483.5 MHz	2495 MHz	2483.5 MHz	2495 MHz	TDD	1.4, 3, 5, 10	5, 10		North America
54	n54	1670 MHz	1675 MHz	1670 MHz	1675 MHz	TDD		5	TD 1700	Ligado TDD

LTE Operating Band	NR Operating Band	UL_Low	UL_High	DL_Low	DL_High	Duplex Mode	LTE Bandwidths	NR Bandwidths	Nickname(s)	Region(s) of Usage
65	n65	1920 MHz	2010 MHz	2110 MHz	2200 MHz	FDD	1.4, 3, 5, 10, 15, 19	5, 10, 15, 20, 50		
66	n66	1710 MHz	1780 MHz	2110 MHz	2200 MHz	FDD	1.4, 3, 5, 10, 15, 20	5, 10, 15, 20, 25, 30, 35, 40, 45		
67	n67	N/A	N/A	738 MHz	758 MHz	SDL	5, 10, 15, 20			
68		698 MHz	728 MHz	753 MHz	783 MHz	FDD	5, 10, 15			
69		N/A	N/A	2570 MHz	2620 MHz	SDL	5, 10, 15, 20			
70	n70	1695 MHz	1710 MHz	1995 MHz	2020 MHz	FDD	5, 10, 15, 20	5, 10, 15, 20, 25		North America
71	n71	663 MHz	698 MHz	617 MHz	652 MHz	FDD	5, 10, 15, 20	5, 10, 15, 20, 25, 30, 35	600 MHz Band	600 MHz Band / North America
72		451 MHz	456 MHz	461 MHz	466 MHz	FDD	1.4, 3, 5			Europe
73		450 MHz	455 MHz	460 MHz	465 MHz	FDD	1.4, 3, 5			China
74	n74	1427 MHz	1470 MHz	1475 MHz	1518 MHz	FDD	1.4, 3, 5, 10, 15, 20	5, 10, 15, 20		Japan
75	n75	N/A	N/A	1432 MHz	1517 MHz	SDL	5, 10, 15, 20	5, 10, 15, 20, 25, 30. 40, 50		EU
76	n76	N/A	N/A	1427 MHz	1432 MHz	SDL	5	5		EU
85	n85	698 MHz	716 MHz	728 MHz	746 MHz	FDD	5, 10	5, 10, 15		
87		410 MHz	415 MHz	420 MHz	425 MHz	FDD	1.4, 3.5			EU PPDR PMR/PMAR
88		412 MHz	417 MHz	422 MHz	427 MHz	FDD	1.4, 3, 5			EU PPDR PMR/PMAR
103		787.1 MHz	787.9 MHz	757.1 MHz	757.9 MHz	FDD	NB-IoT only			Upper 700 MHz
XGP		2545 MHz	2575 MHz	2545 MHz	2575 MHz	TDD	-		XGP (non-3GPP band)	Japan
	n77	3300 MHz	4200 MHz	3300 MHz	4200 MHz	TDD		10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100	C-Band	
	n78	3300 MHz	3800 MHz	3300 MHz	3800 MHz	TDD		10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100	C-Band	
	n79	4400 MHz	5000 MHz	4400 MHz	5000 MHz	TDD		10, 20, 30, 40, 50, 60, 80, 100	C-Band	
	n80	1710 MHz	1785 MHz	N/A	N/A	SUL		5, 10, 15, 20, 25, 30, 40		
	n81	880 MHz	915 MHz	N/A	N/A	SUL		5, 10, 15, 20		
	n82	832 MHz	862 MHz	N/A	N/A	SUL		5, 10, 15, 20		
	n83	703 MHz	748 MHz	N/A	N/A	SUL		5, 10, 15, 20, 25, 30		
	n84	1920 MHz	1980 MHz	N/A	N/A	SUL		5, 10, 15, 20, 25, 30, 40, 50		
	n86	1710 MHz	1780 MHz	N/A	N/A	SUL	5, 10	5, 10, 15, 20, 40		
	n89	824 MHz	849 MHz	N/A	N/A	SUL		5, 10, 15, 20		

LTE Operating Band	NR Operating Band	UL_Low	UL_High	DL_Low	DL_High	Duplex Mode	LTE Bandwidths	NR Bandwidths	Nickname(s)	Region(s) of Usage
	n90	2496 MHz	2690 MHz	2496 MHz	2690 MHz	TDD		5, 10, 15, 20, 25, 30, 40, 45, 50, 60, 70, 80, 90, 101		
	n91	832 MHz	862 MHz	1427 MHz	1432 MHz			5, 10		
	n92	832 MHz	862 MHz	1432 MHz	1517 MHz			5, 10, 15, 20		
	n93	880 MHz	915 MHz	1427 MHz	1432 MHz			5, 10		
	n94	880 MHz	915 MHz	1432 MHz	1517 MHz			5, 10, 15, 20		
	n95	2010 MHz	2025 MHz	N/A	N/A	SUL		5, 10, 15		n34 SUL
	n96	5925 MHz	7125 MHz	5925 MHz	7125 MHz	TDD		20, 40, 60, 80, 100		6 GHz NR-U full band
	n97	2300 MHz	2400 MHz	N/A	N/A	SUL		5. 10, 15, 20, 25, 30, 40, 50, 60, 70, 80 90, 100		n40 SUL
	n98	1880 MHz	1920 MHz	N/A	N/A	SUL		5, 10, 15, 20, 25, 30, 40		n39 SUL
	n99	1626.5 MHz	1660.5 MHz	N/A	N/A	SUL		5, 10		n24 SUL
	n100	874.4 MHz	880 MHz	919.4 MHz	925 MHz	FDD		5		EU Rail 900
	n101	1900 MHz	1910 MHz	1900 MHz	1910 MHz	TDD		5, 10		EU Rail 1900 TDD
	n102	5925 MHz	6425 MHz	5925 MHz	6425 MHz	TDD		20. 40, 60, 80, 100		6 GHz NR-U Lower 500 MHz
	n104	6425 MHz	7125 MHz	6425 MHz	7125 MHz	TDD		20, 30, 40, 50, 60, 70, 80, 90, 100		Licensed 6 GHz
	n105	663 MHz	703 MHz	612 MHz	652 MHz	FDD		TBD - Rel 18		APT 600
	n106	896 MHz	901 MHz	935 MHz	940 MHz	FDD				Anterix private networks

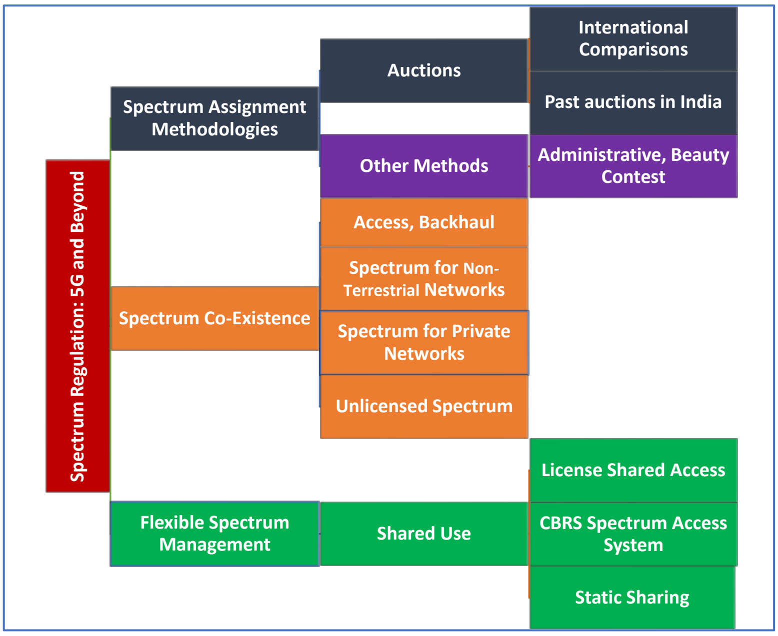
NR Operating Band	UL_Low	UL_High	DL_Low	DL_High	Duplex Mode	NR Bandwidths	Nickname(s)
n257	26.5 GHz	29.5 GHz	26.5 GHz	29.5 GHz	TDD	50, 100, 200, 400	28 GHz Band
n258	24.25 GHz	27.5 GHz	24.25 GHz	27.5 GHz	TDD	50, 100, 200, 400	26 GHz Band
n259	39.50 GHz	43.50 GHz	39.50 GHz	43.50 GHz	TDD	50, 100, 200, 400	41 GHz Band
n260	37 GHz	40 GHz	37 GHz	40 GHz	TDD	50, 100, 200, 400	39 GHz Band
n261	27.5 GHz	28.35 GHz	27.5 GHz	28.35 GHz	TDD	50, 100, 200, 400	28 GHz Band
n262	47.20 GHz	48.20 GHz	47.20 GHz	48.20 GHz	TDD	50, 100, 200, 400	47 GHz Band
n263	57.0 GHz	71.0 GHz	57.0 GHz	71.0 GHz	TDD	100, 400, 800, 1600, 2000	60 GHz Band

Chapter 2: Research Methodology

1 Research Objectives

It is with this background that we analyze spectrum regulations and policies of India and other countries with the advent of 5G and beyond networks. The topics that cover in this study are provided in Figure 2.1.

Figure 2.1: Taxonomy of the Study



2 Research Methodology

2.1 Empirical Analysis

We compiled a panel dataset consisting of 5G spectrum auctions held in 40 countries during 2018-2025 from various sources. The countries spanned the European Union, North America, South America, Africa, Australia, and South and Southeast Asia. We analyzed winning bid prices, reserve prices, spectrum available, and spectrum assigned across various bands, with specific emphasis on sub-GHz and upper mid-band (C-band).

2.2 Interviews with Experts

To supplement our study, we interviewed 12 experts in the area of spectrum auction across different organizations worldwide (Table 2.1). The summary of discussions is provided in Appendix 1.2.

Table 2.1: Summary of Experts Interviewed in the Study

Type of Organization	India	Outside India
Academia		2
Network Equipment Manufacturers	1	1
Regulatory Institutions		1
Telecom Industry Association		2
Telecom and Internet Service Providers	1	
Start-ups in Telecom	3	1
Total	**5**	**7**

3 Thematic Analysis of Interviews with Experts

3.1 Auctions, Pricing, and Market Structure

Across discussions, there was broad recognition that auctions remain the dominant allocation tool owing to their transparency and fairness. However, concerns remained about their effectiveness in markets with limited competition. In countries like India, where three major players remain, auctions often clear at reserve prices, reducing their utility. By contrast, in earlier years that included several bidders, auctions were effective at price discovery and deterring collusion.

Some suggested hybrid approaches included combining lower reserve prices with obligations such as rural coverage or industrial connectivity. Others pointed to administrative renewals with negotiated commitments as a way to avoid service disruptions when the spectrum expires.

Examples:

- In Finland, auctions are kept simple with low reserve prices, maintaining operator sustainability.
- In India, high reserve prices since the 2010 3G auction have locked the system into an unsustainable path.
- In the US, the AWS-3 auction and the Broadcast Incentive Auction demonstrated both the success and extreme complexity of combinatorial and clock auctions.

3.2 Licensed vs. Unlicensed Spectrum: The 6 GHz Debate

The 6 GHz band was heavily debated. Different regions have adopted divergent policies:

- The US opened the full 1.2 GHz for unlicensed Wi-Fi, supported by automated frequency coordination (AFC).
- Europe has allowed only part of the band, with low-power indoor use, and is still debating outdoor permissions.

- India and other countries lean towards splitting the band, with lower portions for Wi-Fi and upper portions for International Mobile Telecommunications (IMT).
- China favours IMT use, aligning with the strengths of its telecom vendors.

Opinions diverged on whether spectrum convergence (Wi-Fi and cellular using similar bands and power levels) implies pricing convergence. Some argued that the logic supports harmonized treatment, while others noted that cellular operators would always demand exclusive rights.

Examples:

- The US AFC system ensures that unlicensed Wi-Fi devices do not interfere with fixed links.
- In India, policymakers are weighing the demand for indoor Wi-Fi against operators' push for licensed mid-band IMT capacity.

3.3 Local and Private Networks

The rise of private and local networks was a recurring theme, particularly for Industry 4.0 use cases (factories, ports, hospitals, mines). Regulators in Europe, the US, and Asia have created frameworks for enterprises to directly access spectrum. Uptake varies:

- The UK has over 1,000 private networks.
- Germany has issued around 400 licences in 3.7 GHz.
- Finland has a few dozen private networks, but many remain operator-managed.
- In the US, the citizen band radio service (CBRS) enabled small ISPs and enterprises, with over 400,000 base stations deployed.

There was a divergence of views, with some viewing private/local networks as vital for innovation while others warned that they fragment scarce IMT spectrum. Some noted that operators can also run private networks under lease, creating a middle ground.

Examples:

- Hospitals using multi-operator shared cores for critical monitoring.
- Ports and factories adopting private 5G for secure, fenced environments.
- Neutral host models in airports and stadiums (e.g., Marina Bay Sands in Singapore) providing shared infrastructure for all operators.
- Vodafone's 5G Standalone network in 26 GHz band at the Harwell Science & Innovation campus in the UK.

3.4 Spectrum Sharing Models and Their Limits

The idea of dynamic sharing has long been promoted, but in practice, adoption has been limited. Most countries prefer static licensing with manual interference checks, which gives users predictability. End users dislike systems that can dynamically reassign frequencies, causing disruptions.

Dynamic models were usually created under special conditions, some of which follow:

- TV white spaces were used for protecting wireless microphones and accommodating consumer-managed access points.
- CBRS (3.5 GHz in the US) was designed to protect Navy radars but is too complex and not harmonized globally.
- LSA in 2.3 GHz Europe was intended for wireless cameras and public safety but was not scaled up.
- 6 GHz AFC usage was justified by consumer-owned Wi-Fi devices and incumbent fixed links.

The consensus was that sharing will expand as no new "clean" bands remain, but most regulators prefer simpler, database-driven or static systems rather than the complexity of CBRS.

3.5 High Frequencies and Future Bands

There was agreement that millimetre-wave bands (26 GHz, 28 GHz, 60 GHz) have not lived up to 5G expectations. Uptake has been minimal, with usage confined to fixed wireless access (FWA) and a few urban testbeds. Some operators have experimented with running Wi-Fi stacks on licensed 26 GHz spectrum to cut costs, reflecting localized improvisation.

Looking ahead to 6G, attention is shifting to upper mid-bands (7–8 GHz). Clearing incumbents for 6G will be harder as political resistance grows against giving mobile operators more spectrum. The preferred path might be re-farming existing 2G–5G bands and adding new high bands.

Examples:

- In India's 26 GHz auction, Jio, Airtel, and Adani bought spectrum, though Adani later sold its holdings.
- Korea and the US found millimetre-wave rollout impractical for wide coverage.

3.6 Satellites, Convergence, and New Frontiers

Satellite integration into mobile networks is rapidly occurring. Business deals in the US have already enabled mobile operators and satellite providers to share terrestrial bands, leading to the Supplemental Coverage from Space (SCS) framework, which is now being studied globally under WRC-27.

Opinions varied on how feasible sharing is:

- FDD bands are easier to share with satellites, while TDD bands create challenges due to latency mismatches.
- Some see satellites as complementary, especially in rural and remote areas. Others caution that regulation must ensure parity with mobile operators if satellites compete in consumer broadband.

Examples:

- Starlink enabling direct-to-device SMS and calls with Samsung phones in the US.
- FCC's SCS framework covering bands like 600, 700, 800, and 1900 MHz.

3.7 Overall Synthesis

Several consistent threads emerged across the discussions:

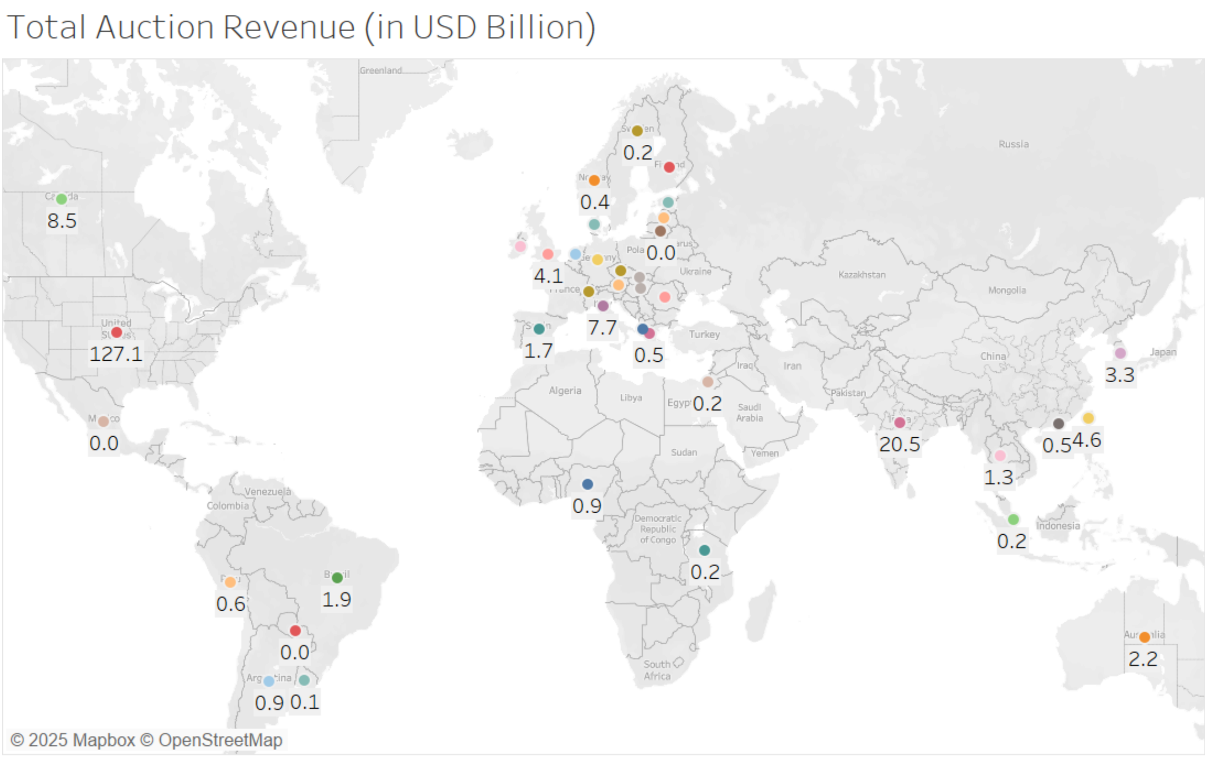
- Auctions remain the preferred tool, but their limits are stark in concentrated markets, with concerns around high reserve prices.
- The 6 GHz band is the battleground, with diverging preferences globally between licensed IMT and unlicensed Wi-Fi, reflecting industrial and geopolitical interests.
- Private/local networks are gaining momentum, reshaping traditional operator-led models.
- Dynamic sharing is mostly rhetorical, with static licensing still being the preferred practical tool, except in special cases.
- High-frequency spectrum is struggling, while upper mid-bands are emerging as the most beneficial for 6G.
- Satellites are entering the terrestrial ecosystem, pushing regulators to develop new sharing and co-existence frameworks.

Chapter 3: Empirical Analysis of 5G Spectrum Auctions across Countries

Auctioning spectrum for 5G networks began in 2018, with South Korea becoming the first country to auction spectrum in the 3.5 GHz and 28 GHz bands. Several countries followed. We collected data from 5G auctions held between 2018 and 2025 in 40 countries. In this chapter, we present empirical analysis of select auctions and discuss notable patterns.

Spectrum auctions have generated significant revenue for state exchequers (Figure 3.1). The 2022 mega auction in India generated close to USD 20 billion for the government. Other examples of mega auctions include the US (USD 127 billion), Canada (USD 8.5 billion), Italy (USD 7.7 billion), and Germany (USD 7.2 billion).

Figure 3.1: Revenue Generated Through 5G Spectrum Auctions Worldwide



Map based on Longitude (generated) and Latitude (generated). Color shows details about Country Code. The marks are labeled by sum of Total Revenue in USD B.

1 5G Auctions in Asia

1.1 The First 5G Auction in South Korea

The South Korean government conducted the first 5G spectrum auction in 2018, managed by the Ministry of Science and ICT (MSIT) and the Korea Communications Commission (KCC). Key details of the auction follow:[10]

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[10] 방송통신위원회. (n.d.). 방송통신위원회. Copyright (C) 2008 Korea Communications Commission. https://www.kcc.go.kr/user.do?mode=view&page=A02060400&dc=K02060400&boardId=1030&cp=1&boardSeq=39994

Table 3.1: Details of the 5G Auction in South Korea

MHz — 3.5 GHz Band	Blocks at 3.5 GHz	MHz — 28 GHz Band	Blocks at 28 GHz
Total mid-band spectrum made available across 28 blocks of 10 MHz each.	Each block sized at 10 MHz, enabling granular and flexible allocation among bidders.	Total high-band mmWave spectrum available, representing a significant pool for dense urban 5G deployment.	Each block sized at 100 MHz, designed for the wide-channel requirements of mmWave 5G technology.

In July 2022, LG Uplus acquired an extra 20 MHz in the 3.40–3.42 GHz range, bringing its total to 100 MHz in the 3.5 GHz band. Notably, all blocks were sold at the end of the second allotment. Results of the auction are presented in Table 3.2.

Table 3.2: Summary Results of the 5G Auction in South Korea

South Korea	**Freq. MHz / Year1**	
Frequency Band	**3.5 GHz**	**28 GHz**
Year	**2018**	**2018**
Avg. Spectrum Available	2,680	2,680
Spectrum Allotted	280	2,400
Gross Revenue (in USD Million)	2,701	561
Price/MHz/Pop (USD)	0.1863	0.0045

The final winning bid prices were about 20% higher than the reserve price. All the spectrum put on the block were picked up by the bidders. The total revenue earned through these auctions was about USD 3.26 billion. Notably, the licence duration for the two bands is different: 10 years for the 3.5 GHz band and five years for the 28 GHz band.

1.2 The High-Priced 5G Upper Mid-Band Auction in Taiwan

Taiwan held a heavily contested high-priced auction for the upper mid-band in 2020.[11] Key details follow.

[11] NCC公布5G首波釋出頻率 28GHz、3.4GHz. https://digi.nstc.gov.tw/Page/1538F8CF7474AB4E/387496b9-6376-43a7-ac0f-391a644338c4

Table 3.3: Key Details of the 5G Auction in Taiwan

Operator	3.5 GHz	28 GHz	Notes
Chunghwa Telecom	90 MHz / NTD 45.675B	600 MHz / NTD 618M	Dominant across both bands — largest allocations and highest total spend.
Far EasTone	80 MHz / NTD 40.6B	400 MHz / NTD 412M	Strong dual-band position; second in both mid-band spend and mmWave allocation.
Taiwan Mobile	60 MHz / NTD 30.4B	200 MHz / NTD 206M	Balanced dual-band participation; smallest 28 GHz block among all winners.
Asia Pacific Telecom	Withdrew	400 MHz / NTD 412M	Unique single-band strategy; mmWave-only positioning for enterprise focus.
Taiwan Star	40 MHz / NTD 19.708B	Did not participate	Smallest 3.5 GHz block; no 28 GHz presence — most limited spectrum portfolio.

Key Takeaways

- **High Costs**: The 3.5 GHz band's unit price per 10 MHz reached NTD 5.075 billion, making it one of the most expensive 5G spectrums globally relative to population size.
- **Market Consolidation**: Post-auction, and following mergers (e.g., Taiwan Star merged with Taiwan Mobile), Taiwan's telecom market was consolidated among three major players (Chunghwa, Far EasTone, Taiwan Mobile).
- **Deployment Commitments**:
  - Winners were required to achieve 50% coverage by 2022 and nationwide coverage by 2025.
  - As of 2025, leading operator Chunghwa Telecom's 5G coverage exceeds 97%.

Taiwan's 5G auction was notable for its high revenue per capita, reflecting strong demand for mid-band spectrum. Compared to Singapore (which allocated spectrum via a hybrid model), Taiwan's pure auction approach led to higher costs but faster rollout.

The results of the auctions in Taiwan and Singapore are provided in Table 3.4 and highlight that the price/MHz/pop for the 3,500 MHz band is one of the highest in the world, at 0.7113.

Table 3.4: Summary Results of the 5G Auctions in Taiwan and Singapore

Taiwan		
	Freq. Band / Year	
Frequency Band	**3.5 GHz**	**28 GHz**
Year	**2020**	**2020**
Avg. Spectrum Available	1,560	1,560
Spectrum Allotted	270	1,200
Gross Revenue (in USD Millions)	4,546	412
Price/MHz/Pop (USD)	0.7113	0.0015
Singapore		
	Freq. Band / Year	
Frequency Band	**2.1 GHz**	**3.5 GHz**
Year	**2021**	**2020**
Avg. Spectrum Available	90	200
Spectrum Allotted	90	200
Gross Revenue (in USD Millions)	103	81
Price/MHz/Pop (USD)	0.2014	0.0715

2 UK: Auction of 700 MHz and Upper Mid-Band

OfCom in the UK conducted two auctions—one in 2018 and another in 2021. Table 3.3 provides summary results of the UK auctions.

2.1 2018 Auction of Upper Mid-Band

In 2018, Ofcom auctioned 40 MHz in the 2.3 GHz band and 150 MHz in the 3.4 GHz band, totalling 190 MHz of spectrum in the year.[12] While the 2.3 GHz band was aimed at augmenting the spectrum holding of operators for 4G, the 3.4 GHz upper mid-band was auctioned to roll out 5G. The auction marked the UK's first major step towards 5G deployment, with subsequent auctions in 2021 further expanding spectrum availability. Unlike the 3G auction (GBP 22.5 billion in 2000), prices were more realistic, reflecting lessons learned from past overbidding.

Vodafone, Three, EE, and O2 won chunks of 3.4 GHz (3410–3580 MGz) for a total bid amount of about USD 1.5 billion. Three had the largest 5G-ready spectrum (160 MHz) due to prior acquisitions, while EE led in total spectrum (378 MHz). All the spectrum that was put into auction was sold at a winning bid price of USD 0.1738/MHz/Pop for the 3.4 GHz band, much higher than the reserve price of USD 0.004/MHz/Pop.

[12] Hutton, G., & Baker, C. (2018). Spectrum auctions 2018. *House of Commons Library*. https://commonslibrary.parliament.uk/research-briefings/cbp-8270/

2.2 2021 Auction of 700 MHz and Upper Mid-Band

Following the success of the upper mid-band auction in 2018, OfCom held a 5G spectrum auction in March 2021 by auctioning both 700 MHz and upper mid-band (3.6-3.8 GHz).[13] All spectrum awards were designated by Ofcom under a "technology-neutral" and "service-neutral" licensing framework, i.e., licensees could use the awarded spectrum for any technology (e.g., 4G, 5G) and any service type (e.g., mobile, fixed wireless), subject to technical conditions (like power limits or coordination requirements).

The auction followed a two-stage format using the SMRA auction model, followed by an assignment stage. All 200 MHz that were put on auction were sold. Table 3.5 provides a summary of the auction results.

Table 3.5: Results of the 700 MHz and Upper Mid-Band Spectrum Auctions in the UK

UK	Freq MHz / Year			
Frequency Band	**700**	**2300**	**3400**	**3600**
Year	**2021**	**2018**	**2018**	**2021**
Avg. Spectrum Available	200	190	190	200
Spectrum Allotted	60	40	150	140
Gross Revenue (in USD Millions)	1,493	366	2,069	1,409
Price/MHz/Pop (USD)	0.2904	0.1143	0.1738	0.1390

3 European 5G Spectrum Auctions

The 5G spectrum auctions in Europe began with Finland. Finland was one of the first movers in Europe to assign the 700 MHz band for 5G, with its first auction taking place in 2016, nearly a decade before some other European countries. For instance, Belgium held its first 5G auction in 2022. Other early adopters like Sweden and Denmark also advanced their 5G deployments through proactive spectrum policies.

3.1 Finland: At the Forefront of 5G Spectrum Auctions

The 700 MHz spectrum auction in 2016 was a significant milestone in Finland's telecommunications landscape and was aimed at enhancing 4G coverage and laying the groundwork for future 5G networks.

Key Details of the Auction[14]

- **Auction Date and Participants:** The auction was organized by the Finnish Communications Regulatory Authority and concluded on 24 November 2016. The

[13] Ofcom. (2021, March 25). *Publication of the results of the principal stage of the auction under regulation 49 of the Wireless Telegraphy (Licence Award) Regulations 2020*. https://www.ofcom.org.uk/siteassets/resources/documents/spectrum/spectrum-management/spectrum-awards/700-mhz-and-3.6-3.8-ghz/notices/publication-ps-results-reg-49.pdf?v=326148

[14] Elisa Oyj. (2016, November 24). *Elisa successful in the Finnish 700 MHz 4G spectrum auction*. https://news.cision.com/elisa-oyj/r/elisa-successful-in-the-finnish-700-mhz-4g-spectrum-auction,c2816508

three major Finnish telecom operators—Elisa, DNA, and Telia (operating as Sonera)—participated, each securing 2x10 MHz of spectrum for EUR 22 million.

- **Spectrum Allocation and Fees:** A total of six frequency pairs (5 MHz each) in the 703–733 MHz and 758–788 MHz bands were auctioned, with a reserve price of EUR 11 million per pair. The government raised EUR 66 million, with each operator paying their fee in five annual instalments.
- **Licence Terms and Coverage Obligations:** Licences were valid from 1 February 2017 to 31 December 2033 (17 years). Operators were required to provide 4G coverage to 99% of Finland's population by 2020, though Elisa and DNA had already met this target at the time of the auction.
- **Purpose and Technological Impact:** The 700 MHz band was prized for its long-range propagation, which is ideal for improving coverage in rural and sparsely populated areas.

While the 700 MHz spectrum was initially targeted for 4G expansion, operators noted its future compatibility with 5G networks. The spectrum attracted a winning bid price of about USD 0.2224/MHz/Pop, matching the reserve price. All the spectrum that were auctioned were acquired by the three bidders who participated in the auction.

Finland traditionally used beauty contests (or comparative hearings) and used auctions for the first time in 2013 for the 800 MHz spectrum band. The 2016 auction followed an SMRA-based auction procedure. Results of subsequent auctions in Finland are presented in Table 3.6.

Table 3.6: Results of 5G Spectrum Auctions in Finland

	Freq MHz / Year		
Frequency Band	**700**	**3500**	**26000**
Year	**2016**	**2018**	**2020**
Avg. Spectrum Available	60	390	2,400
Spectrum Allotted	60	390	2,400
Total Revenue (EUR Millions)	66	78	21
Price/MHz/Pop (in USD)	0.2224	0.0411	0.0018

Subsequently, 5G auctions were held in the other European countries. In general, European countries started auctioning the upper mid-band spectrum in 2018, and in most cases, all the spectrum put on auction was sold. For detailed results, see Table 3.7.

Table 3.7: Results of 5G Spectrum Auctions in Select European Countries

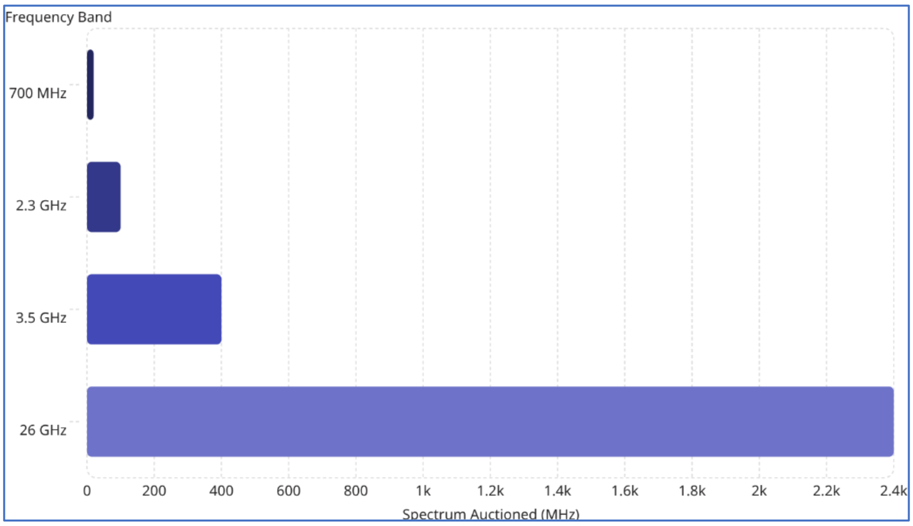
Germany		
	Freq MHz / Year1	
Frequency Band	**2000**	**3600**
Year	**2020**	**2020**
Avg. Spectrum Available	420	420
Spectrum Allotted	120	300
Gross Revenue (in EUR Millions)	2,375	4,174
Price/MHz/Pop (USD)	0.2591	0.1665
Spain		
	Freq Band / Year	
Frequency Band	**3.6 GHz**	**700 MHz**
Year	**2018**	**2021**
Avg. Spectrum Available	200	60
Spectrum Allotted	200	60
Gross Revenue (in EUR Millions)	438	1,010
Price/MHz/Pop (USD)	0.0552	0.4170

4 5G Spectrum Auctions in Latin America

Latin American countries began auctioning the upper mid-band in 2021. However, roadblocks such as political instability have challenged auctions in several countries.

In Brazil's 2021 multi-band 5G auction, 3.7 GHz (or 3,700 MHz) of total spectrum was auctioned across frequency bands.[15] Figure 3.2 provides a summary of the auctioned spectrum.

Figure 3.2: Breakdown of Spectrum Auction in Brazil in 2021



[15] Tomás, J. P. (2021, November 8). *Brazil raises a total of $8.5 billion in 5G spectrum auction*. RCR Wireless News. https://www.rcrwireless.com/20211108/featured/brazil-raises-total-8-billion-5g-spectrum-auction

Brazil's 2021 5G spectrum auction stands as a case study in multi-band spectrum policy design—one that balances immediate commercial imperatives with long-term public interest goals. The auction architecture reflected several deliberate policy choices worth examining in depth for their implications on competition, deployment, and digital inclusion.

The auction results are provided in Table 3.8. As seen, the price for the upper mid-band spectrum is very low. This is due to the two-part assignment process, where, after the SMRA assignment phase, bidders had to commit an infrastructure obligation fund. However, in general, the rollout obligations were prioritized.

Table 3.8: Results of 5G Spectrum Auctions in Brazil

	Freq Band / Year				
Frequency Band	**2.3 GHz (40 MHz)**	**2.3 GHz (50 MHz)**	**3.5 GHz**	**26 GHz**	**700 MHz**
Year	**2021**	**2021**	**2021**	**2021**	**2021**
Avg. Spectrum Available	15,870	15,870	15,870	15,870	15,870
Spectrum Allotted	720	1,050	3,280	10,800	20
Gross Revenue (in EUR Millions)	880	1,483	6,079	348	1,410
Price/MHz/Pop (USD)	0.0132	0.0045	0.0205	0.0001	0.0641

In Mexico, the upper mid-band auction in 2022 was cancelled due to high spectrum fees; regulatory uncertainty due to the planned dissolution of the Federal Telecommunications Institute by early 2026, complicating auction oversight; and market saturation, with Telcel and AT&T having already rolled out 5G using existing spectrum, which reduced the demand for new acquisitions. The cancellation slowed Mexico's 5G expansion by forcing it to rely on incremental upgrades to existing networks. Table 3.9 provides a summary of 5G auctions in the upper mid-band held in some other countries in Latin America.

Table 3.9: Results of 5G Spectrum Auctions in Select Latin American Countries

Uruguay	
	Freq Band / Year
Frequency Band	**3.5 GHz**
Year	**2023**
Avg. Spectrum Available	200
Spectrum Allotted	200
Gross Revenue (in USD Millions)	59
Price/MHz/Pop (USD)	0.0843
Paraguay	
	Freq Band / Year
Frequency Band	**3.5 GHz**
Year	**2023**
Avg. Spectrum Available	250
Spectrum Allotted	250
Gross Revenue (in USD Millions)	875
Price/MHz/Pop (USD)	0.0767

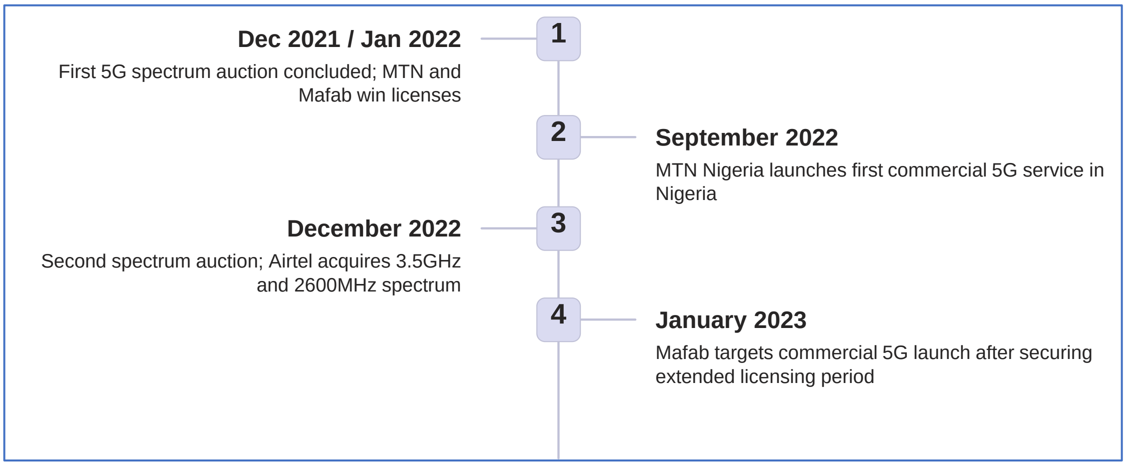
5 5G Auctions in Africa

African nations have lagged behind other countries in assigning 5G spectrum. The first 5G spectrum auction in the continent was held in Nigeria in December 2021/January 2022, marking a pivotal moment in the country's telecommunications landscape. Conducted by the Nigerian Communications Commission (NCC), the auction had three major participants: MTN Nigeria, Mafab Communications, and Airtel Nigeria. The process was designed to allocate spectrum in the strategically important 3.5 GHz band, which is universally recognized as the primary mid-band frequency for early 5G deployments globally.

The auction generated considerable competitive tension, with final bid prices substantially exceeding the established reserve. Both MTN Nigeria and Mafab Communications each secured 100 MHz in the 3.5 GHz band, paying USD 273.6 million per lot, which significantly outpaced the reserve price of USD 199.3 million and signalled strong industry confidence in Nigeria's 5G market potential. Airtel Nigeria, however, withdrew from the bidding process, citing the high cost as commercially unviable at that stage.

The gap between the reserve price and the winning bid in the first auction is a notable indicator of market demand. At USD 273.6 million per 100 MHz lot against a reserve of USD 199.3 million, winning bids exceeded the floor by approximately 37%, reflecting both spectrum scarcity and the strategic imperative for operators to secure 5G-capable frequencies ahead of competitors. The total amount raised from the first auction alone reached USD 547.2 million, with each of the two winning lots contributing equally. The timeline of deployment of 5G in Nigeria is presented in Figure 3.3.

Figure 3.3: The Timeline of 5G Deployment in Nigeria



The second country to auction 5G spectrum was Tanzania in 2022, the results of which are presented in Table 3.10.

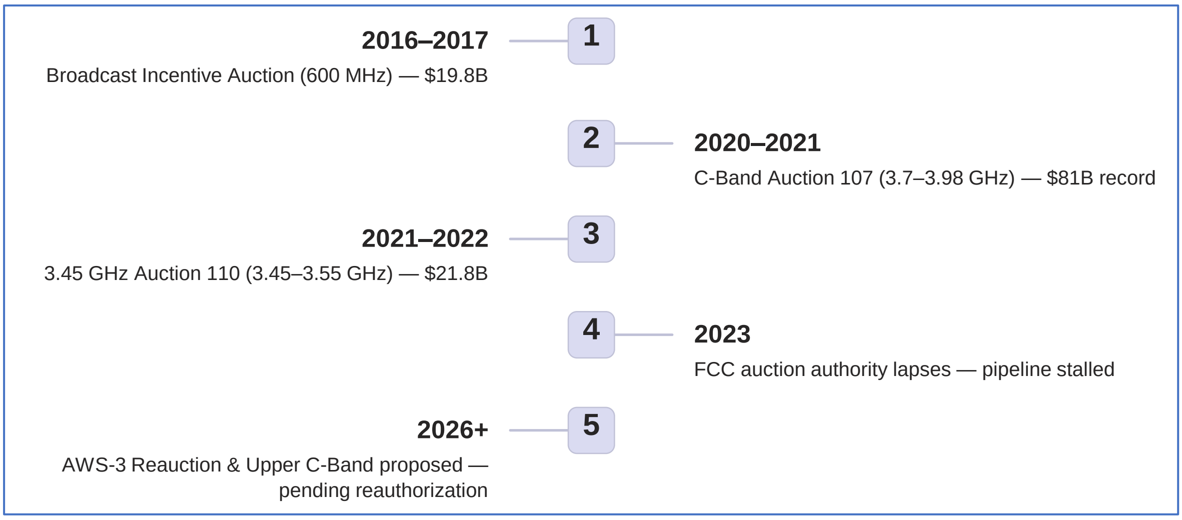
Table 3.10: Results of 5G Spectrum Auctions in Nigeria and Tanzania

Nigeria			
	Freq Band / Year		
Frequency Band	2.6 GHz	3.5 GHz	
Year	2023	2021	2023
Avg. Spectrum Available	210	200	210
Spectrum Allotted	10	200	200
Gross Revenue (in USD Millions)	46	548	293
Price/MHz/Pop (USD)	0.0202	0.0129	0.0064
Tanzania			
	Freq Band / Year		
Frequency Band	2.3 Ghz	3.5 GHz	700 MHz
Year	2022	2022	2022
Avg. Spectrum Available	230	230	230
Spectrum Allotted	70	120	40
Gross Revenue (in USD Millions)	34	76	46
Price/MHz/Pop (USD)	0.0078	0.0101	0.0181

6 5G Auctions in the US

The FCC in the US conducted several significant spectrum auctions after 2015 (see Figure 3.4 for details).

Figure 3.4: Timeline of Spectrum Auctions in the US



The Broadcast Incentive Auction is one of the most structurally complex spectrum re-allocation exercises in FCC history. Conducted between 2016 and 2017, it repurposed television broadcast spectrum in the 600 MHz band for wireless broadband, which is widely regarded as ideal for rural coverage due to its superior propagation characteristics over longer distances and through building materials. T-Mobile was the dominant winner, securing substantial low-band spectrum holdings that became the cornerstone of its nationwide 5G strategy. The 600 MHz licences enabled T-Mobile to rapidly extend 5G coverage to rural and suburban markets where mid-band spectrum struggles to reach.

The C-Band auction was a watershed moment in US spectrum policy. Running from December 2020 to January 2021, Auction 107 covered the 3.7–3.98 GHz portion of the mid-band spectrum—a range that engineers and policymakers have described as "beachfront property" for 5G, offering an unmatched balance of geographic coverage and network capacity. When bidding closed, the FCC had recorded USD 81 billion in total proceeds, shattering every prior FCC auction record and surpassing the combined revenue of all previous US spectrum auctions. The competitive dynamics were intense. Verizon, facing a significant deficit in mid-band spectrum compared to its rivals, committed approximately USD 45 billion—more than half the total auction revenue—in an aggressive campaign to shore up its 5G network's capacity and competitive positioning. AT&T and T-Mobile also made major investments. Consequently, all three national carriers emerged with meaningful C-Band holdings to anchor their mid-band 5G roadmaps.

Less than a year later, the FCC launched Auction 110, covering the 3.45–3.55 GHz band—a 100 MHz slice of mid-band spectrum that had been exclusively reserved for federal use, primarily by military radar systems. The auction ran from October 2021 through January 2022, ultimately generating USD 21.8 billion in proceeds and further cementing mid-band spectrum as the dominant commercial battleground for 5G network densification. A defining regulatory feature of Auction 110 was the FCC's decision to cap individual bidder acquisitions at 40 MHz per licence area. This constraint was deliberately designed to prevent any single carrier from monopolizing the band, ensuring that multiple competitors could acquire meaningful spectrum positions. The rule reflected a broader FCC philosophy of promoting competitive balance in mid-band holdings, particularly as the agency recognized the strategic importance of the 3 GHz range for next-generation wireless. AT&T emerged as the most aggressive bidder, driven by a recognized shortfall in mid-band spectrum relative to T-Mobile's substantial 2.5 GHz portfolio. Dish Network, which was then pursuing its ambitious buildout of an open-RAN 5G network, and T-Mobile were also notable participants. The auction underscored the increasingly stratified nature of spectrum competition, with carriers making calculated bets on specific band combinations to optimize their network architectures.

The trajectory of US spectrum policy beyond 2023 is defined as much by institutional uncertainty as by technical opportunity. The FCC's auction authority—the legal mandate enabling the agency to license spectrum through competitive bidding—lapsed in March 2023, creating a policy vacuum that has delayed several planned proceedings. Restoring that authority through congressional action is considered a prerequisite for the next generation of spectrum auctions, and the debate over re-authorization has become entangled in broader legislative negotiations over spectrum policy, federal pre-emption, and revenue allocation.

The results of the upper mid-band auctions and the 600 MHz auctions are provided in Table 3.11.

Table 3.11: Results of 5G Spectrum Auctions in the US

	Freq Band / Year			
Frequency Band	**3.5 GHz**	**3.7-3.98 GHz**	**3.45 GHz**	**600 MHz**
Year	**2020**	**2021**	**2021**	**2017**
Avg. Spectrum Available	22,631	56,840	40,600	1,32,700
Spectrum Allotted	22,631	56,840	40,420	27,760
Gross Revenue (in USD Millions)	4,578	80,917	21,888	19,311
Price/MHz/Pop (USD)	0.1245	1.2619	0.4043	0.5072

7 5G Auctions in Canada

Canada's landmark 3500 MHz combinatorial clock auction (CCA) held in 2021 and the subsequent 3800 MHz auction in 2023 shaped the country's 5G spectrum landscape.[16]

In summer 2021, Innovation, Science and Economic Development Canada (ISED) administered Canada's most consequential spectrum auction till date. The auction targeted the 3450–3650 MHz band—a critical 200 MHz swath of upper mid-band spectrum that serves as the primary mid-band foundation for 5G deployment across the country. This band offers the ideal balance of coverage and capacity, making it among the most commercially valuable spectrum ever auctioned in Canada.

The CCA format allowed bidders to place bids on combinations of licences rather than individual lots as a means to reduce exposure risk for bidders and improve overall efficiency in licence allocation. The CCA format had been used in previous Canadian spectrum auctions and was well understood by major market participants. The auction ran from June 15 to July 23, 2021, spanning 25 business days and completing 103 rounds of bidding, the duration reflecting the intense competition among national carriers and regional operators seeking to secure 5G-critical spectrum. The opening bid floor was set at approximately CAD 590 million, signalling the substantial value that ISED placed on this mid-band resource from the outset.

This auction was followed by a 2023 auction of the upper mid-band spectrum in the 3800 MHz band. The results of both auctions are provided in Table 3.12. As indicated, the price/MHz/pop in both the auctions was very high.

Table 3.12: Results of 5G Spectrum Auctions in Canada

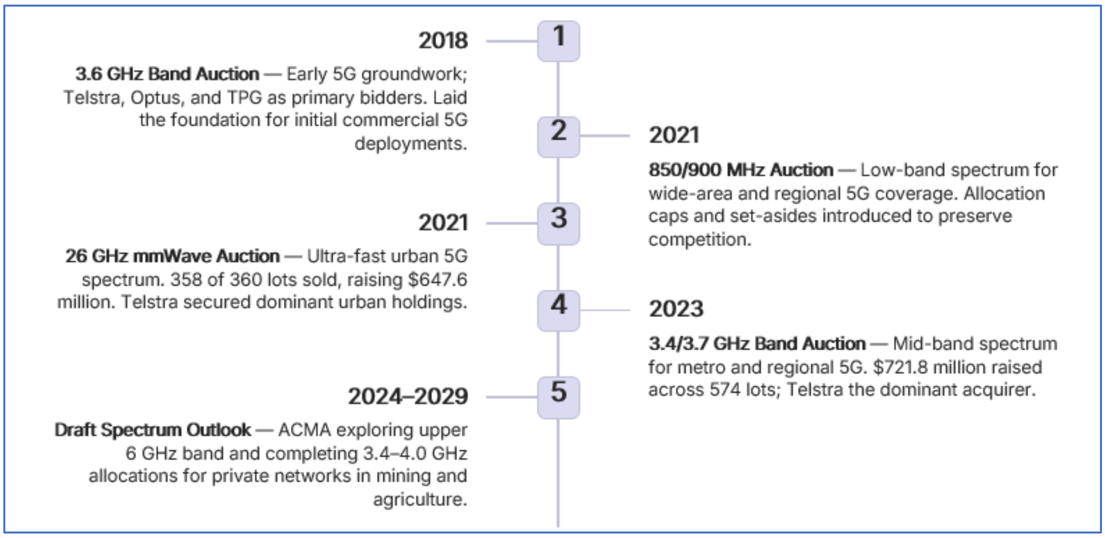
	Freq Band / Year	
Frequency Band	**3.8 GHz**	**3.5 GHz**
Year	**2023**	**2021**
Avg. Spectrum Available	40,970	15,040
Spectrum Allotted	40,990	14,800
Gross Revenue (in USD Millions)	1,619	7,068
Price/MHz/Pop (USD)	0.3180	1.6377

16 https://ised-isde.canada.ca/site/spectrum-management-telecommunications/en/spectrum-allocation/auctions/auction-spectrum-licences-3500-mhz-band/3500-mhz-auction-final-results

8 5G Auctions in Australia

Australia's 5G spectrum landscape has been shaped by a series of landmark auctions and policy decisions administered by the Australian Communications and Media Authority (ACMA). From low-band coverage spectrum to millimetre-wave urban deployments, these auctions have allocated billions of dollars in radiofrequency assets, determined the competitive structure of the mobile industry, and set the trajectory for next-generation connectivity across the country. The timeline of the 5G spectrum auctions held in Australia is given in Figure 3.5.

Figure 3.5: Timeline of 5G Spectrum Auctions in Australia



The 2018 auction of the 3.6 GHz band was Australia's first major 5G spectrum event and served as the launchpad for the country's initial commercial 5G deployments. Telstra, Optus, and TPG were the primary participants, acquiring spectrum that would underpin the first wave of 5G network launches in capital city markets from 2019 onwards. While detailed public data on bidding outcomes is limited compared to later auctions, the 2018 event was nonetheless pivotal in establishing the competitive framework for 5G in Australia. The 3.6 GHz auction preceded the more comprehensive mid-band strategy that ACMA would later execute through the broader 3.4–4.0 GHz programme. It provided carriers with early-mover spectrum holdings to initiate 5G infrastructure deployment, allowing them to build vendor relationships, test network equipment, and develop commercial 5G propositions ahead of more substantial spectrum allocations. For Telstra and Optus in particular, these early 3.6 GHz holdings were critical in delivering Australia's first 5G services. The 2018 auction was followed by auctions on 2021 and 2023. Table 3.13 provides key results of the auctions held in Australia.

Table 3.13: Results of 5G Spectrum Auctions in Australia

	Freq MHz / Year				
Frequency Band	**800**	**900**	**3400**	**3700**	**26000**
Year	**2021**	**2021**	**2023**	**2023**	**2021**
Gross Revenue (in USD Millions)	410	984	17	425	135
Price/MHz/Pop (USD)	1.2904	1.0914	0.0351	0.1534	0.0030

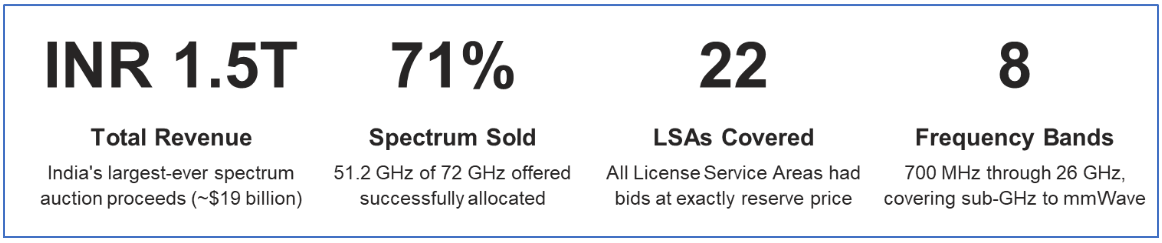
9 India's 2022 Mega 5G Auction

The August 2022 spectrum auction stands as a watershed event in Indian telecommunications history. With total proceeds of INR 1.5 trillion (~USD 19 billion), it was not only the largest spectrum auction India had ever conducted but also one of the most significant 5G licensing exercises globally. The Department of Telecommunications (DoT) offered a total of 72 GHz of spectrum across eight frequency bands, signalling the government's ambitions to fast-track 5G rollout across all 22 licence service areas (LSAs).

Of the spectrum put on the block, 51.2 GHz was successfully sold, representing a clearance rate of approximately 71%. While this figure reflects genuine demand from the top three incumbent operators, it also reveals a structural gap: roughly 25% of offered spectrum went unsold, much higher than in comparable 5G auctions in countries such as Germany, South Korea, and the US. This metric warrants scrutiny, particularly in the context of India's ambitions to be a global 5G leader.

A critical observation further complicates the demand narrative: across all 22 LSAs, the winning bid price equalled the reserve price without exception. This uniform outcome, where no competitive bidding pushed prices above the floor, is a strong indicator that either reserve prices were calibrated at or above true market value, or that actual demand among operators was insufficiently competitive to generate price discovery. Figure 3.6 provides a summary of the auction.

Figure 3.6: Summary of the 2022 5G Spectrum Auction in India



If the 2022 auction represented the euphoric high-water mark of India's 5G spectrum market, the June 2024 auction delivered a sobering reality check. Held over 13 bidding days between June 6 and June 26, 2024, the auction offered spectrum valued at INR 963 billion across eight bands, yet generated total proceeds of just INR 113 billion, representing a take-up rate of approximately 11.8% of the offered value. This precipitous decline in auction proceeds—from INR 1.5 trillion in 2022 to INR 113 billion in 2024—demands careful interpretation. Summary results of the auctions held in India in 2022 and 2024 are provided in Tables 3.14 and 3.15.

Table 3.14: Results of 5G Spectrum Auctions in India

India	**Freq M Hz / Year**											
Frequency Band	**700**	**800**	**900**		**1800**		**2100**		**2500**		**3300**	**26000**
Year	**2022**	**2022**	**2022**	**2024**	**2022**	**2024**	**2022**	**2024**	**2022**	**2024**	**2022**	**2022**
Gross Revenue (in USD Millions)	4,620	124	41	831	1,221	421	374	64	76	18	9,480	1,725
Price/MHz/Pop (USD)	0.3216	0.0704	0.0823	0.1442	0.1691	0.0950	0.1815	0.0396	0.0659	0.0125	0.0539	0.0012

Table 3.15: Winning Prices for 3300 MHz Spectrum in the 2022 Auction Across LSAs

Region	**Price (USD/MHz/pop) for C-Band**
Andhra Pradesh	0.0371
Assam	0.0194
Bihar	0.0106
Delhi	**0.2887**
Gujarat	0.0459
Haryana	0.0329
Himachal Pradesh	0.0353
Jammu & Kashmir	0.0096
Karnataka	0.0356
Kerala	0.0325
Kolkata	**0.1285**
Madhya Pradesh	0.0160
Maharashtra	0.0368
Mumbai	**0.2298**
Northeast	0.0088
Odisha	0.0144
Punjab	0.0378
Rajasthan	0.0194
Tamil Nadu	0.0370
Uttar Pradesh (E)	0.0127
Uttar Pradesh (W)	0.0220
West Bengal	0.0139
Average	0.0511
Median	0.0327

10 Broader Conclusions

The goldilocks spectrum of the upper mid-band (3300-4200 MHz) is one of the most sought-after spectrum for 5G. The average price/MHz/pop across all countries of the upper mid-band (C-band) is USD 0.182, while the median is 0.061.

From the analysis of spectrum prices for the 5G spectrum bands, especially the upper mid-band spectrum (i.e., 3.4–4.2 GHz), the following inferences can be drawn:

- The winning bid price for upper mid band (USD 0.054/MHz/pop) is in line with the world median price. However, the prices in Delhi, Mumbai, and Kolkata were very high, mainly due to the high reserve price.
- In most of the bands, the winning bid prices are at the same level as reserve prices, indicating a possibility of higher reserve prices.
- In the upper mid-band and the 26 GHz band, a significant amount of spectrum was unsold, indicating the possibility of insufficient demand.

Chapter 4: Spectrum Co-existence in the 5G Era

1 Introduction

The rollout of 5G networks is bringing a diverse set of services—mobile broadband, satellite communications, and unlicensed wireless—closer together. Increasingly, these services seek access to similar bandwidth ranges, driven by rising data needs and expanding indoor usage. There is also a measure of functional equivalence among them as they can all deliver communication services to end users. Further, there is notable convergence in certain technical characteristics, such as transmission power levels and deployment environments. Backhaul services, which complement access services, are also provided using similar frequency bands.

However, the ways in which these services are delivered, the network architectures they use, the nature of their backhaul and last-mile connections, and the profiles of the stakeholders involved differ substantially. These convergences and continuing differences shape how spectrum is used in practice and complicate the task of designing policies that enable efficient sharing, fair competition, and continued innovation.

This chapter examines these issues and recommends spectrum co-existence—a policy and technical framework that enables multiple types of services, such as mobile, satellite, backhaul and unlicensed wireless, to operate in the same or neighbouring frequency ranges without causing harmful interference. It goes beyond interference management to account for the simultaneous substitutability (functional equivalence) and complementarity among these services, the diversity of stakeholders involved, and the convergence in technical characteristics such as power levels and indoor usage patterns. Effective spectrum co-existence policies ensure that allocation and assignment decisions recognize both the competitive tensions and the synergies between different uses, enabling optimal utilization of finite spectrum resources while supporting innovation and fair market participation.

2 Growing Demand for Mid-Band Spectrum

The contestation among services over bandwidth is best exemplified by the increased demand for mid-band (3-6 GHz) and upper mid-band (7-20 GHz) spectrum. These frequencies are highly valued for their combination of capacity and coverage, making them ideal for delivering enhanced mobile broadband services in both urban and suburban environments. While low-band spectrum offers broad coverage with limited throughput and high-band spectrum provides ultra-high capacity but limited range, the mid-band offers a “sweet spot” that is especially attractive for 5G access services. This balance also made the upper mid-band suitable for backhaul, both in its traditional role of connecting base stations to the core network and in newer configurations such as fixed wireless access (FWA) and satellite direct-to-device (D2D). Further, the mid-band spectrum is attractive for unlicensed use because its high bandwidth enables high-speed connectivity and indoor use, where coverage limitations are less critical.

3 Convergence of Spectrum Bands Across Mobile Access, Backhaul, Unlicensed, and Satellite Spectrum

As 5G technologies mature, a degree of functional equivalence is emerging between mobile, unlicensed, and satellite systems. For households and enterprises, each of these systems can be a viable last-mile solution: a household may access broadband through a 5G mobile connection, Wi-Fi, or even a low-earth orbit satellite terminal; similarly, enterprises may rely on fixed wireless access using 5G, Wi-Fi, or satellite links. While the operational characteristics—latency, reliability, and coverage—differ across platforms, they are becoming functionally equivalent as their roles in delivering connectivity in indoor environments and fixed wireless contexts increasingly overlap. Backhaul also uses overlapping bands. The convergence of bands, technical characteristics, and functions is creating the conditions for spectrum co-existence in which various stakeholders and technologies occupy proximate bands and often provide similar services.

Table 4.1: Spectrum Uses Across Bands and Power Levels

Spectrum Bands	Power Levels		
	Low (Restricted to Indoor)	*Medium*	*High*
mmWave: ➢ **≥ 60 GHz (V-Band: 57-71 GHz, E-Band: 71-86 GHz)**	**W, P**	**A, P**	**A, B**
High: ➢ **26, 28 GHz, and Ka (26-40 GHz)**	**W, P**	**A, F, P**	**A, B, S**
Upper Mid Band: ➢ **7-20 GHz (Ku: 12-18 GHz)**	**W, P**	**A, F, P**	**A, B, S**
Mid Band: ➢ **6 GHz**	**W, P**	**A, F, P**	**A, B, S**
Mid Band: ➢ **3300 MHz**	**P**	**A, F, P**	**A**
Lower Mid Band: ➢ **1800, 1900, 2100, 2300, 2500, 2600 MHz**		**A**	**A, S**
Sub GHz Band: ➢ **450, 800, 900 MHz**		**A**	**A**

A: Mobile Access; B: Backhaul; F: Fixed Wireless Access; P: Private Network; S: Satellite Non-Terrestrial; W: Wi-Fi

Table 4.1 maps different wireless systems along two dimensions—frequency (as rows) and transmission power (as columns)—to illustrate spectrum co-existence by mapping different use cases—access, backhaul, fixed wireless access, private networks, satellite, and Wi-Fi—across frequency bands (low, mid, high) and power levels (low, medium, high). Each cell in represents a combination of frequency and power and lists the use cases that typically operate under those conditions. Shared cells highlight situations where multiple services co-exist in the same spectrum environment. For example:

- Mid- and high-frequency bands with medium power enable the co-existence of mobile access, FWA, and private networks, indicating functional equivalence since all can deliver broadband connectivity using similar technical parameters.
- In the high-frequency, low-power cell, Wi-Fi and private networks co-exist, providing functionally equivalent indoor connectivity solutions.

Complementary co-existence arises where different services share the same spectrum cell but serve distinct roles. For instance, in both mid- and high-frequency bands with higher power levels, mobile access, backhaul, and satellite networks co-exist. These are not functionally equivalent but are complementary: access provides end-user connectivity, while backhaul supports transport between network nodes.

Exclusive use cases exist as well. For example, low-frequency, high-power is dominated by mobile access (A), reflecting its efficiency for wide-area coverage.

As spectrum use intensifies, convergence occurs along three dimensions:

- Bands (low, mid, high frequencies),
- Technical characteristics (power levels), and
- Users/use cases (access, FWA, Wi-Fi, satellite, private networks, backhaul).

Where all three converge, there is full co-existence (functional equivalence). Where only some converge (e.g., access + backhaul in mid-frequency, high-power), there is incomplete co-existence, which, while important, reflects complementary rather than substitutable uses.

The grid thus shows how once-distinct systems—Wi-Fi, private 5G, fixed wireless, traditional cellular access and backhaul, and satellite—are now clustered in overlapping frequency and power. This convergence highlights the regulatory challenge: spectrum that was once allocated to discrete services is now simultaneously demanded by multiple technologies with converging power levels over the last mile and pursuing similar use cases, particularly broadband access, enterprise connectivity, and Wi-Fi.

This convergence calls for new regulation that balances competing claims, promotes efficient spectrum use, and minimizes harmful interference. It should also provide flexibility for dynamic sharing and re-allocation across mobile, unlicensed, and satellite systems as demand and technologies evolve.

Determining how to allocate a particular band across different uses requires careful consideration of operational realities and market structures. Many of these uses are not merely substitutable but also complementary. FWA, which is increasingly deployed as a last-mile solution for delivering fibre-like data speeds, is a good example. FWA may use either optical fibre or wireless backhaul to reach a customer's premises, and then distribute the signal via Wi-Fi or licensed spectrum, often using frequencies like 6 GHz. In the last mile, Wi-Fi and licensed spectrum can seem to be equivalent, but before that point, they fulfil very different roles: Wi-Fi, unlike licensed spectrum or fibre, is not used in backhaul. This creates layered complementarity and last-mile competition between spectrum types, where one technology enables the reach of another, then competes over the last mile.

Similar scenarios may arise for satellite operators and traditional mobile operators. Until recently, satellite services were largely confined to niche markets such as remote rural regions or maritime connectivity. Today, however, they are poised to enter areas already served by mobile operators, creating a new overlap. Unlike the case of FWA—where the same transport layer can support different last-mile technologies such as Wi-Fi and licensed spectrum—the satellite–mobile overlap is reversed. Here, the backhaul layer relies on different technologies (satellite links vs. terrestrial 3GPP backhaul), while the access layer converges around 3GPP standards. This produces competition in the backhaul but complementarity in access.

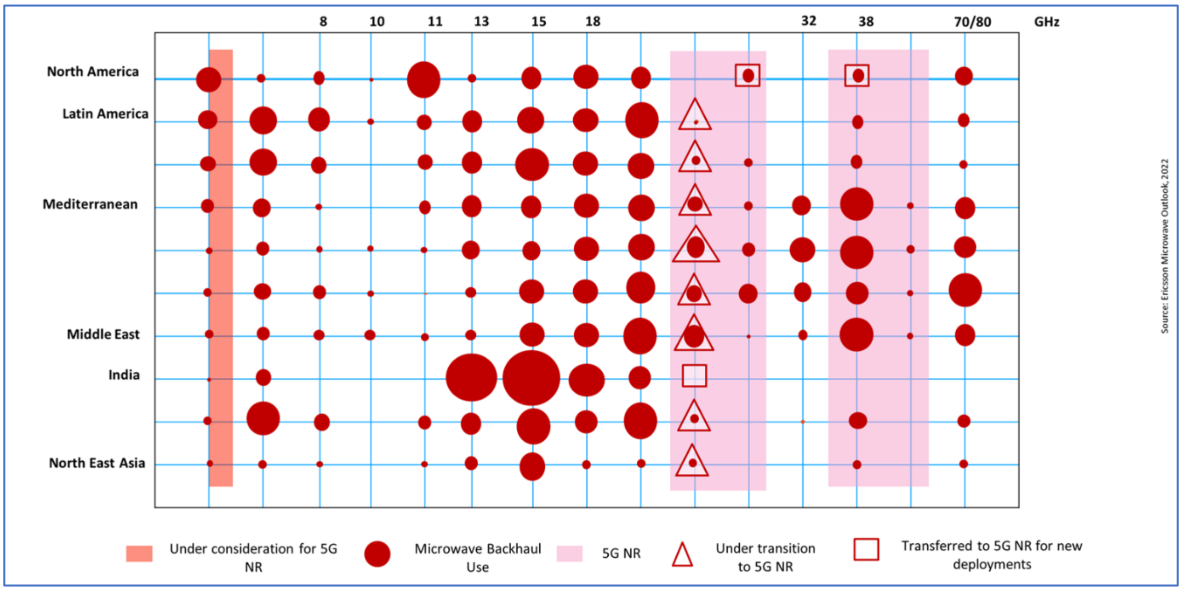
The differences extend beyond operational divergences to encompass the structure of the industries involved. Mobile services are typically provided by licensed mobile network operators. Wi-Fi, by contrast, is embedded in consumer devices by equipment manufacturers and deployed through access points by lightly licensed/unlicensed internet service providers. Satellite broadband introduces another configuration, combining specialized equipment vendors, satellite operators, and mobile operators. This diversity of players—ranging from pure service providers, pure equipment vendors, and hybrids of the two—means that spectrum policy affects not just technical deployment but also the competitive dynamics across entire value chains.

4 Co-Existence of Access and Backhaul Spectrum

Figure 4.1 illustrates the allocation and use of spectrum for access and backhaul across various mid- and high-frequency bands in different regions.[17]

[17] Ericsson. (2025). *Ericsson Microwave Outlook*. https://www.ericsson.com/en/reports-and-papers/microwave-outlook

Figure 4.1: Spectrum Maps Across Various Uses



The columns represent specific frequency bands (in GHz), while each row corresponds to a geographic region. The size of the red circles reflects the extent of microwave backhaul use in that frequency band, while overlaid shapes indicate the status of that band for 5G NR. The pink shaded areas represent bands already in use for 5G NR; red triangles show bands transitioning from microwave backhaul to 5G NR; red squares denote bands transferred to 5G NR for new deployments; and light orange shading highlights bands under consideration for 5G NR.

The figure captures the growing overlap between the spectrum used for backhaul and that required for 5G access, especially in higher-frequency ranges. It indicates that bands such as 26 GHz and 28 GHz are critical for 5G NR but also share adjacency or partial overlap with bands used for high-capacity backhaul links, raising coordination challenges. This convergence in spectrum demand stems from parallel trends: access networks require ever wider channels to support high data rates, while backhaul systems need matching capacity to carry that traffic to the backbone Internet.

From a regional perspective, what was once a relatively uniform pattern of spectrum allocation worldwide is now diverging in the 5G era. Historically, certain frequency bands were globally harmonized for specific functions, such as microwave backhaul, making equipment design and cross-border coordination more straightforward. With the arrival of 5G, however, different regions are repurposing these bands at different speeds and in different sequences. For instance, some regions, such as the Mediterranean and Northeast Asia, are transitioning multiple backhaul bands to 5G NR, while others, such as Latin America, retain more traditional allocations. This uneven repurposing reflects variations in market maturity, existing infrastructure, regulatory priorities, and the urgency of 5G rollout, leading to a more fragmented global spectrum landscape.

It should be noted that WRC-27 will consider 7 GHz and 15 GHz for International Mobile Telecommunications (IMT) access services. As shown in Table 4.1, these bands will co-exist across mobile access, FWA, and backhaul. Similarly, the V-band is being promoted for IMT access while it is being extensively used for backhaul in India. In India, the 15 GHz is widely used for backhaul, followed by 18 GHz and 21 GHz. There is moderate utilization in both the 6 GHz and 7 GHz bands for backhaul.

4.1 Technologies for Integrated Access and Backhaul

Integrated access and backhaul (IAB) is a key 5G NR feature defined by 3GPP in Release 16 and subsequently enhanced. IAB allows the radio spectrum to be used simultaneously for wireless backhaul (connecting to the core network) and access (serving end users), enabling dense and cost-effective network deployments. The spectrum bands for IAB are not defined as a new, separate list. Instead, IAB operates in any frequency band that supports 5G NR and has the required physical-layer features. The critical factor is that the band must support time division duplexing (TDD) or supplementary uplink (SUL).

The architecture of an IAB network, as defined in 3GPP Release 16, consists of "IAB donors" and "IAB nodes". IAB donors connect to the core network with optic fibre backhaul and can provide wireless access services to mobile users as well as wireless backhaul to the IAB nodes in the network. The IAB nodes provide wireless access services to mobile users and wireless backhaul to other IAB nodes.[18] This architecture provides the operator flexibility in apportioning their assigned spectrum for access and backhaul. The key TDD NR bands commonly associated with IAB are presented in Table 4.2.

Table 4.2: Key Spectrum Bands for IAB

Band	Range	Notes
n41 (2.5 GHz)	2496-2690 MHz	A key band, especially in the US
n77 (3.5 GHz)	3300-4200 MHz	Primary C-band for 5G globally
n78 (3.5 GHz)	3300-3800 MHz	A subset of C-band used for 5G globally
n79 (4.5 GHz)	4400-5000 MHz	Used in some regions, such as China and Japan
FR2-1 bands (mmwave band): n257 (28 GHz), n258 (26 GHz), n260 (39 GHz), n261 (28 GHz)	26.5-29.5 GHz, 24.25-27.5 GHz), 37-40 GHz, 27.5-28.35 GHz respectively	Critical for IAB due to very high capacities and directional beam forming

[18] Telecom Regulatory Authority of India (2025). *Recommendations on Assignment of the Microwave Spectrum in 6 GHz (lower), 7 GHz, 13 GHz, 15 GHz, 18 GHz, 21 GHz Bands, E-Band, and V-Band.*

5 Co-Existence of Spectrum for Mobile and Wi-Fi

The prevailing view among policymakers is that the licensed spectrum provides the most economic value. Unlicensed spectrum, such as spectrum in the 2.4 GHz and 5 GHz bands used for Wi-Fi, has always been undervalued. However, many studies in the US have illustrated the economic value of unlicensed spectrum under different scenarios, including cellular-Wi-Fi offloading, Wi-Fi internet service provisioning, Wi-Fi in communication-intensive locations such as hospitals and malls, community Wi-Fi in public spaces, and residential Wi-Fi. According to Katz's recent work, the sum of consumer and producer surplus for technologies operating in unlicensed spectrum bands in the US amounted to USD 222 billion in 2013 and contributed USD 6.7 billion to the nation's GDP. He also estimated that, by 2027, unlicensed spectrum and associated technologies will contribute at least USD 547.22 billion in economic value and USD 49.78 billion in GDP.[19]

There is also growing technical convergence at the last mile between the licensed spectrum for mobile services and unlicensed systems, with both increasingly deployed to deliver broadband connectivity in similar use cases, particularly in indoor environments with the greatest demand for high-speed and reliable coverage. Mobile networks, traditionally designed as wide-area outdoor systems, now rely heavily on small cells, indoor distributed antenna systems, and localized spectrum deployments to ensure adequate capacity. This mirrors the roles historically played by Wi-Fi, which has long dominated indoor connectivity through unlicensed spectrum.[20]

As access patterns shift towards indoor and small-cell deployments, the transmission powers and interference footprints of licensed and unlicensed systems are converging over the last mile. Earlier generation macrocells transmitted at high power over wide areas, creating a clear technical distinction from low-power Wi-Fi. In contrast, 5G small cells and indoor base stations operate at much lower power levels and shorter ranges, bringing their operating characteristics closer to those of Wi-Fi access points. Thus, there is convergence among the bands and key parameters in the method for using them.

However, there is growing tension in spectrum management due to the increasing overlap between the frequency bands needed for mobile access services (such as 4G and 5G) and those allocated for licence-exempt technologies like Wi-Fi. For example, in the mid-band range, the 6 GHz band, which is traditionally used for fixed links and satellite services, has emerged as a prime candidate for both 5G access and Wi-Fi 6E/7, leading to competing demands from mobile operators and the unlicensed community.[21] This convergence in spectrum demand stems from parallel trends: access networks require wider channels to support high data rates, while Wi-Fi continues to push into higher frequencies to meet indoor broadband needs.

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[19] Prasad, Rohit., & Sridhar, V. *5G and beyond: Rewiring telecom regulation in India* [Unpublished]. Oxford University Press.

[20] Naik, G., & Park, J.-M. J. (2021). Coexistence of Wi-Fi 6E and 5G NR-U: Can we do better in the 6 GHz bands? In *Proceedings of the IEEE INFOCOM 2021 – IEEE Conference on Computer Communications* (pp. 1–10). IEEE. https://doi.org/10.1109/INFOCOM42981.2021.9488780

[21] Keshtiarast, N., & Petrova, M. (2025). *Coexistence analysis of Wi-Fi 6E and 5G NR-U in the 6 GHz band.* In *Proceedings of the 2025 International Conference on ns-3*.

6 Co-Existence of Mobile Access, Backhaul, and Satellite Spectrum

Earlier satellite systems were mainly used in remote areas, but their use is increasingly expanding to residential, enterprise, and community broadband environments. The growing need for satellite communications in the same geographies that constitute prime markets for mobile, Wi-Fi, and FWA is creating significant overlap in spectrum requirements between satellite access and terrestrial backhaul. Satellite systems, particularly those in non-geostationary orbits (NGSO), require spectrum not only for the direct user access link but also for feeder links that connect the satellites to terrestrial gateways.[22]

The L-band (1.5–2 GHz), typically used and exclusively assigned for geostationary satellite systems, is today being used by low earth and medium orbit (LEO/MEO) satellite operators such as AST SpaceMobile (LEO), Lynk Global (LEO), Iridium NEXT (LEO), Globalstar (LEO), and Orbcomm (LEO) to provide satellite connectivity. A notable example is Apple's emergency SOS and roadside assistance services that use Globalstar's L-band spectrum to provide mobile-to-satellite service.

On the other hand, satellite systems and 5G mobile communications need to co-exist. A key example of overlapping needs is the C-band, which was traditionally central to satellite communications. Over the past decade, large portions of the lower C-band (around 3.3–3.8 GHz) have been repurposed globally for IMT-Advanced and 5G and are becoming one of the most important mid-bands for mobile broadband. At the same time, satellite operators, particularly those deploying NGSO constellations, continue to require C-band spectrum for feeder links and gateway operations, especially in regions where higher bands (Ka/Q/V) face atmospheric or infrastructure constraints. As a result, satellite operators now seek either continued access, shared use, or protection zones in parts of the same band assigned to IMT.

6.1 Spectrum Sharing Between Mobile Network Operators and Satellite Service Providers

While certain bands are exclusively assigned to satellite service providers, the partnership between mobile network operators (MNOs) and satellite operators is an emerging business model. Termed "Tower in the Sky", this approach uses existing 4G and 5G IMT spectrum to provide direct-to-device (D2D) connectivity.

For example, AST SpaceMobile, in addition to operating on its exclusive L-Band, uses spectrum that it shares with its MNO partners in the sub-GHz band, the lower mid-band, and the mid-band (i.e., C-band). The partner mobile operator dedicates a portion of its nationally licensed spectrum for AST to use only over its satellite network. Similarly, Starlink has partnered with T-Mobile and shares the 1900 MHz band to provide D2D service for T-Mobile customers in the US. Starlink has made similar agreements with Optus in Australia, Rogers in Canada, KDDI in Japan, Salt in Switzerland, and others. When a subscriber is out of terrestrial coverage, their

[22] Pelton, J.N. (2011). *Satellite communications*. Springer Science & Business Media.

phone connects to the satellite using this partner-dedicated spectrum as part of its roaming arrangements. The standard smartphone connects to the Starlink satellite using a partner MNO's LTE spectrum. The satellite translates the cellular signal and beams it via a Ka/Ku-band inter-satellite link to other satellites in the system. The signal is then routed to a ground station ("gateway") connected to the partner MNO's core network. From there, it enters the public internet or telephone network.

The best model for efficient, interference-free spectrum allocation is a partnership between MNOs and satellite providers to share part of the IMT spectrum allocated to the MNOs. This method will allow existing mobile phones to be used, obviating the need for expensive end-user equipment.

6.2 Co-Existence of Satellite Spectrum and Terrestrial Backhaul

The co-existence of spectrum satellite services and backhaul, especially in the Ka band (12–18 GHz), is also noteworthy. For example, Amazon's Kuiper systems use non-geostationary Ka-band satellites, including the 17.7–19.7 GHz ("18 GHz"), band for fixed satellite service (FSS) operations. However, as discussed, the 18 GHz band is also used for terrestrial backhaul. While interference between FSS and terrestrial backhaul can be managed, satellite-to-device connectivity in these bands is likely to affect the backhaul spectrum. Table 4.3 summarizes the satellite systems that are deployed and the spectrum bands they use. As seen, the Ku, Ka, and V bands co-exist with terrestrial backhaul.

Table 4.3: Spectrum Bands Used in Satellite Systems

Satellite System	Deployment Frequency Bands	Planned Satellite Numbers
SpaceX	Ku/Ka (1st Generation)	4,408
	Ku/Ka/E (2nd Generation)	30,000
	V-Band	7,518
Kuiper (Amazon)	Ka Band	3,236
	Ku/V Bands	7,774
Boeing	V Band	5,921
Astra Space	V Band	13,620
OneWeb	Ku/Ka (Phase 1)	648
	V (Phase 2)	6,372
O3B	Ka-Band	70
	V Band	24
Telesat	Ka Band	300
	V Band	1,671

7 Spectrum for Private Networks

Enterprises in manufacturing, logistics, mining, ports, and other sectors are increasingly seeking dedicated 5G capacity to run mission-critical applications with guaranteed performance, low latency, and high security. This demand is being met through a combination of locally licensed spectrum (including making enterprises licensees), shared-access arrangements, and Wi-Fi. As a result, a wide variety of entities are competing for spectrum to serve not only public networks but also a proliferating private-network market, which intensifies the competing demands for licensed and unlicensed spectrum.

The mid-band spectrum (3300–4200 MHz) is being allocated in many countries for captive non-public networks or private networks. Nations like Germany (3.7–3.8 GHz), the UK (3.8–4.2 GHz), and Japan (4.6–4.9 GHz) have dedicated spectrum bands available for enterprises to license directly for their private networks. However, some countries prohibit licensed telcos from providing private networks using set-aside spectrum bands. Mobile operators often argue that enterprises often do not have the required capability and expertise to set up a 3GPP network by themselves, and so, fear that the spectrum will be underutilized. Operators can use network slicing on their mainstream commercial spectrum, especially the mid-band, to create a virtual, logically isolated private network for an enterprise. This is suitable for applications that do not require on-premises physical equipment but do need guaranteed quality of service (QoS).

An interesting case study is that of South Korea. Until 2021, the government reserved specific spectrum (4.72 GHz and 28.9 GHz bands) exclusively for non-telecom companies (e.g., Samsung, LG, POSCO, Hyundai) to build their own private 5G networks. This was intended to spur competition and innovation outside the traditional telecom oligopoly. Mobile operators were largely locked out of this dedicated private network spectrum. Facing pressure from operators and recognizing slower-than-expected adoption by enterprises, the government relaxed the rules after 2021. The Korea Communications Commission (KCC) permitted mobile operators to share portions of their licensed commercial 5G spectrum with enterprises for private network use. In 2022, the KCC also auctioned new spectrum in the 4.7 GHz band (100 MHz) specifically for local 5G networks, and this time, mobile operators were allowed to bid alongside manufacturers. Apart from SK Telecom and KT, which picked up 40 MHz each, Korean Electric Power Corporation, a non-telco, picked up 20 MHz. However, the response from private operators to acquiring spectrum has been weak despite the KCC’s efforts to induce competition in the private network space.

8 Spectrum for Fixed Wireless Access

FWA is further amplifying demand for both mid-band and high-frequency spectrum, as it is increasingly deployed as a last-mile solution capable of delivering fibre-like data speeds. Unlike traditional mobile access, FWA often serves as a primary broadband connection for homes and businesses, requiring sustained high throughput and low latency over a fixed location. This places pressure on spectrum resources that were earlier used predominantly for mobile services or for backhaul. In the mid-bands, operators seek large contiguous blocks to balance capacity and coverage, while in the millimetre-wave ranges, they require wide channels to support gigabit-class speeds and high user density.

FWA has become one of the prominent technologies being used today for connecting rural and remote areas. Termed "air fibre", FWA is being pursued by several operators worldwide in areas where it is difficult and expensive to roll out optical-fibre-based broadband services. It is estimated that the number of FWA connections worldwide had reached more than 120 million at the end of 2023 and is forecasted to reach 260 million by 2028.[23] Most deployments are in the mid-band (C-band) to serve less dense semi-urban areas. However, it is predicted that FWA using mmWave will become an important use case, especially in urban and semi-urban areas of developing countries. Next-generation mmWave radios and outdoor (rooftop) CPEs can extend range up to ~10km in an ideal case, greatly expanding coverage.

FWA and mobile access co-exist. Typically, operators use the same spectrum that is used for mobile access for FWA by apportioning the band. Therefore, FWA and mobile access complement each other in enhancing coverage. However, FWA in the mmWave band can be in conflict with the spectrum allocated for microwave backhaul. The issues of spectrum co-existence are best illustrated by a case study of the 6GHz band, further discussed in section 4.9.

9 Case Study: Allocation of 6 GHz

The 6 GHz band, spanning 5.925–7.125 GHz, has become the focus of the global debate on spectrum allocation in the 5G era. As mentioned, this band is a natural candidate for multiple uses: licensed mobile broadband, unlicensed Wi-Fi, fixed wireless access, and satellite feeder links. As a result, the band has become the most contested spectrum frontier of the decade.

IEEE 802.11ax is the first amendment in the Wi-Fi family to go beyond small indoor environments and aim to optimize its performance in large outdoor deployments, such as FWA. Whereas Wi-Fi has operated in the 2.4 and 5 GHz bands, the Wi-Fi 6E standard includes the 6 GHz band (5.925–7.125 GHz). Given increasing demand from consumers and enterprises, the 6 GHz band is also expected to be a key mid-band spectrum for 5G expansion.

Historically, the 6 GHz band has hosted a combination of incumbent services, including fixed microwave links used by utilities and broadcasters, satellite uplinks and feeder links, and government communications.[24] These users remain active and continue to demand protection. However, mobile operators argue that the band is essential for meeting 5G capacity targets, with the GSMA estimating that around 2 GHz of mid-band spectrum per country is required for robust 5G deployment. In parallel, Wi-Fi advocates, led by the Wi-Fi Alliance, have pushed for unlicensed use of the band to support Wi-Fi 6E and Wi-Fi 7, arguing that most household and enterprise data traffic is already offloaded to Wi-Fi and that additional spectrum is needed to relieve congestion in the 2.4 GHz and 5 GHz bands. Satellite operators, represented by the Global Satellite Operators Association, emphasize the need to preserve critical feeder link operations and are also exploring co-existence models with terrestrial services.

[23] Mobile Experts. (2024). *Enhancing FWA with millimeter wave: NBN story*. https://mobile-experts.net/reports/p/white-paper-increaselocalizedpeakcapacitymmwave-mkwse

[24] Ghosh, M. (2023). Evolution of sharing in 6 GHz. *IEEE Wireless Communications, 30*(5) (2023), 4–5.

9.1 Divergent Global Approaches

The World Radiocommunication Conference 2023 (WRC-23) made critical decisions regarding the 6 GHz spectrum, balancing competing demands from international mobile telecommunications (IMT/5G/6G) and Wi-Fi/wireless access systems (WAS). While WRC 23 left the apportionment of the spectrum for IMT and Wi-Fi use to each country, it recommended that countries consider allocating the upper band for IMT services (referred to as n104). Pro-IMT countries (e.g., China, Russia, France) advocated for exclusive IMT use in the entire 6 GHz band. Citing mid-band spectrum shortages for 5G/6G, pro-Wi-Fi regions (e.g., US, EU) pushed for unlicensed Wi-Fi access, arguing that splitting the band would reduce Wi-Fi 6E/7 performance.

Thus, the global allocation of 6 GHz is sharply fragmented.[25] The US, Brazil, South Korea, and Saudi Arabia have opened the entire 6 GHz band for unlicensed use, enabling Wi-Fi 6E and Wi-Fi 7 to operate over a vast 1.2 GHz band. The UK and parts of Europe have restricted unlicensed use to the lower 6 GHz portion (5.925–6.425 GHz) while reserving the upper portion for licensed or shared arrangements. China, by contrast, has reserved the entire 6 GHz band for licensed mobile use, reinforcing its commitment to IMT-based 5G.

OfCom, the UK regulator, proposed a phased approach to sharing the upper 6 GHz band between commercial mobile and Wi-Fi services.[26] In phase 1, the plan is to authorize low-power indoor Wi-Fi (up to 250 mW) across the entire band as early as possible, ideally before the end of 2025. However, the exercise has not been completed as of March 2026. Phase 2 aims to introduce mobile services into the band, contingent on the outcomes of European harmonization discussions, which are expected to conclude by 2027. The lower part of the band has been delicensed for both indoor and outdoor use.

This phased strategy aims to maximize the benefits of spectrum sharing, providing immediate advantages to Wi-Fi users while paving the way for mobile integration in alignment with European standards. This marks a departure from earlier generations of mobile spectrum allocation, where global harmonization was stronger and device ecosystems benefited from economies of scale. With 6 GHz, fragmentation threatens to raise equipment costs, slow device availability, and create a patchwork of incompatible policies across regions.

9.2 Convergence of Uses and Functional Equivalence

What makes the 6 GHz debate particularly complex is the convergence across both service use cases and technical characteristics. Mobile operators envision deploying the 6 GHz spectrum primarily to achieve indoor small-cell coverage, where transmission power is much lower than in traditional macrocell networks. This brings mobile deployments closer to the

[25] Ghosh, M. (2023). *World Radiocommunications Conference 2023 (WRC-23).* IEEE.

[26] Leach, S. (2024). Hybrid sharing in upper 6 GHz. https://mentor.ieee.org/802.18/dcn/24/18-24-0070-00-0000-hybrid-sharing-in-the-upper-6-ghz-band.pdf

technical profile of Wi-Fi, which also operates at low power and short range. From the user's perspective, the two services can be functionally equivalent: a household may use a 5G indoor small cell or a Wi-Fi router, often over the same device, to access high-speed broadband.

Yet, operational differences remain. Wi-Fi depends on broadband backhaul—often owned by telecom operators—while mobile operators typically control both the last mile and backhaul. Satellite operators, in turn, may provide backhaul via feeder links, while access is delivered through terrestrial networks. This creates a mix of competition in the last mile and complementarity in transport layers, complicating regulatory choices.

The allocation of 6 GHz is not only a technical and economic question but also a geopolitical one. Countries favouring Wi-Fi, such as the US, see unlicensed spectrum as a way to strengthen their domestic device ecosystems, given US leadership in consumer electronics and software. China, by contrast, has prioritized licensed mobile use, aligning with its ambition to dominate global 5G infrastructure markets. This divergence runs the risk of creating entrenched industrial blocs, where equipment ecosystems fragment along geopolitical lines.

9.3 Complementarity of Unlicensed Spectrum

In the debate on dominance over the 6 GHz, the use of unlicensed spectrum within the ambit of IMT is the dark horse. While 3GPP and IEEE have approached spectrum management from opposite sides, namely licensed vs. unlicensed, there is a convergence of ideas in 5G NR. NR-based access to unlicensed spectrum (5G NR-U) intends to expand the applicability of 5G NR access technology to support operation in unlicensed bands.[27]

LTE-LAA (License Assisted Access) is the 4G technology that aggregates a licensed "anchor" band with an unlicensed 5 GHz spectrum, which was made part of 3GPP Rel 13/14. The 5G NR-U is a step ahead of earlier technologies, as envisioned in 3GPP Rel 16/17/18 that aims to provide seamless co-existence of IMT access across the licensed and unlicensed spectrum in 5/6 and 60 GHz bands. Since the methodology of medium access is different in Wi-Fi and 5G NR-U, the mobile operators deploying 5G NR-U may have to implement listen-before-talk (LBT) for providing equitable access to spectrum resources across IMT and Wi-Fi users. Several countries, including the US, China, India, and South Korea, permit unlicensed operation without mandating LBT, while regions like Europe and Japan enforce LBT as a prerequisite for unlicensed spectrum access.[28] Hence, for mobile operators, the 3GPP standards pave the way for leveraging the unlicensed spectrum, especially indoors, to provide seamless connectivity without offloading onto Wi-Fi networks.

[27] Prasad, Rohit., & Sridhar, V. (2026). *5G and beyond: Rewiring telecom regulation in India*. Oxford University Press.
[28] ETSI, 6 GHz WAS/RLAN; Harmonized Standard for Access to Radio Spectrum, ETSI EN 303 687 V1.1.1, June 2023

10 Policy Guidelines for Spectrum Allocation

In summary, the 6 GHz band epitomizes the broader challenge of spectrum co-existence in the 5G era. It is simultaneously the site of convergence in technical and service use-cases, divergence in regulatory treatment, and overlap among incumbent and new claimants. Policymakers must craft allocation strategies that recognize functional equivalence at the last mile, complementarity in backhaul, and the industrial and geopolitical stakes of divergent approaches.

Because service types now resemble one another in both function and power, policies that treat them as fundamentally different (auctioned exclusive rights versus free commons) produce stark market asymmetries. From a technical side, co-existence requires a toolbox that mixes: power limits and emission masks, guard bands, automated coordination (AFC in 6 GHz; SAS in CBRS), geographic exclusion zones around satellite earth stations, and intelligent beamforming and spatial reuse techniques. From a policy side, it requires choices about exclusive licensing, shared/tiered access (e.g., priority access licence (PAL) / generalized authorized access (GAA) models), preserving unlicensed capacity for innovation, predictable refarming mechanisms for incumbent users, and non-discriminatory access to essential infrastructure like fibre backhaul. We recommend the following policy approaches:

- **Redefining Liberalization: From Technology Choice to Use-Case Freedom:** Spectrum liberalization must be reinterpreted for the 5G and post-5G era. Traditionally, liberalization meant allowing licensees to provide a given service using any technology of their choice. Going forward, liberalization should mean something more fundamental: allowing licensees to deploy any service or use-case on their assigned spectrum**,** whether for mobile access, fixed wireless access, backhaul, private networks, or satellite gateways. As network architectures converge and spectrum bands are increasingly capable of supporting multiple functions, rigid service-specific usage constraints are no longer economically or technically justified.

- **Precisely Defined, Technology-Aware Licence Conditions:** Greater flexibility in usage must be complemented by more carefully specified license conditions. Regulators should define clear technical parameters, such as power limits, emission masks, geographic scope, beamforming rules, and coordination obligations, to enable co-existence across diverse uses while minimizing interference. In a world of shared and converging spectrum demand, regulatory certainty at the technical layer becomes more important.

- **Neutrality Across Functionally Equivalent Services**: Spectrum allocation and pricing regimes must ensure neutrality across functionally equivalent services. Where licensed cellular networks and unlicensed technologies such as Wi-Fi are used to deliver similar outcomes—particularly indoor broadband connectivity—policy should avoid imposing sharply divergent cost structures. This calls for lower reserve prices, rationalized spectrum fees, and allocation models that prevent distortions in competition arising purely from regulatory asymmetries rather than underlying efficiencies.

- **Mandated Open Access where Infrastructure is Complementary:** Where competition exists at the service or access layer but relies on complementary infrastructure—such as backhaul, fibre networks, towers, or satellite gateways—regulation should mandate open and non-discriminatory access. Open access obligations prevent foreclosure, reduce unnecessary duplication, facilitate entry by smaller or specialized providers, and ensure that spectrum-enabled infrastructure serves as a shared platform for innovation rather than a bottleneck.

Chapter 5: Spectrum Sharing: Case Studies

Realizing the need for efficient use of radio spectrum due to the exponential increase in wireless broadband penetration and associated data usage, countries around the globe are transitioning from the traditional command and control mode of spectrum management to flexible use. Country regulators and policymakers who define a stringent set of administrative rules for assignment and usage of spectrum have started to adopt flexible use policies, including the creation of an active secondary spectrum market and the deployment of associated technologies.

Spectrum sharing was one of the focal points in the US during 2010–2015 towards improving wireless broadband access in the US, with the Defense Advanced Research Projects Agency soliciting innovative research proposals aimed at efficient and reliable sharing of spectrum. Spectrum sharing has also been in vogue in Australia, New Zealand, as well as some European countries. However, spectrum sharing has not been successful in these countries.

Since then, several new licensing schemes have emerged from regulatory entities and from the industry to enable a more efficient spectrum usage, such as opportunistic usage of TV white spaces (TVWS),[29] light licensing,[30] licensed shared access (LSA),[31] and spectrum access system (SAS).[32] The need for associated regulatory governance and licensing mechanisms has also been highlighted.[33]

TVWS refers to unused radio spectrum on terrestrial TV broadcast frequencies. In the US, the FCC holds the TVWS regulation. In Singapore, the Inforcomm Media Development Authority (IMDA) has released regulatory guidelines. Ofcom and Industry Canada are in the process of creating the regulations for the UK and Canada, respectively. The European Commission is preparing for the European-level technical framework in the FM53 working group. All TVWS regulations so far have been licence-exempt, which is the most suitable model for deploying the TVWS version of the IEEE 802.11af Wi-Fi standard. The first applications of TVWS have been FWA for industries and communities. However, as discussed later, licensing models can also be considered in specific use cases for TVWS.

The European Commission released the ECC Report 205 on LSA in February 2014.[3] LSA is a complementary spectrum management tool that facilitates the introduction of new users in a frequency band while maintaining incumbents' existing services on the same band. It ensures a certain level of guarantee in terms of spectrum access and protection against harmful interference for both the incumbents and LSA licensees.

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[29] Electronic Communications Committee. (2013, January). *Technical and operational requirements for the operation of white space devices under geo-location approach* (ECC Report 186).
[30] Electronic Communications Committee. (2009, June). *Light licensing, license-exempt and commons* (ECC Report 132).
[31] Electronic Communications Committee. (2014, February). *Licensed shared access* (ECC Report 205).
[32] Federal Communications Commission. (2012). Notice of proposed rulemaking and order, FCC 12-148.
[33] Peha, J.M. (2012). Spectrum sharing in the gray space. *Telecommunications Policy*, *37*(2), 167–177.

In 2012, the FCC proposed the release of 150 MHz in the 3550–3650 MHz (3.5 GHz) band, which is currently used for military and satellite communication, for shared use.[4] In line with the recommendations of the President's Council of Advisors on Science and Technology, the SAS envisions three tiers of service: incumbent access, priority access, and general authorized access (GAA).

In this chapter, we analyze the LSA and SAS systems for shared access and examine the advantages and disadvantages of these systems.

1. Licensed Shared Access

LSA allows limited, licensed users to access underutilized spectrum bands while ensuring protection for incumbents from harmful interference. It was developed to address spectrum scarcity, especially for 5G and Internet of Things (IoT) applications, by optimizing existing resources.

Key Features

- **Licensed and Controlled**: Unlike unlicensed spectrum (e.g., Wi-Fi), LSA operates under individual licences with strict technical rules to prevent interference.
- **Dynamic Sharing**: Uses a centralized database or "LSA controller" to allocate spectrum dynamically based on real-time incumbent usage (e.g., in the 2.3–2.4 GHz band for wireless cameras).
- **Quality of Service (QoS)**: Guarantees exclusive access to LSA licensees within specific times/areas, ensuring reliable performance

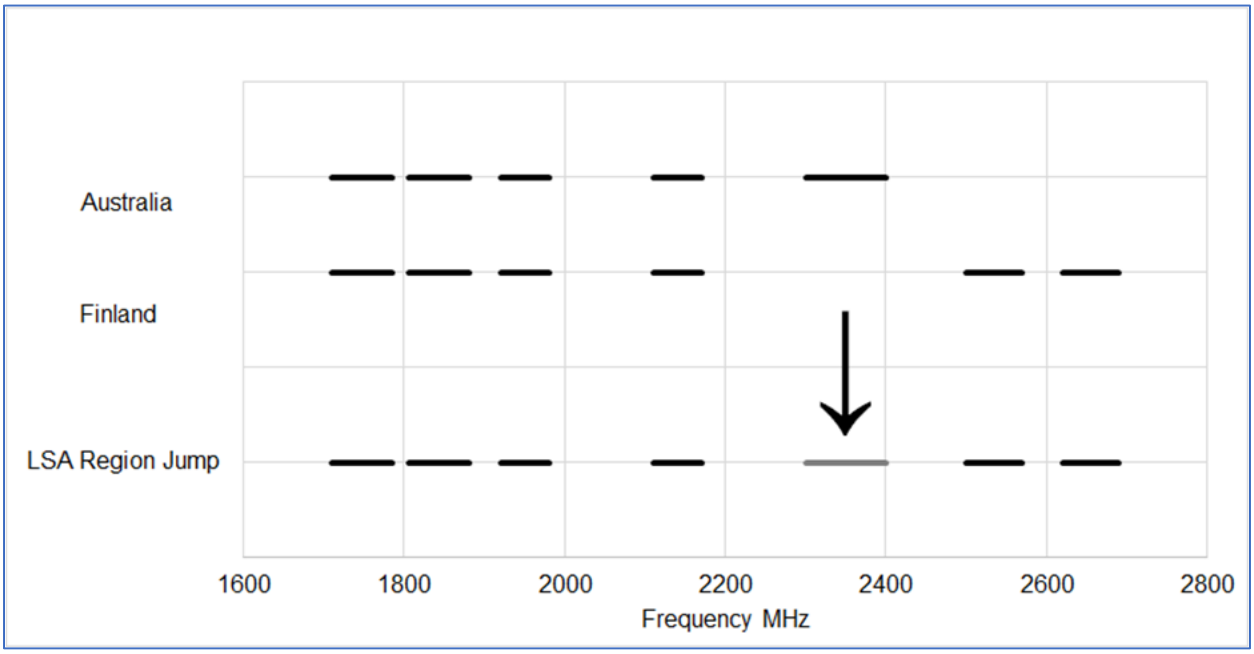
There are two different approaches for LSA technologies: LSA Region Jump and LSA Band Fill. In LSA Region Jump, a country demarcates a frequency band that is used in another region for mobile communication and opens that band under the LSA licensing scheme. In LSA Band Fill, mobile operators have licences for only part of a 3GPP band. The rest of the band is licensed to other users. The mobile operators can put the missing parts of the band into use by utilizing the LSA licensing scheme. The same approach can be used to extend the geographical coverage of the existing mobile operator licences to cover the areas that have been restricted from their licence.

1.1 LSA Region Jump in 2.3 GHz

An example of LSA Region Jump is to use Band 40 of TDD 2.3 GHz, which is used in 19 countries, including Australia and India, with the help of LSA technology from Europe. The advantage of the LSA Region Jump is that the chipsets, mobile devices, and base stations already exist in a different market area. The investments required to initiate deployment are modest compared to specifying a new band, developing a new chipset, and integrating it into the devices.

Figure 5.1 provides an overview of LSA Region Jump. In this example, while Australia uses the 3GPP Band 40 in 2300–2400 MHz, the same can be used in Europe using LSA so that it does not cause harmful interference with existing users.

Figure 5.1: Illustration of Region Fill in 2300 MHz in Europe



This approach will also complement the rollout of services where Band 40 is currently being used. For example, Indian operators who acquired Band 40 in the 2010 auction at very high prices were unable to roll out networks due to the high cost of equipment and handsets in this band. The Region Jump option, if adopted in Europe, would have provided the required scale economies and reduced equipment and handset costs. The same is true for the upper mid-band (3200–4200 MHz), which has considerable fragmentation of the spectrum across geographies.

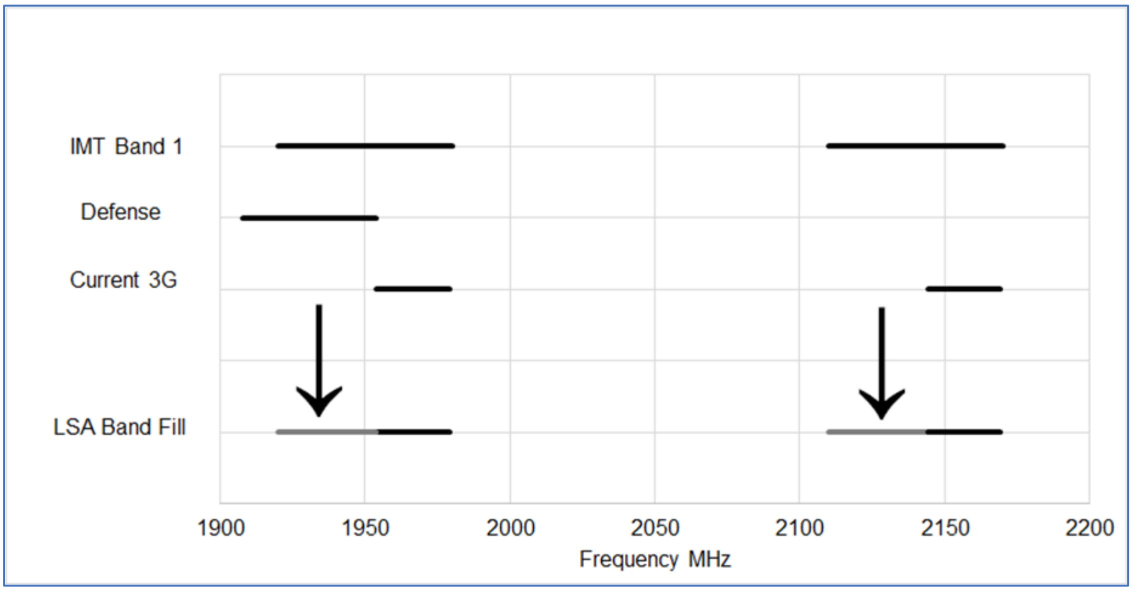
In April 2013, Finland became the first country to trial the LSA on the 2.3 GHz band, where the incumbents are Program Making Special Events licensees that use professional wireless camera links of broadcasting and TV production companies. The Electronic Communications Committee Decision (1)02 on harmonized technical and regulatory conditions for the use of the 2300–2400 MHz band for mobile/fixed communications networks, which was approved in June 2014, paved the way for LSA deployments in Europe. The European CEPT Report 55 provides common and minimal technical conditions for wireless broadband usage of the 2300–2400 MHz frequency band. The technology allows co-existence between wireless broadband applications in the 2300–2400 MHz band and those with the services and applications below and above the 2400 MHz band.

The European Commission mandated (M/512) ETSI Reconfigurable Radio Systems M/2013 in November 2012, which includes the development of harmonized standards for TVWS and LSA with geolocation database control. The objectives cover commercial, civil security, and military applications, and synergy between those applications. The requirements and system architecture documents are expected to provide large-scale adoption of LSA in Europe.

1.2 LSA Band Fill: In 1800 and 2100 MHz

In areas where a 3GPP band is partially licensed to other users, LSA Band Fill introduces the possibility to open missing parts of the band to mobile operators so that existing users can continue their use of the spectrum. In LSA Band Fill, user equipment currently available on the local market can be immediately used. New base stations will need to be installed in the network as mobile operators would want to differentiate between the exclusive parts of the spectrum and the LSA extension of the frequency band. An illustration of LSA Band Fill is shown in Figure 5.2.

Figure 5.2: Illustration of Band Fill in 1800 and 2100 MHz in Europe



Incumbent users, such as the defence forces, use part of the IMT band, which restricts the licensed allocation of spectrum in these bands. For example, only part of IMT Band 84 (1920–1980 MHz) is available to the mobile operators, leading to inefficient allocation. Using LSA, it is possible to allocate the part that is used by defence for commercial mobile services.

Whatever may be the chosen methodology, an important regulatory intervention at this stage would be to set up a country-wide geospatial spectrum database that contains the spectrum used across different areas by various operators. Without this first step, the dynamic spectrum access methods will not take off in the country.[34]

[34] Sridhar, V., & Kokkinen, H. (2022, July 4). *Prerequisites for dynamic spectrum access. Business Line.*

2. Spectrum Access System in the US

SAS is a revolutionary framework for spectrum management used in the US, primarily governing the shared use of the 3.5 GHz Citizens Broadband Radio Service (CBRS) band (3550–3700 MHz). This cloud-based coordination system represents a significant advancement in spectrum utilization, allowing multiple users to dynamically share frequencies while preventing harmful interference. The following section provides an overview of the SAS ecosystem in the US.

2.1 Core Functionality and Architecture

SAS serves as an automated spectrum coordinator that manages wireless communications in the CBRS band through three key components:[35]

- **SAS Portal**: Includes the user interface and API for managing CBRS devices (CBSDs)
- **SAS Backend**: Contains all spectrum-management services
- **SAS Database**: Stores registered CBSD information, active grants, and interference data

This architecture enables dynamic frequency allocation while maintaining a complete record of all devices operating in the shared spectrum.

2.2 Three-Tiered Access Framework

The FCC established a hierarchical access model for CBRS spectrum sharing:[36]

1. **Incumbent Access (Tier 1)**: Highest priority for federal users like navy radar systems and fixed satellite stations. These users are fully protected from interference.
2. **Priority Access Licence (PAL—Tier 2)**: Commercial users who obtain county-level licences through FCC auctions. PAL holders get interference protection from lower tiers but must vacate when incumbents operate.
3. **General Authorized Access (GAA—Tier 3)**: Unlicensed users who can access any available spectrum not used by higher tiers, with no interference protection.

2.3 Key Operational Mechanisms

SAS performs several critical functions:

- **Device Registration**: All CBSDs must register with location, capabilities, and owner information
- **Spectrum Allocation**: Dynamically assigns channels and power levels based on priority tiers and real-time availability

[35] Google Cloud. (2025). *Spectrum Access System overview*. https://cloud.google.com/spectrum-access-system/docs/overview

[36] Hardesty, L. (2020, August 26). *What is a CBRS spectrum access system?* Fierce Network. https://www.fierce-network.com/private-wireless/what-a-cbrs-spectrum-access-system

- **Interference Prevention**: Uses propagation models and environmental sensing capability (ESC) networks to protect higher-tier users
- **Heartbeat Monitoring**: Requires CBSDs to check in every 240 seconds to maintain active grants

The system employs six standardized message types for CBSD-SAS communication: registration, spectrum inquiry, grant request, heartbeat, relinquish grant, and deregistration.

2.4 Environmental Sensing Capability (ESC)

A critical component of the SAS ecosystem is the ESC network—coastal radar sensors that detect incumbent military activity. When ESCs detect naval transmissions, they activate dynamic protection areas, trigger spectrum re-allocation by the SAS, and create temporary exclusion zones to prevent interference. Google, Federated Wireless, and CommScope operate FCC-approved ESC networks. These administrators must synchronize their databases daily through Coordinated Periodic Activities to maintain consistent allocations.

2.5 Applications and Impact

The SAS framework has enabled diverse wireless applications:

- **Private LTE/5G Networks**: Enterprises deploy localized cellular networks for industrial IoT and smart facilities[37]
- **Mobile Network Expansion**: Carriers like Verizon use CBRS for capacity augmentation
- **Rural Broadband**: Wireless internet service providers (WISPs) deliver fixed wireless access in underserved areas
- **Neutral Host Solutions**: Venues implement shared infrastructure for multiple carriers[38]

As of 2023, over 128,000 CBSDs were active in the US, with 70% deployed in rural areas. The US SAS represents a landmark achievement in spectrum policy, demonstrating that sophisticated sharing mechanisms can balance commercial innovation with protection for critical federal operations. By combining cloud-based automation with tiered access rights, SAS has enabled flexible spectrum utilization across diverse applications. As wireless demands grow, the SAS framework will continue evolving to address emerging challenges in dynamic spectrum sharing.

While SAS is complex to implement, the method provides opportunities for co-existence of spectrum across various use cases. One compelling use case is 5G private networks, where the same spectrum can be used for both private and public cellular mobile networks.

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[37] Celona. (2021, August 16). *CBRS SAS: Simple explanation of the Spectrum Access System*. https://www.celona.io/cbrs/cbrs-sas

[38] Brown, L. (2023). *CBRS SAS players: Who are they and what do they do?* STL Partners. https://stlpartners.com/articles/private-cellular/cbrs-sas/

2.6 Auction of the CBRS band for PAL

Below, we provide a detailed synthesis of the US CBRS (spectrum auction results, primarily from Auction 105, 2020), including winners, spending, geographic trends, and auction implications.

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1. Auction Overview

- **Spectrum Band:** 70 MHz of Priority Access Licenses (PALs) in the 3.55–3.65 GHz range, divided into seven 10 MHz blocks per county[39]
- **Total Licences Offered:** 22,631 licences across 3,233 US counties
- **Auction Format:** Combinatorial clock auction (CCA), allowing package bidding
- **Gross Proceeds:** USD 4.58 billion (net bids: USD 4.54 billion), with 20,625 licences sold (91% of total)

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2. Top Winners and Spending

Major Carriers and Cable Companies

- **Verizon:**
  - Spent USD 1.89 billion for 557 licences (avg. 38.7 MHz depth in 144 counties), focusing on urban markets like Los Angeles and New York
- **Dish Network (Wetterhorn Wireless):**
  - Spent USD 913 million for 5,492 licences (avg. 30.2 MHz across 1,819 counties), targeting rural and urban areas for its 5G buildout
- **Cable Operators:**
  - **Comcast:** USD 459 million for 830 licences
  - **Charter:** USD 464 million for 210 licences
  - **Cox:** USD 213 million for 470 licences

Utilities and Enterprises

- **Southern California Edison:** USD 119 million for 20 licences
- **Alabama Power:** 271 licences across 103 counties
- **Chevron & John Deere:** Secured licences for industrial IoT (e.g., oil fields, agriculture)

[39] Alleven, M. (2020, August 26). *CBRS 3.5 GHz auction concludes, raising $4.58B.* Fierce Network. https://www.fierce-network.com/regulatory/cbrs-3-5-ghz-auction-concludes-raising-4-58b

Other Notable Participants

- **T-Mobile:** Minimal bids (USD 5.5 million for 8 licences) due to existing 2.5 GHz holdings
- **Universities (e.g., University of Virginia):** Acquired licences for campus networks[40]

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3. Geographic and Price Trends

- **Highest Demand:** Urban counties like Los Angeles (USD 364 million total) and Cook County, Illinois (USD 279 million)
- **Price per MHz-POP:**
  - **National average:** USD 0.217 4
  - **Highest:** Loving County, Texas (USD 141.46/MHz-POP for 82 residents)
- **Utilities' Premium:** Paid USD 0.3615/MHz-POP on average (vs. national USD 0.217) due to urban-focused bids

Table 5.1 provides an overview of the outcome of the CBRS auction:

Table 5.1: Summary of Auction 105 CBRS Auction in the US

	Freq M Hz / Year
Frequency Band	3550–3650
Year	2020
Avg. Spectrum Available	6,15,160
Spectrum Allotted	1,98,380
Gross Revenue (in USD Millions)	5,010
Price/MHz/Pop (USD)	0.7580

3. Conclusions

The stakeholder interviews indicated that the CBRS and SAS implemented in the US are considered the most advanced spectrum-sharing methodologies and are considerably complex. On the other hand, the LSA methodology being used in Europe has not yet been widely deployed, but it has promise for wide-scale deployment as the demand for radio spectrum increases in the years to come. Further, it is easier to coordinate spectrum sharing in high-frequency bands due to the limited propagation of radio waves. However, any spectrum sharing, static or dynamic, requires a spectrum geolocation database (GLDB) that tracks the spectrum usage in both the space and time domains. The secondary access holder identifies free bands by querying the GLDB, where a list of available channels is stored. The importance of GLDB for dynamic spectrum access, especially in the context of IoT systems, is widely advocated.[41]

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[40] Alleven, M. (2020, September 10). *CBRS spectrum auction maps: Who won what, and where.* Light Reading. https://www.lightreading.com/5g/cbrs-spectrum-auction-maps-who-won-what-and-where

[41] Guimarães, D. A., Pereira, E. J., Alberti, A. M., & Moreira, J. V. (2021). Design guidelines for database-driven Internet of Things-enabled dynamic spectrum access. *Sensors, 21*(9), 3194.

Chapter 6: Analysis of Spectrum Regulation in India

1 Introduction

In this section, we discuss the history of spectrum allocation in India, followed by a discussion of the spectrum auction in 2022, which was the first auction of the 600 MHz spectrum and in which the mid-band spectrum in the C-band and the 26 GHz mmWave bands were first put on block.

We build on issues of spectrum co-existence across mobile access and backhaul, followed by spectrum for private networks, mixed use of spectrum between mobile access and Wi-Fi, co-existence of FWA, co-existence of spectrum for FWA, mobile access and backhaul, and flexible use of spectrum, including spectrum sharing. We recommend the need for a tiered architecture for spectrum licensing instead of the current LSA-based spectrum licence. We also provide our proposal for a spectrum surrender policy.

Before the introduction of mobile services, spectrum intended for commercial usage in the 800 MHz, 1800 MHz, and 1900 MHz bands was entirely in the control of the national defence force of India. The utilization of spectrum for commercial purposes began with the release of a limited amount of spectrum in 1995. The management of spectrum in the country can be divided into three stages, based on different degrees of liberalization of the spectrum market. In the first stage, from 1995 to 2003, the market was relatively nascent, but auctions were the preferred method for the allocation of spectrum. In the second phase, from 2003 to 2008, the market matured and grew at a rapid pace, but spectrum was allocated through the administered route. The highly controlled spectrum environment unravelled with allegations of the misuse of discretionary power by the government and gave way to the third phase, starting in 2012, where far-reaching liberalization of the spectrum is being attempted.[42] Currently, the National Frequency Allocation Plan 2022, entrusted to the Wireless Planning and Co-ordination wing, outlines the allocation of different parts of the frequency spectrum for various purposes.

The current allocation of spectrum bands in India is provided in Table 6.1.

[42] Prasad, R., & Sridhar, V. (2014). *The dynamics of spectrum management: Legacy, technology, and economics*. Oxford University Press.

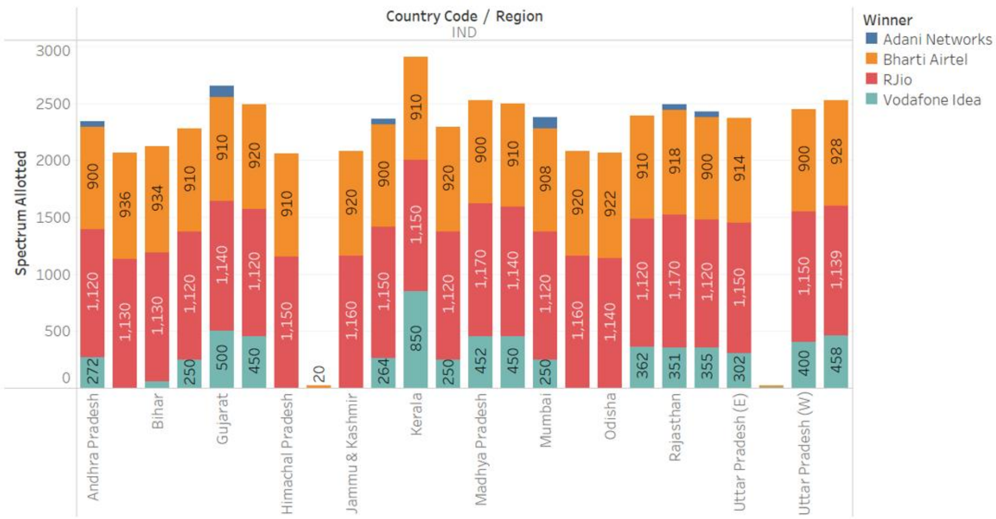
Table 6.1: Spectrum Bands in Use in India

LTE Operating Band	NR Operating Band	UL_Low	UL_High	DL_Low	DL_High	Duplex Mode	Band Category
1	n1	1920	1980	2110	2170	FDD	Mid Band: 2100 MHz
3	n3	1710	1785	1805	1880	FDD	Mid Band: 1800 MHz
5	n5	824	849	869	894	FDD	Sub GHz: 850 MHz
8	n8	880	915	925	960	FDD	Sub GHz: 900 MHz
28	n28	703	748	758	803	FDD	Sub GHz: 700 MHz
40	n40	2300	2400	2300	2400	TDD	Mid Band: 2300 MHz
41	n41	2496	2690	2496	2690	TDD	Mid Band: 2500 MHz
	n78	3300	3800	3300	3800	TDD	Upper Mid Band: 3300 MHz
	n258	24250	27500	24250	27500	TDD	High Band: 26 GHz

The spectrum holdings by various operators across bands and across LSAs are provided in Appendix 6.1.

Figure 6.1 provides a summary of auctioned spectrum allocated to various private operators. As can be seen, Bharti Airtel and Reliance Jio hold the majority of the spectrum and, on average, have about 1000 MHz per LSA.

Figure 6.1: Summary of Spectrum Holdings by Various Private Operators

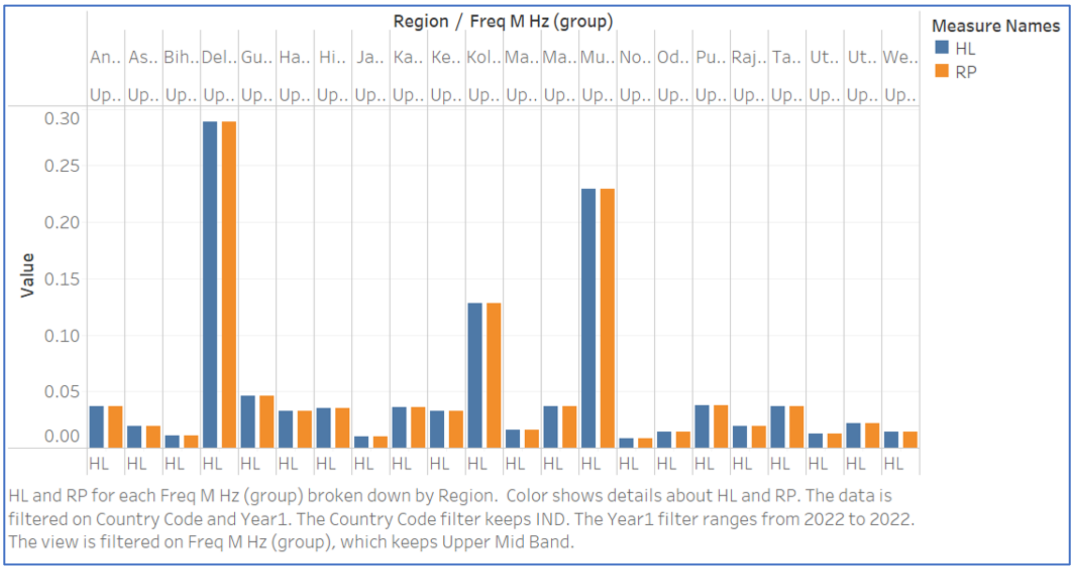


Sum of Spectrum Allotted for each Region broken down by Country Code. Color shows details about Winner. The marks are labeled by sum of Spectrum Allotted. The data is filtered on Freq M Hz (group), which keeps Null, High Band, Mid Band, Sub GHz and Upper Mid Band. The view is filtered on Country Code, which keeps IND.

2 Spectrum Prices

In India, the SMRA auction is being used to allocate spectrum bands to various operators. However, the higher reserve prices of the auction have been widely debated. Figure 6.2 provides a comparison of the winning bid price versus the reserve prices of the upper mid band (3300 MHz) across LSAs in India.

Figure 6.2: Winning vs. Reserve Price of the Upper Mid-Band in the 2022 Auction in India



As can be seen, in all the LSAs, the winning bid prices are equal to reserve prices, indicating either that the reserve prices are high or that there is insufficient demand for this spectrum. Across all LSAs, out of the 330 MHz of spectrum put on auction in the upper mid-band, only 250 MHz was allocated at the reserve price. In the subsequent auction in 2024, none of the 3300 MHz put on the block was picked up, which is a matter of concern, with the spectrum staying unallocated and unutilized for the past three years.

In the 2022 auction, of the 3500 MHz of paired spectrum put on auction, only 20% was picked up by operators; of the 70000 MHz of unpaired, including the 26 GHz band, only 10000 MHz were picked up, resulting in an uptake of about 16–17%. This resulted in gross revenue for the government of about INR 1.37 lakh crores compared to the total reserve price of all blocks in auction at INR 4 lakh crores. As also highlighted by a recent DoT study, it is time that the government reviews the reserve price of 5G spectrum and revises it to make use of the scarce resource.[43]

3 Pricing and Allocation of Sub-GHz band

The sub-GHz band, especially 800 and 900 MHz, was always scarce in India due to incumbent ownership by the Department of Defence. These bands are critical for wide area coverage. A spectrum refarming exercise by the government in 2012 re-allocated part of the 900 MHz for commercial mobile services. Most of the spectrum has been refarmed from 2G to 4G services by private operators. The state-owned BSNL still runs part of the rural network in 2G mode in the 900 MHz band. However, high reserve prices inhibited operators from acquiring more spectrum. In the 2022 auction, only 20 MHz of the 140 MHz in the 800 MHz band and 12 MHz out of 75 MHz in the 900 MHz band were picked up by operators.

[43] https://dot.gov.in/sites/default/files/smra_analysis.pdf?download=1

Of the other sub-GHz bands, the 600 MHz band was allocated only in the US in 2017 for mobile services using the incentive auction. However, many countries, including Saudi Arabia, the UAE, and Brazil, are actively considering the 600 MHz for 5G Stand Alone (SA) deployments. Further, the n71 band (663–698; 617–652 MHz) was approved by 3GPP as the 5G spectrum band and is being widely deployed in the US.

On the other hand, due to various reasons, including better management of the sub-GHz spectrum bands, India put the APT 600 MHz band (adopted by 3GPP in 2022 as n105 band (663–703; 612–652 MHz) on auction in 2022, with a total of 2 × 40 MHz in each LSA. However, due to various reasons, including higher reserve prices and the uncertainty in equipment availability, no one picked up spectrum in this band.

With the handset ecosystem expected to develop due to the interest in the Asia Pacific and the Middle East, it is possibly time to revisit the unsold 600 MHz in the forthcoming auctions, with substantially revised reserve prices. The Telecom Regulatory Authority of India (TRAI) released a consultation paper in 2025 to this effect and sought stakeholder comments on whether the n71 or n105 should be put on auction again.[44]

The following are our recommendations on 600 MHz:

- Given that the n71 band has gained more traction, especially in the US and possibly in Germany, and due to the availability of equipment, n71 should be considered for auction instead of n105.
- Since the 600 MHz band is not yet allocated for commercial mobile services in many countries, India would make a breakthrough by auctioning the n71 band at relatively low reserve prices, as this will, to some extent, give the TSPs long-range 5G coverage band due to the non-availability of much spectrum in the 700 MHz band.

3.1 Advantages and Disadvantages of Revisions in Spectrum Pricing

Higher reserve prices artificially place constraints in the bidding process and have the effect of increasing the winning bid prices. Since the SMRA process with eligibility points and activity rules has proven to be robust, lowering the reserve prices is most likely to induce truthful bidding, leading to correct evaluations. Lowering reserve prices need not necessarily lead to reduced revenue for the government auctioneer.

4 New Approach to Allocation of Spectrum for Backhaul

In India, before the introduction of 5G mobile networks, only the spectrum in the 6 GHz (lower), 7 GHz, 13 GHz, 15 GHz, 18 GHz, and 21 GHz bands was used for providing microwave backhaul. These bands are often referred to as “the traditional microwave backhaul bands”.

[44] TRAI (2025). Consultation Paper on the Auction of Radio Frequency Spectrum in the Frequency Bands Identified for International Mobile Telecommunications (IMT).

The DoT has classified traditional microwave backhaul bands into two categories: microwave access (MWA) bands and microwave backbone (MWB) bands.[45]

MWA bands that normally carry traffic over relatively shorter distances include:

- 13 GHz band (12.75–13.25 GHz)
- 15 GHz band (14.5–15.5 GHz)
- 18 GHz band (17.7–19.7 GHz)
- 21 GHz band (21.2–23.6 GHz)

MWB bands that normally carry traffic over relatively longer distances include:

- Lower 6 GHz (5.925–6.425 GHz)
- 7 GHz (7.125–7.725 GHz)

As per industry estimates, India has about 500,000 wireless backhaul links, which have been deployed by using the spectrum in traditional microwave backhaul bands. When an access service provider obtains the right to use a carrier in a particular MWA band in a licensed service area, it deploys that carrier to build several radio backhaul links across the licensed service area. The network of a typical access service provider could have thousands of microwave backhaul links operating on a particular carrier of a traditional microwave backhaul band in a licensed service area.

The 2025 guidelines by the Department of Telecommunications (DoT) in allowing the lower 6 GHz for unlicensed use for indoor use are unlikely to affect this band for backhaul use. However, the 7 GHz band (specifically 7.125–8.4 GHz; FR3 band) is actively being considered as a key spectrum range for 6G deployments, offering a balance between coverage and capacity. Hence, the 7 GHz band being used for backhaul needs further consideration.

The WRC-23, which concluded in December 2023, added co-primary space-to-space allocations for the intersatellite service (ISS) in the 18.1–18.6 GHz band. India is likely to allocate the same spectrum for ISS. While this does not affect the allocation of the same band for use of other services such as backhaul, the 18 GHz band is also used by non-terrestrial systems such as Amazon's Kuiper for downlink from non-geostationary orbit satellites to earth stations or user terminals. With more satellite systems operating in the Ku band (15, 17, and 18 GHz bands), more allocation in these bands may be required.

There will also be considerable traction in 6G standardization effects towards licensing spectrum in the upper mid-band (7–15 GHz) for IMT use. As can be seen in Figure 4.1, more countries have opted for 23 GHz and 38 GHz for backhaul operations. As indicated in earlier chapters, the co-existence of multiple services in the same spectrum bands poses challenges for backhaul spectrum allocation.

[45] TRAI (2025). Consultation Paper on Assignment of the Microwave Spectrum in 6 GHz (lower), 7 GHz, 13 GHz, 15 GHz, 18 GHz, 21 GHz Bands, E-Band, and V-Band. https://trai.gov.in/sites/default/files/2025-05/CP_28052025.pdf

TRAI has floated a consultation paper and invited stakeholder responses regarding the allocation of the above bands for different services. Any re-allocation of spectrum from backhaul to access will deprive operators of continuing to use it for backhaul.

In India, while the bands that have been designated as MWA are assigned on an LSA basis to the operators with access service authorizations, the bands designated as MWB are assigned on a link-by-link basis to those with access service authorization. Given spectrum co-existence, MWA and MWB shall be merged and allocated to operators with access service authorization. This will lead to simplified assignments while providing flexibility to operators for using the spectrum effectively.

Given that access and backhaul spectrum are complements, it is in the interest of operators to acquire spectrum that can be useful for both access and backhaul through suitable demarcation. In general, complementary goods such as these are auctioned using a combinatorial package auction to maximize the complementary benefits. Given the complexities of the package auction, one option is to allow the operators to use the assigned spectrum, especially in the 7–20 GHz band for both access and backhaul, as may be required. However, as specified in the First Schedule of the Telecom Act 2023, the backhaul spectrum shall be allocated using an administrative process,[46] and as per clause 5(a) of the Act, the government can amend the first schedule with suitable justification.

Accordingly, we propose the following recommendations regarding backhaul spectrum:

- Combine MWA and MWB spectrum bands into one set of bands for backhaul.
- The upper mid-band (7–15 GHz), where there is co-existence between IMT access and backhaul, is allocated for flexible use, for access or backhaul, or both, and the service provider should demarcate the assigned bands as per its requirements.
- For a flexible use between access and backhaul, the ideal methodology would be to auction spectrum with suitable amendments to the First Schedule of the Telecom Act 2023. The period of the spectrum licence should be the same as that for mobile access. This is also in line with the Integrated Access and Backhaul (IAB) as standardized in 3GPP Release 16.
- For higher bands in 18–60 GHz, where the 26, 28, 39, and 47 GHz bands are being standardized for 5G NR/6G, we recommend an auction for flexible use (for both access and backhaul) on a micro-LSA basis. This will future-proof the methodology even though these bands are not extensively used for backhaul in India. The period of spectrum licensing should be reduced to five years to allow for technology evolution.

[46] Ministry of Law and Justice, Government of India. (2023). The Telecommunications Act 2023.

- For all auctioned spectrum, the SUC should be nil as applicable for access spectrum. One of the important developments in this area is the use of high-frequency spectrum for FWA service to provide high-bandwidth last-mile connectivity.
- Enable sharing, leasing, trading, and surrender of assigned spectrum for the incumbents holding backhaul spectrum as provided in clause 8(2) of the Telecom Act 2023. This will facilitate optimal utilization of backhaul spectrum while not interrupting existing service provisioning.

4.1 Advantages and Disadvantages of Our Approach

Advantages:

- It recognizes the co-existence of radio spectrum across different uses and provides TSPs with an opportunity to make efficient use of spectrum, instead of artificially blocking certain uses through regulation.
- Administrative pricing of backhaul spectrum has been debated, as the price thresholds are not clearly visible to the regulator. Auction is a proven methodology, which, if appropriately designed, will extract truthful bidding in line with the valuation.
- The micro LSA-wide auction of the mmWave band will provide enough flexibility to TSPs to deploy access and backhaul (as well as FWA) and, at the same time, deploy efficient networks.

Disadvantages:

- As per the First Schedule of the Telecommunications Act 2023, clause 12, backhaul spectrum shall be assigned using an administrative process. Hence, to auction backhaul spectrum, a modification or amendment to the first schedule as per clause 5(a) of the Act will be required.
- Current incumbents are holding substantial backhaul spectrum in 7, 8, 13, 15, 18, and 21 GHz on a block basis. However, the proposal to shift from administrative assignment to auction will disrupt existing network operations.

5 Spectrum Allocation for Private Networks

In India, the spectrum in the 3300–3630 MHz frequencies was put on auction in 2022, and most of the operators picked it up. As per NFAP 2022, frequencies up to 3670 MHz can be used for IMT services. Frequencies beyond 3670 MHz are being reserved for fixed satellite services in the C-band. There have also been concerns raised in India as well as in many countries, including the US, about interference with aircraft altimeters that operate in the

4200 MHz.[47] However, 3GPP has standardized the n77 band that extends from 3300 to 4200 MHz for IMT services.

The DoT issued the guideline for captive non-public networks (CNPNs) in 2022.[48] This guideline included the following four options for providing CNPN service:

[1] Telecom service providers (TSPs) with an access service licence may provide private networks as a service to an enterprise by using network resources (such as through network slicing) over its public land mobile network.

[2] TSPs with an access service licence may establish an isolated CNPN for enterprises using IMT spectrum acquired by them.

[3] Enterprises setting up private captive networks may obtain the spectrum on lease from TSPs and establish their own isolated network.

[4] Enterprises setting up private captive networks may obtain the spectrum directly from the DoT and establish their own isolated network.

While the first three options include licensed TSPs, the fourth option allows non-TSPs to acquire spectrum and construct CNPNs. Further, in line with the government's move to replace the telecommunications licensing regime with authorization as specified in clause 3(1) of the Telecom Act 2023, TRAI released its recommendations on authorization of services in February 2025,[49] which explicitly stated that authorization for CNPN is warranted for establishing, maintaining, operating, and expanding CNPN networks for enterprises, in conformance with options [3] and [4] above.

While TSPs are in a better position to provide carrier-grade services in public network spaces, private networks are similar to Wi-Fi and local area networks, as they provide connectivity within limited geographical locations. Enterprises normally have secure networks, and the same can be extended to local private networks that operate over licensed spectrum bands. Since CNPNs, by definition, are not directly connected to public networks and are intended to provide connectivity to niche applications, service providers other than licensed TSPs should be considered for private network provisioning.

Recently, the DoT also conducted a demand estimation exercise to determine the interest of private entities other than telcos in acquiring spectrum for CNPNs.[50] Though details of the survey are not available in the public domain, it appears that the response to this survey was not promising.

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[47] Sridhar, V. (9 December 2022). What are the concerns around 5G services and the functioning of Altimeter. The Hindu In Focus podcast.

[48] Department of Telecommunications. (2022). Guidelines for Captive Non Public Network License. https://dot.gov.in/circulars/guidelines-captive-non-public-network-cnpn-license

[49] Telecommunications Regulatory Authority of India (2025). Recommendations on the Terms and Conditions of Network Authorisations to be Granted Under the Telecommunications Act, 2023

[50] Ministry of Communications. (2025). Module launched on Saral Sanchar portal for carrying out demand survey to identify frequency bands for the direct assignment of spectrum to CNPN. https://www.pib.gov.in/PressReleasePage.aspx?PRID. =2140830&reg=3&lang=2

5.1 Spectrum Carve-Outs for Private Networks

While non-TSPs can lease the IMT spectrum from TSPs for constructing CNPNs as allowed under option [3] above, separate carve-outs of spectrum for private networks, as was done in South Korea, are required to give impetus to private network operations (refer to section 4.4.1 for details). TRAI, in its April 2022 recommendations, specified the following spectrum carve-outs for CNPNs, taking into consideration the co-existence of these bands with fixed satellite service:[51]

[1] At least 40 MHz in the 3700–3800 MHz frequency range for low power indoor use for CNPNs

[2] At least 40 MHz in the 4800–4990 MHz

[3] At least 400 MHz in 28.5-29.5 GHz

However, the TRAI recommendations do not include the methodology for assignment. Further, the First Schedule of the Telecom Act 2023 does not include private networks for administrative assignment of spectrum. Taking into account the above, we propose the following with respect to spectrum management for private networks:

- Conduct an audit of the use of C-band and, if possible, extend the C-band allocation beyond 3630 up to 4000 MHz for IMT mobile services. This will open up huge opportunities for telcos to expand their 5G coverage. As recommended by TRAI in 2022, these frequency bands might interfere with the C-band-receive antenna of fixed satellite systems. Hence, as recommended by TRAI, the government should include all existing satellite C-band-receive stations in the spectrum geolocation database (as proposed) so that the TSPs implement geographically limiting mid-band spectrum deployment accordingly. The NFAP should be revised accordingly.
- Instead of TRAI's recommendations of 3700–3800 MHz, spectrum in the 4000–4200 MHz frequencies should be considered as spectrum carve-outs for private networks. This band has not been allocated in India due to the risk of interference with aircraft altimeter systems. However, most altimeters in aircraft are being shifted from 4200 MHz to avoid possible interference with mobile systems. Hence, 200 MHz should be considered exclusively for allocation to CNPNs. Due to the availability of the device ecosystem in the n77 bands for 5G, the government should consider allocation of 4000–4200 MHz for CNPNs to enterprises. The power limits and other parameters should be specified such that the coverage is limited to the private network space to prevent any possible interference.

[51] Telecommunications Regulatory Authority of India. (2022). Recommendations on Auction of Spectrum in frequency bands identified for IMT/5G. https://trai.gov.in/sites/default/files/2024-09/Recommendations_11042022.pdf

- Spectrum carve-outs in 4.8 and 28 GHz, as recommended by TRAI, should also be considered for exclusive allocations for CNPNs.
- Since the CNPNs are not substitute services but only complement campus connectivity and are spatially limited, they cannot be compared to cellular mobile services that are licensed across the entire LSA. However, in terms of functionality, it is equivalent to cellular mobile broadband services. Hence, due to the functional equivalence, we advocate auctioning the carve-out spectrum solely for CNPNs with a suitable reserve price. The auction invites should be extended to both the existing TSPs and non-TSPs authorized to provide CNPNs as per TRAI's recommendations on service authorization.
- We recommend private network service area (PNSA) based auctioning of spectrum for CNPNs. This is because private networks, by definition, are confined to specific areas, and hence, LSA-wide allocation is not a suitable methodology for assigning spectrum for CNPNs. The assignment of spectrum in granular geographical regions will provide incentives for non-TSPs to acquire spectrum for enterprise, factory, ports, and airport connectivity, among others (See section 6.9 for details on PSNA-based spectrum licensing).

5.2 Advantages and Disadvantages of Spectrum Carve-outs

The primary advantage of spectrum carve-outs is that spectrum bands that could not be allocated to commercial mobile services in the IMT bands due to interference with existing users should be put to effective use, as is the case with the spectrum in the 4000–4200 MHz frequencies. The carved-out spectrum provides exclusive coverage of geographically constrained private networks, thereby providing superior QoS as may be required, especially in ultra-reliable low latency communication use cases. It will also allow non-TSPs to provide opportunities for network equipment manufacturers, venue owners, and managed service providers to build customized network offerings for enterprises. The PNSA-based spectrum licensing creates new options for enterprises to construct private networks in targeted geographical areas.

However, there are disadvantages. The spectrum carve-out may not be fully utilized, leading to underutilization of scarce resources, which could otherwise have been assigned to TSPs for coverage of public networks. The non-TSPs may lack the expertise of TSPs in installing and maintaining carrier-grade networks. The PNSA-based licensing requires defining the granular areas for allocating spectrum as well as the spectrum GLDB for monitoring spectrum allocation and use. The DoT can factor in these advantages and disadvantages when deciding on spectrum carve-outs and including non-TSPs to acquire spectrum for private networks.

6 Mixed Use of 6 GHz and 60 GHz Between Unlicensed and Licensed Use

6.1 Allocation of 6 GHz for Mixed Use

The Ministry of Communications published the draft rules on "Use of Low Power and Very Low Power Wireless Access System, including Radio Local Area Network in the Lower 6 GHz band (Exemption from Licensing Requirement) Rules, 2025", in which the lower band in the 5925–6425 MHz band was allowed for indoor use with appropriate power restrictions.[52] Therefore, it is expected that the upper portion in 6425–7125 MHz may be allocated for licence use in the near future.

The recent TRAI "Consultation Paper on the Auction of Radio Frequency Spectrum in the Frequency Bands Identified for International Mobile Telecommunications (IMT)" noted that, "In the 6 GHz band, satellite-based services (uplink) are coexisting with IMT-based services" and that only 400 MHz spectrum in two fragmented chunks of 6425–6725 MHz (300 MHz) and 7025–7125 MHz (100 MHz) are immediately available for IMT services. The remaining 300 MHz in the frequency band 6725–7025 MHz will be available by December 2030.[53] This is due to the upper portion of the 6 GHz band being used for satellite uplink.

In India, the amount of spectrum release for unlicensed use includes 83.5 MHz in 2.4 GHz (2400–2483.5 MHz) and about 605 MHz (5150–5350; 5470–5725; 5725–5825; 582–-5875) in 5 GHz, amounting to a total of about 689 MHz. Countries such as the UK have released about 1105 MHz in the 5 GHz band for unlicensed use. Hence, it is appropriate that India reserves the lower 500 MHz of the 6 GHz spectrum for unlicensed use, given the proliferation of Wi-Fi networks, both for indoor and public outdoor use.

Our recommendations for backhaul spectrum follow:

- The lower 500 MHz of the 6 GHz band (5925–6425 MHz) should be allocated for delicensed use. This will augment the limited availability of unlicensed spectrum in the 5 GHz band.
- The upper 700 MHz (6425–7125 MHz) should be allocated through auction for IMT use, as this will also provide contiguous spectrum for IMT use in the 7 GHz band, as will be finalized in WRC 27.

6.2 Allocation of 60 GHz for Mixed Use

Besides 6 GHz, the IEEE 802.11 ad and ay specifications included 60 GHz for unlicensed use in Wi-Fi systems. Countries have different stances on the usage of 60 GHz (Table 6.2). The V-band (57–71 GHz) is suitable for short-range transmission with potentially high bandwidth.

[52] https://dot.gov.in/circulars/draft-use-low-power-and-very-low-power-wireless-access-system-including-radio-local-area

[53] Telecommunications Regulatory Authority of India. (2025). The Auction of Radio Frequency Spectrum in the Frequency Bands Identified for International Mobile Telecommunications (IMT)n the 6 GHz band, satellite-based services (uplink) are co-existing with IMT-based services.

This band is typically split into two sets of frequencies: 57–64 GHz and 64–71 GHz. While some countries have allowed V-band for use by TISPs in both sets, some have restricted licensed use to the lower band of 57–64 GHz. However, on both sets, the bandwidth is 7 GHz, providing large capacities. This band can be used for short-range communication for point-to-point and point-to-multipoint configurations, making this V-band an interesting case study.[54]

Wireless access systems in the 60 GHz band in unlicensed mode have been developed through a series of amendments in IEEE 802.11 protocols (notably .ad and .ay) and adopted by the Wireless Gigabit Alliance (WiGig) to provide gigabit speed "wireless fibre". These developments have enabled firms to innovate around this critical band to offer various solutions. Internet companies like Facebook and Google have been working on technologies using WiGig standards to deploy high-speed public networks.

On the other hand, telcos lobby for licensing the V-band for high-powered line-of-sight point-to-point links that can act as high-speed backhaul. OfCom, after its regulatory impact assessment of V-band, opted for a licence-exempt authorization method. Countries such as Austria, Belgium, Poland, Slovakia, Spain, China, South Korea, Malaysia, Australia, and New Zealand have delicensed the V-band. Through several regulatory directives, the US FCC has released spectrum in 57–71 GHz for licence-exempt use. TRAI has recommended delicensing this band for access and light licensing for backhaul.

Table 6.2: Regulations on the Use of the 60 GHz Band

Region Frequency	Range	Notes
US (FCC)	57–71 GHz	Unlicensed, 4× 2.16 GHz channels
EU (ETSI)	57–66 GHz	Requires LBT (Listen-before-talk)
China (MIIT)	59–64 GHz	Restricted to indoor use
Japan (MIC)	57–66 GHz	Supports WiGig and 5G mmWave

While countries such as the US and the UK have opted for delicensing the entire V-band, Canada, Japan, Singapore, Australia, and the EU have opted for licence-exempt use for 57–64 GHz and LBT for the upper portion of the 64–71 GHz band. The 6G standardization efforts have not yet indicated potential standardization of 60 GHz.

However, taking into account the extensive requirement for spectrum for backhaul in India, we recommend the following:

- As in practice in other countries, the lower portion of the V-band, 57–64 GHz, should be licence-exempt for use in Wi-Fi networks as per the IEEE 802.11 ad specification.
- The upper portion of the band, 64–71 GHz, should be set aside for backhaul.

[54] A detailed analysis of the V-band for consideration for both access and backhaul is provided in Prasad, Rohit., and Sridhar, V. (Expected in 2025). 5G and Beyond: Rewiring Telecom Regulation in India. Oxford University Press.

6.3 Advantages and Disadvantages of Mixed Use

Unlicensed use enables non-TSPs to provide broadband service, especially for augmenting coverage indoors. It also ushers in lower usage charges for traffic offloads. Additionally, it enables better harmonization with the rest of the world, especially the US and Europe, on leveraging unlicensed spectrum.

However, disadvantages exist, including fragmentation of the spectrum, thereby leading to inefficiencies, especially in IMT bands for the TSPs. It also reduces the amount of spectrum for macro cellular coverage.

7 Co-Existence of FWA, Mobile Access, and Backhaul

The two major operators in India (i.e., Airtel and RJio) are deploying FWA in their respective assigned mid-band (e.g., 3.3 GHz). One of the operators in India is also deploying FWA in the 26 GHz spectrum band to supplement its mobile broadband offering. FWA is often viewed as a complement to mobile access services as it extends coverage. In the mmWave bands, there is possible co-existence between FWA and backhaul. The recent TRAI recommendations on spectrum for backhaul specify that no spectrum in traditional microwave backhaul bands should be earmarked for last-mile connectivity (FWA) to customer equipment. This is due to the non-recognition of the spectrum co-existence issue. As indicated in section 4, IAB is being recognized as the way forward to provide co-existence of access and backhaul spectrum by 3GPP.

Two regulatory constraints impede the recognition of access and backhaul co-existence:

- The backhaul spectrum is required to be administratively assigned as per the First Schedule of the Telecom Act 2023.
- The LSA-based assignment for all types of spectrum.

To optimally use spectrum across access, FWA, and backhaul, we propose the following (also see section 6.4):

- Allocate spectrum for IAB so that the operator can allocate it appropriately for access, FWA, and backhaul.
- For the mmWave band (> 18 GHz), allocate spectrum at the sub-LSA level for efficient allocation, details of which are discussed in the next section.

8 Spectrum Sharing for Optimal Utilization

The Department of Telecommunications released spectrum-sharing guidelines in 2015.[55] By allowing scarce spectrum to be pooled by operators (which were restricted to two at that time), the government allowed mobile operators to take advantage of the spectral efficiency

[55] Sridhar, V. & Prasad, R. (12 August 2014). A step forward in spectrum sharing. Hindu Business Line.

and trunking gain offered by larger spectrum blocks. At the time, India was the only country with extreme spectrum fragmentation (i.e., spectrum HHI of 0.13) and minuscule average spectrum holding per operator in a licensed service area of 3.5–6.2 MHz in any of the 800, 900, 1800, and 2100 MHz bands. With such a small spectrum (compared to international practices) doled out by the government, the recommendations were a welcome step for the industry. This fragmentation of the spectrum resulted in more mobile towers to enable increased spectrum reuse and is the main reason behind the growth of the mobile tower industry during 2004–2008.

Inevitably, gaps exist in the recommendations. By restricting sharing within the respective bands, i.e., intraband (i.e., 900 MHz only with 900 MHz and not with 1800 MHz), the guidelines became an improved version of the intra-circle roaming arrangement. Though a small step, spectrum sharing was the first step taken by the government to migrate from its extant “command and control” mode of spectrum management to a flexible regime.

Almost 10 years later, TRAI’s recommended expansions (as of 24 April 2024) allowed interband spectrum sharing (across different frequency bands) and enabled spectrum leasing. TRAI recommended that interband sharing be allowed only after a two-year lock-in period from when the spectrum was acquired. This was to ensure fairness and avoid undue influence on auction processes. Table 6.3 provides a summary of spectrum-sharing guidelines in India.

Table 6.3: Summary of Spectrum Trading and Sharing Guidelines in India[56]

Aspect	Current Status/Recommendations
Trading	Allowed
Intraband sharing	Allowed, after a one-year lock-in period
Interband sharing	Recommended by TRAI, subject to a two-year lock-in. A TSP should not be allowed to enter interband sharing with more than one TSP in a spectrum band category in an LSA. Further, interband spectrum sharing in an LSA should be permitted subject to the condition that, post sharing, there should be at least two independent wireless access networks in the LSA.
Spectrum leasing	Recommended by TRAI

The authority further recommended the possibility of implementing authorized shared access (ASA) technique-based spectrum sharing in India, under which the spectrum assigned to government agencies or other entities (non-TSPs) in the globally harmonized spectrum bands for IMT services can be assigned to access service providers as secondary users. A field trial of the ASA-technique-based spectrum sharing between willing access service providers should be conducted under the supervision of the DoT. This approach is similar to the LSA Band Fill option discussed in section 5.1.2.

[56] TRAI. (2024). Recommendations on Telecommunication Infrastructure Sharing, Spectrum Sharing and Spectrum Leasing. https://trai.gov.in/sites/default/files/2024-09/Recommendation_24042024_0.pdf

While technology-intensive methods such as SAS may not be appropriate for the Indian context, geolocation-based spectrum sharing, much like the LSA being practised in Europe, may be an available option.

8.1 Spectrum Sharing in 700 MHz

A total of 2×25 MHz in each LSA in the 700 MHz band (n28: 758–803; 703–748) was put on auction in 2022. Of these, only 2 × 10 MHz were picked up by one operator (RJio) in each LSA. However, after the auction, 2 ×10 MHz was assigned to the state-owned BSNL. A block of 2×5 MHz was assigned to Indian Railways for augmenting the Kavach anti-collision system. Indian Railways is seeking an additional 2×5 MHz for the same, which is under consultation by TRAI. This leaves no spectrum in the 700 MHz for commercial mobile services. The 700 MHz frequency is being used by operators around the world for better coverage. The first 700 MHz auction was held in the US in 2000, with subsequent assignments in the succeeding three to four years. Many countries, including Argentina, Canada, Germany, Finland, and Switzerland, have allocated 700 MHz. With no more spectrum left in the 700 MHz band for allocation to commercial mobile services in India, what is the way forward?

There is a possible use case for shared spectrum at 700 MHz. In India, only one mobile operator picked up 2 **×** 10 MHz pan-India when the 700 MHz band was auctioned in 2022. The following is the current allocation of 700 MHz, besides this allocation:

[1] 2 × 10 MHz to the Ministry of Defence

[2] 2 × 5 MHz to Indian Railways (for safety applications like Kavach, the anti-collision system)

[3] 2 × 5 MHz to the National Capital Region Transport Corporation (NCRTC) (for RRTS corridors)

[4] 2 × 10 MHz to BSNL (for 5G rollout)

[5] 2 × 5 MHz remaining, which is being requested by the Indian Railways to augment Kavach

In the above, the spectrum allocated for [2], [3], and [5], if assigned, have very specific use cases and are geographically constrained. Hence, these provide opportunities for implementing ASA.

Section (8)(2) of the Telecom Act 2023 specifies that spectrum sharing may be permitted. Section (7)(1) provides that non-interference-based secondary access to spectrum shall also be developed for optimal utilization of spectrum. Further, clause 3.7 of the draft NTP 2025 states that a framework for spectrum sharing and secondary usage shall be developed for optimal utilization of spectrum.

In line with these policy directives, we recommend that the government set up a geolocation spectrum database for monitoring and allocation of spectrum, both for static and dynamic use. Given the superior propagation characteristics of the 700 MHz band, and that two of the four telcos do not have this spectrum band, shared access of the 700 MHz band with defence, railways, and NCRTC is worth considering. Since the defence, railways, and NCRTC use the 700 MHz spectrum band in very limited geographical areas, there is a possibility of sharing these bands with TSPs using ASA.

8.2 Advantages and Disadvantages of Spectrum Sharing

Sharing can lead to optimal utilization of the spectrum and improve the use of unutilized and underutilized spectrum. Sharing or leasing spectrum resources by MNOs to VNOs provides impetus to competition and increases choices of broadband and content services for consumers.

However, spectrum sharing, especially dynamic sharing, is complex and requires coordination between operators to avoid possible interference. Secondary sharing of spectrum from primary incumbent owners, if not properly coordinated, may interrupt critical services (e.g., defence, avionics) of the incumbent primary spectrum holder. Spectrum sharing is useful and optimal only if the spectrum bands used in a spectrum geolocation database are registered. The government needs to fulfil the minimum infrastructure requirements to make the best use of spectrum-sharing technologies.

9 Sub-LSAs for Improving Competition

LSAs in India are defined at the circle level. This structure was designed for an era dominated by macro-cell mobile networks operating in the low- and mid-band spectrums. These bands offered relatively larger propagation ranges, and service providers needed contiguous rights across wide geographies to build uniform coverage networks. India has 22 such LSAs in which the spectrum is licensed to operators.

However, the evolution of 5G and beyond, particularly the growing importance of high-frequency spectrum (e.g., upper mid-band and millimetre wave), renders many of these legacy geographical units suboptimal. Beyond the reduced propagation characteristics of higher-frequency spectrum, a defining feature of the 5G era is the sharp increase in market heterogeneity, which in turn necessitates finer geographic granularity in spectrum licensing.

In such an environment, assigning spectrum over large service areas such as LSAs leads to inefficiencies: spectrum is often underutilized in low-demand areas while being congested in high-demand clusters. Smaller service areas allow spectrum to be aligned more closely with actual demand, enabling tailored network deployments and encouraging entry by specialized or local providers. This geographic disaggregation improves allocative efficiency, supports innovative niche use cases, and reduces the cost of entry for new players. In a 5G world characterized by heterogeneous demand and differentiated services, spectrum policy must move beyond uniform, large-area licensing and embrace more granular service areas as a central design principle. There is a compelling argument for moving toward sub-LSA spectrum licensing, potentially at the district level. There is also a precedent to district-level licensing in the case of VNOs that are authorized to provide wireline service.

9.1 Advantages of Sub-LSA-Based Licensing

Alignment with the Propagation Characteristics of Higher Bands

Higher-frequency spectrum, including mid-band extensions such as 6 GHz and millimetre-wave bands like 26/28 GHz, has limited propagation range and poor indoor penetration. Network planning for these bands necessarily occurs at much finer spatial granularity—dense urban cores, enterprise campuses, industrial clusters, ports, logistics hubs, and transport corridors. Assigning such a spectrum at the circle level leads to a mismatch between the geographical unit of planning and the size of the licensed area.

Variety of Use Cases

Unlike earlier generations of mobile networks that were designed to deliver relatively uniform services across large territories, 5G supports a wide variety of use cases—enhanced mobile broadband, fixed wireless access, private networks, ultra-reliable low-latency applications, and massive IoT—each with highly localized demand patterns. Further, in a country like India, several subscribers' primary use relates to the classic services associated with 2G, 3G, and 4G technologies.

Subscriber needs are extremely varied, even within districts and neighbourhoods, at the level of the traditional LSA. Allocating spectrum only at the LSA level risks leaving large portions of spectrum unused outside dense demand clusters.

District-level allocation would enable operators—traditional or new entrants—to acquire spectrum where demand justifies the investment. This targeted approach also encourages new high-value use cases in areas currently considered underserved—for example, rural clusters requiring FWA or hotspots around industrial hubs. The approach also promotes new types of entities, such as local ISPs offering FWA in a district town. It can catalyze a vibrant ecosystem of niche providers that complement national operators.

9.2 Risks and Challenges in Sub-LSA Allocation

While sub-LSA flexibility brings clear benefits, several structural risks must be acknowledged.

Patchy Uptake and Market Failure

Not all sub-LSA units will attract bidders. This creates the possibility of unassigned pockets of spectrum, complicating coordination with national networks and reducing the efficiency of the licensing process.

Moreover, while small areas lower entry barriers, they also raise the risk of fragmented ownership, where no single entity acquires sufficient contiguous geography to support coherent network planning.

Aggregation Challenges

High-frequency deployments often need geographic continuity even if licence areas are small. If the spectrum is held by multiple small entities, large operators may find it difficult or prohibitively expensive to aggregate neighbouring districts into a workable footprint. This creates a holdout problem, where small players strategically raise prices for critical districts. These aggregation externalities can discourage participation from major infrastructure providers.

Coordination Costs and Technical Complexity

Bringing inexperienced or hyper-local providers into the ecosystem may raise concerns regarding coordination of interference management; alignment of power levels; interoperability and handover issues; and backhaul arrangements relying on infrastructure owned by national players.

Large operators may also perceive sub-LSA models as a threat to strategic control over high-frequency spectrum, fearing loss of valuable capacity-building spectrum.

9.3 Balancing Benefits and Risks: Policy Design Options

To make sub-LSA licensing workable, regulators could consider:

- **Market-mediated aggregation paths** to ensure that district-level licensees make spectrum available for leasing or trading, lowering aggregation barriers for national players.
- **Harmonized technical rules** around power limits, indoor vs. outdoor usage, emissions masks, and coordination zones to mitigate interference risks.
- **Open access** to the services of network providers on commercial but neutral terms to allow niche operators to provide service over a wide area. It would also allow large operators to use the infrastructure of niche operators in areas where they do not have spectrum. Open access would also lead to the emergence of virtual network operators that would address all market niches. Open access need not be mandated; it can be incentivized by commercial incentives, including tax structures.

9.4 The Need for Four-Tier Architecture

Apart from sub-LSA level high-frequency spectrum licensing, we also advocate for highly targeted, geography-based licensing (i.e., Private Network Service Area – PNSA) for the construction of private networks. Private networks are being deployed in ports, airports, manufacturing facilities, and industrial corridors, among others, which are geographically very small compared to even the district level. This warrants spectrum licensing at the granular level of PNSAs.

A four-tier spectrum licensing architecture—comprising national-level, traditional LSA-level, district-level, and private-network service area-level—is necessary in a 5G and post-5G world. National and LSA-level licences are well suited to wide-area mobile operators seeking scale and uniform coverage, while private-network licences cater effectively to highly localized use cases such as factories, campuses, ports, and enterprise premises. However, if spectrum policy stops at these two extremes, it leaves a critical missing middle unaddressed: demand that is larger than a single campus or enterprise but far more localized and heterogeneous than an entire LSA. Many economically meaningful connectivity needs—such as district-level fixed wireless access, smart city deployments, logistics corridors, or clusters of small towns and industrial zones—fall in this intermediate space. Without a district-level or multi-district licensing option, such demand is either underserved by national operators, for whom it may not be commercially attractive, or inaccessible to smaller players who cannot justify acquiring spectrum at the LSA level. Introducing an intermediate tier allows spectrum to be aligned more closely with real patterns of demand, encourages the emergence of regional or niche service providers, and improves overall spectrum utilization. In this sense, a four-tier architecture is not merely an administrative refinement but a necessary response to the increasing geographic and service-level heterogeneity of digital connectivity markets.

9.5 Spectrum Assignment Methodology

The important question is what the methodology should be for assigning spectrum in our proposed four-tier architecture.

[1] The current SMRA auction that is being used for the LSA-wise spectrum can continue for non-mmwave high-frequency spectrum. There is even an argument for opening up a national-level licensing as is being done in all the EU countries, the UK and some South American countries. If we intend to adopt it, then the National license can be a package and is auctioned along with individual LSA-based items. This is not optimal as it would miss a collection of LSAs as a package. However, this will reduce the complexity of the auction process.

[2] For mmwave and high frequency spectrum, as discussed in the previous section, spectrum blocks can be put on auction at the sub-LSA level using a package auction methodology. The package auction, as is being practised in the US and some other countries, allows the bidders to opt for a package of complementary sub-LSAs that meet their spectrum requirements and investment capacity. Apart from national TSPs, niche TSPs with access service authorization that would like to operate in certain market areas can also be allowed to participate.

[3] For the PNSA in which carved-out spectrum is proposed for the construction of CNPNs, the assignment methodology can be a very simple single-item ascending clock auction, in which the bidders bid for that specific area and the spectrum block. The bidders in this case shall also include, apart from TSPs, the non-TSPs who are interested in constructing and facilitating private networks.

The summary of our recommendations is provided in Table 6.4.

Table 6.4: Summary of Spectrum Assignment Methodology in the 4-tier Architecture

Tier	Area	Spectrum Band	Assignment Method	Eligible Participants
LSA	Current LSAs	<20Ghz	SMRA with the national package on offer	National TSPs
Sub-LSA	District Level	>20 GHz	Package Auction	National TSPs, niche telecom service providers
PNSA (For private networks Service Area	Campus, ports, airports, stadium, industrial parks, etc	>20 GHz	Single unit Ascending clock auction	National TSPs, niche TSPs, non-TSPs (e.g. enterprises, facility owners)

Properly implemented, sub-LSA licensing and PNSA licensing can unlock previously untapped value, stimulate innovation, and allow spectrum to be used far more efficiently—supporting India's broader goals of digital inclusion, industrial transformation, and resilient telecommunications infrastructure in a 5G+ world.

10 Spectrum Surrender Policy

Under the Telecommunications Act, 2023, the Central Government is empowered to permit sharing, trading, leasing, and surrender of assigned spectrum, subject to prescribed terms and conditions. This statutory backing for surrender rights replaces earlier ad hoc guidelines and is intended to promote efficient use of spectrum as a national resource. The Act's provisions make explicit that satellite frequencies, mobile bands, and other radio resources can be reassigned or repurposed when not in active use, enabling flexibility while maintaining regulatory oversight.

The detailed regime for the surrender of spectrum is set out in the Telecommunications (Assignment of Spectrum Through Auction) Rules, 2025.[57] These rules provide that an assignee or licensee may apply to surrender spectrum after holding it for a minimum period (typically 10 years for post-2022 auctioned spectrum, with shorter periods in some circumstances). Upon application, the Central Government issues conditional approval specifying any outstanding dues that must be paid before final approval to surrender is granted. Importantly, the rules also clarify that no refund of spectrum fees or other charges paid will be made on surrender and that entities surrendering spectrum are barred from participating in auctions for the same band and service area for a defined period. A central policy question in designing a spectrum surrender regime concerns the treatment of remaining payment obligations when spectrum is returned before the end of its assignment period.

[57] Department of Telecommunications. (2025). Telecommunications (Assignment of Spectrum through Auction) Rules, 2025. https://dot.gov.in/sites/default/files/Draft%20Telecommunications%20Assignment%20of%20Spectrum%20through%20Auction%20Rules%2C%202025.pdf

The DoT currently offers two payment options for spectrum acquired through auction.[58] Under the first option, the successful bidder pays the entire auction amount upfront. Under the second option, the bidder pays the auction amount in equal annual instalments over 20 years, with the instalment schedule calibrated such that the net present value (NPV) of all future payments equals the bid amount at the time of assignment.

In the case where the licensee has opted for full upfront payment, the treatment of surrender is relatively straightforward. If the licensee chooses to surrender spectrum before the end of the licence term, then, after serving the prescribed notice period, the licensee is liable only for a prorated portion of the licence value, corresponding to the period for which the spectrum has actually been held (including the notice period). Any amount paid in excess of this prorated value should, in principle, be refunded by the DoT, since the spectrum is returned early and becomes available for reassignment.

However, if the licensee opts for the second option, a more careful calculation of arrears is required.

Consider a spectrum assignment where the winning bid amount is INR 10 million, payable over a 20-year licence period through equal annual instalments. The instalment amount is determined by discounting future payments appropriately, yielding an annual payment of INR 1.17 million. This instalment structure is a financing mechanism; the underlying economic value of the spectrum remains the bid amount determined at the time of auction.

Suppose the licensee chooses to surrender the spectrum after 16 years, having enjoyed 80% of the licence term. The first principle that must govern surrender is straightforward: because the spectrum has been returned early, the total amount payable to the government must be less than the full bid amount that would have been paid had the licence run for the entire 20 years.

The more difficult question is how much less. A purely linear approach would suggest that if 80% of the licence period has elapsed, then 80% of the economic value has been realized, and the licensee should be liable only for that proportion of the bid amount. However, there is a plausible alternative view: that the economic value of spectrum accrues more heavily in the earlier years of the licence, when networks are rolled out, customers are acquired, and first-mover advantages are realized. Under this logic, although only 80% of the licence period has been used, a larger share—such as 90% of the economic value—may already have been extracted. This could be operationalized through a non-linear function, such as taking the square root of the proportion of the licence period utilised.

Under either approach, the core idea remains the same: the amount due upon surrender must reflect partial realization of spectrum value and not the full bid amount. The difference

[58] DOT. Notice Inviting Applications For Auction of Spectrum in 800 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2300 MHz, 2500 MHz, 3300 MHz, and 26 GHz Bandshttps://www.communicationstoday.co.in/wp-content/uploads/2024/03/Notice-Inviting-Applications-2023-24_0.pdf

between what has already been paid and what is deemed economically due, whether positive or negative, should then be settled at the time of surrender. Such a framework preserves economic fairness, avoids penalizing efficient exit, and recognizes that early surrender does not imply zero value extraction but also does not justify full payment for unused years.

10.1 Illustrative Example: Non-Linear (Square-Root) Assessment of Spectrum Surrender Dues

10.1.1 Part 1: Surrender in Year 16

Suppose a spectrum licence is assigned for 20 years with an auction value of INR 10 million. The licence fee is payable in equal annual instalments over the licence period, based on appropriate discounting.

Now, assume that the licensee surrenders the spectrum at the end of Year 16, meaning that Years 17, 18, 19, and 20 are not used. The licensee has therefore utilized 16 out of 20 years, or 80% of the licence period.

We first measure the economic value already accrued. Instead of assuming that value accrues linearly with time, let us assume that economic value accrues faster in the earlier years of the licence. One simple way to model this is to take the square root of the proportion of licence duration utilized.

Accrued Value Proportion = $\sqrt{0.8} \cong 0.9$

This implies that although only 80% of the licence period has elapsed, approximately 90% of the economic value of the spectrum has already been realized by the licensee.

Thus, under this non-linear approach, the total amount that should be payable to the government upon surrender in present value terms is INR 9 million, not the full INR 10 million.

The annualized payment over the 20 years is INR 1.17 million. At the end of 16 years in NPV terms, a payment of INR 9.15 million has already been made. Therefore, the government has to refund INR 0.15 million. However, recognizing the difficulties in the government paying back the operator, we recommend that the operator be allowed to surrender the spectrum without any further financial obligations.

10.1.2 Part 2: Surrender in Year 8

The licensee has therefore utilized 8 out of 20 years, or 40% of the licence period. By the square-root rule, although only 80% of the licence period has elapsed, approximately 65% of the economic value of the spectrum has already been realized by the licensee. Thus, the total amount that should be payable to the government upon surrender in present value terms is INR 6.5 million.

Given the annualized payment of INR 1.17 million, at the end of eight years in NPV terms, a payment of INR 6.24 million has already been made. So, the telco has to pay the government an additional INR 0.26 million.

What these examples illustrate is that, even under a non-linear, front-loaded accrual trajectory, the amount economically due to the government upon early surrender can be substantially lower than what the nominal outstanding instalments might suggest. This is because the annualized payment schedule itself is derived using a net present value framework, under which payments scheduled for the later years of the licence carry very little weight when valued at the time of assignment. As a result, once a licensee has held spectrum for most of the licence period, the residual economic value of the unused years is often quite small, even if several nominal instalments remain unpaid. Recognizing this interaction between front-loaded value accrual and discounted payment structures is essential for designing a surrender policy that is economically coherent, transparent, and fair—one that facilitates efficient spectrum re-allocation without imposing disproportionate exit penalties.

Importantly, under either interpretation, there is a strong case that no further spectrum usage charges (SUC) should be payable once the spectrum is surrendered. SUC is conceptually linked to the use of spectrum; once usage ceases and control reverts to the government, there is no economic justification for continuing usage-based levies. Including future SUC obligations in surrender dues would risk converting a usage charge into an implicit penalty for exit, potentially discouraging efficient surrender and re-allocation of underutilized spectrum.

Clarifying these principles explicitly in the surrender policy is essential. A transparent, economically coherent framework would reduce uncertainty, avoid litigation, and ensure that surrender functions as a tool for improving spectrum efficiency rather than as a punitive mechanism that traps firms in unviable holdings.

Though the draft spectrum rules 2025 advocate spectrum surrender only after a 10-year lock-in period, the government should also consider earlier surrender on an equitable basis for making efficient allocation of scarce spectrum.

11 Conclusion

In conclusion, the efficient management of the radio spectrum, which is a finite national asset, is critical for India’s digital future. The emergence of 5G/6G, satellite constellations, and private networks creates a dynamic landscape where services are both complementary and competitive, rendering traditional allocation models inadequate. Our analysis provides concrete guidelines for transitioning to a flexible-use spectrum regime. By learning from past allocations and anticipating technological convergence, we chart a pragmatic pathway that maximizes social and economic value, promotes innovation, and ensures that the telecommunications sector can meet the nation’s evolving needs.

Appendix 6.1: Spectrum Holdings by Various Operators

LSA	TSP	700 MHz	800 MHz	900 MHz	1800 MHz	2100 MHz	2300 MHz	2500 MHz	3300 MHz	26 GHz
Andhra Pradesh	Adani									50
	Aircel				4.4	5				
	Bharti			9	21.4	S	30		**100**	800
	BSNL	10		6.4		5				
	Reliance Jio	10	10		10		40		100	1000
	Vodafone Idea			5	10	5		20	50	200
Assam	Aircel			4.4	1.8	5				
	Bharti			11.8	15.45	10	40		100	800
	BSNL			6.4		5		20		
	Reliance Jio	10	9.5		10		40		100	1000
	Reliance Telecom		5			5				
	Vodafone Idea				25	S		20		
Bihar	Aircel				6.2	5				
	Bharti			11.2	18	15	40		100	800
	BSNL			6.4		5		20		
	Reliance Jio	10	10		10		40		100	1000
	Reliance Telecom					5				
	Vodafone Idea				17.8	5		10	50	
Delhi	Aircel				4.4					
	Bharti			6	7	15	30		100	800
	MTNL			5		S				
	Reliance Communications		3.75			5				
	Reliance Jio	10	10		10		40		100	1000
	Vodafone Idea			10	10.6	5		20	50	200
Gujarat	Adani									100
	Bharti			4.2	10	15	40		100	800
	BSNL			6.4		S				
	Reliance Communications		6.25							
	Reliance Jio	10	10		20		40		100	1000
	Vodafone Idea			11	20.8	10		30	50	450
Haryana	Bharti		5		10	15	40		100	800
	BSNL			6.4		10		20		
	Reliance Communications		1.25		0.6					
	Reliance Jio	10	10		10		40		100	1000
	Vodafone Idea			12.2	1S.8	15		20	50	400
Himachal Pradesh	Bharti			10	20	S	40		100	800
	BSNL			6.4		10		20		
	Reliance Communications		2.5							
	Reliance Jio	10	10		10.4		40		130	1000
	Reliance Telecom			5		5				
	Vodafone Idea				112	5		10		
Jammu & Kashmir	Aircel			4.4	1.8	5				
	Bharti			11.2	15	10	40		100	800

LSA	TSP	700 MHz	800 MHz	900 MHz	1800 MHz	2100 MHz	2300 MHz	2500 MHz	3300 MHz	26 GHz
	BSNL			6.4		5		20		
	Reliance Communications		5		5	5				
	Reliance Jio	10	9.S		10		40		130	1000
	Vodafone Idea				17	5		10		
Karnataka	Adani									SO
	Aircel				4.4	5				
	Bharti			8.8	20	10	30		100	800
	BSNL			6.4		5				
	Reliance Communications		3.75		0.6					
	Reliance Jio	10	10		10		40		130	1000
	Vodafone Idea			5	15	10			50	200
Kerala	Aircel				4.4	5				
	Bharti			4.6	10	15	30		100	800
	BSN L			6.4	2	S		20		
	Reliance Communications		3.75							
	Reliance Jio	10	10		10		40		130	1000
	Vodafone Idea			12.4	20	10	10	20	50	800
Kolkata	Aircel				4.4	5				
	Bharti			7	15		30		100	800
	BSN L			6.4		5				
	Reliance Communications		5							
	Reliance Jio	10	10		10		40		100	1000
	Reliance Telecom					5				
	Vodafone Idea			7	15	10		20	50	200
Madhya Pradesh	Bharti		5		15	10	30		100	800
	BSNL	10		6.4		5		20		
	Reliance Jio	10	10		20		40		130	1000
	Reliance Telecom			5		5				
	Vodafone Idea			7.4	18.6	5	10	20	50	400
Maharashtra	Adani									
	Bharti		5		20	10	30		100	800
	BSNL			6.4		S				
	Reliance Jio	10	10		20		40		100	1000
	Vodafone Idea			14	12.4	15	10	30	S0	400
Mumbai	Adani									100
	Aircel				4.4					
	Bharti			5	IS	5	30		100	800
	MTNL			5		S				
	Reliance Communications				0.6	5				
	Reliance Jio	10	15		10		40		100	1000
	Vodafone Idea			11	14.6	10		20	50	200
Northeast	Aircel			4.4	1.8	5				
	Bharti			14	10	10	40		100	800
	BSNL	10		6.4		S		20		
	Reliance Jio	10	9.5		10		40		130	1000
	Reliance Telecom		S		S	5				

LSA	TSP	700 MHz	800 MHz	900 MHz	1800 MHz	2100 MHz	2300 MHz	2500 MHz	3300 MHz	26 GHz
	Vodafone Idea				25.8	5		20		
Odisha	Aircel				4.4	5				
	Bharti			11.2	19.6	S	40		100	800
	BSNL			6.4	2	S		20		
	Reliance Communications		1.25							
	Reliance Jio	10	10		20		40		100	1000
	Reliance Telecom				5	5				
	Vodafone Idea			5	17	5		20		
Punjab	Aircel				4.4	5				
	Bharti			10	15		40		100	800
	BSNL	10		6.4		10		20		
	Reliance Communications		2.S		0.6	S				
	Reliance Jio	10	10		10		40		100	1000
	Vodafone Idea			S.6	15	10		20	S0	300
Rajasthan	Adani									50
	Aircel				6					
	Bharti			6	10	1S	40		100	800
	BSNL	10		6.4		5		20		
	Reliance Communications					5				
	Reliance Jio	10	10		20		40		130	1000
	Vodafone Idea			6.4	10	15		20	S0	300
Tamil Nadu	Adani									S0
	Aircel				10	5				
	Bharti			5	20	10	30		100	800
	BSNL			6.4	2	5				
	Reliance Communications		3.75							
	Reliance Jio	10	10		10		40		100	1000
	Vodafone Idea			5	11.4	15			50	300
Uttar Pradesh (East)	Aircel				6.2	5				
	Bharti			11.2	16.8	5	40		100	800
	BSNL			6.4		10		20		
	Reliance Jio	10	10		20		40		100	1000
	Vodafone Idea			5.6	10	20		20	50	250
Uttar Pradesh (West)	Bharti		5		15	10	40		100	800
	BSNL			6.4		10		20		
	Reliance Communications		5							
	Reliance Jio	10	9.5		10		40		130	1000
	Vodafone Idea			10	15	10		20	50	350
West Bengal	Aircel				5.6	5				
	Bharti			9.4	10	15	40		100	800
	BSNL			6.4		5		20		
	Reliance Communications		5							
	Reliance Jio	10	10		10.6		40		100	1000
	Reliance Telecom					5				
	Vodafone Idea			7.4	23.4	5		20	SO	400

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