LAST MILE CONNECTIVITY

ADDRESSING THE AFFORDABILITY FRONTIER

Jonathan Brewer, Yoonee Jeong, and Arndt Husar

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Notes:
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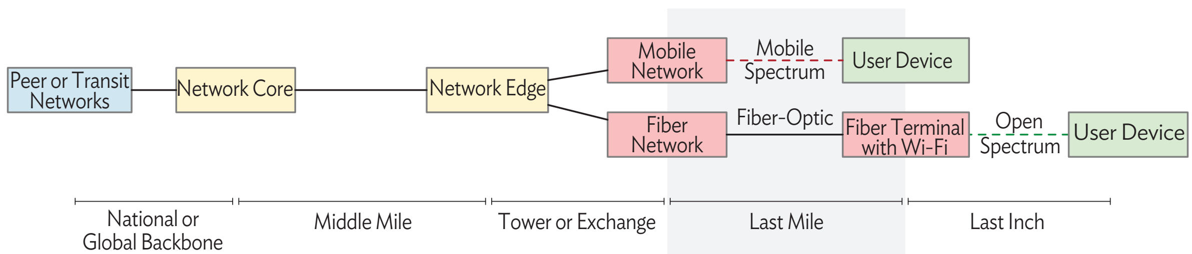
ABBREVIATIONS

ADB	–	Asian Development Bank
A4AI	–	Alliance for Affordable Internet
COVID-19	–	coronavirus disease
DMC	–	developing member country
FCC	–	Federal Communications Commission (United States)
FTTP	–	fiber to the premises
FWA	–	fixed wireless access
GHz	–	gigahertz
GNI	–	gross national income
GPON	–	Gigabit Passive Optical Network
GSM	–	Global System for Mobile Communications
IMT	–	international mobile telecommunications
IP	–	internet protocol
ISM	–	industrial scientific, and medical
ISP	–	internet service provider
ITU	–	International Telecommunications Union
km	–	kilometers
LEO	–	low earth orbit
LTE	–	long-term evolution
MHz	–	megahertz
MNO	–	mobile network operator
MOCN	–	multi-operator core network
MORAN	–	multi-operator radio access network
OpenRAN	–	open radio access network
OLT	–	optical line terminal
OTT	–	over the top
USF	–	universal service funds
WISP	–	wireless internet service provider

EXECUTIVE SUMMARY

The "last mile" is the part of a telecommunications network that delivers connectivity directly to a user's device or to a local terminal in a home, business, or community location that provides last-inch service using Wi-Fi (figure 1). Over the past decade, last mile in developing Asia has been synonymous with wireless technologies. The maturation of fiber to the home technologies has begun to change this, and emerging satellite networks could bring change yet again. But while all technologies are becoming more common, few are breaking new ground when it comes to affordability for rural and remote populations.

Figure 1: The Last Mile in Telecommunications Networks



Source: Author.

In Asia and the Pacific, 93% of the region's population live within reach of 3G and 4G networks but only 42% were connected to mobile internet at the end of 2020. Network coverage and mobile internet adoption are both growing, but the GSMA predicts only 52% of the population will be connected by 2025. They also warn that extending rural coverage is becoming difficult for carriers to justify financially.[1] The GSMA's concerns are legitimate as coverage of a population trends toward 100%, an inflection point is eventually met beyond which traditional cellular network designs may never be economic.[2]

The necessity of bridging the digital divide and providing universal broadband connectivity has been agreed since the International Telecommunication Union (ITU) and the United Nations Educational, Scientific, and Cultural Organization (UNESCO) founded the Broadband Commission in 2010. It was never felt so acutely until the coronavirus disease (COVID-19) pandemic necessitated movement restrictions and lockdowns, at times keeping more than a billion people away from work and school. These lockdowns exposed a new dilemma for governments and carriers to consider—simply providing mobile broadband coverage is no longer enough to meet the peoples' needs. E-learning and remote work have put unprecedented demands on network quality and capacity that must be met. New frameworks for examining access, including the idea of meaningful universal connectivity, will be essential to meet the needs of this new digital era.[3]

This Asian Development Bank (ADB) Sustainable Development Working Paper is the third in a series reviewing emerging innovations in connectivity technologies. With a focus on extending the affordability frontier and closing the digital divide, the paper (i) examines access gaps and frameworks to assess them; (ii) quantifies the growing demand for mobile broadband data; and (iii) explores technologies, business models, investment strategies, and regulations for effective, economic interventions.

1 The GSM Association. 2021. *The Mobile Economy Asia Pacific 2021.*
2 C. Chauhan-Sims et al. 2019. *Costing Mobile Coverage Obligations: UK 700 MHz Case Study*. PolicyTracker.
3 International Telecommunication Union and United Nations Educational, Scientific and Cultural Organization. 2019. *State of Broadband Report*. Geneva.

I. INTRODUCTION

Traditional last mile infrastructure designs struggle with commercially unviable populations and geographies. Addressing the lack of commercial viability, referred to as the "affordability frontier" in this paper, requires a thorough understanding of barriers to building last mile networks, technologies for building them, and policy and financial interventions to enable their success.

The coronavirus disease (COVID-19) brought unprecedented challenges to governments tasked with keeping their people safe without stopping work and learning. Many challenges were around affordability.

In Mongolia, the government partnered with telecom operators to make access to their government's education portal free, addressing affordability concerns for students learning from home.[1] Indonesia and Sri Lanka also worked with carriers to provide free e-learning.[2]

The Government of India asked carriers to increase prepaid plan validity during COVID-19 lockdowns. Reliance Jio responded by doubling 4G data for all its prepaid plan subscribers.[3] Malaysia's Prihatin Rakyat initiative led to carriers providing 1 gigabyte (GB) of free internet each day during movement control orders.[4]

In Singapore the government launched a Seniors Go Digital program to promote digital adoption among the elderly, and a Hawkers Go Digital program to help food sellers learn about e-payments and delivery platforms. Key to these skill development programs is low-cost device access and subsidized mobile plans for eligible senior citizens in the case of Seniors Go Digital.

This is a paper focused on solutions that meet the needs of people today and for years to come. It begins with an introduction to "meaningful connectivity," the quality and affordability people require from their telecommunications networks in a post-COVID-19 world.[5] It moves on to discuss the concepts of market and affordability gaps and recommends that governments take the lead in identifying such gaps.

Barriers to connectivity are critical for regulators and investors to understand. Population density, spectrum availability, energy, access to land, safety, and licensing are topics any carrier will be familiar with. They are not always considered by those asking carriers to deliver more.

A section on technology focuses on solutions relevant to the problem space: fiber, 4G, open spectrum fixed wireless, and Wi-Fi. It passes over technologies that might not be affordable for rural users in developing countries for years to come.

We also discuss contemporary business models and market structures and provide two sets of advice for governments and development agencies: finance strategies and policy recommendations.

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1 Government of Mongolia, Communications and Information Technology Authority. 2020. *COVID-19 Crisis Response in ICT Sector of Mongolia*. Ulaanbaatar.

2 Government of Indonesia, Bureau of Communication and Public Service, Ministry of Education and Culture and Kementerian Pendidikan Dan Kebudayaan. *Main blog.*
ADB. 2021. *COVID-19 and Education in Asia and the Pacific: Guidance Note*. Manila.

3 The GSM Association. 2020. *The Mobile Economy Asia Pacific 2020.*

4 Footnote 3.

5 "Meaningful connectivity," a concept promoted by A4AI and the Broadband Commission, is explored in Chapter 3.

Affordable connectivity is key to social inclusion and opening opportunities for people around the world. It is also the most sustainable and lowest-friction method for governments to engage with their constituents to help provide services, support, and education.

The aim of this paper is to help all stakeholders gain a better understanding of how affordable connectivity can be promoted.

II. BACKGROUND: LAST MILE INTERNET CONNECTIVITY

This paper focuses on the policies, commercial models, and technologies that can help deliver internet connectivity into the hands of people who need it.

New paradigms of working, learning, shopping, and communicating have emerged in response to the COVID-19 pandemic. As central governments introduced restrictions on movement and gathering, private companies, schools, and health providers around the world responded with internet-based telework, new delivery services, distance learning, and telemedicine.

The ability of people throughout the world to make this transition has varied. Hundreds of millions of people have missed out entirely, not having regular or reliable internet connectivity. Hundreds of millions more have been constrained by internet affordability or quality of service issues.

Achieving social inclusion for those not yet online or those who struggle with the cost of data will require a paradigm shift in the delivery of low-cost services. This shift is most needed in rural and remote communities, which face challenges of low population densities, low incomes, and low levels of supporting infrastructure.[6] Critically, plans to expand coverage need to recognize that demands on networks grow continually, and that sustainable solutions must scale to meet future demands.

A. In Asia and the Pacific, the Internet Is Mobile

Globally, around four smartphones were shipped in 2021 for every personal computer, desktop or laptop.[7] Internet use reflects this on a global basis and in Asia and the Pacific. In a 2020 study, Contentsquare found 72% of Asia and the Pacific web traffic originated from smartphones.[8]

Where there is fixed broadband connectivity at home, work, or school, smartphones connect the internet via Wi-Fi routers. Where there is no fixed connectivity, phones attach to cell towers or public Wi-Fi access points. The mobile-first reality of developing member countries (DMCs) of the Asian Development Bank (ADB) directly informs the analysis in this paper.

[6] The GSM Association. 2016. *Connected Society Unlocking Rural Coverage: Enablers for Commercially Sustainable Mobile Network Expansion*.

[7] Canalys Newsroom. 2022. *Half a billion PCs and tablets shipped worldwide in 2021*.
C. Reichert. 2022. Samsung Led Smartphone Shipments for 2021, Beating out Apple. *CNET*. 27 January.

[8] S. Williams. 2021. Two Thirds of APAC Website Traffic Now Mobile – Study. *eCommerce News*. 22 March.

B. Universal Service and Universal Access

In the 20th century, the primary telecommunications development goal was “universal service”; the idea that all households have connectivity to public facilities and services.[9] “Universal service” had an easy test: the presence of a telephone in each home and the ability to make a call.

“Universal Access” was a parallel goal that recognized affordability. It acknowledged the difficulty of building “universal service” in developing economies and set a different target: once achieved, everyone in a population can access networks. This could be through pay telephones, community telecenters, or in the internet age, community internet access sites.

Neither concept translates well to today’s mobile voice and internet services, which can rarely be evaluated in binary terms of available or not available.

Mobile service does not always support modern internet applications.

The presence of mobile voice or internet service at an address does not mean service is available inside a building, has the quality to support video calls or data access, or has network capacity to support the applications users today require for social inclusion.

Access is no longer a question of affordable per-minute-use tariffs and shared devices are no longer the norm. Different internet activities have different device and network performance requirements, consume vastly different amounts of data, and often have a large cost variance for a given amount of use. Accessing email and web pages might be affordable while remote work or e-learning remains unaffordable.

C. A New Framework: Meaningful Universal Connectivity

In September 2019, the Broadband Commission[10] and global nonprofit Alliance for Affordable Internet[11] (A4AI) independently introduced new frameworks extending the idea of “universal access.” Both frameworks (figure 2) use the term “meaningful connectivity” and have facets influenced by affordability, content availability, user education, and the presence of infrastructure.

A4AI assigns specific targets to their facets, suggesting a fast connection is a minimum of 4G service, an appropriate device is a personal smartphone, enough data is “unlimited”, and regular access is daily use at home, school, or work. They promote personal smartphones as having a role in reducing the gender gap and as a particularly relevant means of providing access to people with disabilities.[12]

Meaningful universal connectivity can be affected by both supply and demand side factors. Promoting useful, local language content and providing information and communication technology, education can stimulate demand and help ensure new connectivity is financially sustainable. Promoting infrastructure

9 P. Benjamin and M. Dahms. 1999. *Background Paper on Universal Service and Universal Access Issues*. Background paper for the Telia Telecommunications in Society 1999 Seminar. June 1999.

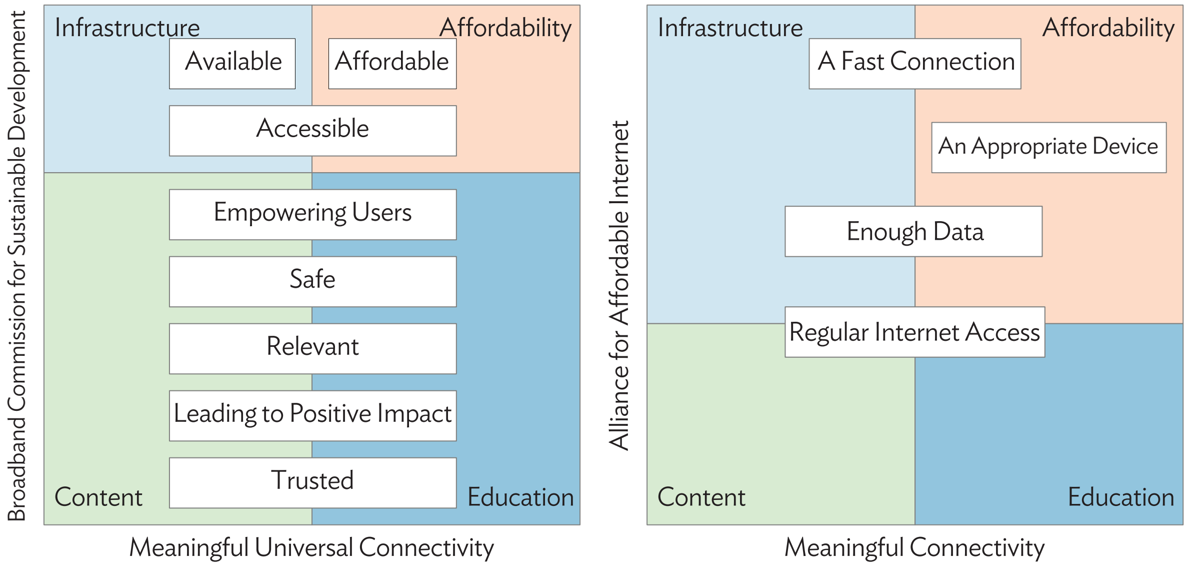
10 J. Garrity. 2019. The State of Broadband 2019. *International Telecommunication Union and United Nations Educational, Scientific, and Cultural Organization*.

11 S. Jorge. 2019. *Raising the Bar for Internet Access: Introducing “Meaningful Connectivity”. Alliance for Affordable Internet*. 16 September.

12 Alliance for Affordable Internet. 2020. *Meaningful Connectivity: A New Target to Raise the Bar for Internet Access.*

can ensure that demand is well met. Making it affordable is the key—all other facets of "meaningful connectivity" depend on it.

Figure 2: Frameworks for Meaningful Connectivity



Source: International Telecommunications Union, 2019; The State of Broadband: Broadband as a Foundation. Sustainable Development, A4A1, 2020. Meaningful Connectivity: A New Target to Raise the Bar for Internet Access.

D. Evaluating Affordability

Mobile carriers in Asia and the Pacific generally sell broadband with fixed data allocations, so affordability is a function of how the service is used. These allocations are known as caps or data buckets. Caps can be a tool for controlling access to limited radio spectrum resources and as a funding source for network upgrades when demand requires them.[13]

When carriers sell "unlimited" plans (a growing trend in Western markets), they often allow users to consume a fixed monthly data cap at full speed, then reduce speed for data that exceeds the cap. Belgium's regulator finds that for mobile internet plans, these unlimited caps are typically between 20 GB and 40 GB.[14]

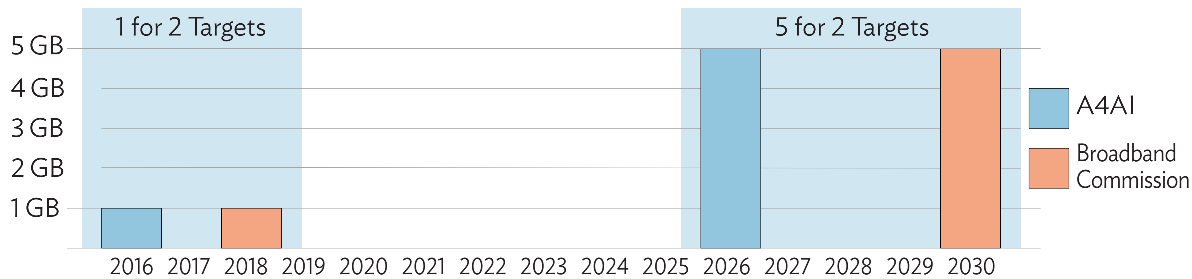
Capped mobile data makes activist and regulatory calls for unlimited broadband difficult to reconcile with commercial realities. It makes measuring affordability problematic, as commonly proposed caps are often insufficient for remote working and e-learning.

[13] N. Economides and B. Hermalin. 2015. The Strategic Use of Download Limits by a Monopoly Platform. RAND Corporation, vol. 46(2), pages 297-327, June.

[14] J. Medts. 2022. *Meer duidelijkheid over onbeperkt surfen: Belgisch Instituut voor Postdiensten en Telecommunicati (BIPT)*. 23 February.

One measure of affordability is target prices for data allocations relative to 2% of gross national income (GNI) per capita. Both A4AI and the Broadband Commission have set such targets for 1 GB allocations in 2016 and 2018, and for 5 GB allocations in 2026 and 2030 (Figure 3).[15]

Figure 3: A4AI and Broadband Commission Affordability Targets



A data bucket available at 2% of GNI per capita meets the target.

A4AI = Alliance for Affordable Internet, GB = gigabyte, GNI = gross national income.

Source: Authors' analysis of A4A1 and Broadband Commission targets.

E. COVID-19 and Its Lasting Impact on Affordability

Lockdowns imposed by governments across the region in 2020 and 2021 caused a step change in people's requirements for mobile data. They also exposed a significant mismatch between the affordability targets discussed in the last section and the requirements of students and office workers stuck at home.

Schools able to offer online distance learning created high demands on connectivity. A study of Indonesian tertiary students during COVID-19 found they spent between 2.2 and 2.7 hours per day on distance learning. For the 41% able to use mobile learning apps and online schooling for distance learning, traffic use was typically around a gigabyte a day.[16]

Technology and services employees with sufficient broadband to telework can consume 0.15 to 0.6 GB per hour of work.[17] The Institute of Development Studies found home working unsuitable for many business process outsourcing workers due to "poor yet expensive internet connectivity."[18] Some workers unable to transition to work from home essentially lived at their offices to keep their jobs during COVID-19 lockdowns.[19]

15 Alliance for Affordable Internet. 2017. *Nigeria Becomes First Country to Endorse A4AI's '1 for 2' Affordability Target.* Alliance for Affordable Internet. 2018. *UN Broadband Commission Adopts A4AI '1 for 2' Affordability Target*. 23 January. Alliance for Affordable Internet. *Affordable Internet – Journey from 1 to 5.*

16 World Bank. 2021. *Rewrite the Future: How Indonesia's Education System Can Overcome the Losses from the COVID-19 Pandemic and Raise Learning Outcomes for All*. Washington, DC.

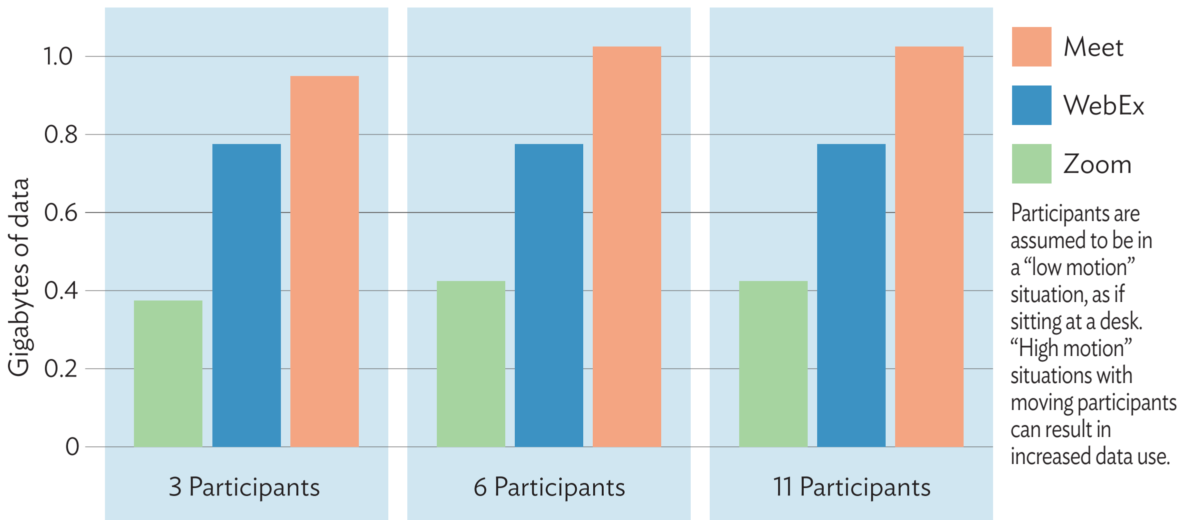
17 J. Bai. 2020. How Much Data Does VoIP Use? Tips to Save Bandwidth. *Nextiva Bolg.* 16 January.

18 S. Enfield. 2021. *Covid-19 Impact on Employment and Skills for the Labour Market*. Brighton, UK: Institute of Development Studies.

19 Business & Human Rights Resource Centre. 2020. *Unions File OECD Complaint against Contact Co. Teleperformance, Following Concerns of Union Busting & Workers' Health and Safety during Pandemic.*

Video calls on popular platforms like Google Meet, WebEx, and Zoom are particularly resource-intensive and can consume up to a gigabyte of traffic in a single hour (figure 4).[20]

Figure 4: Data Consumption for a One-Hour Full Screen Video Call



Source: Adapted from Chang, Hyunseok, Matteo Varvello, Fang Hao, and Sarit Mukherjee. 2021. *"Can You See Me Now? A Measurement Study of Zoom, Webex, and Meet."* In Proceedings of the 21st ACM Internet Measurement Conference, 216–28. New York, NY, USA: Association for Computing Machinery, 2021. https:doi.org/10.1145/3487552.3487847.

E-learning, teleworking, and temporary work from home are now activities essential to full social and economic inclusion. Their data requirements represent a new paradigm for connectedness. It is unlikely that use will ever retreat to former levels, so existing targets for affordability should be updated.

F. How Much Data Is Enough Data?

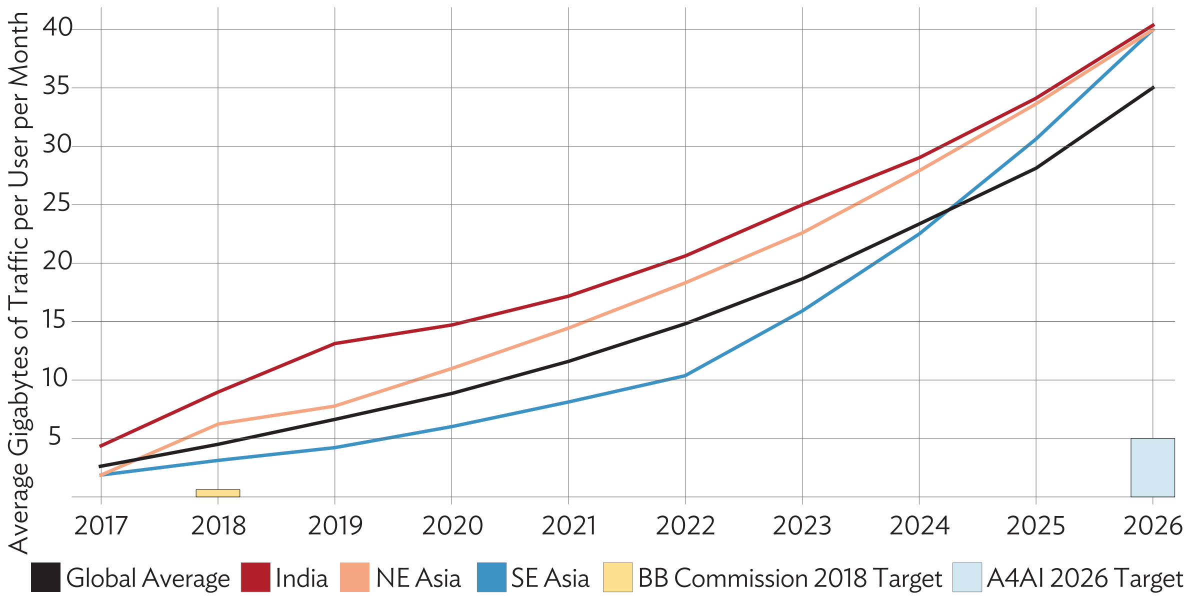
If 1 GB or 5 GB a month is not enough data in a post-COVID-19 world, and affordable unlimited connections are not achievable in the near term, what does a reasonable affordability target look like?

All governments should strive to make average mobile broadband use affordable and understand average broadband use is an ever-increasing target.

Ericsson's 2021 mobility report found the monthly global average mobile data consumed per user exceeded 10 GB in 2021. It predicts global average use will reach 35 GB/month in 2026. Perhaps due to Asia's high reliance on mobile broadband, all its regions are expected to reach 40 GB/month in 2026, exceeding the global average by an additional 5 GB/month (Figure 5).

[20] H. Chang et al. 2021. *Can You See Me Now? A Measurement Study of Zoom, Webex, and Meet*. Prepared for the 21st ACM Internet Measurement Conference. New York, USA November 2021.

Figure 5: Ericsson's Actual and Predicted Utilization Versus Mobile Broadband Targets



A4AI = Alliance for Affordable Internet, BB = Broadband, NE = northeast, SE = southeast.

Source: Adapted from Ericsson. 2021. *Ericsson Mobility Report June 2021*.

As the Broadband Commission targets reflect, ensuring affordability of the average mobile broadband is an important policy target for all governments. This means an ever-increasing bucket of data should be available for 2% of GNI per capita. In areas of poverty, assistance might be needed to help the lowest decile of earners achieve "meaningful connectivity," but for most people average data use must be affordable. Affordable data for everyone is a reasonable target from a technology perspective. Solutions discussed in this guide aim to help carriers meet these targets for the next 10 years or longer.

G. Meaningful Connectivity Requires Network Capacity

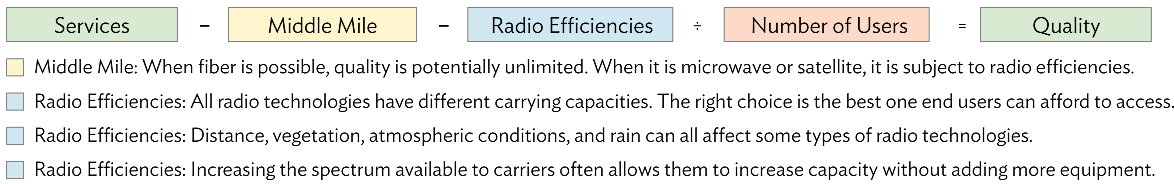
Available, Affordable, Fast, and Enough Data are all "meaningful connectivity" metrics affected by the capacity of an internet connection.[21]

For fiber-optic networks, capacity is a simple function of the capabilities of a technology divided by a static number of connected users. For mobile networks the equation is more complex (figure 6).

The capacity of mobile networks is subject to radio efficiencies. Capacity can vary throughout the day depending on the number of users on the network, the physical locations of those users, and impacts of weather to the last mile, or to satellite and microwave-based middle-mile segments of the network.

[21] Footnote 11.

Figure 6: Factors Impacting Meaningful Connectivity on Mobile Networks



Source: Author.

Data quality suffers when demand for data exceeds the network's capacity to deliver. While it is possible to prioritize traffic on mobile networks (discussed in Appendix 3), in practice the over the top (OTT) internet applications most people use on their smartphones are all treated as equal by network operators.

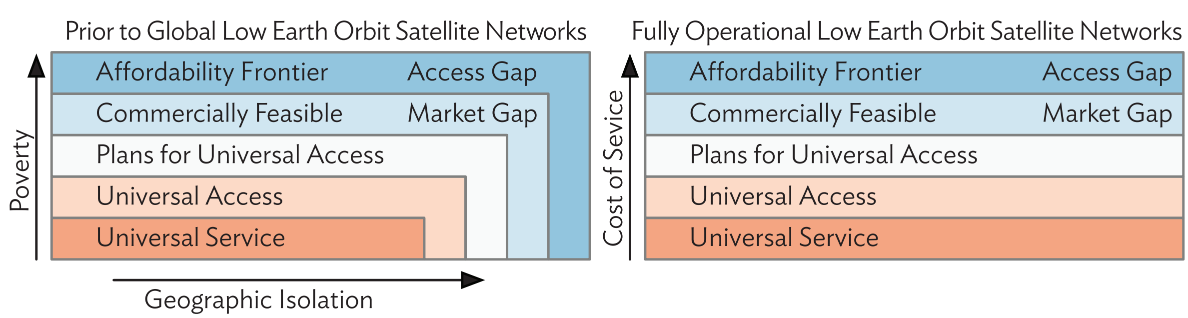
Capacity is the most important factor for mobile data quality when all traffic is equal. With sufficient capacity to provide the data subscribers need, applications can provide a good user experience even if they are not optimized by carrier networks.

A peak hour demand model developed for this paper (Appendix 2) finds that networks will need to deliver 0.25 Mbps/user by 2026 to support Ericsson's predicted demand, and 1.29 Mbps/user by 2032 if demand continues to increase at the same rate. Few networks can provide such data rates and quantities today, but it is likely that carriers in Taipei,China are more than half-way there. A Tefficient industry analysis found them delivering 25.7 GB per month to end users in 2021, implying throughput of at least 0.125 Mbps/user.[22]

H. Market Efficiency Gaps and Access Gaps

A market efficiency gap is the difference between the current level of coverage and that which can be provided in a commercially feasible manner under the right market conditions (figure 7).[23] It can be closed by providing optimal regulatory and investment conditions.

Figure 7: Market and Access Gaps Conceptual Frameworks



Source: Adapted from Navas-Sabater, Juan, Andrew Dymond, and Niina Juntunen. *Telecommunications and Informatic Services for the Poor: Toward a Strategy for Universal Access*. Washington, DC: World Bank, 2002.

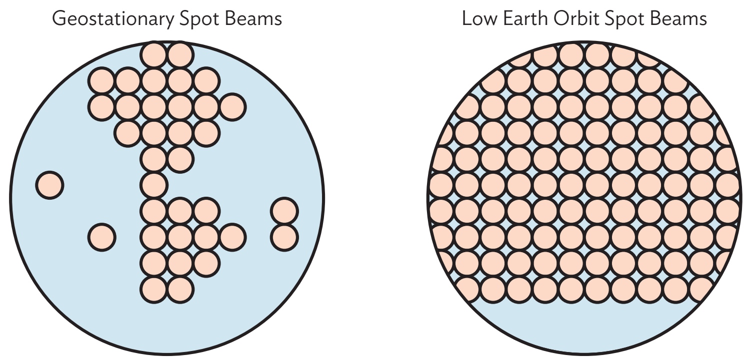
22 tefficient AB. 2022. *Industry Analysis #3 2021*.

23 World Bank. 2002. *Telecommunications and Information Services for the Poor: Toward a Strategy for Universal Access*. Washington, DC.

An access gap is where the market is limited by affordability, either because it is too expensive to build services due to geography, poverty limits participation, or both. This gap can be closed by eliminating poverty or subsidizing connections.

Until recently, the market struggled with persistent market gaps due to commercially unviable geographies. There were places that even for service providers targeting wealthy individuals or corporations in Western markets it was not reasonable to offer commercial telecommunications services. Even geostationary satellite services, with their potentially global reach, focused their services on limited areas due to spectrum availability and commercial feasibility as illustrated in Figure 8.

Figure 8: Satellite Spot Beams



Source: Author.

The introduction of global low earth orbit (LEO) satellite networks is likely to remove geographic isolation from the equation when considering market and access gaps. Companies like Starlink Services, OneWeb, and Amazon Kuiper are set to deliver consistent services anywhere on Earth, provided regulators allow them to operate. LEO services, discussed in *ADB Sustainable Development Working Paper Series* No. 76, will lead to a reconfiguration of the conceptual access gap framework to one where cost of service is the primary consideration.[24]

The problem to tackle in the future will be one of affordability and sustainability. One LEO operator has promised the United States (US) government its network can meet strict performance targets requiring 2,000 GB of data per month at speeds of 100 Mbps, a service likely to satisfy Western user demand for at least 10 years.[25] Their $110/month price point is reasonable in Western markets but exceeds 20% of monthly GNI per capita in 33 of ADB's 41 DMCs. The global nature of LEO networks means that where earth stations are available, the low cost of adding users can be low. This could lead to pricing and access options more affordable than individual retail satellite subscriptions.

I. Identifying Gaps

Gap finding, or broadband mapping, is a multidisciplinary activity that aggregates and analyses data to find underserved populations and geographies. The process of gap finding starts with collecting the information described in Figure 9 using a geographic information system platform with appropriate layers accessible to central government, local government authorities, carriers, and utility operators.

[24] J. Garrity and A. Husar. 2021. Digital Connectivity and Low Earth Orbit Satellite Constellations: Opportunities for Asia and the Pacific. *ADB Sustainable Development Working Paper Series*. No. 76. Manila: Asian Development Bank.

[25] Federal Communications Commission. 2020. WC Docket No. 09-197, Starlink Services LLC Application for ETC Designation. Washington DC.

Figure 9: Data Used in Identifying Coverage Gaps

Population	Geography	Utilities	Mobile Coverage	OTT Data
Household Income	Digital Surface Map	Road Network	Tower Locations	Geolocation Reports
School-Aged Children	Land Cover	Electrical Connections	Technologies in use	OTT Quality Assessments
Address Points	Land Use	Fixed Telecoms Networks	Frequencies, power levels	Speed Reports

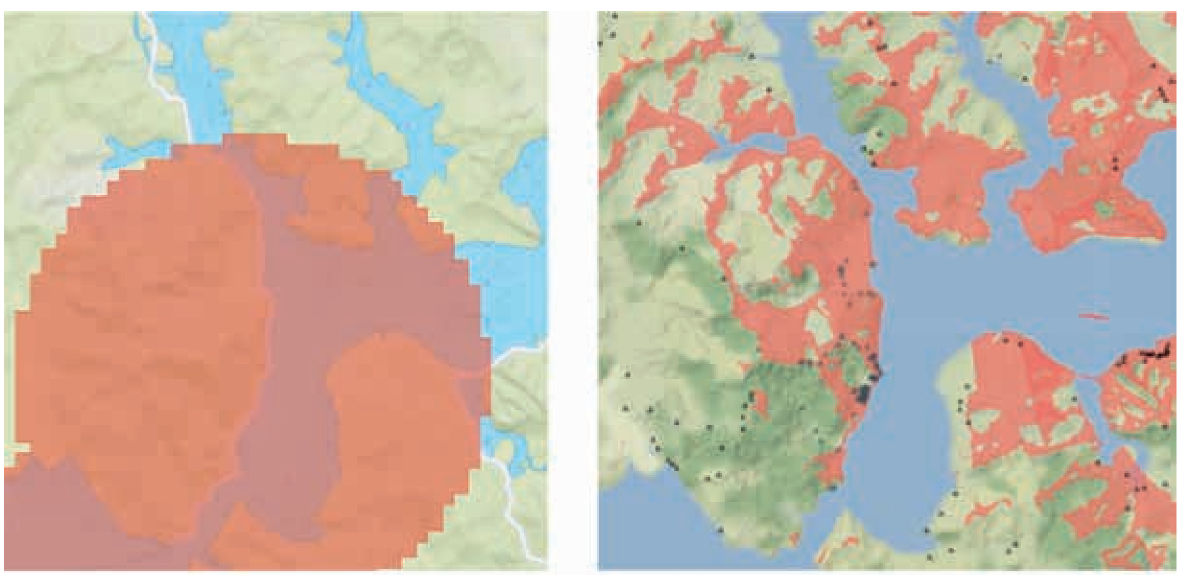
OTT = over the top.

Source: Author.

The data required for gap finding are often siloed and can have commercial sensitivity and privacy issues. This makes the task of managing gap finding activities best suited to government or a neutral third party rather than to industry associations or civil society organizations.

One notable exclusion of information availability is coverage maps. In many markets, there is a lack of transparency around where users are served by mobile networks, even when network coverage maps are public. Optimistic or low-resolution modelling can hide areas of poor or no coverage. Accurate high-resolution modelling is a difficult technical problem, especially when evaluating indoor or fringe coverage, and it is a problem operators have no incentive to solve. Mobile coverage mapping for gap finding purposes should always be created independently of operator reports.

Figure 10: Carrier Supplied and Government Generated 4G Coverage Map



Low Resolution Coverage Model High Resolution Coverage Model

Source: GSMA–Network Coverage Maps. Accessed 9 February 2022 at https://www.gsma.com/coverage/#565 Author. Northland Broadband Map. Northland New Zealand Digital Enablement Group, 3 October 2021.

Drive testing, crowd-sourcing data, collecting data from OTT providers, or independent coverage modelling are all potential inputs to accurate cellular coverage maps. Figure 10 shows how coverage maps can vary. The map on the left was supplied by a carrier, while the map on the right was generated with a radio frequency prediction model and a high-resolution digital terrain map. The image on the right in Figure 10 is an example of a regional government's broadband map used for finding gaps. Coverage is displayed along with a layer showing the precise locations of households in the area reliant on mobile or satellite coverage for broadband.

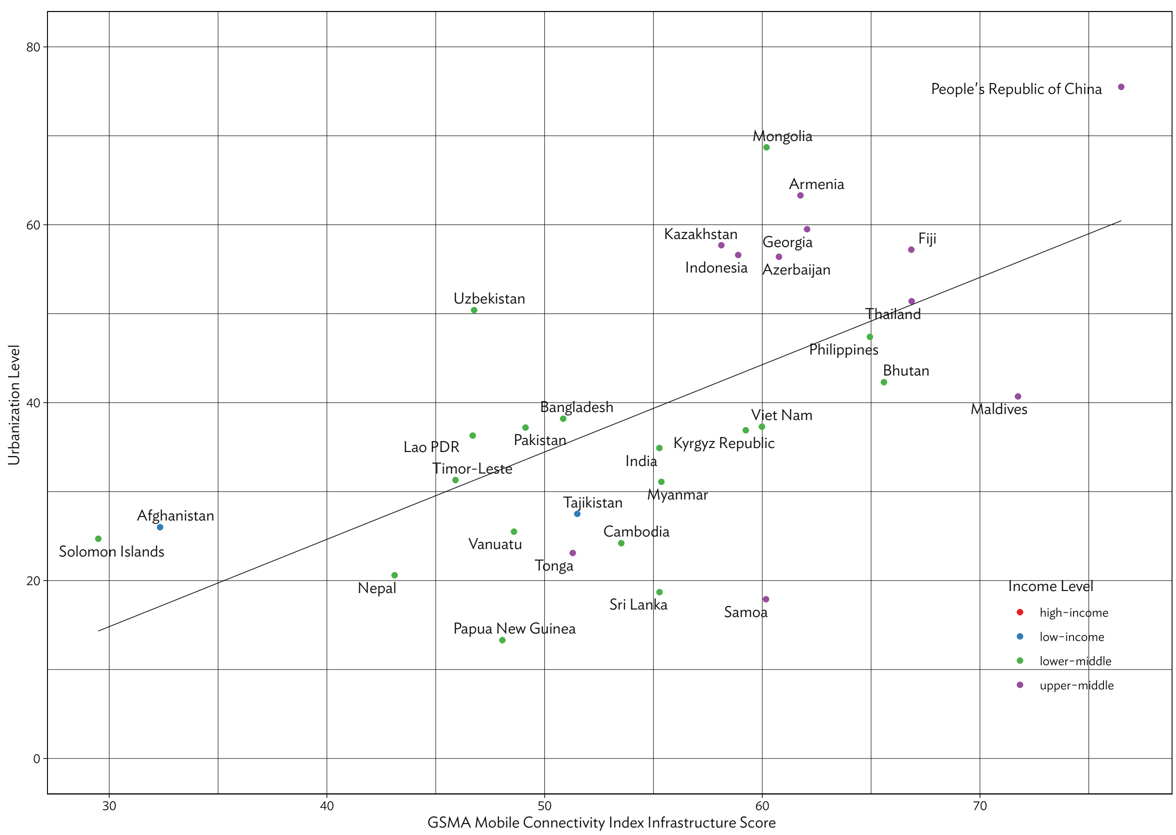
With gaps accurately identified and with accurate data, governments can decide where service obligations should be applied, where network operators should be funded to build more infrastructure, or where households should receive direct subsidies to help pay for broadband service.

Gap finding and broadband mapping is a complex subject worthy of deeper treatment. The ITU's Last Mile Internet Connectivity Solutions Guide is a good resource for learning more about the topic.[26]

III. BARRIERS TO UNIVERSAL MEANINGFUL CONNECTIVITY

With an understanding of what needs to be delivered and where, closing market and affordability gaps could be a matter of adjusting policies, then adding technology and finance. Barriers remain though, slowing or stopping governments and carriers seeking to address the affordability frontier.

Figure 11: Urbanization and Mobile Infrastructure in ADB Developing Member Countries



ADB = Asian Development Bank, Lao PDR = Lao People's Democratic Republic.

Sources: GSMA. Mobile Connectivity Index. https://www.mobileconnectivityindex.com/ (accessed 9 February 2022); World Bank. World Development Indicators. https://databank.worldbank.org/source/world-development-indicators (accessed 9 February 2022).

[26] International Telecommunication Union. 2020. *The Last mile Internet Connectivity Solutions Guide: Sustainable Connectivity Options for Unconnected Sites*. Geneva.

A. Geography and Population Density

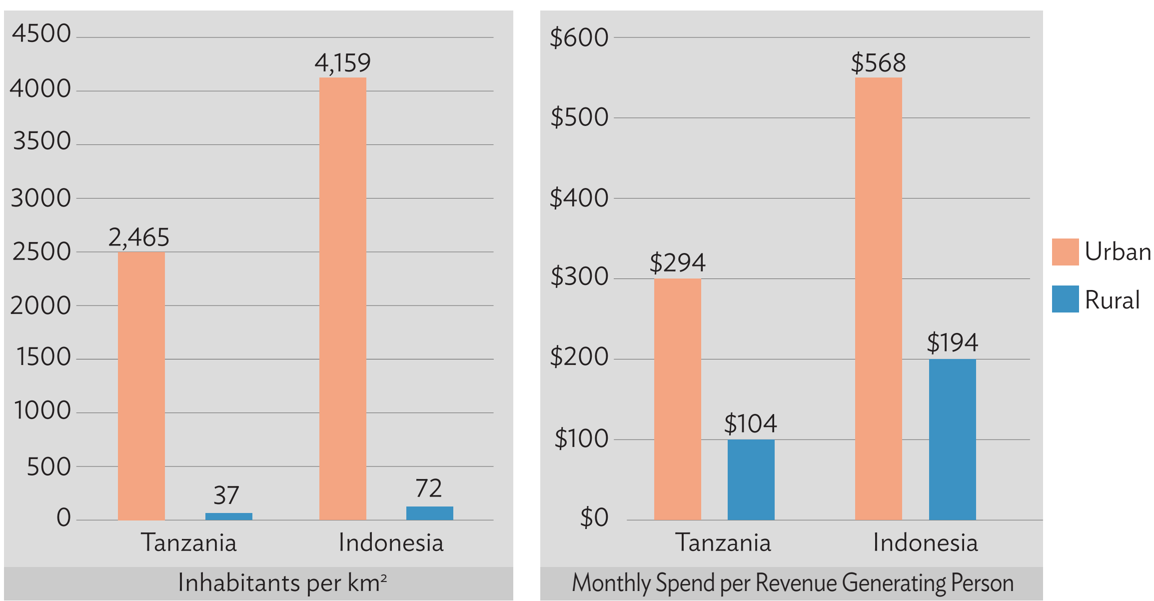
The cost and complexity of delivering terrestrial connectivity increases as population density drops. Longer, more remote last mile connections cost more to build and cost more to maintain than shorter urban ones. This is reflected by lower levels of mobile network development across ADB's less urbanized DMCs (figure 11).

In some countries, lack of development is due to sparse populations, in others, to rough geographic terrain, which itself can be the cause of low population density. Islands, mountains, dense forests, vast deserts, and swampy ground all make it difficult to live, travel, work, source electricity, build towers, and install high-capacity fiber-optic or microwave backhaul.

Rough terrain and sparse populations are also associated with poverty. Land values are lower, resources more difficult to extract, and work is often seasonal. A 2016 GSMA paper finds that "rural and remote areas across developing world markets are typically inhabited by the poorest segment of the population living significantly below the country's average GDP per capita."[27]

An urban–rural divide comparison of population density and economic activity from the same paper illustrates the dual gaps of density and wealth well (figure 12).

Figure 12: Urban Versus Rural Inhabitants and Monthly Expenditures in Tanzania and Indonesia



km² = square kilometer.

Source: Adapted from GSMA Intelligence. Unlocking Rural Coverage: Enablers for Commercially Sustainable Mobile Network Expansion. GSM Association, 22 July 2016.

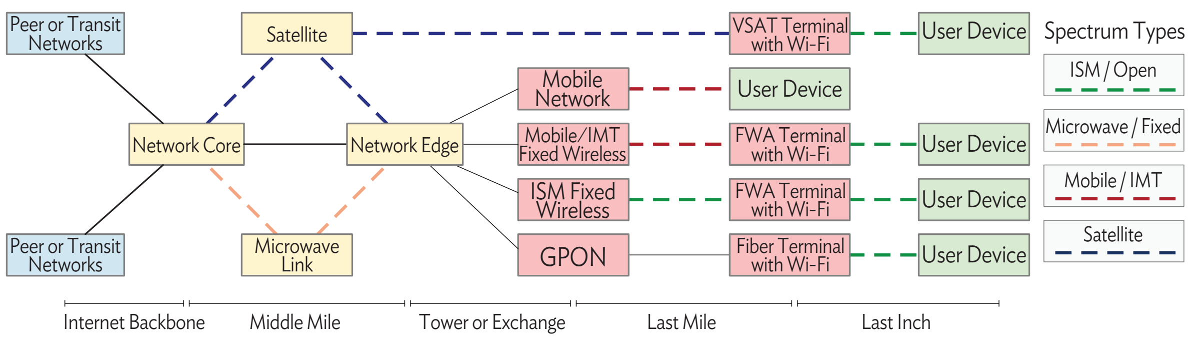
B. Access to Radio Spectrum

Radio spectrum is critical in broadband communications to mobile devices. Spectrum scarcity—in many cases an artificial scarcity—holds back telecommunications services in many of ADB's DMCs. Its cost adds to the price consumers pay for their services every month.

[27] Footnote 6.

Spectrum allocations in ADB's DMCs are a fraction of those in developed countries and could be increased in many markets. Spectrum licenses that grant exclusive access without requiring widespread geographic implementation fail to deliver value to poor and sparsely populated areas. Inadequate or overpriced spectrum resources, and delays in spectrum assignment for both legacy and new bands are important barriers for governments to address.

Figure 13: Radio Spectrum in Last Mile Connectivity



FWA = fixed wireless access, GPON = Gigabit Passive Optical Network, IMT = international mobile telecommunications, ISM = industrial scientific and medical, VSAT = very small aperture terminal.

Source: Author.

Three primary radio spectrum bands are used in last mile communications to service the four roles illustrated in Figure 13. They are summarized here and explained more fully in Appendix 1.

Table 1: Radio Spectrum Bands and Roles

Band	Low Band: < 1 GHz	Mid Band: 1–6 GHz	High Band: > 6 GHz
Mobile/IMT (International Mobile Telecommunica-tions)	Low bands provide 3g/4G cells with long distance coverage. In urban areas low bands penetrate buildings, in rural areas they penetrate vegetation. Availability is low and demand high.	Mid band spectrum is key to adding mobile broadband capacity. Cell radii range from 2–15 km. Fixed wireless can operate to 30 km or more. Hundreds of MHz of spectrum is available.	High band could bring gigabit speeds to handsets in metro areas. High band cells cover areas in the low hundreds of meters, often using hundreds of MHz of radio spectrum.
Open/ISM	In most of the world a small amount of low band spectrum is available for ISM use – often 868 or 923 MHz IoT protocols like Zigbee and LoRaWAN operate at these frequencies.	The 2.4 and 5 GHz bands in many markets provide hun-dreds of MHz of spectrum for Wi-Fi and fixed linking use. Some markets are tran-sitioning the 6 GHz band to ISM for use with WiFi6.	ISM is available at 24 GHz and between 57 and 64, 66, or 71 GHz (market depend-ent). 60 GHz is used for Wi-Fi (IEEE 802.11ad) and fixed systems: i.e. Telecom Infra Program's Terragraph.
Microwave		The 6 GHz band was histori-cally used for long-distance links for microwave back-bones. As fiber has supplant-ed backbone microwave, demand for mid-band fixed linking has waned.	High bands have far more spectrum than lower bands and are ideal for backhaul links. Atmospheric impacts mean they are best used with large dish antennas and high transmit powers.

Continued on next page

Table 1: continued

Band	Low Band: < 1 GHz	Mid Band: 1–6 GHz	High Band: > 6 GHz
Satellite	Nascent satellite networks plan to offer Mobile/IMT services direct to handsets from space.	C band, or 3-4 GHz range, was an important band for satellite broadcasting and data. Most links have been migrated out of the mid -band as the spectrum has been re-assigned for mobile use.	Fixed and satellite have similar needs and the two applications compete for spectrum. Antennas for MEO and LEO need to steer physically or electronically to track moving satellites.

GHz = gigahertz, IMT = International Mobile Telecommunications, IoT = Internet of Things, ISM = industrial scientific and medical, km = kilometers, LEO = low Earth orbit, LoraWAN = Long Range Wide Area Network, MEO = medium Earth orbit, MHz = megahertz.

Source: Author.

Adequate low band spectrum is the most important building block for providing continuous rural and remote coverage. The 700 MHz band (International Mobile Telecommunications [IMT] band 28) has helped carriers in seven of ADB's DMCs build rural and remote 4G coverage.[28] DTAC Thailand's deployment of 700 MHz to 11,800 towers has helped them bring 4G to 93% of Thailand's population.[29]

While low bands provide continuous rural coverage, the mid bands are required for high capacity. To deliver 4G speeds to end users in the tens of megabits per second, cellular towers need at least 20 MHz of mid-band spectrum as a block on every antenna and not divided between frequencies or sectors.

Carriers need to dedicate around 1 MHz of mid-band Time Division Duplex spectrum for each eight users regularly connected to a long-term evolution (LTE) antenna to deliver the 40 GB per month of traffic an average user will demand in 2026. By 2032, that same 1 MHz will support around 1.6 users. Advanced transmission techniques like MU-MIMO (multi-user multi-in-multi-out) can help reduce spectrum requirements but are rarely economical for deployment at the affordability frontier.[30] An explanation of network demand modelling is provided in Appendix 2, but as a rule more spectrum leads to higher network capacity with the same equipment.

C. Access to Energy

Macrocell towers consume hundreds of watts per frequency, per antenna. With a typical total power draw of several kilowatts, standard mobile towers require access to mains power or significant alternative energy installations.

In rural areas where it is possible to connect to the grid, an electrical connection can be a significant cost component of a new tower build, occasionally exceeding all other costs.

Where power is available, rural connections are often less reliable than city connections and outages take longer to restore. Rural and remote sites call for large battery banks, generators, and fuel tanks to provide electrical availability equivalent to that of an urban site. Fuel use is significant, with mobile network operators (MNOs) in developing markets spending an estimated $3.8 billion per annum on fuel for their infrastructure.[31] Heavy reliance on fossil fuel also makes the operating cost of towers vulnerable to energy market fluctuations.

Areas without grid connections require solar, wind, diesel, or hybrid solutions which add cost and space which can sometimes be significant. Some sites will require 3–4 square meters of panels for every 100 watts of power load to provide adequate collection during winter or rainy months.

[28] Halberd Bastion. B28 (700 MHz).
[29] DTAC Thailand. 2021. *Dtac's 700 MHz Network to Back Up Thailand Reopening*.
[30] Electronics Notes. *4G LTE MIMO: Multiple Input Multiple Output » Electronics Notes*.
[31] Bloomberg New Energy Finance. *Powering Last Mile Connectivity*.

This shared rural LTE tower has three sectors and one microwave backhaul link. Supporting it requires a large solar array plus a diesel generator. Energy requirements take up more than 100 square meters of land (photo by Chris Parker. *RCG at TECT Park Cell Tower*, 2021. https://www.youtube.com/watch?v=9LlgH_mp2d4).

D. Access to Land, Towers, and Buildings

Telecommunications is as much a real estate problem as it is a technology problem. In many countries incumbent carriers, often former government entities, tend to have the upper hand in securing key last mile rights-of-way, which include hilltops, government properties, and commercial rooftops. Competitive carriers may need to negotiate with the owners of transport corridors or utility poles to use or create conduits, to erect new poles, or to hang cables from existing poles. They may find poles or conduits full, incumbents who ignore their requests, or encounter agencies that want high fees or revenue shares for use. Regardless of the market status of the carrier, securing rights-of-way and related permits is a time-consuming and resource-intensive process involving central, provincial, and local government units and utility and infrastructure owners.

Private developers, often owners of office parks or housing developments, may ask for revenue-sharing arrangements or enter exclusive arrangements with a carrier or carriers, preventing competition. Commerce regulators in the Philippines and Pakistan have acted against developers who have engaged in anti-competitive behavior, but the route to prosecute and remedy such issues is often lengthy.[32]

[32] Government of the Philippines, Philippine Commerce Commission. 2021. *PCC Charges Condo Developer for Abuse of Dominance in Exclusive Internet Deal.* Manila.
Government of Pakistan, Competition Commission of Pakistan. 2016. *CCP issues show cause notice to bahria town for abuse of dominance.* Islamabad.

Mobile operators often face unrealistic expectations of rent from private and government landowners, who may not understand the relationship between a tower, its catchment area, its potential revenue, and its operating costs.

In urban and suburban markets, competitive mobile carriers find residents do not want new towers, either because of aesthetic concerns[33] or unfounded fears over the health effects of mobile frequencies.[34] In remote areas, indigenous residents sometimes consider mountains or high points on land to be sacred and not to be disturbed by the construction of a tower.[35]

On traditionally or customary-held land, it can be far more difficult to negotiate access and tower lease than on individually held land with a clear freehold title.[36] In countries without a national land title database, obtaining assurance of a legitimate lease can be impossible.

In rural and remote locations, mobile carriers can face unimproved roads not suitable for construction vehicles or concrete trucks. The cost of improving and maintaining roads or tracks for access can be high. The cost of helicopter-assisted construction and ongoing access is high, especially where fuel deliveries are necessary due to the lack of grid power.

E. Safety and Security of People and Property

Maintaining the security of cellular tower sites is a major challenge in delivering rural connectivity, as attested by the experience of Digicel in Papua New Guinea.[37] Even carriers in developed nations like New Zealand are not immune.[38]

Cellular towers are targets for theft and vandalism. Off-grid sites contain solar panels, diesel generators, fuel, and batteries which are easily stolen and re-deployed for private use. Urban sites can be soft targets for thieves looking for sections of steel or lead from batteries to recycle.

Staff of mobile operators carry expensive tools in modern utility vehicles and can be direct targets for theft, as are fuel delivery trucks and tanks for remote sites with generators.[39]

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33 N. Corrales. 2020. Taguig Village Residents Oppose Dito Cell Sites. *INQUIRER.net.* 7 September.

34 FDA. 2020. Review of Published Literature between 2008 and 2018 of Relevance to Radiofrequency Radiation and Cancer.

35 T. A. Hurihanganui. 2019. *Hapū Ready to Occupy Mountain to Stop Cell Phone Tower.* Radio New Zealand Scoop News. 21 August.

36 C. Newens. 2021. Connecting Papua New Guinea, One Tower at a Time. *Rest of World*. 5 January.

37 Tech Pacific. 2019. *Disgruntled Landowners Burnt Digicel Tower Equipment in Bougainville*. 14 February. Footnote 31.

38 J. Pasley. 2020. 17 Cell Phone Towers in New Zealand Have Been Vandalised since the Lockdown, Coinciding with a Boom in 5G Conspiracy Theories. *Business Insider Australia*. 19 May.

39 M. A. Khan, et al. 2017. Context Aware Fuel Monitoring System for Cellular Sites. *International Journal of Advanced Computer Science and Applications (Ijacsa)*. 8 (8). pp. 30.

Cellular tower maintenance is a risky activity in the best of conditions.[40] In remote areas, the risk goes up again as emergency services and treatment are often distant if accessible at all. If service is disrupted due to a disaster, mobile operators are under time pressure to restore service against physical challenges such as impassable roads. Carriers can mitigate this risk by sending extra staff and those with advanced rescue and medical training to remote sites, but it adds cost over servicing urban towers where help is closer at hand.

F. Operator Licensing

Many regulatory regimes in the Asia and Pacific region make it easy for service-based organizations to operate by creating service-based operator licenses. Value-added resellers and internet services providers (ISPs) are common examples of licenses that allow companies to offer products built on the infrastructure of incumbent carriers.

Few regimes make it easy for facilities-based operators to enter the market, i.e., companies that build their own infrastructure. Facilities-based operator licensing can ensure only adequately resourced companies build critical infrastructure. It can be used to ensure legislatively franchised companies participate in the market. And it can be used to protect incumbents and monopolies.

Regulating builders of critical infrastructure is a responsible step for governments to take, but restrictive facilities-based operator licensing can be a serious barrier to competition, especially in the last mile. It precludes ISPs in urban areas from installing their own infrastructure to avoid incumbent bottlenecks or predatory pricing. It frequently blocks community networks and wireless ISPs from installing their own infrastructure to service communities that would be uneconomic for larger operators.

Reporting requirements on network quality of service and connected subscribers meant to ensure large companies deliver quality services might be inappropriate for micro-operators in remote areas. Fixed fees that might be reasonable for a large operator could be onerous to a small one.

Multiple license categories can help create competition where it is needed, but over-fragmentation of the value chain is a danger when a government limits participation in some categories. This can incentivize rent-seeking from intermediaries with protected market segments, leading to degradation of the overall quality of networks.

G. Access to Finance

Finance is readily available for network operators with spectrum licenses and cellular infrastructure on the ground to service large population centers. It can be difficult to obtain for smaller operators or those addressing the affordability frontier.

Rural and remote infrastructure often has sub-commercial returns. Networks that operate without dedicated spectrum are seen by some financers as risky ventures. Small operators can have few assets to borrow against and short operational histories. Finally, building at the affordability frontier can mean spending heavily on installation expenses for small amounts of long-life span infrastructure.

[40] L. Day. 2017. OSHA Takes a Closer Look at the Most Dangerous Job in America. *Pacific Standard*. 3 May.

Universal service funds (USF) established with mandatory contributions from mobile operators are a popular policy instrument to extend telecommunication services to unserved and underserved areas. However, challenges remain in managing and using USF effectively in many countries.[41] Prescriptive or technology-specific requirements of some funds can prevent diverse operators from participating in the program. For example, some USFs only allow projects that expand mobile coverage, an untenable activity for most small operators.[42] USFs are also frequently assigned as smart subsidies that require the covered area to become sustainable through network revenues. For the most remote and impoverished areas, lack of ongoing operational funding will preclude success.[43]

Geography, population density, spectrum, power, land, safety, operator licensing, and finance can all be barriers to "meaningful connectivity". Not all can be overcome with technical innovation, but those that can are discussed in the next section.

IV. LAST MILE CONNECTIVITY TECHNOLOGIES

Access to the internet in developing countries started with copper cable and modems. Technologies like digital subscriber line enabled broadband via the public switched telephone network. Data over cable service interface did the same for cable TV networks. These technologies continue to evolve in the copper networks found in economically developed countries. In the mobile-first world of ADB's DMCs, they have little relevance. Fiber and wireless are important for DMCs.

If telephone and radio were the communications innovations of the 19th century, fiber-optic communications were the key for the 20th. Only a decade elapsed between Corning's perfection of low-loss fiber-optic cables in 1970 and their deployment by carriers AT&T and MCI for long-haul projects in the United States (US). By the 1980s, fiber was the technology of choice for new submarine cables linking the world, and by 2008, with the ITU's standardization of gigabit passive optical networks (GPON), fiber became the best last mile technology available.

Wireless technologies have been the main innovation of the 21st century. Wi-Fi's 802.11b standard was ratified in 1999, and 3GPP's 3G mobile standard in 2000. Both are foundational direct-to-device technologies used by billions of people every day. Both can serve as last mile or last-inch technologies, providing stationary or itinerant communications, but only 3GPP networks support mobile broadband.

Satellite communications gained broadband capabilities with the Digital Video Broadcasting Satellite Second Generation standard in 2005. Satellite connections have been the last mile connectivity of choice for remote homes and communities since then but an expensive option not without their share of drawbacks. A revolution in broadband satellite communications is now underway, led by low earth orbit (LEO) networks. *ADB Sustainable Development Working Paper Series* No. 76 covers the topic in detail.[44]

41 Hurukke, Gayani and Samarajiva, Rohan. 2019. *Metrics to improve universal-service fund disbursements*
42 Plum Consulting. 2020. Universal Service: providing voice telephony to remote users – an international review.
43 GSMA. 2020. Comments of the GSMA before the Department of Commerce, Docket No. 210503-0097, Washington DC.
44 Footnote 24.

This section covers fiber, mobile broadband, fixed wireless, and Wi-Fi as they are relevant for extending last mile connectivity. All have a place in delivering the robust, high-quality broadband needed to boost education and productivity at the affordability frontier.

A. Fiber-Optic Communications

The history of fiber-optics in communications parallels that of copper cabling. Small test systems rapidly gave way to continent-spanning point-to-point backbone systems. Fiber replaced coaxial cables and chains of microwave links, enabling high-capacity digital communications between central telephone exchanges and large corporations around the world.

With the evolution of transmission technology, by the early 2000s carriers were using it to build middle-mile networks and beginning to connect buildings in dense urban environments.

Nortel's Digital Multiplexing Switch revolutionized copper telephone networks in 1977 and a similar multiplexing innovation revolutionized fiber in 2008: GPON, that has allowed fiber to make the jump from a backbone and middle-mile technology to the last mile.

Today more than a billion people in Asia and the Pacific have fiber-optic internet at home.[45] Nearly all of them are serviced by GPON systems.

B. GPON Networks

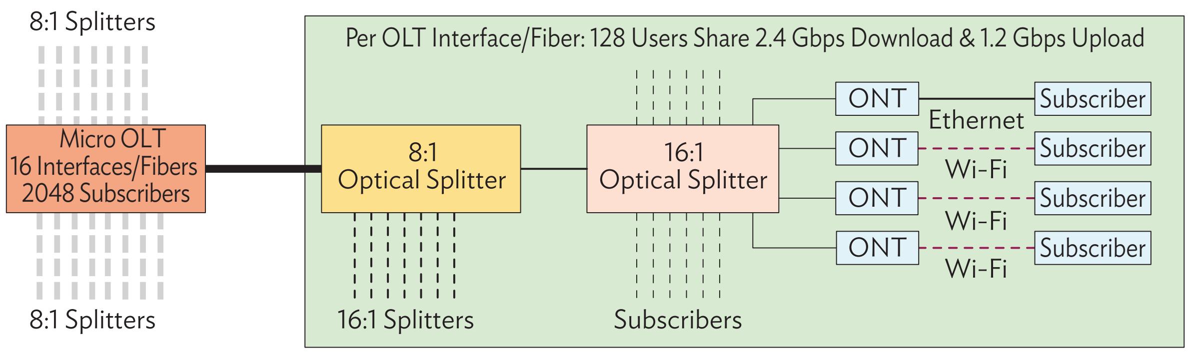
Backbone fiber systems use dedicated optical modules at each end and a pair of fiber strands between them. Point-to-point technologies like this do not scale well, either physically or economically. The physical infrastructure and power consumption requirements of point-to-point links are beyond what an operator can recover from a retail broadband connection. In 2020, only 4% of all fiber to the premises (FTTP) networks in Asia links used point-to-point technologies.[46]

GPON FTTP networks use a single master transmitter to provide a multiplexed service to a group of subscribers. GPON allows for both a densification of circuits and a power savings of at least 10x when compared to point-to-point technologies. In some configurations, the power required on the network side can be less than 1 watt per subscriber.

[45] FTTH Council Asia Pacific "FTTH APAC Panorama 2020" reports 459 million FTTH/B subscribers. Each of the markets covered by the report has a household size > 2.3 people, allowing us to infer at least 1.055 billion people in Asia and the Pacific are connected to fiber.

[46] FTTH Council Asia Pacific. 2020. *FTTH APAC Panorama 2020, Fiber (FTTH/B) deployment trend in Asia-Pacific*.

Figure 14: Gigabit Passive Optical Network System Topology



OLT = optical line terminators, ONT = optical network terminators

Source: Adapted from Mirandilla-Santos, Mary Grace, Jonathan Brewer, and Jaie Faustino. *From Analog to Digital: Philippine Policy and Emerging Internet Technologies.* The Asia Foundation, October 2018.

In a GPON system, head end transmitters (optical line terminators [OLTs]) broadcast encrypted data to subscribers on one wavelength of a single fiber, which is split into multiple end user fibers. OLTs listen for return traffic mediated through time division duplex technologies on another wavelength. OLTs can be housed in a telephone exchange, installed in a roadside cabinet, or even attached to a utility pole. Most GPON configurations allow between 16 and 128 subscribers to share each transmitter in an OLT, as illustrated in Figure 14. Typical distances between the OLT and subscribers range from 5 kilometers (km) to 40 km.

GPON networks are called "passive" because they require no active, powered network equipment on the 5–40 km outdoor route between the transmitter and the subscriber. Passive splitting equipment (optical splitters in Figure 14) are often no larger than a textbook and can hang on poles or be concealed in pits near subscriber locations.

GPON networks do not require power between the transmitter and subscribers.

FTTP subscriber terminals (optical network terminators) receive the signal, decrypting broadcasts intended for their device, and terminate traffic to an Ethernet cable, or most often to an in-built Wi-Fi router. User devices remain untethered, while their broadband comes from a fixed terminal.

The main cost components for a GPON network are the OLT, fiber cables, and user terminals. Software and licensing make only a small contribution to the capital and operational network costs, an important point to consider when comparing GPON networks to mobile networks discussed later in this section.

With more than a billion people connected to FTTP networks in the Asia and Pacific region, and many networks operating in low average revenue per user markets, the scale of GPON infrastructure manufacturing is high and costs low.[47] In 2018 the infrastructure cost for an urban GPON network was less than $100 per subscriber, provided existing utility poles were available to carry the cables, and prices have decreased since then.[48]

[47] Footnote 46. States 459 million FTTH/B subscribers. Each of the markets covered by the FTTH APAC Panorama report has a household size > 2.3 people, allowing us to infer at least 1.055 billion people in Asia Pacific are connected to fiber.

[48] The Asia Foundation. 2018. *From Analog to Digital: Philippine Policy and Emerging Internet Technologies*. USA.

Much of the decrease in cost is due to the price of fiber-optic cables, which have dropped in cost due to the immense scale of regional deployments and cable overproduction, especially in the People's Republic of China.[49] Lead-in cables, which connect buildings and houses to splitters on utility poles, cost less than $35 per km in 2021 and, if well-installed, have a reasonable lifetime of 50 years.[50]

GPON terminal equipment (optical network terminators), including Wi-Fi radio, has halved in price in recent years. Basic terminals that cost $23 per device in 2018 can now be purchased in quantity for $10 per device.[51] Terminals with Wi-Fi allowing untethered connectivity to phones, tablets, and laptops enable private and personal use of the internet, key to empowering women's autonomy over their internet use and habits.[52]

Box 1: Pole Mount and Plug and Play GPON

Pole-mount optical line terminators (OLTs) are a niche product but an important one for addressing the affordability frontier. For green field builds with low population density they can be the foundation of a broadband network that does not require any buildings.

A thousand subscribers can be served from a pole-mount OLT the size of a backpack, which can consume as little as 45 watts of electricity.

In the early years of fiber to the premises (FTTP) networks, technicians often climbed poles with fusion splicers to join fibers together and to splitter boxes. Today's Gigabit Passive Optical Network (GPON) networks can be completely plug and play.

Pre-terminated aerial splitter boxes provide sockets that allow unskilled laborers to connect buildings using pre-manufactured patch cables in a matter of minutes.

Self-tensioning cables mean installers can take one cable to service properties that may be as little as 5 meters or as far as 30 meters from a utility pole.

In most plug and play GPON networks, no testing or special equipment is necessary. Technicians connect a user terminal including Wi-Fi. After a short and automated software provisioning process, service generally works at high speed without any further configuration.

[a] Hangzhou Softel Optic Co., Ltd. Outdoor GPON OLT.
[b] B. A. Zeeshan. 2021. AirPON's Complete Guide! Planning, Deployment, Configuration till Testing & Finalization. *Huawei Enterprise Support Community*. 11 April.

Source: Top Photo, Softel pole mount FTTH OLT with integrated backhaul.[a] Middle and bottom photos, Huawei AirPON GPON System.[b]

[49] Official Journal of the European Union. 2021. *Making imports of optical fiber cables originating in the People's Republic of China subject to registration*. 29 March.
[50] Europacable. 2020. *Expected Life Time of Passive Optical Infrastructure*.
[51] Footnote 39. Made-in-China.
[52] Footnote 10.

C. Radio Spectrum Technologies

ADB's DMCs in Asia and the Pacific are mobile-first economies. Smartphone ownership far outpaces fixed line subscriptions. While smartphones imply mobile technologies, fixed wireless and Wi-Fi are equally important when it comes to how people connect to the internet.

D. Technologies: Mobile Networks–3G/4G/5G

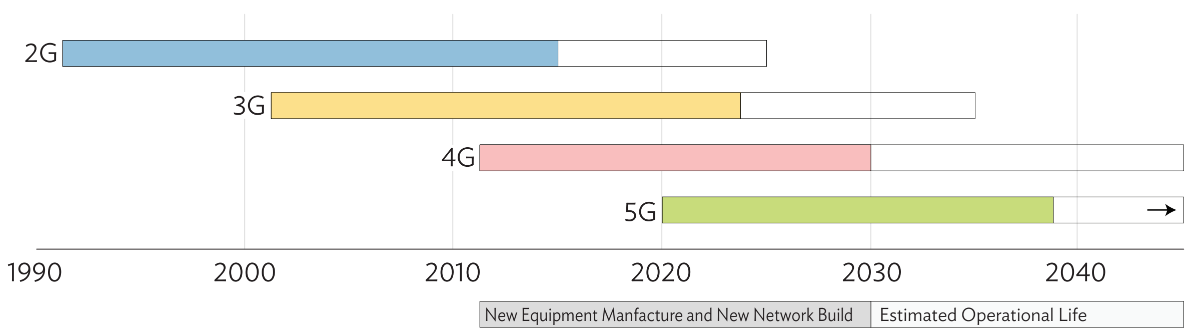
Mobile networks are used by over 5 billion people around the world.[53] Their primary use is telephony, messaging, and mobile broadband, but a growing number of operators are also using them to provide fixed wireless broadband.

Technical requirements for mobile networks set by the ITU ensure the global interoperability of networks. Industry organization 3GPP develops the standards we know as 3G, 4G/LTE, and 5G, which correspond to and generally comply with the ITU requirements for IMT-2000, IMT-Advanced, and IMT-2020.

Mobile broadband was introduced over 20 years ago in IMT-2000 with a circuit-centric architecture, mirroring that of voice calls. IMT-Advanced (4G/LTE) and its enhanced packet core was the first global standard for internet protocol (IP) native mobile broadband.

The robustness and phenomenal commercial success of mobile networks has led to their proliferation and longevity around the world. 2G networks built decades ago are still in use today, and new 2G handsets will still be manufactured in 2023. New 4G networks will continue to be built until at least 2030 and operated well into the 2040s (figure 15). Encouraging the rollout and uptake of 4G in DMCs should be a priority for both governments and operators.

Figure 15: Estimate of New Network Build and Operational Life of Mobile Technologies



Source: Author.

E. Carrier Mobile Network Macrocell

Mobile networks require a considerable investment in capital and radio spectrum resources, and few countries support more than three or four[54] MNOs. Operators seek to provide continuous coverage over wide areas using large towers called macrocells. These towers are spaced from a few kilometers to a few tens of kilometers apart and can support thousands of users.

53 The GSM Association. 2021. *The Mobile Economy 2021.*

54 The GSM Association. Operator Membership.

The main capital components for carrier networks are tower equipment like base stations and antennas, and mobile core software and systems that handle call and data routing to devices.

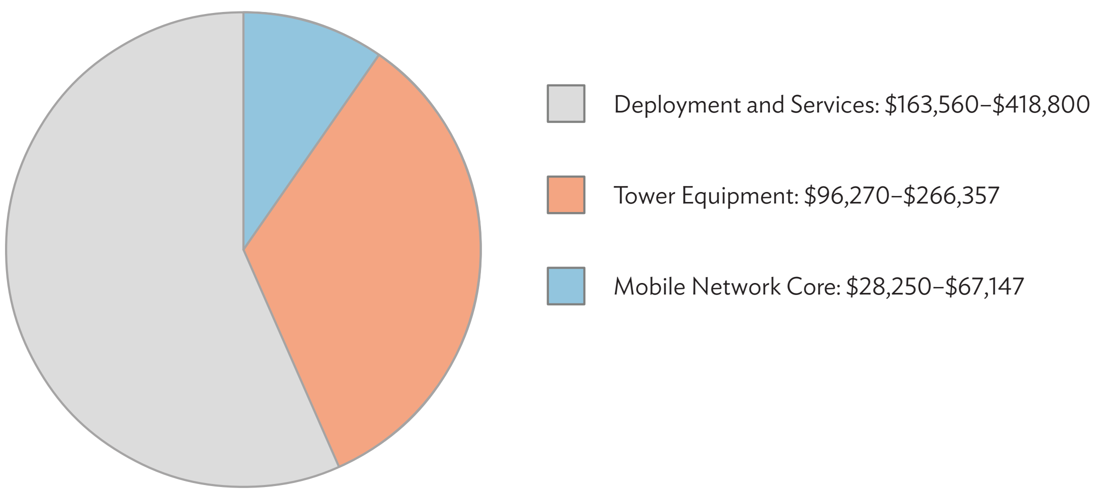
Most carrier networks are built with tower equipment manufactured by one of five companies: Ericsson, Huawei, Nokia, Samsung, and ZTE.[55] The closed nature of tower equipment from these top vendors means a single supplier is almost always chosen by a mobile network operator for each generation of technology in their networks.

The mobile core market is similarly concentrated, with most networks running software supplied by Cisco, Ericsson, Huawei, Nokia or ZTE. These firms collectively control over 75% of the $8 billion a year market.[56] Core network offerings can have both capital and operational expenses that scale with the number of users supported; building a mobile network is rarely a matter of paying once for a system.

The latest public cost data for mobile networks comes from an analysis Widelity produced for the US Federal Communications Commission (FCC) in 2021 (Figure 16). Chinese vendors were absent from the survey due to trade restrictions imposed by the US, but are a major force in the world's networks.[57] Market leader Huawei and its local competitor ZTE have equipment and software that are as advanced and perform as well as that of Western vendors but is available for 30%–50% less.[58]

Carrier macrocells are the most power-hungry options for mobile network connectivity and require access to mains power or significant alternative energy sources.

Figure 16: Per Tower Costs for a 50-Tower Rural Network in the United States Reported to the Federal Communications Commission in 2021



Source: Widelity, Supply Chain Reimbursement Program Study, 25 March 2021.

55 Telecom Lead. Huawei to Grab Share from Ericsson and Nokia in Base Station Market.
56 I. Morris. 2020. Rakuten's 4G Core Will Not Survive NEC Shift. *Light Reading*. 6 May.
57 VentureBeat. 2020. FCC Finalizes Huawei and ZTE Ban, Citing Threats to U.S. Security. 30 June.
58 A. Moon and T. Virki. 2019. Exclusive: In Push to Replace Huawei, Rural U.S. Carriers Are Talking with Nokia and Ericsson. *Reuters*. 25 June.

F. Mobile Network Sharing

Traditional mobile networks have largely expanded their footprint to all areas where service is profitable.[59]

The GSMA estimates that to be profitable, a mobile tower needs at least 3,000 active users daily, concentrated in a coverage area of less than 25 km^2.[60] In competitive markets with traditional owner-operator towers, the problem of finding those active users can be harder than it needs to be due to the duplication of tower infrastructure.

Addressing the affordability frontier means adopting new models for deployment. Infrastructure sharing, for example, can reduce capital investment and ongoing operating costs by between 50% and 80% depending on the market structure and sharing model implemented.[61] Radio access network sharing goes beyond the tower and passive network element sharing common in mobile networks today.

Multi-operator core network (MOCN) is a concept where two or more carriers share every element of a cellular tower, including the equipment and the radio spectrum, while using their own core networks. End users of MOCN arrangements receive the same last mile performance no matter which carrier network they are connected to. Features, throughput, and coverage from participating carriers are all the same.

MOCN can help carriers expand into uneconomic areas but can be a contentious arrangement due to its requirement for spectrum license holders to share their spectrum with other carriers. Contributions of spectrum by the government or involvement of spectrum by a neutral third party is an ideal solution for helping competitive network operators accept an MOCN model for coverage.

Multi-operator radio access network sharing (MORAN) is a configuration where multiple carriers share the physical equipment of a cellular tower, again using their own core networks, but bringing their own radio spectrum, network features, and network optimizations to the arrangement. End users of a MORAN network receive the same last mile coverage but can receive very different network performance.

MORAN solutions, found today in New Zealand[62] and Japan,[63] are a form of co-opetition.[64] Carriers cooperate on the capital expenses of building and operating rural networks while keeping hold of what they feel is their competitive advantage.

Both MOCN and MORAN networks differ from roaming agreements or wholesale open access networks in that customers do not know or care that they are on a shared network. Handovers or transitions between the shared infrastructure and carrier-owned infrastructure are transparent. The user experience is identical to being directly connected to an operator tower.

[59] K. Heimerl et al. 2021. *Whale Watching in Inland Indonesia: Analyzing a Small, Remote, Internet-Based Community Cellular Network*. Proceedings of the Web Conference 2021 Association for Computing Machinery. New York, NY, USA. 21 April.
[60] Footnote 6.
[61] Footnote 6.
[62] Two Degrees Mobile.
[63] A. Weissberg. 2021. Nokia deploys shared 5G RAN (MORAN) with SoftBank and KDDI in Japan. *IEEE.org*. 14 October.
[64] A. Brandenburger and B. Nalebuff. 2021. The Rules of Co-Opetition. *Harvard Business Review*. 1 January.

This small multi-operator core network (MOCN) tower, located at the Whangarei Heads in New Zealand, allows three carriers to share equipment and radio spectrum to provide long-term evolution (LTE) in the 700 MHz band to a remote location (photo by Rural Connectivity Group).

G. Low-Cost Small Cells

Several low-cost small cell LTE vendors have entered the market in the past 5 years, targeting fixed wireless providers and private LTE networks. Most of these vendors offer relatively low-power transmitters designed to serve small areas, but at prices one-half or one-third that of dominant vendors.[65] Their products and pricing could have a significant impact on addressing the affordability frontier.

Solutions in the small cell space are mainly based on all-outdoor equipment, with transmitters co-located with or combined inside antennas. They generally do not support more than 128 users per sector. Small cell network configurations can be compared to traditional solutions with the diagram in Appendix 4.

Many small cells are based on commodity hardware components like Systems on a Chip from Intel, Freescale, and Qualcomm. Some can operate in open radio access network (OpenRAN) environments, a concept discussed in Appendix 5. Most are designed to interoperate with core network software from a wide range of vendors and even open source software solutions (see the Mobile Core Network Innovations section below for more information).

[65] Airspan Networks. 2021. *Protecting Against National Security Threats to the Communications Supply Chain Through FCC Programs*. Docket No. 18-89 6 October.

While power requirements for small cells are a fraction of traditional mobile networks, they are still frequently 100–200 watts per sector. This is a significant amount of power for an alternative energy system to support and outdoor small cells are best installed in locations with access to mains power.

Table 2: A Selection of Small Cell Vendors and Capabilities

Manufacturer	4G Mobility	4G FWA	Integrated Core Supplier	OpenRAN Support
Airspan	Yes	Yes	No	Yes
Baicells	Yes	Yes	Yes	Yes
Blinq	Yes	Yes	Yes	No
CableFree	Yes	Yes	No	Yes
Cambium	No	Yes	Yes	No
Huawei	Yes	Yes	No	No
Mikrotik	Yes	Yes	No	No
Parallel Wireless	Yes	Yes	No	Yes
Redline	Yes	Yes	No	No
Ruckus	Yes	Yes	No	No
Tejas Networks	Yes	Yes	Yes	No
Telrad	Yes	Yes	Yes	No
Vanu	Yes	Yes	Yes	Yes
VNL	Yes	Yes	Yes	No

FWA = fixed wireless access; OpenRAN = open radio access network.

Source: Author

H. Mobile Core Network Innovations

Mobile core networks are a significant contributor to the capital expense of cellular networks. They can also be a significant operational expense, especially when operators have low-revenue subscribers.

Free, open source mobile core network software is now available, which eliminates both the capital and operational license fees involved in running a mobile network.[66] Two of the best developed options are Open5GS and Magma, the latter supported by the Linux Foundation, the Open Infrastructure Foundation, and the Telecom Infra Project. Operating a mobile core without vendor support can be challenging, so some companies have begun to offer paid support for open source offerings.[67]

Some small cell manufacturers supply their own integrated mobile core networks. These offerings, generally pitched at networks with hundreds or thousands of users, incorporate all the software and systems required to run a mobile network into a single box. They are often configurable from a web browser and can make running a mobile broadband network as easy as running a corporate Wi-Fi network.

[66] M. Mazur. 2021. Evolution of Open-Source EPC — A Revolution in the Telecom Industry. *Ubuntu*. 9 September.

[67] Magma Core. Implementation Partners.

In December 2021, Amazon announced a new Network-as-a-Service offering they call Private 5G.[68] Unlike open source or integrated mobile cores, the mobile core for Amazon's Private 5G will run in the cloud. Although Amazon's offering is aimed at corporate networks and not the affordability frontier, it is a validation of the idea that one day mobile network cores and operations could be entirely outsourced.

I. Community LTE

Community LTE (CoLTE) is based on the idea that any community should be able to operate its own LTE network. It starts with the concept of small cells and brings down cost and complexity further by eliminating the requirement for a mobile network core. CoLTE configurations allow LTE to operate much in the same way as a Wi-Fi hot spot but with LTE's licensed, interference-free radio spectrum, and support for a huge ecosystem of mobile and fixed wireless terminals.

CoLTE configurations have the software required for bridging mobile devices to the internet running either on the transmitter itself or on a commodity low-cost, low-power computer co-located with the transmitter. This arrangement is often called an embedded core.

By removing the mobile core from the configuration, CoLTE networks lose mobility functions like handovers between cells and roaming. Most CoLTE operators forgo native voice and SMS services entirely. It is difficult for small organizations to acquire the mobile network operator code and interconnection agreements with incumbent operators required by traditional telephony services.

The cost and complexity of these functions is also forgone, with users encouraged to communicate using over-the-top voice and messaging applications. CoLTE is an ideal solution for remote communities and islands where there is no reasonable solution for continuous coverage or multiple cells but users can benefit from mobile broadband connectivity.

CoLTE network power requirements depend on their transmitters and coverage requirements, starting at around 20 watts for indoor microcells, increasing up to 200 watts for standard small cell transmitters.

[68] R. Chua. 2021. AWS Surprises with AWS Private 5G. *Fierce Wireless*. 1 December.

Box 2: Community LTE in Bokondini, Indonesia

Remote communities in Indonesia have hosted micro-cellular community networks since 2013, when California startup Endaga helped a missionary school in the highlands of Papua build a financially sustainable 2G network with hundreds of subscribers.[a] Using ultra-low-cost equipment based on open standards enabled a $6,000 piece of equipment to net $2,000 in revenue per month for its operators for voice and SMS traffic.

This same school has hosted a data-only CoLTE network since 2018, with backhaul via a 3/1 Mbps satellite link. As a data-only network, network users need a smartphone to access it and need to rely on OTT applications like WhatsApp, Facebook Messenger, or Viber for messaging. Many use dual-SIM phones, with one SIM for 2G voice and SMS from an incumbent carrier, and a second SIM for prepay 4G data.[b] Coverage is available around 2 km from the antennas.[c]

Over a year-long period of study, the network had around 50 active users, who paid around $10 per GB of traffic, purchased in data packages of 10 Mb, 100 Mb, or 1 Gb. Given Indonesia's GDP per capita and income distribution, it is likely 1 Gb of data is affordable (≤ 2% GNI/capita) only for the top two deciles of the rural population. This was reflected in network income: median ARPU was less than $100 but three users spent more than $1,000.

km = kilometers, OTT = over the top.

[a] L. Gannes. 2014. Endaga Brings Rural Villages Online With a Cell Network in a Box. *Vox*. 1 December.
[b] Footnote 10.
[c] M. Johnson. 2018. Building a Community LTE Network in Bokondini, Indonesia. *Internet Society (blog)*. 27 September.

Source: Dr. Matthew Johnson, University of Washington

J. LTE Fixed Wireless Access

Using LTE as a substitute for fixed line terrestrial broadband has been common since 2012.[69] A decade ago the practice was called fixed mobile substitution (FMS), today it is commonly known as fixed wireless access (FWA). In a typical configuration, end users have an antenna installed on their roof or in their window and a terminal indoors. The terminal acts as a router and Wi-Fi hot spot, allowing a household full of devices to share one LTE connection.

Long-term evolution (LTE) small cell in use for fixed wireless access (FWA) service in Malaysia (photo by Tejas Networks).

Operators generally offer FWA anywhere they have excess network capacity and can offer a broadband service at lower cost, or higher margin than they could using a terrestrial fixed network. Seventy percent of the world's service providers are offering FWA services today and Ericsson expects connections to grow by 20% annually through 2026.[70]

FWA is possible from any LTE network but several implementation options are available. Some small cell vendors have produced special base stations and terminals explicitly for fixed wireless, eliminating mobile functions much in the way CoLTE does.

Distances supported are in the range of 30 km, but it is possible to extend links to 200 km where tower height and terrain conditions support it.[71]

FWA LTE towers based on small cells can deliver hundreds of megabits per second of traffic, making them practical and economical for small remote communities.

K. Wi-Fi

Wi-Fi is a key component of most last mile connections. As shown in Figure 13, it is used as the last inch between a fixed terminal and a mobile device.

Wi-Fi is a low-power technology that uses shared, open spectrum to operate. It is tolerant of interference but works best when there are no obstructions between the access point and a user's device. Outdoor hot spots can provide tens of meters of coverage, but beyond these distances access can be unreliable.

Public Wi-Fi has been a focal point of universal access programs like Pipol Konek in the Philippines, JakWiFi in Indonesia, and Net Pracharat in Thailand. Google and Meta (formerly Facebook) also launched public Wi-Fi networks to tackle problems of affordability in the form of Google Station and Express Wi-Fi. Both commercial projects have since been shut down[72] but innovation in the public Wi-Fi space continues. The latest ambitious public Wi-Fi project in Asia is India's PM-WANI, discussed in Box 3.

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69 J. Brewer. 2013. *Overview of Fixed Mobile Substitution for the New Zealand Commerce Commission.* InternetNZ, TUANZ, Consumer NZ.

70 Ericsson. 2021. *Ericsson Mobility Report*.

71 Ericsson. 2020. *Ericsson and Telstra Extend Reach on an LTE Network up to 200km*. 27 February.

72 M. Singh. 2020. Google Ends Its Free Wi-Fi Program Station. *TechCrunch (blog)*. 17 February.
M. Alleven. 2022. Meta Winds down Express Wi-Fi Program. *Fierce Wireless*. 31 January.

Community Networks, a network infrastructure ownership model promoted by A4AI,[73] the Digital Empowerment Foundation,[74] ISOC,[75] and many other organizations often use Wi-Fi[76] in the last inch of their networks. They also frequently use Wi-Fi derived equipment for backhaul, a phenomenon described in the next section.

Box 3: PM-WANI

4G data is affordable for over 90% of the Indian population where it is available.[a] Connectivity is still out of reach for many rural people without 4G coverage. The PM-WANI scheme will enable any entrepreneur, society, or nonprofit to sell Wi-Fi access to their communities from their shop or a home fixed broadband connection without needing a license, or expertise as an internet service provider.

The scheme has a well-developed architecture that establishes several commercial and technical roles in an open marketplace.[b] It ensures open, unbundled systems and a low-touch and maintenance-free hosting experience for participating hot spot operators.

PM-WANI is unique in helping non-technologists sell connectivity and by explicitly allowing an activity that usually requires a license. Should PM-WANI prove to be a success, the scheme could be a model for providing low-cost internet access in areas lacking mobile broadband coverage or capacity.

[a] Based on World Bank's 2011 PovCalNet Income distribution and ITU WICT 2020 price data, a 1.5 GB plan costs less than 2% of GNI per capita for rural income deciles 2-10 and urban income deciles 3-10.
[b] Government of India, Telecom Regulatory Authority of India. 2020. *Public Open Wi-Fi Framework Architecture and Specification (Version 1.0)*. New Delhi.

L. Open Spectrum Fixed Wireless Networks

In regimes with open spectrum and relaxed regulations around internet service, wireless ISPs (WISPs) thrive in delivering service to homes and businesses. Some, like NYC Mesh, operate in cities. Many find competition for urban spectrum resources difficult, and instead serve suburban, rural, and remote populations.

The first WISPs emerged around 30 years ago with the introduction of packet networking equipment designed to operate in open spectrum.[77] The emergence of Wi-Fi and the rush to market by low-cost manufacturers like Linksys and D-Link were key to the next step in WISP evolution. Software developers altered Wi-Fi protocols and their timings to change from last-inch to last mile technologies.

[73] M. Nakagaki. 2019. Why Community Networks Matter to Advance Internet Access for All. *Alliance for Affordable Internet*. 20 March.
[74] Digital Empowerment Foundation. Community networks – a boon in times of pandemic and lockdown.
[75] Internet Society. Community Networks Success Stories.
[76] P. Micholia et al. 2018. Community Networks and Sustainability: A Survey of Perceptions, Practices, and Proposed Solutions. *IEEE Communications Surveys & Tutorials*. 20 (4). pp. 3581-3606.
[77] J. Pollock. 2018. It is a Watershed Moment for Wireless ISPs. *AGL (Above Ground Level) (blog)*. 28 June.

Tens of billions of Wi-Fi chipsets have been manufactured since the standard emerged and today wholesale device pricing is a few dollars per unit.[78] Basing fixed wireless equipment on Wi-Fi chipsets allows for ultra-low-cost base stations and terminals. In the US, market leader Ubiquiti sells FWA devices at $49 each which can act as a base station or a subscriber unit, capable of links spanning tens of kilometers. In Asia, similar devices are available at $20 to $30 each.

While many open spectrum FWA devices are based on Wi-Fi chipsets, the protocols they use are generally not Wi-Fi compatible. Specially configured customer premises equipment is required to attach to these access networks, often in a weatherproof, roof-mounted antenna enclosure.

Besides a price advantage orders of magnitude below that of a low-cost LTE base station, Wi-Fi chipset-based fixed wireless equipment has a power advantage. Most low-cost devices consume between 5–10 watts, compared to the 100–200 watts consumed by an LTE small cell or the 2–5 kW required by a macro scale LTE tower. Even high-performance MIMO FWA base stations, capable of hundreds of megabits per second of throughput, rarely consume more than 30 watts per antenna.

Dynamically licensed spectrum based on spectrum access systems is opening new opportunities for open WISP networks to achieve higher performance by using dedicated spectrum.[79]

Wireless Internet service provider (WISP) tower in Zardaly, Kyrgyz Republic (photo by Talant Sultanov).

Box 4: Thailand's Net2Home

Fixed line broadband and limited free Wi-Fi is available in thousands of villages around Thailand.[a] Wi-Fi is available in many public locations for free, and fixed connections are available at market price. What many villagers want is unlimited internet in their homes but at around $24/month, fixed line connections are only affordable for around half the population.[b]

Net2Home helps solve the affordability problem by setting up and helping to administer community networks using open spectrum wireless in a mesh topology.[c]

The Net2Home social enterprise company, a charity funded by the country's domain name registry, acts as a purchasing aggregator and distribution network for internet access. Each Net2Home community shares a fixed broadband connection, typically VDSL or FTTP. Participating households host a mesh wireless router providing access to themselves and passing

Continued on next page

[78] Cisco. 2020. *Cisco Annual Internet Report (2018-2023) White Paper*.
[79] CommScope. Spectrum Access System (SAS) Frequently Asked Questions.

Box 4: continued

the connection on to their neighboring subscribers using open spectrum in the industrial scientific and medical (ISM) bands. Users of the service pay $6/month to the Net2Home foundation, which provides the equipment, purchases the fixed broadband circuits, and monitors the networks.

Internet in the home "holds the potential to substantially reduce the digital gender gap in regions where expectations about women's participation in public life and presence in public spaces may limit their ability to use public access points," making Net2Home far more impactful to women than public Wi-Fi hot spot programs.[d]

In its first 4 years of operation, Net2Home connected 11 communities. In its second four years, that number grew to 44. As a proven, financially sustainable connectivity model, Net2Home expects its growth to continue going forward.

FTTP = fiber to the premises, VDSL = very high-speed digital subscriber line.

[a] Asia-Pacific Telecommunity. 2019. *Village Broadband Internet Project (Net Pracharat) of Thailand*.
[b] Based on World Bank's 2019 PovCalNet Income distributions, an 800 Baht ($24/month) fixed broadband plan exceeds 5% of GNI per capita for deciles 1-5.
[c] Net2Home. Net2Home | Home Internet.
[d] Footnote 11.

M. 5G, OpenRAN, and Neutral Host Antenna Systems

Some of the most talked about developments in last mile networks are 5G technologies.

Although 5G can provide long-range coverage for rural broadband[80], in practice most 5G implementations are based on mid-band spectrum and cells with a 10–15 km radius. High band 5G networks almost always have cell sizes below 1 km radius. In areas of low population densities, mid and high band 5G systems will never be viable for last mile internet connectivity.

OpenRAN is a concept frequently discussed along with 5G. It is a set of interface standards intended to make equipment and software components from many vendors interoperable.

Neutral host antenna systems are an infrastructure-sharing arrangement where open-access wireless equipment is installed in high-density locations like transport hubs, stadiums, or large buildings. Commercially they are operated by a neutral third party and capacity is leased to MNOs. The inherent interoperability of OpenRAN 5G networks could accelerate the use of such systems.

Low-cost 5G systems have not yet reached the market and may not eventuate for some years. Neither OpenRAN nor neutral host systems are simple or inexpensive, and McKinsey finds "broad consensus that 5G will drive up the total cost of network ownership."

A full discussion of 5G and its associated technologies is available in Appendix 5.

[80] J. Lun, P. Frenger, A. Furuskar and E. Trojer, "5G New Radio for Rural Broadband: How to Achieve Long-Range Coverage on the 3.5 GHz Band," 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), 2019, pp. 1-6

V. ADDRESSING THE AFFORDABILITY FRONTIER

Each technology discussed has strong and weak points and exposure to the issues covered in the Barriers to Meaningful Connectivity section. Choosing the right combination of technology is a matter of considering population, territory, and available infrastructure and working toward the most financially sustainable solution. Technologies should be used as building blocks, with the most appropriate components chosen for each barrier encountered. Such tailored and variable solutions will not always suit large MNOs and there may be many cases where only niche wholesale providers or community networks can deliver in physically and economically challenging circumstances.

A. Last Mile Solutions

Table 3 considers a few options for last mile connectivity that can address the affordability frontier. Examples are based on market pricing and published specifications for equipment from Airspan, Baicells, Cambium, Huawei, Nokia, Softel, and Ubiquiti. The Macrocell example supports predicted average mobile traffic demand through 2031. Other examples will support predicted demand well beyond 2032.

Table 3: Options for Last Mile Connectivity

Technology and Mobility	Configuration and Distance	Barriers	Users	Peak Mbps	Mbps / User	CapEx / User	Power / User
GPON FTTH (Fixed)	19" Rack OLT, 16 Ports, 1-40 km	Operator Licensing, Geography, Access to Buildings	1,024	1,000	19	$193	0.8 W
GPON FTTH (Fixed)	Pole mount OLT – 1 port, 1-40 km	Operator Licensing, Geography	96	1,000	104	$70	0.5 W
LTE Macro (Mobile)	3 sector, 160 W, 4x4 MIMO, 1-30 km	Operator Licensing, Geography, Access to Towers, Access to Buildings, Radio Spectrum, Access to Electricity	768	109	0.9	$243	2.5 W
LTE Small Cell (Mobile)	2 sector, 20 W, 2x2 MIMO, 1-10 km	Operator Licensing, Geography, Radio Spectrum, Access to Electricity	128	109	2	$353	3.6 W
LTE FWA (Fixed)	2 sector, 20 W, 2x2 MIMO, 1-30 km	Operator Licensing, Geography, Radio Spectrum, Access to Electricity	128	109	2	$353	3.6 W
LTE CoLTE (Fixed)	1 sector, 0.25 W, 2x2 MIMO 1 km	Operator Licensing, Geography, Radio Spectrum	32	80	2.5	$135	0.6 W
ISM FWA (Fixed)	1 sector, 2 W, 8x8 MIMO, 1-30 km	Geography, Radio Spectrum	128	91	2.9	$370	0.6 W
ISM FWA (Fixed)	1 sector, 1 W, 2x2 MIMO, 1-20 km	Geography, Radio Spectrum	24	91	3.8	$85	0.3 W

Legend:
Geography Population Density Radio Spectrum Access to Towers Access to Buildings
Access to Electricity Operator Licensing

CapEx = capital expenditures, CoLTE = community long-term evolution, FTTH = fiber to the home, FWA = fixed wireless access, GPON = gigabit passive optical network, ISM = industrial scientific, and medical, km = kilometers, LTE = long-term evolution, Mbps = megabits per second, MIMO = multi-in-multi-out, OLT = optical line terminal, W = watt.

Source: Author.

It is important to recognize that the lowest cost, lowest power, and highest throughput solutions do not support mobility. Absent any mobile network cover, for example existing 2G/3G providers, users of fixed wireless, GPON, CoLTE, and FWA systems will not easily be able to use internet functions that depend on sign-up or authentication by text message. This could prevent them from using some e-commerce, messaging, and online banking applications. Nascent satellite-based mobile networks have the potential to serve mobile phones directly from space which may resolve this issue.[81]

B. Backhaul for Last Mile Connectivity

Last mile connectivity does not exist in isolation. All the technologies and solutions discussed above need backhaul. Point-to-point fiber is the best choice for backhaul but for rural and remote networks, GPON can be an excellent low-cost choice. The latest ITU standards for GPON offer symmetric 10 and 40 Gbps links using the same passive infrastructure as older GPON networks, allowing a low-cost network to be built today and scaled to higher speeds at any point in its 50-year life span.

Microwave is the world's most common choice for mobile network backhaul, which has led to a competitive market and high-performing products that will service networks for a decade to come.[82] However, for small remote communities on alternative energy, microwave can be expensive and power-hungry. Open spectrum FWA can be a reasonable choice for backhaul of small GPON networks, other FWA networks, and even small cell or CoLTE mobile networks.

LEO networks are an exciting potential backhaul source for addressing the affordability frontier. Isolated communities on islands or in mountainous terrain will soon be able to access practical, low-cost, and high-speed connectivity for the first time.

The 2 terabytes a month supported on Western-market residential user plans could service 50 mobile users in ADB's DMCs, meeting 2026 average consumption predictions, and would be sufficient for daily e-learning or telework use. Higher data caps with the same download speed could service the 50 users through 2032. LEO networks designed specifically for backhaul and wholesale are on their way, and commercial services could start in 2022.[83]

Earth to space broadband is power intensive and power use is the main drawback of emerging LEO backhaul solutions. While an open spectrum or LTE fixed wireless terminal requires 3–8 watts of power, and a microwave link 30–50 watts, LEO satellite terminals available today consume between 50 and 150 watts.

C. A Closer Look at Population Density

Average urbanization rates and statistical population density do not always accurately describe a population or geography. Outside developed nation agricultural areas, populations are rarely scattered evenly across a landscape. Small remote populations tend to cluster around roads and passes, navigable waterways, sources of fresh water, and arable land. Figure 17 is an example of a pattern of settlement seen throughout South Asia and Southeast Asia.

Such remote communities may not be economical to adequately service given traditional macro-cellular coverage designs, which cover wide areas with low frequencies. They could become economical given the use of innovative solutions. The topology observed here is ideal for GPON FTTP given existing electrical utility poles. Mobile coverage could be added with utility pole-mounted 4G small cells at a few key locations, without the need to build a macrocell tower.

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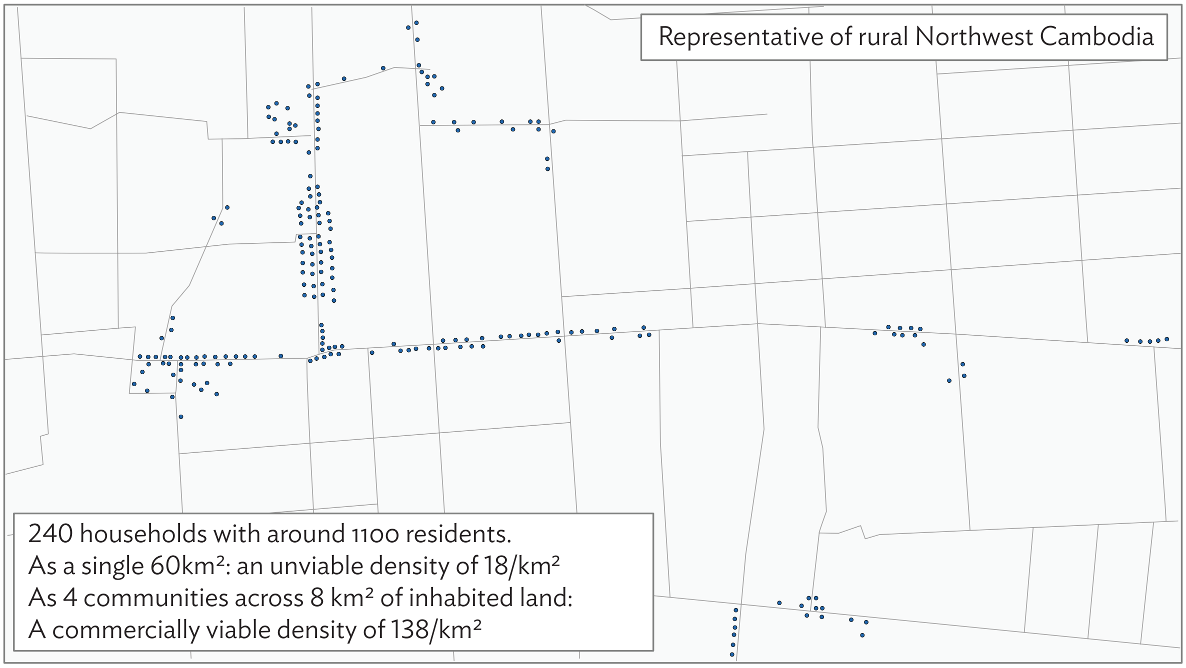
81 L. Hardesty. 2021. AST's Satellite Service Connects Directly to Cell Phones on Carriers' Networks. *Fierce Wireless*. 24 June.

82 The GSM Association. 2021. *Spectrum for Wireless Backhaul: GSMA Public Policy Position*.

83 A. Burkitt-Gray. 2022. Successful Launch for OneWeb, but Continuing Mystery about service start. *Capacity*. 6 January.

Figure 17: Household Clustering in Rural Southeast Asia



km^2 = square kilometer.

Source: Author.

VI. BUSINESS MODELS AND MARKET STRUCTURES

Fully integrated retail providers are the dominant structure among the world's largest telecommunications providers. Often former monopolies, these companies tend to own all parts of a fixed and mobile network, including backhaul and shares in international submarine cables. They provide a range of retail services direct to customers, aspiring to sell triple-play (voice, television, and internet data) or quadruple-play (adding mobile telephony) bundles that maximize revenue potential while increasing switching costs.[84]

The second most common structure is mobile-only or mobile-first operators. These companies typically enter a market as low-cost options to incumbents, often relying heavily on microwave linking and leased fiber to build coverage fast. Building a new mobile network from scratch to compete can be more efficient in improving access than adding a mobile network to a monopoly carrier.

Both traditional business models rely on facilities-based competition and often on control of market bottlenecks to suppress competition and keep margins high. In most countries, neither model has succeeded in delivering "meaningful connectivity" to rural and remote populations.

[84] OECD. 2015. Triple and Quadruple Play Bundles of Communication Services. *OECD Science, Technology and Industry Policy Papers, No. 23.* OECD Publishing, Paris.

Figure 18: Telecommunications Business Models

	Type of Company	Description
Wholesale	FibreCo	Owns physical fiber and supporting infrastructure. Leases it to operators.
Wholesale	TowerCo	Owns physical towers, land, property leases, rooftop leases, provides managed space on towers and rooftops to operators.
Wholesale	InfraCo	Can combine the holdings of a FibreCo and a TowerCo or might focus on one asset type. Adds middle-mile network services, typically using fiber, microwave, or satellite.
Wholesale	Neutral Host	Extends a TowerCo, adding services including antennas, distribution systems, IMT & Wi-Fi access, radio spectrum. Customers are MNOs and ISPs where infrastructure competition is difficult.
Wholesale	OpCo	Provides Network Services to retail providers that can be sold directly to consumers. May act solely as an operator (Nucleus Connect Singapore), or may own InfraCo assets (Alita).
Wholesale	SpectrumCo	Owns radio spectrum and leases it to wholesale or retail providers.
Pure Retail	ServCo	Provides retail services using infrastructure provided by others. Can own network core & BSS/OSS, leases middle & last mile. Common strategy for utility retailers from other industries like electricity.
Pure Retail	Network as a Service (NAAS)	Like a ServCo focussed on delivering to large corporates, government departments, and ISPs. Their products are typically software defined wide area networks (SD-WAN).
Pure Retail	Mobile Virtual Net. Operator (MVNO)	Provides retail mobile services using infrastructure provided by others. Although a range of models exist, typically an MVNO owns marketing, billing, and support.
Pure Retail	Demand Aggregator	Traditionally a billing intermediary for the demand-side organizations - allowing them to act as a single buyer. Emerging micro-aggregation models exist in Thailand and India.
Retail + Infrastructure	CATV ISP	Evolution of a Cable TV provider, a CATV ISP typically starts delivering Internet via Hybrid Fibre Coax (HFC) then migrates to GPON to leverage existing passive infrastructure or agreements.
Retail + Infrastructure	Wireless ISP (WISP)	Provides Internet service and occasionally VoIP direct to consumers using their own infrastructure, typically based on fixed wireless access, often using open spectrum.
Retail + Infrastructure	FTTH ISP	Provides Internet service and occasionally VoIP direct to consumers using their own infrastructure, typically based on GPON, most often with cables hung on existing utility poles.
Retail + Infrastructure	Mobile Network Operator (MNO)	Provides IMT mobile voice and broadband using its own radio access and core network infrastructure. Sells direct to consumers. Own or lease towers, buildings, fiber, microwave, spectrum.
Retail + Infrastructure	Full Service	Vertically integrated provider owning or leasing the infrastructure required to provide triple-play or quadruple-play services direct to retail subscribers.

CATV = Cable Television, FTTH = fiber to the home, GPON = gigabit passive optical network, IMT = international mobile telecommunications, ISPs = internet service providers, MNOs = mobile network operators, SD-WAN = software-defined wide area network, VoIP = voice over internet protocol

Source: Author.

New models for operators have emerged around the world, disrupting the vertically integrated models of previous decades. In some cases, they have emerged due to regulation or financial incentives, and in other cases because they are the best approach to the market.

Structural separation is the idea that separate companies or business units handle the component parts of a utility or telecommunications provider such as operating last mile infrastructure or selling retail services. The concept was first seen in electricity markets around 20 years ago but has been applied to gas and rail utilities as well as telecoms.[85]

[85] OECD. 2016. *Structural separations in regulated industries: Report on implementing the OECD Recommendation*. Paris.

Profile	Activities	Example
Long term assets, low borrowing costs, often controls a bottleneck. Higher bandwidth than available substitutions.		NetLink Trust, Gigatel Solutions India
Long term assets and low borrowing costs. Greater competition than FibreCo but larger customer base.		Frontier Tower Associates Engro Enfrashare
Higher margins than passive InfraCos. Generally low borrowing costs. More complex business to operate.		Fibre@Home ProtelIndo, Sacofa
Higher complexity and profit than Infracos. Can control bottlenecks in some locations. Mixed borrowing costs.		Asia Networks (Equis) DenseAir
Low risk for monopoly OpCos. Higher risk in competitive markets. Potential mix of assets & borrowing costs.		Alita Indonesia NBNCo, Chorus
Viability varies by market. In some regimes, spectrum can be financed or traded without restrictions.		Columbia Capital Hautaki, Silke Comms.
ServCo's primary expenses are marketing, support, and billing. Low-risk if additional to an existing business.		MyRepublic Trustpower
Nascent model found in evolved, disaggregated markets. Few assets beyond core switches and software systems.		PacketFabric, Megaport
Low-risk way for existing brands to expand offerings into mobile. As a stand-alone business it's a higher risk activity.		Line Mobile Penguin
Established model for govt procurement. Nascent model for micro-scale purchasing promoting Internet access.		Consip (govt buyer) Net2Home, PM-WANI
Evolutionary model based on existing infrastructure, CATV ISPs can be low-risk, high margin businesses.		Asian Vision Buenavista
Where regulations permit WISPs in open spectrum, a lowrisk micro enterprise that can scale organically.		Wantok AirJaldi
Viability and risk depends on pole-hanging rights. Lowcost if aerial fiber, high cost if trenched or in conduit.		Link3 Bangladesh WorldLink Nepal
Viability and risk depends on the company's ability to acquire radio spectrum and tower co-siting.		Digi Malaysia Tashicell Bhutan
Traditional telco, most common amongst incumbents. Complex, expensive, high-risk for new entrants.		Telecom Fiji Uztelcom Uzbekistan

Activities Key

- Ducts & Vaults
- Poles
- Towers
- Buildings
- Dark Fiber
- Lit Fiber
- Microwave
- Core Network
- Copper/Fiber Access
- Radio Access
- Spectrum

Separation is a tool some regulators apply to address market failures when a vertically integrated company has competitive activities (like the provision of retail broadband) that are linked to a bottleneck (non-competitive activity, often upstream of the value chain) like ownership and maintenance of towers, utility poles or fiber-optic cables, thus giving the vertically integrated company an unfair advantage.[86]

Bottleneck assets are placed under the control of an open-access infrastructure company, sometimes called an InfraCo, a NetCo, or an OpCo. Open access is the principle that a provider offers their services to all market participants on fair and nondiscriminatory terms and conditions. When initiated by a

[86] UNESCAP. 2021. *Towards Meaningful Connectivity: Insights from Asia-Pacific Case Studies*. Bangkok.

regulator, the open-access infrastructure company created is often a regulated monopoly for some or all the country.

The new roles and commercial entity types that have developed to compete in separated markets are summarized in Figure 18.

When incumbents structurally separate, it is often due to regulatory pressure. Notable regional cases include the split of Telecom New Zealand, Singapore's Next Gen NBN, Australia's NBNCo, and Papua New Guinea's creation of PNG Dataco, all actions intended to improve market efficiencies. Cambodia's government has intervened to address unsustainable overbuild, compelling ISPs to seek infrastructure services from one of the country's two licensed fiber operators.[87] Impacts have varied. Singapore and New Zealand's separated networks led to ubiquitous low-cost, high-speed fiber, Australia's did not, and the impacts of Cambodia's actions are yet to be fully understood.

Structural separation is not always the result of regulation and does not always start with incumbents. McKinsey found numerous benefits to splitting infrastructure out of integrated retail providers[88] including, for InfraCos, improved capital access, lower borrowing costs, and greater addressable markets.[89] CapGemini found economic savings and lowered carbon footprints enabled by separation and the resulting infrastructure sharing between competitive MNOs.[90]

Entities in markets with a degree of separation have different risk and return profiles from fully integrated providers and attract different types of investors. Infrastructure companies own assets they can manage over long periods. They are a favorite of pension funds and institutional investors for equity type returns without the volatility.[91] Retail companies plan and execute in short cycles, typically 2 or 3 years at a time, and are often publicly listed. Companies in other industries with strong brands but no telecommunications experience can enter the market as ServCos or mobile virtual network operators with relatively low risk.

Commercial motivations, a predicted (and later realized) increase in shareholder value, drove the Czech Republic's O2 into a voluntary structural separation in 2014.[92] Commercial necessity can also motivate the formation of InfraCos and their use by facilities-based operators. Due to overloading of their utility pole assets by as many as eight providers in some cases, the Nepal Electrical Authority significantly raised fees for their poles.[93] ISPs in Nepal could soon find using a single InfraCo to share fiber will be more economic than paying increased rates.

A healthy and active TowerCo market in Asia is a good example of economic benefits of separation. TowerCos exist to build, own, and operate mobile towers but do not offer mobile services. As specialist telecommunications real estate companies, TowerCos can be efficient at what they do and maximize the use of their assets by leasing them to multiple operators. MNOs in turn save money on rent and maintain focus on their core business by outsourcing what can be a complicated and time-consuming task.

87 S. Turton. 2022. Cambodia Creates New Snarls as It Tries to Untangle Its Internet Mess. *Nikkei Asia*. 3 June.
88 G. Grundin et al. 2020. Can Telcos Create More Value by Breaking Up? *McKinsey & Company*. 22 January.
89 DT Economics LLP. 2021. *Safeguarding the Road to 5G in Malaysia*.
90 N. Bhattacharjee et al. 2021. Telco Network Infrastructure: Structural Separation Is the Key to Maximize Value. *Capgemini Invent*. 22 November.
91 OECD. 2012. *OECD Working Papers on Finance, Insurance and Private: Trends in Large Pension*.
N. Anderson. 2021. The Infrastructure Bill & Pension Funds – A $3 Trillion Action Item. *Forbes.* 21 June.
92 D. Vavruska. 2015. Is Telecom Structural Separation the Right Response to New Digital Era Challenges?. *CitiGPS*. 3 June 3.
93 Online Khabar.

The International Finance Corporation found that developing markets with significant penetration of TowerCos had better coverage, higher speeds, lower costs, and less concentrated markets than those without. Their evaluation of TowerXChange data shows the South Asia and Southeast Asia regions to be leading the world in the share of towers managed by TowerCos.[94]

VII. FINANCE STRATEGIES

Addressing the affordability frontier can be aided by the removal of barriers, by using innovative technology, by introducing new business models, and with the introduction of innovative finance strategies. The following government interventions can help steer operators toward delivering on "meaningful connectivity" where the market has failed.

A. Service Obligations

From a budgetary perspective, obligations on carriers are attractive to regulators as they can help governments achieve universal access targets without making a cash commitment. Obligations can be tied to operating licenses, and often include a requirement to provide a certain threshold of quality in terms of performance and speed across a country. When tied to radio spectrum allocations, they often require a carrier to cover a particular percentage of the population with the spectrum within a particular time frame. Obligations can also be in the form of a revenue commitment to a USF or other fees, which are then used by the government to provide subsidies where coverage is needed.

Spectrum auctions are an opportune time for regulators to achieve additional rural and remote coverage through service obligations. France's regulator offered heavily discounted 4G spectrum in exchange for commitments focused on rural areas.[95] Brazil's regulator has attached a condition to its mid-band 5G auction requiring winners to roll out 4G/LTE to all towns with more than 600 inhabitants.[96]

B. Smart Subsidies

Rural markets without connectivity can sometimes be commercially sustainable if a one-time subsidy is provided. Such smart subsidies, often funded from a USF, can be the incentive carriers need to expand into a new area.

A wide range of smart subsidy situations are possible. Technical assistance and used hardware might be enough to help a community network start up. Funding the extension of mains power lines to a hilltop could make a cellular tower viable. Concessional loans might change a business case. Vouchers distributed by governments to rural households can help pay for connections to commercial services.[97] The key to a smart subsidy is that it is the minimum required to help the market move in the right direction.

[94] International Finance Corporation, World Bank Group. 2021. *Enabling A Competitive Mobile Sector in Emerging Markets Through the Development of Tower Companies*. Washington, DC.
[95] ARCEP.
[96] A. Mari. 2021. Brazil kicks off 5G auction. *ZDNet*. 5 November.
[97] The Social Market Foundation. 2020. *Funding fiber*.

C. Subsidies for Open Access Infrastructure

Subsidies can unfairly advantage incumbent operators and have the potential to discourage competition from challengers. They can also fail if a firm later fails to maintain or abandons unprofitable infrastructure. Restricting one-time subsidies to open-access infrastructure is a way to lower these risks. Open-access towers, fiber conduits, and optical ground wire fiber backbones are all potential targets for investments that can lift the market while maintaining competition.

D. Limited Subsidies for Managed Services

Another approach to subsidies is to fund service for an anchor tenant to be served by new connectivity. This might be a school, library, government organization, or health care provider. Such a subsidy would provide an ongoing fee for provision of a service of particular technical characteristics, without being proscriptive about the method of delivery. It might include requirements for community access, wholesale access, or roaming to be provided from the funded connection. In the case of a funded service, governments leave capital contributions to the winning bidder and financing to the market.

Limited subsidies for managed services help governments avoid the strain of large capital contributions but can result in solutions that disappear when ongoing funding dries up.

E. Sending Party Pays

Governments frequently pay to provide services to their constituents. This could be through sponsoring toll-free phone numbers, paying for printing and postal rates for mailing paper documents, or by funding travelling teachers or nurses to visit remote communities. Many of these services could be provided digitally if key constituencies had reliable connectivity.

Since the COVID-19 pandemic, governments around the world have worked to deliver affordable e-learning to school-aged children using a range of strategies. In Mongolia the government mandated carriers provide educational traffic at zero-rate.[98] Some governments have provided internet vouchers to students, some have funded students directly, and others have funded providers for ongoing subscriptions.[99]

An alternative is for governments to directly pay carriers for government and educational traffic served on mobile networks. In this case, the traffic would come at zero cost to end users but would be accounted by the carriers and charged on a utilization basis. Such a scheme could help carriers earn revenue from rural and remote towers that might not otherwise be commercially sustainable.

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98 Bolor-Erdene, ICT in Mongolia, DigitalxADB Conference, 2021-10-12

99 S. Vella. 2021. Introducing Our Free Internet for Students Voucher. *Go Malta*. 20 May.
ADB Education. 2021. Towards Universal Digital Access in Education.
J. Gerritsen. 2021. Principals Worried about Students with No Internet. *RNZ*. 4 March 4.

VIII. POLICY RECOMMENDATIONS

Guidance for Enabling Last Mile Connectivity to Address the Affordability Frontier

The success of the region's collective digital future hinges on how well and how soon we provide the affordable, accessible, resilient, and reliant digital connectivity needed for the foundation and operation of an inclusive digital society. Securing an inclusive digital future for all, including the most vulnerable, is an urgent policy priority. Achieving this ambition will require rethinking how we view and address the digital divide and last mile connectivity.

A. Adopt and maintain a national broadband plan

- Frameworks like national broadband plans and digital strategies can help achieve low-cost broadband and internet connectivity. They can be the basis for regulatory regimes that encourage development.
- Best practices for plans and strategies were first identified by the 2004 Global Symposium for Regulators and have been expanded on by A4AI, the Broadband Commission, and UNESCAP.[100]
- Frameworks should be reviewed every 5 years to ensure they are keeping pace with technology.
- The following policy recommendations could be key parts of a national digital strategy to address the affordability frontier.

B. Focus on bringing the internet into the hands of all people

- Public internet access in the form of Wi-Fi hot spots is an important but limited method of providing equitable access. Closing the digital gender gap and promoting access for people with disabilities means bringing internet into the home where it can be used in private.
- Personal device ownership is key for private use but is still unaffordable for many. Elimination or reductions in value-added tax, import and customs duty, excise taxes, and telecom sector-specific taxes on low-end smartphones can help increase ownership where it's needed the most.

C. Streamline administrative processes to improve the efficiency of network investments

- National regulations should establish approved norms for telecoms infrastructure. Consistent and well-defined rules should be set around where and in what manner a licensed operator can install telecommunications infrastructure. Short masts, low-powered antennas, street furniture, conduits, and fiber-optic cable pathways installed in public spaces conforming to national regulations should never need permits or approvals from regional or local bodies and should be allowed without fees. National regulations eliminate many barriers to land access faced by telecommunications providers.

[100] SSRN Electronic Journal. 2011. *Implementation of National Broadband Plans: Agreed Regulatory Principles and Their Evolution.*

- For more significant infrastructure, a consultation and permitting process and timelines should be defined that puts the onus on officials to cooperate. Applications presented to a local body or an office of government should be deemed granted after a pre-defined period if not refused.
- Co-deployment—in particular the use of public transportation and utility corridors for broadband—should be enabled and promoted. "Dig once" regulations and nondiscriminatory corridor access policies should require infrastructure projects to make room for telecommunications conduits and cables on a cost-sharing basis.
- Charging for right-of-way access to public infrastructure and lands should be done on a nondiscriminatory, cost recovery basis. Regulations for co-deployment access should extend to corporatized public infrastructure companies such as railways, gas pipelines, and electrical grids which may seek commercial returns for access to their rights-of-way.

D. Encourage competition, innovation, and investment with flexible licensing regimes

- **Allow small internet service providers and community networks to fill the digital infrastructure gap in the last mile.** Regulations and licensing conditions intended for facilities-based operators can be too onerous or expensive to allow small ISPs and community networks to participate. These providers are often the key to addressing barriers of geography and population density.
  Operations licenses for small networks should be made available through a single-window administrative process that does not require lobbying, high fees, bonds, proof of capital, or an act of parliament. Such basic licenses should allow operators to build fiber or ISM wireless on private property or by taking advantage of commercial rights-of-way agreements.
  Additional licensing conditions could be imposed on operations growing beyond a threshold defined by the competition regulator thereby allowing networks grow the processes and support functions needed to support a communications business in an organic and sustainable way. Higher license tiers could allow growing businesses to access public rights-of-way and the ability to access licensed radio spectrum.
- **Improve competition by easing market entry restrictions of international operators.** Many countries restrict participation in local telecommunications markets to firms partly or majority owned from within their own countries, often due to concerns over national security or to ensure overseas firms do not exploit developing markets. Competitive national providers rarely have the resources to compete with incumbents at an infrastructure level and struggle to raise capital from within their own countries. International operators often see passive infrastructure like towers, conduits, and dark fiber as a low-risk, long-term investment in the future of a developing country but market entry requirements such as foreign ownership restrictions or partnership obligations can discourage investment. Open-access infrastructure can be of equal benefit to competitive providers and incumbents and can be the only efficient way of reaching rural and remote areas.
- **Allow global satellite companies to participate in the market on a fair and open basis.** Current licensing regimes in Asia are not conducive for global satellite broadband providers to enter the market and deploy the soon-to-be global coverage of their networks. For example, requirements to obtain retail service provider licenses or franchises to sell capacity into the wholesale market to carriers, ISPs, and community networks can slow market entry. Another example is the requirement to partner with local operators or land traffic onto incumbent operator network only, which may limit the benefits of the added bandwidth to reaching the last mile. Emerging non-geosynchronous orbit networks like StarLink, OneWeb, O3b, Telesat, Kuiper, and projects yet to come have great advantages over existing geosynchronous satellites. It would be prudent for policymakers and regulators to critically assess the potential impact of these emerging technologies in closing the digital divide in their country and facilitate market entry on a fair and nondiscriminatory basis. Allowing all

satellite broadband providers to sell capacity into the wholesale market without onerous localization or mandatory partnership requirements would be an example of such facilitation.

E. Manage spectrum in a way that supports investment predictability, optimizes spectrum efficiency, and maximizes social gain

- **A spectrum road map is an effective mechanism to identify and allocate spectrum** where it is idle or underutilized and sets out a timetable for future spectrum releases and license renewal decisions. Such a framework encourages investment by improving regulatory stability and transparency, especially when developed in consultation with the private sector. A regular review and update of radio regulation is also needed to be in line with the ITU Radio Regulations, which are updated regularly. National frequency allocation tables should be amended to reflect those updates. Unless compelling local circumstances necessitate otherwise, national band use and channel plans should be updated to match the latest ITU recommendations.
- **Make sufficient spectrum available for services that deliver the greatest benefits to society.** When the international community decides to allocate a new band to mobile telecommunications, regulators should proactively re-align spectrum use to open it up for use, a process also called re-farming or re-stacking. The low bands most effective for extending the affordability frontier are around 700 MHz for 4G and 600 MHz for 5G. Many of ADB's DMCs still do not have adequate low band spectrum available for carriers to service rural populations. Keeping the assignment of spectrum technology-neutral is another best practice that ensures technological and market efficiency. Sufficient spectrum can enable today's 4G networks to deliver the capacity users will need 5 years from now.
- **Spectrum pricing needs to strike the right balance between raising revenue and maximizing socioeconomic benefits of connectivity.** Research shows a strong link between high spectrum pricing and lower performance and coverage.[101] Governments also lose out on potential revenue and citizens lose out on the socioeconomic benefits from better quality network and coverage if high reserve prices during spectrum auctions leave spectrum unsold and therefore unused. Annual spectrum fees based on an operator's size can discourage them from growing their customer base, while fees based on the size of the network may deter network investment.
- **Open and harmonize ISM spectrum bands.** While licenses provide exclusivity use of radio spectrum, small providers throughout the world have found that—especially in rural and remote areas—exclusivity is unneeded. Open spectrum can be used without licenses, fees, coordination, or specialized equipment.

  The rules governing ISM spectrum are not negotiated in the ITU, but many regulators publish standards for short range devices that operate in ISM spectrum. Short range devices by design have a low risk of interfering with each other and with other radio services and include equipment like Wi-Fi routers, metering devices, RFID tags, telemetry, industrial control, and ISM band fixed wireless equipment. ETSI, the FCC, the UK's Office of Communications, the Australian Communications and Media Authority, and New Zealand's RSM all have permissive and compatible regulations for open spectrum. Harmonizing with these regimes for short range devices addresses barriers beyond just spectrum availability and equipment designed for open spectrum is less costly and uses less power than licensed band equipment.
- **Provide a public registry of radio spectrum.** Transparency of radio frequency assignments is the default position of many developed countries. Accurate public registries allow local governments, development agencies, and civil society to help understand where spectrum has been deployed, and where it goes unused.

[101] The GSM Association. 2019. *The Impact of Spectrum Prices on Consumers.*

- **Enable spectrum sharing and dynamic spectrum access to gain maximum efficiency.** Unused radio spectrum rarely benefits society, but it is a fact of life in most markets throughout the world. Mobile operators frequently acquire exclusive access to radio spectrum on a national basis, then deploy services only in densely populated or profitable areas. Dynamic spectrum access regimes allow secondary access to licensed radio spectrum, typically while ensuring primary rights holders are protected from interference. Secondary users can use lower cost equipment intended for lower population densities and may have lower operational costs due to their local presence and low costs for labor. Spectrum might be free for secondary use or charged on a usage basis, taking into consideration transmitted power, geographic coverage, and population coverage.
  Primary spectrum holders could be mobile operators, satellite or microwave networks, or television broadcasters. Enabling technologies include Citizens Broadband Radio Service, Automatic Frequency Controller, and Television Whitespace. The success of Citizens Broadband Radio Service rural LTE networks in the United States[102] is an excellent example of the potential for spectrum sharing.

F. Digital finance has an important role to play

While digital investment has been and will continue to be the remit of the private sector, there are unique and important roles for development finance from multilateral development banks or other donors to play in closing the digital gap.

- Assist governments in closing the market efficiency gap by addressing market failures and optimizing regulatory and investment conditions for the private sector. In many developing countries, regulations and market interventions have not kept pace with technological advances and licensing structures are not conducive to competition or innovation. As private sector investment in digital connectivity requires heavy up-front investment and a long runway to recoup costs, governments need to crowd in the private sector for much-needed investment and promote market-based solutions by streamlining rules and regulations and improving the business environment.
- Contribute to closing the access gap in communities deemed by the private sector to be too expensive to serve due to low population density, difficult terrains or poverty levels. Here, development finance can support governments to fill the gaps through targeted measures like smart subsidies or universal service funds.
- Encourage innovation in technologies, business models, and use cases and help identify and demonstrate the feasibility and viability of innovation and emerging technologies in serving the unconnected.
- Augment government efforts to build a digitally literate and skilled society. Lack of digital skills currently prevents many from getting online or limiting their ability to get the most out of digital opportunities, creating a usage gap. Poor digital literacy also exposes vulnerable populations to potential threats and abuse such as cyberattacks or scams.

Collaboration among governments, the private sector, and development partners is the key to creating a more prosperous, inclusive, resilient, and sustainable digital future.

[102] Wireless Infrastructure Association. 2020. *CBRS Could Help Close Urban and Rural Coverage Gaps*. 9 July.

APPENDIX 1: RADIO SPECTRUM PRIMER

Radio spectrum relevant to last mile communications is discussed with four uses cases in the main body of the paper. This section provides a more thorough explanation.

Figure A1.1 categorizes spectrum in common commercial use in Asian Development Bank (ADB) developing member countries (DMCs) into the three bands mentioned in the paper: low, medium, and high, and the four use cases: mobile (3G, 4G, 5G), ISM or open, fixed or microwave, and satellite.

A. Mobile or International Mobile Telecommunications Spectrum

International Mobile Telecommunications (IMT) is the International Telecommunication Union (ITU) designation for broadband cellular mobile systems. The term is used in the industry and in this paper interchangeably with "mobile" when discussing radio spectrum.

Mobile spectrum can be used to provide itinerant, fully mobile, or fixed wireless access (FWA) connectivity.

Frequencies and band plans for mobile spectrum are agreed on a regional basis through ITU World Radiocommunication Conferences. Most ADB's DMCs are part of ITU Region 3 but its Commonwealth of Independent States members are aligned with ITU Region 1.

ITU processes are important for cross-border coordination but in the end, it is up to the regulators in each country what spectrum will be used locally and for what purposes.

B. Mobile Spectrum Assignment

Regulators can assign mobile spectrum through an administrative process, sometimes attaching utilization or universal service conditions to its use, but most often spectrum is auctioned for national use.

Spectrum auctions operate under the premise that those who value the spectrum the most will put it to the best economic use. Many auctions turn spectrum into a property right that can be used, leased, traded, or left idle for a specified period, of time—often 20 or more years.

Auctions are not without their drawbacks:

- Funds spent by an operator on spectrum auctions are not spent on infrastructure.
- Operators who take on debt to fund spectrum pass interest costs on to customers.
- Auction returns are rarely dedicated to universal service activities.
- The most economic use of spectrum for an operator may not align with the best use for the country.

This last drawback is often seen with high-capacity mid-band spectrum. Carriers may find it profitable to use mid-band spectrum only in cities, leaving it idle in rural areas.

Governments who divide spectrum into geographic parcels with urban–rural splits may find different companies are interested in using the spectrum in different ways and paying a different price based on the population density and terrain of the parcel.

Coordinated secondary use is an option to get idle spectrum into use without formally dividing national rights into urban and rural parcels. The Federal Communications Commission (United States) Citizens

Broadband Radio Service program for the 3.5 GHz band enabled a huge amount of innovation in rural and remote connectivity and low-cost long-term evolution (LTE) ecosystem development. Spectrum access systems and priority access licenses are also being developed for other bands including 6 GHz.

Figure A1.1: Spectrum Bands in Common Use in ADB's DMCs

	Frequency Band	3G	4G	5G	ISM	MW	SAT	Description	Band Properties
Low Band Spectrum	450 MHz							450 MHz provides the best possible rural and remote coverage, though at low capacities.	Low band spectrum easily travels tens of kilometers. It penetrates into buildings and through vegetation well and is never impacted by rain. It's scarce and valuable, and fetches the highest price per MHz at auction. Its properties mean its best use is providing consistent coverage, not high capacity data. The largest blocks of low-band spectrum available are in the 600 and 700 MHz bands, which were previously used for television.
	600 MHz							Typically used for TV broadcasting, the 600 MHz band will be used in some markets for rural and remote 5G coverage.	
	700 MHz							700 MHz is the original Digital Dividend from analog TV shutoff. Harmonized across Asia, it's used extensively for 4G rural networks.	
	850 MHz							Originally a CDMA band aligned with North American networks, today most operators use it for 4G networks.	
	900 MHz							The most common band for 2G & 3G services, also used for 4G. ISM use is typical from 915-928 MHz with protocols like Zigbee and LoRaWAN.	
Mid Band Spectrum	1.5 GHz							1.5 GHz is used most often for GPS and mobile satellite voice and data. Some countries are opening it to use with 5G.	Mid band spectrum is key to adding more capacity for rural mobile networks in Asia building penetration & vegetation penetration decrease, but the amount of available spectrum goes up. Radio waves in the mid band are smaller than those in the low band, enabling far smaller antennas. In the 2.6 GHz band, cellular antennas around 1.2 meters tall are common. In the 3.5 GHz band, antennas are often less than a meter tall and a few hundred mm wide, enabling them to be mounted on utility poles. Mid band mobile cell radii typically range from 2-15 km, especially for 5G but for 4G fixed wireless use it's common to have connections to towers 30 km distant. Most developed markets have transitioned the 3.5 GHz band from satellite to 5G, but some developing markets have not. The 2.4 and 5 GHz ISM bands are both mid-band spectrum. They're used heavily for both local access Wi-Fi and, where regulations allow, for long-distance fixed wireless use.
	1.8 GHz							1.8 GHz is the second most common band for 2G and 3G services. Today it's mainly used for 4G/LTE in high and medium density areas.	
	2.1 GHz							2.1 GHz is the most common band for 3G services. It now has extensive 4G use also.	
	2.3 GHz							The 2.3 GHz band is the lowest common Time Division Duplex (TDD) band used for mobile 4G/LTE services.	
	2.4 GHz							2.4 GHz ISM is used for Wi-Fi, Bluetooth, and electronics throughout the world. A small part is allocated to mobile satellite service.	
	2.6 GHz							Contains both Full Duplex (FDD) and TDD bands used for mobile 4G/LTE services.	
	3.5 GHz							The band from 3.3-3.8 GHz is a popular band for new 5G deployments, and the first where many countries are offering 80 or 100 MHz channels.	
	4 GHz							The band from 3.8-4.2 GHz and the band around 4.8 GHz are typically used by satellite links but are candidates for 5G services.	
	5 GHz							5 GHz ISM band is used for Wi-Fi and consumer electronics, but also for license-assisted supplementary LTE capacity and ISM FWA.	
	6 GHz							6 GHz has historically been used for microwave backhaul. Some markets are opening it to ISM devices (Wi-Fi 6), others considering 5G.	
High Band Spectrum	7-11 GHz							7-11 GHz is critical for linking rural and remote communities via microwave. It has a good balance of capacity and high immunity to rain.	High band spectrum is high capacity, and often short distance. Above 10 GHz it doesn't penetrate buildings, vegetation or rain. When used for mobile, it's intended for the dense cities and cell radia around 100m. When used for fixed linking, high band spectrum needs highly directional antennas and high power levels to cope with rain fade. LEO/MEO satellite networks require antennas that can mechanically or electrically steer their energy to moving targets.
	12-20 GHz							Some fixed linking use and extensive satellite use.	
	20-30 GHz							Little used today aside from satellite, it will soon be the foundation of mmWave 5G. Fixed links present around 23 GHz	
	50-70 GHz							In many advanced markets, the lower half of the band is open access, and used for broadband systems both indoors and outdoors.	
	70-90 GHz							Mainly used for fixed linking up to a few kilometers, E-band can provide connections of 40 Gbps today and 100s of Gbps in the future.	

CDMA = code-division multiple access, FWA = fixed wireless access, GHz = gigahertz, ISM = industrial scientific, and medical, km = kilometers, LEO = low earth orbit, LTE = long-term evolution, m = meter, mm = millimeter, MW = Microwave, MEO = medium Earth orbit, MHz = megahertz.

Source: Author

Nascent or future use

C. Open Spectrum

Open spectrum is not auctioned or assigned but left open for anyone to use. The best-known blocks of open spectrum are the international medical and scientific (ISM) bands. These bands are intended for devices that can be operated without explicit permission, although conditions of use (for example applications or power levels) are often regulated. Some countries have chosen to open spectrum adjacent to the ISM bands to improve their utility.

The 2.4 GHz band used by Wi-Fi and Bluetooth is the best-known open spectrum band and the most used on a global basis; billions of devices use it daily. Less commonly known open spectrum bands exist across the spectrum, from below 1 MHz through to 245 GHz.

In some economies, open spectrum bands are used outdoors for FWA and for fixed point-to-point linking. Lightly regulated globally harmonized bands in developed markets have led to inexpensive, readily available equipment suited for the task. Open spectrum band FWA devices are available from the low tens of dollars with ranges into the high tens of kilometers. They are the foundational devices of most wireless internet service providers (ISPs) and community networks.

Whether open spectrum FWA can be used effectively varies by market but is contingent upon

- regulations that allow use of open spectrum outdoors, with sufficient power levels;
- availability of spectrum beyond the most popular 2.4 GHz band (for example 5GHz);
- attention by regulators to market demands to expand bands when needed (Wi-Fi 6e); and
- ability of entities (ISPs, WISPs, community networks) to use open spectrum FWA to provide internet service without a license, or with a low-cost administratively granted license.

Some ADB's DMCs allow the use of ISM FWA by individuals or companies for their own use but disallow its use by ISPs without a facilities-based telecommunications license.

D. Fixed Linking or Microwave Spectrum

Microwave spectrum is used for point-to-point links of a few megabits up to tens of gigabits per second, depending on the band and distance. Links of up to two gigabits per second are viable up to 100 kilometers (km), while links of 40 Gbps rarely reach beyond 5 km.

Microwave tied together nations and continents in the days before ubiquitous fiber backbones. At 2 Gbps per channel in many bands, it is fast and performs well enough to provide backhaul for small, fixed networks today, even those offering fiber to the premises (FTTP) services. Its use as a backbone now is mainly restricted to mountainous and island areas where it is not practical to install fiber, but its use overall is extensive. Today and for the foreseeable future, microwave is still the most common backhaul method worldwide.[1]

The most common use for microwave is to connect cell towers without fiber access, or to provide resilience in case of a fiber break. In countries with less developed fiber infrastructure, up to 90% of cellular towers use microwave; in other countries the rate is only 20%–30%.[2] Microwave is also used by ISPs and companies in urban markets to connect buildings where terrestrial fiber is not available for commercial reasons.

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1 Digital Empowerment Foundation. Community networks – a boon in times of pandemic and lockdown.

2 B. Hussain. 2021. Facebook, Nayatel Partner to Invest in Fiber Networks in Pakistan. *SAMAA*. 26 May.

E. Microwave Spectrum Assignment

Microwave channels are rarely auctioned—they are most often assigned through an administrative process. Assignment can be on a national or regional basis as with mobile spectrum, or spectrum can be shared and coordinated on a per-location basis.

In the Asia and Pacific region, Australia and New Zealand use a public registry of radio spectrum and independent engineers to coordinate use of the microwave spectrum. In the Philippines and Singapore, the regulator provides coordination services. In India, channels are allocated on a regional basis instead of being coordinated.

F. Microwave Spectrum Cost

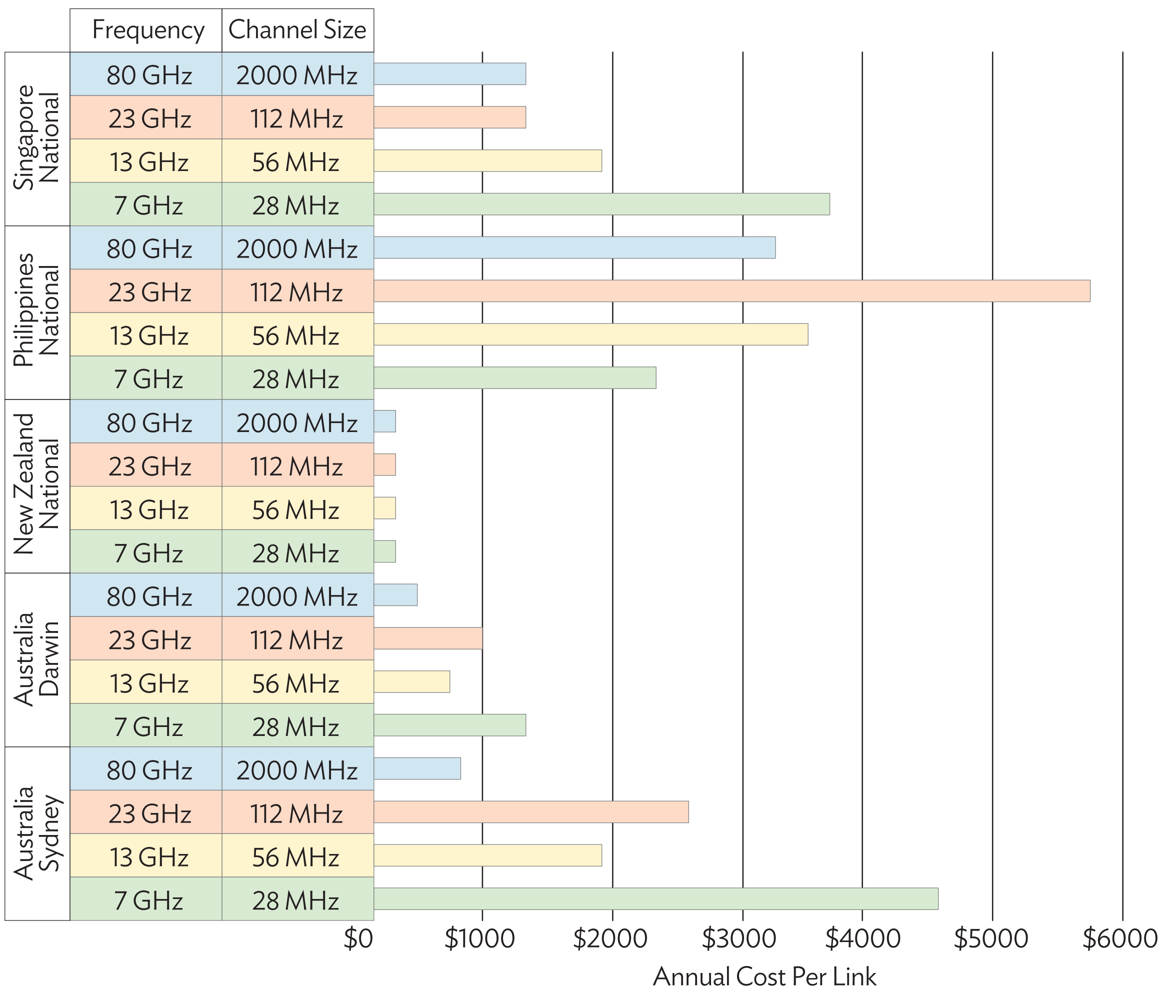
Charging methods for using microwave spectrum range from fixed-fee administrative levies to formulas that consider the frequency, bandwidth, population density, and distance of the link.

The most typical charging regimes set a price per MHz which varies with the band, growing lower as frequencies and spectrum reusability increase. Such tables are problematic in many markets, as the amount of spectrum used by modern microwave systems is far higher than systems designed 20 years ago. Several methods of charging are illustrated in Figure A1.2, including table-based (Singapore and the Philippines), flat rate (New Zealand), and spectrum scarcity and geographic differentiation (Australia).

Figure A1.2: Microwave Spectrum Costs in Selected Markets

Frequency	Channel Size	Capacity (XPOL*)	Distance (Typical)	Distance (Max)
80 GHz	2000 MHz	20 Gbps	2 km	10 km
23 GHz	112 MHz	2 Gbps	3 km	15 km
13 GHz	56 MHz	1 Gbps	15 km	40 km
7 GHz	28 MHz	0.5 Gbps	30 km	100 km

*XPOL or cross-polarization uses the same frequency with two or more sets of waves in different orientation, increasing spectral efficiency



Source: Australian Communications and Media Authority. Fees for Apparatus Licences | Australian Communications and Media Authority. https://www.acma.gov.au/fees-apparatus-licences (accessed 1 March 2022); Spectrum Management Handbook, Issue 1 Rev 2.14. Infocomm Media Development Authority of Singapore, January 2022; Kintanar, Simeon L., Fidelo Q. Dumlao, and Consuelo S. Perez. Memorandum Circular No. 10-10-97, Subject: Spectrum User Fees. National Telecommunications Commission of the Philippines, October 10, 1997; Zealand, Radio Spectrum Management New. Annual Licence Fees. Radio Spectrum Management New Zealand. Accessed March 1, 2022. https://www.rsm.govt.nz/licensing/fees-for-licences-and-certification/annual-licence-fees/.

G. Satellite Spectrum

Most satellite spectrum was dedicated to broadcasting or broadcasting support 2 decades ago. A major shift has occurred since then and much of the C-Band or 3–4 GHz spectrum used for satellite broadcasting has been re-assigned to mobile for use with 5G.

The bands used for satellite downlinks to subscribers are now mainly around 12, 19, and 29 GHz.

Satellite bands have gained additional spectrum in the 18 and 27 GHz bands for use in backhaul. In the 18 GHz band this has come at the expense of fixed linking spectrum, which has had its allocation reduced. The 18 and 27 GHz bands used for connecting satellites to Earth stations have immense capacity. They will be critical in enabling the predicted tenfold growth in sellable satellite capacity between 2019–2025.[3]

H. Satellite Spectrum Assignment

UN member states can apply for use of satellite spectrum through the ITU. Commercial space ventures apply for use of satellite spectrum with the support of the regulator of a member.

I. Satellite Spectrum Use and Cost

Straightforward fees are associated with securing licenses to operate satellites in space, and to use a resource that consists of transmitting on a frequency from a particular orbit (orbit-spectrum).

Ease of spectrum use, once secured, can vary depending on the end market. Australia and New Zealand allow satellite operators to radiate signals onto their territories (provide a downlink) without authorization, individual licenses, or fees. They provide a free, automatic general user license for unprotected return communications from user terminals on the ground. Other countries can impose license conditions and fees on any downlinks that can vary depending on the commercial value of the service on offer. The set of rules and fees is often informally called landing rights and is different in every country.

J. Terrestrial Frequencies in Space

While some bands are allocated on an international basis through the ITU Radio Regulations for terrestrial use, nascent satellite providers are testing their use from low Earth orbit. These providers plan satellite networks that will provide Internet of Things (IoT) connectivity and mobile voice and data services from space directly to standard smartphones and IoT devices that would normally connect to a cellular tower. Use of terrestrial frequencies from space does not conform with existing allocations and these providers might need to seek waivers from regulators in every country where they want to operate.

[3] H. Chang et al. 2021. Can You See Me Now? A Measurement Study of Zoom, Webex, and Meet. Prepared for the 21st ACM Internet Measurement Conference. New York, USA November 2021.

APPENDIX 2: NETWORK DEMAND MODELLING

Network demand modelling helps plan network capacity to ensure quality of service. It is a tool that considers current and future network utilization and the capacity of access networks and backhaul links. Planning considers current peak hour demand, demand growth, and for third-party backhaul, contract length and ability to increase capacity as time goes on.

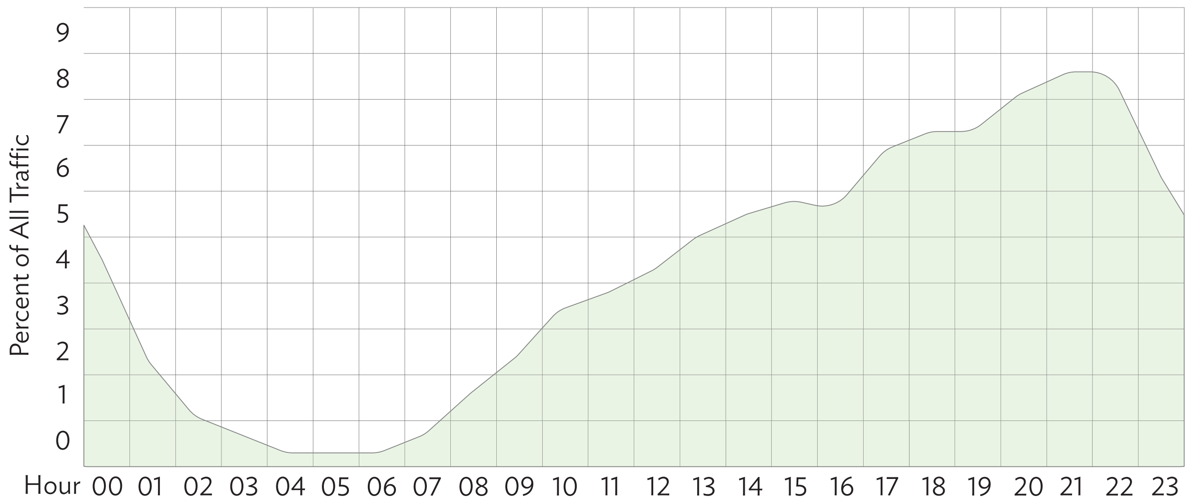
Peak hour is the time of day when most traffic is consumed. The model in Figure A2 is an example based on a common utilization pattern that can be seen on Google's Transparency Report[1] or at regional internet exchanges like BKNIX[2], GetafIX[3] or NPIX.[4] Little traffic occurs in the early morning, and a peak hour or hours occurs in mid-evening when around 8%–9% of all daily traffic is consumed in each hour. While the magnitude of daily peaks varies between networks, regular peaks and lulls are always present.

Networks should be dimensioned based on a peak hour utilization of 80%. This ensures blocking, or denial of resources, is lower than 1% based on the Erlang formula.[5] It is common practice among many providers to order additional capacity when utilization reaches 60%, so the new capacity is ready before the 80% threshold is reached and service begins to degrade.

For fiber backhaul networks, full capacity of links is available 100% of the time. For modern radio-based backhaul links like microwave and satellite, capacity can vary based on conditions. A link might be available 99.995% of the time but running at peak capacity only 99.9% of the time.[6] The potential for increased blocking in times of adverse weather conditions should be considered when designing service level agreements and negotiating with regulators when services are subject to universal service commitments.

1 Google. Google transparency report.
2 BKNIX | Bangkok Neutral Internet EXchange. https://bknix.co.th/en/.
3 GetaFIX. https://ixp.getafix.ph/statistics/infrastructure.
4 Internet Exchange Nepal. Traffic.
5 T. Bonald and J. Roberts. 2012. Internet and the Erlang Formula. *ACM SIGCOMM Computer Communication Review 42, no. 1 (January 16, 2012): 23–30*. 16 January.
6 S. Axelsson. 2020. How to Increase Capacity in Microwave Networks with the New Normal. *Ericsson*. 6 May.

Figure A2: Internet Traffic Utilization and Peak Hour



Source: Author

For mobile traffic, if an average user in 2026 consumes 40 GB of data as estimated in Figure A2, we can expect per-user traffic will be around 0.25 Mbps during the peak hour(s) of the day. This figure is expected to increase 30% annually, as it has done over the past 10 or more years.

A. Mobile Spectrum Requirements

Modelling last mile network capacity for mobile networks is not just a matter considering the peak efficiency of the equipment deployed. Mobile networks provide service to a wide range of receivers at different distances and across different radio conditions—some of which could be stationary and some mobile. Some receivers may have high signal levels and be able to receive and decode complex information, while other receivers may have weaker signal and may require less complex modulations to communicate. For this reason, access network capacity should be based on average spectral efficiencies rather than peak efficiencies.

ETSI finds LTE-Advanced average spectral efficiencies are between 2.7–5.2 bit/s/Hz[7], and the ITU finds 5G average spectral efficiencies are between 3.3–9 bit/s/Hz[8]. These figures are far lower than the peak efficiencies per ITU-R requirements[9] that are often cited in media reports.

Assuming an LTE sector has a 20 MHz carrier operating at 3.5 bits/Hz efficiency, end users would share a pool of 42 Mbps of network downlink capacity. That sector could support 168 users at 2026 data rates, and 54 users at 2032 data rates.

7 ETSI. 2018. *Technical Report 3GPP TR 36.912 Version 15.0.0 Release 15*.
8 International Telecommunication Union. 2017. *Report ITU-R M.2410-0 Minimum Requirements Related to Technical Performance for IMT-2020 Radio Interface(s)*. Geneva.
9 European 5G Observatory. 5G Performance.

APPENDIX 3: MOBILE NETWORK QUALITY OF SERVICE

Modern mobile networks—from the 3G standard on—were designed to cope with limits on spectrum and high user demand by providing quality of service for key applications offered by mobile carriers. Quality controls can prioritize traffic into categories with attributes including permissible loss and delay, guarantee of delivery, and priority when facing network congestion (figure A3).

Figure A3: Mobile Network Quality of Service

QoS Class Identifier (Quality of Service ↑)	Guaranteed Resources?	Allowed Latency in miliseconds	Example of Service
1	Y	100	Carrier Voice Call
2	Y	150	Carrier Video Call
3	Y	50	Carrier Real Time Gaming
4	Y	300	Carrier Video Streaming
5	N	100	Carrier IMS Signalling
6	N	300	Video, TCP Web Traffic (Premium)
7	N	100	Voice, Live Stream Video, Gaming
8	N	300	Video, TCP Web Traffic (Premium)
9	N	300	Video, TCP Web Traffic

While carrier voice calls are still an important network service and source of revenue, they're not what people primarily use mobile networks for anymore.

The mobile applications preferred by most people are not high priority voice or media services, but instead over-the-top (OTT) TCP Web Traffic. In general these applications fall into the lowest level of quality on a mobile network, with little consideration for latency and no guarantee of timely delivery.

TCP Web Traffic:
OTT Messaging, Voice, Video, Conferencing, e-Learning, e-Medicine, Social Media, Web access
Premium:
For networks that support priority services, premium content, or offer premium service tiers, QoS markings can be used to ensure some services or users are prioritized over others.

Imperceptible network delay (green: 100, 150, 50, 100, 100) — Noticeable network delay (orange: 300)

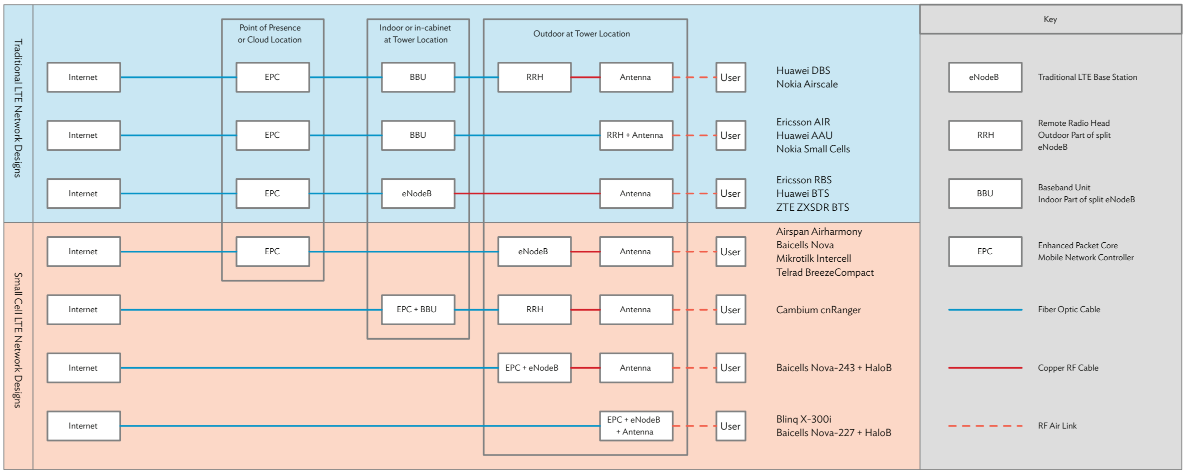
Source: Adapted from 3GPP TS 23.203 Version 15.4.0 Release 15

In practice, what most people use on mobile networks are not prioritized carrier offerings, but internet-based over the top (OTT) applications. A video call with a doctor or a lesson on an e-learning platform generally will not have priority over video streaming or social media use. Such apps can work to optimize their performance when they detect they are in a low-data or mobile environment, but mobile networks generally treat all OTT data as best effort.

APPENDIX 4: LTE NETWORK ARCHITECTURES

Small cell network architecture intended to support rural and remote connectivity varies from traditional network design. In the most tightly integrated designs, all hardware and software elements required to provide basic LTE service can be found in a single antenna unit. In the most common designs, outdoor eNodeB units are attached directly to antennas, and communicate with a network core located off-site. Seven common architectures are illustrated below (figure A4).

Figure A4: Long-Term Evolution Network Architectures



Source: Author.

APPENDIX 5: 5G TECHNOLOGIES

The most talked about disruptions to mobile networks in 2021 are disaggregated, open, and virtualized radio access networks. Three key concepts underpin this trend: the splitting or disaggregation of mobile network functions into software modules, the ability for those software modules to operate on general purpose computing devices (servers), and the opening of interfaces that connect the network functions.

The only architectural change necessary for 5G networks is disaggregation. Splitting components is necessary for new networks to meet the high-performance latency specifications set by 3GPP for 5G.

Disaggregated software functions can be run on specialized systems, on general purpose computing devices, or inside virtual machines or containers run on general purpose servers or in the cloud. The latter technique, sometimes called Cloud RAN, is a way of abstracting software from hardware that can have benefits for resiliency and scale.

Standard, open interfaces between software functions are not necessary to meet 5G specifications but are the goal of the O-RAN Alliance. Founded by mobile operators in 2018 O-RAN is seeks to guide the industry away from single-vendor solutions and toward interoperable, multi-vendor solutions for 5G.

There are several possible configurations of these technologies in modern networks, and most 5G solutions today do not employ them all. Closed, single-vendor networks will persist for years to come as the default business model of the incumbent suppliers.

A. OpenRAN

OpenRAN is a group within the Telecom Infra Project (TIP) with the express mission to combine them all. They seek to define and publish hardware and software designs for 2G, 3G, 4G, and 5G networks that are disaggregated in design, capable of running in containers or on general purpose computing devices, and use open interfaces to communicate. OpenRAN vendors building off these designs do so with the knowledge they are participating in an ecosystem that will be a major shift from the single-vendor solutions of the past decades.

OpenRAN is not likely to reduce the cost or complexity of building 5G networks over 4G networks, and prices for OpenRAN equipment are not low. Widelity found and Nokia reaffirmed that for rural networks: "the heart of the pricing range is the same for open RAN and integrated RAN."[1] The concept will increase the flexibility of carriers: to choose best-of-breed systems; to de-risk investment strategies by engaging diverse suppliers; and to speed up or slow down investment cycles by upgrading specific components or compute resources when demand requires, and budget allows.

B. Neutral Host Distributed Antenna Systems

Distributed antenna systems (DAS) are a set of antennas and transmission equipment installed in high-density locations like transport hubs, stadiums, or large buildings. Neutral host DAS are those run by a third party—not a mobile carrier—as open-access infrastructure.

DAS are installed to solve coverage problems where a traditional tower or street furniture cannot provide coverage due to limits on physical space or radio propagation or cannot provide enough capacity.

Antennas range in size from that of a Wi-Fi hot spot through some the size of a briefcase. Most often they are installed in ceilings or on walls, but sometimes outdoors on streetlights or stadium lights. Fiber or coaxial cables connect antennas to a central hub where they attach to one or more mobile base stations.

DAS can be installed for a single carrier, but the real innovation in this space is neutral host systems. These are typically installed and operated by a third party to support multiple operators, frequencies, and technologies, including 3G, 4G, and 5G.

Ninety percent of CTOs surveyed by McKinsey believe third-party neutral hosts will supply parts of networks shared by multiple operators.[2]

1 M. Dano. 2021. Mavenir to FCC: Yes, Open RAN Is Cheaper. *Light Reading*. 27 May 27.
2 F. Gripink et al. 2019. Cutting through the 5G Hype: Survey shows telco's nuanced views. *McKinsey & Company*. 13 February.

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Last Mile Connectivity

Addressing the Affordability Frontier

This working paper addresses the challenge to implement 'last mile' solutions that deliver affordable internet connectivity to communities in Asia and the Pacific region. It examines how COVID-19 increased demand for internet access and explains why new technologies are failing to deliver affordable connectivity to rural and remote populations. It explores access gaps and details technological, regulatory, and investment strategies that can help close the digital divide. Explaining how last mile connectivity can provide affordable, resilient, and reliable solutions, it shows why it is central to building an inclusive digital future for all.

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