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A Multi-Layer Framework for Enhancing Satellite Connectivity in Remote and Rural Areas

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Abstract

In this research paper, a multi-layer approach is proposed to improving satellite connectivity in remote and rural locations, where the average revenue per user, the strength of the power infrastructure, the backhaul quality, and the terrain are oftentimes not conducive to a profitable terrestrial broadband service. The study adopts a research-synthesis and design-science approach, incorporating recent peer-reviewed research on satellite communications, the 3GPP non-terrestrial networks (NTN), satellite Internet, rural broadband, direct to device connectivity, satellite IoT, and field deployments and integrating them with prevailing ITU guidance. The proposed architecture has six layers: space, transport, access, edge/service, energy, and governance, all of which are coordinated by a cross-layer orchestration function. The framework does not view satellite broadband as an alternative solution to terrestrial infrastructure; instead, it considers GEO, MEO, LEO, cellular, Wi-Fi, fixed wireless and IoT links as complementary technologies to be used depending on the need for latency, capacity, coverage, cost, reliability and local services. The paper suggests a hybrid, multi-connectivity model as the most suitable: fibre/microwave except where impractical; satellite should fill geographic and resilience gaps; local access networks group demand at community level. Three analytical tables compare orbital options, define the proposed framework and map use cases to performance requirements. The authors conclude that though technical integration is essential, the sustainable rural connectivity also needs renewable power, affordability of terminals, transparency of spectrum and licensing process, local maintenance capability, community involvement, cybersecurity, and outcome-based universal-service policy.

Keywords: satellite connectivity; rural broadband; remote areas; non-terrestrial networks; LEO; GEO; 5G-NTN; satellite backhaul; direct-to-device; digital inclusion

Introduction

The global connectivity challenge has gone from a communications technology issue to a geography and economic issue. A dense fibre, cable, and cellular investment is warranted in urban areas because there are a number of paying users in a relatively small physical space. The reverse situation is true

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of settlements that are remote, where roads may be difficult to access, access roads are seasonal, highways have limited grid electricity, the population is sparse, and household purchasing power is low. According to the International Telecommunication Union (ITU), the proportion of the population using the Internet in urban areas was 1.62 times greater than in rural areas in 2023 and the gap in Africa was even greater. The same report highlights the possibility of land-based infrastructure being too costly in remote or harsh environments (ITU, 2). The reasons for this are explained by these conditions and why rural connectivity can't be tackled just by applying an urban engineering model further out.

A new economic geography of coverage is created with satellite communication, where extensive geographic footprints can be covered without establishing a back-to-back terrestrial path to all households. Satellite broadband has evolved into a new and different service with modern high throughput satellites, digitally processed payloads, steerable beams, inter-satellite links and electronically steered user terminals that have altered the performance and cost profile of satellite broadband. Low Earth Orbit (LEO) systems have significant benefits in terms of propagation distance and can better support delay-sensitive broadband, but also have a number of drawbacks including lack of infrastructure, immature infrastructure, lack of broadcast efficiency and limited backhaul to a broad area. The present satellite era is characterized by the introduction of new constellation designs, new on-board processing, integration with 5G and more flexible networking architectures, says Kodheli et al. (109). From a policy perspective, the use of the term satellite is no longer a single technical option, but a collection of orbit, spectrum, payload and service options.

With the development of satellite-based systems that are non-terrestrial, the role of the satellites is further altered. Previous satellite systems tended to be closed, with dedicated terminals, interfaces and modest interworking with mobile networks. In 3GPP Release 17, important mechanisms have been defined to support NR and cellular IoT over non-terrestrial links, including long propagation delay, Doppler shift, moving beams, timing, and mobility. Instead, it takes coordinated efforts and changes in the radio access network, system architecture, core network, terminal procedures, and IoT support to standardize NTN, as demonstrated by Lin et al. (153). The standardization path opens up a chance for rural consumers to switch effortlessly between terrestrial and satellite coverage and for operators to share ecosystems and devices. The problem that is addressed in this research is that many satellite-connectivity discussions are still technology-focused. They discuss or compare orbits, compare or link budgets, discuss or compare terminal antennas or constellation capacity; but, that is a systems problem when deployed in rural environment, where several problems are interacting. A high-capacity satellite link may be unsuccessful as a development intervention if local Wi-Fi is poorly engineered; a low-latency LEO connection can be unsuccessful if power storage is undersized; direct-to-device coverage can have limited social impact if service pricing is beyond rural incomes. A systematic review of satellite Internet by Chen, Ma, and Wu also reveals that the focus of the field is

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as varied as architecture, applications, technological functions, and impacts; they argue that conceptual models must be integrated, not fragmentary and isolated, or else there will be no point in having them at all (Wu, 3).

It is especially apt that it is presented in a research-based framework, given the convergence of satellite and terrestrial systems. Integration of terrestrial and non-terrestrial networks can provide roaming and end-to-end connectivity to users more easily than with fixed user terminals and direct-to-cell and direct-to-device services are growing the number of devices able to communicate with satellites (Broadband Commission, 8). This convergence enables rural network design to leave behind the dichotomy between “satellite” and “terrestrial” and shift to a more useful question: What combination of resources should be used to provide a particular service at a particular place at a particular time at an acceptable life-cycle cost? Rural networks also become service critical infrastructures. The demand for connectivity in telemedicine, digital education, agri-decision making, logistics, emergency communication, payments, e-government and environmental monitoring is growing. These applications have very different performance needs. While a soil-moisture sensor might be okay with seconds or minutes of lag, and only a few bytes coming in and out, a remote medical consultation calls for stable two-way video and minimal jitter. The resilient framework should thus be tailored to service classes rather than be designed for a common rural use case based on broadband services. The principle of this service awareness is the basis of the multi-layer framework that is developed below.

Research Methodology

The study is based on structured research-synthesis and design-science method. The evidence base is made up of peer-reviewed surveys, standards-oriented research, empirical field studies and ITU policy reports, mostly between 2020 and 2026. The literature was chosen with the following six themes: Satellite-system architecture; LEO, MEO and GEO performance; 3GPP integration of NTN; Rural and remote connectivity; Satellite IoT and community backhaul; Policy, power, spectrum and sustainability. This approach is suitable due to the fact it is not aimed at estimating some individual causal coefficient, but at creating a deployable conceptual architecture based on the technical and institutional evidence. In their systematic review, Chen, Ma and Wu found 69 studies that met their criteria, and determined that the research on satellite Internet can be divided into architecture, applications, technology and impact aspects. The present paper further develops this integrative orientation but restricts the field of application to remote and rural connectivity.

The framework was based on five design principles. The first is complementarity. Satellite links are to be used as complements to fibre, microwave, cellular, Wifi, fixed wireless and low power wide area, not as a substitute for all of those. The second is service awareness: The selection of the network should be based on the following characteristics of the application: latency, throughput, reliability, mobility, security, and cost sensitivity. The third is locality: where this can reduce the number of

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terminals that need to be duplicated and makes for a cheaper option to accessibility, the rural architecture should aggregate users at the community level. The fourth is that it is resilient: multiple paths, local caching and energy autonomy should ensure that essential communication is maintained in case of an outage or disaster on the land. Life-cycle sustainability: capital cost, capacity fees (recurring), terminal replacement, power, local maintenance, regulatory fees, technical training must all be taken into account before deployment.

The framework also makes a distinction between coverage availability and service availability. A satellite might be able to be seen from a point and a user may be unable to get a service that is acceptable due to rain attenuation, obstruction, congestion, gateway unavailability, power failure, or lack of local distribution capacity. Evaluation of reliability needs to be done end to end. This concept aligns with performance studies recently conducted that outline the need for emerging satellite Internet to be managed and performed in ways different from mere coverage. But connectivity is not enough to achieve rural digital inclusion if network operations are complicated in remote areas and end-to-end performance is not reliable, Hu asserts. Monitoring, orchestration, local fail over, and maintenance are thus first-class functions in the framework.

Table 1. Comparative Characteristics of Satellite-Orbit Options for Rural Connectivity

Dimension	GEO	MEO	LEO
Typical altitude	~35,786 km	~2,000–20,000 km	~160–2,000 km
Coverage per satellite	Very wide	Wide	Smaller; constellation dependent
Propagation latency	High	Moderate	Low relative to GEO
User-terminal tracking	Usually fixed pointing	Tracking/managed mobility	Frequent tracking and handover
Best rural roles	Backhaul, broadcast, bulk traffic, resilient wide-area service	Regional broadband, navigation-linked services, hybrid transport	Interactive broadband, mobile backhaul, low-latency services
Key constraints	Latency, rain fade at higher bands	Smaller ecosystem than GEO/LEO in some markets	Handover, constellation complexity, terminal cost, gateway/space sustainability
Framework recommendation	Retain for wide-area and cost-efficient service classes	Use where regional economics and performance fit	Prefer for latency-sensitive and high-throughput

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			applications; combine with fallback paths
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Source: Synthesized from Kodheli et al. (2021, 109)

The comparison in table 1 shows how the rural planner cannot practise absolutism. A single-orbit based approach can give rise to new weaknesses: LEO-only solutions can be very dependent on a proprietary terminal ecosystem and dense constellation operations, GEO-only solutions can be challenged by strongly interactive applications, and MEO-only solutions may not be able to achieve coverage density and terminal ecosystem in all regions. Multi-orbit routing enables a network to route the traffic based on the service class. Where LEO is available, delay-sensitive video can be transmitted through LEO, low-cost, high-capacity traffic for bulk content can be sent through low-cost high-capacity paths, and emergency control traffic can be sent through the least resilient path. The third methodological option is to analyse the network using engineering and inclusion measures. Round trip time, downlink/uplink throughput, jitter, packet loss, availability, Handover interruption, energy consumption, backhaul utilization, and mean time to repair are examples of engineering metrics. Inclusion metrics are based on monthly costs of the inclusion service as a fraction of household income, number of users per shared access point, the compatibility of the devices, the adoption of the inclusion service, local language access, number of trained local maintainers and continuity of essential services. It is clear that energy supply, community participation, access and digital skills are integral to more than just external social issues when it comes to rural connectivity (ITU, 27). This more comprehensive measure avoids declaring a technically sound network successful if it is not used or is too expensive. The framework is thus abstract yet based on real-world examples. It doesn't assume that for each geography one configuration will be optimal. Rather, it defines the variables to be measured and the architecture to be tested. Gateway and maritime backhaul considerations may be most significant in an island chain; weather and obstruction may be most significant in a mountainous area; solar energy and thermal management may be most significant in a desert; and long-range IoT and community Wi-Fi may be most economically significant in an agricultural plain. The advantage of the model is to allow comparative design whilst maintaining the deployment flexibility of the context.

Proposed Multi-Layer Satellite Connectivity Framework

The proposed framework consists of six operational layers (space, transport, local access, edge and service, energy and governance) supervised by a cross-layer orchestration function. The space layer provides the capacity which is not on Earth, and can include GEO, MEO, LEO and/or a mix of orbital resources. The transport layer continues the satellite gateways, terrestrial fibre or microwave, mobile core networks and inter-satellite or feeder links. The local access layer brings backhauls to life by providing usable connectivity within the village via 4G/5G, Wi-Fi, fixed wireless or LPWAN. Caching, local compute, content, security and application gateways are hosted in the edge and service

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layer. The energy layer includes solar, storage, power conditioning and energy-aware scheduling. The governance layer includes licensing, issues of the spectrum, affordability, ownership, service-level commitments, privacy, cyber security, local skills, and financing universal services. The diversity of resources is the primary source of flexibility at the space layer.

The interactive services can be supported with LEO satellites due to their short propagation delays and new constellations can offer high throughput on aggregate. Typically, LEO systems are deployed at altitudes ranging from approximately 160 km to 2,000 km and can deliver performance for applications like real-time videoconferencing and industrial applications (ITU, 2024, 2). A single GEO satellite provides continuous coverage over a large area, and ground terminals do not have to track fast-moving satellites, so GEO satellites do not lose their value. MEO systems offer intermediate propagation delay and large coverage. The framework enables dynamic mapping of traffic on these assets based on service type, price, traffic, weather and availability. The transport layer makes non-terrestrial resources connected to the general Internet or mobile core. It may have a satellite feeder link to a gateway in remote areas, an inter-satellite path to a distant gateway, a terrestrial fibre segment with fibre already in place and microwave links between clusters of settlements.

Image 1: Integration of GEO, MEO, and LEO Satellite Networks with Terrestrial Communication Systems



This layer is significant as satellite access can still require ground infrastructure access that is away from the user. Gateway diversity and disaster isolation should therefore be taken into account for backhaul selection. By disrupting the main terrestrial gateway route, a fibre cut can render otherwise functional satellite capacity useless. Geographically distributed gateways, flexibility in routing, and where possible, inter-satellite links are needed to ensure transport resilience. Local access layer

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provides affordable community access from a high capacity backhaul. Multi-layer approach can yield significant economic benefits here. A village may share one or more satellite terminals equipped with Wi-Fi 6/7, 4G/5G small cells or point-to-multipoint fixed wireless or long-range IoT gateways instead of having one satellite terminal per household. The distribution of service is done by lower-cost local radios and the core connection is provided by satellite backhaul. This design also gives the operators the ability to take control of the local quality of service, implement content filtering as required by law, prioritize emergency and education traffic and track the local radio coverage and satellite performance separately. Community aggregation is especially effective when the primary barrier to use is terminal cost. The second access is called direct-to-device (D2D) or direct-to-cell (D2C). According to the Broadband Commission, D2D and D2C are being implemented to directly link terrestrial devices to communication satellites, and can provide connectivity to rural areas where terrestrial infrastructure construction is extremely expensive or impractical (Broadband Commission, 8). D2D in the proposed framework is not taken as an alternative of the village broadband. Rather, it's viewed as a messaging, voice, emergency alert, basic IoT and future standardized broadband-access service that provides coverage continuity and low bandwidth use. This is important because unlike dedicated satellite terminals, direct handset links will have more stringent power and antenna requirements. The edge and service layer is required because rural experience is not solely dependent on link speeds, it's also dependent on location of computation and content. Commonly-used education video, government forms, agriculture information, software updates and health information can be downloaded and stored locally to avoid the need to re-pull the content over the satellite link and thereby use up precious satellite bandwidth. Local DNS, authentication, learning-management systems, farm analytics, security functions and delay-sensitive processing are other possibilities for running on edge servers. If the satellite link fails, a community will still be able to access local digital services and sync with the cloud when the satellite link is restored. This “disconnected operation” capability is particularly relevant for schools, clinics, disaster shelters and field operations. One of the most underestimated limitations in rural telecom is the energy constraint, which is being addressed in the energy layer. Continuous and clean power is essential to terminals, routers, Wi-Fi access points, cellular base stations, edge servers and battery systems. The ITU classifies renewable energy as a feasible solution to the problem of power supply shortages in remote areas, and mentions a solar communication system as useful in rural areas (ITU, 27). The proposed framework thus considers the energy system as a network element.

The orchestrator can decrease the transmit power, wait for non-urgent synchronization or turn off secondary access points, or move computing workloads if battery state drops below set thresholds. The governance layer transforms engineering capability to a sustainable service. Satellite networks rely on landing rights, spectrum allocation, authorisation of user terminal, licence and authorisation of gateways, import regulations and competition policy. The ITU's rural-connectivity report suggests

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simplified and predictable processes for NGSO services, general authorization or blanket licensing for the terminals and gateways, protection of relevant satellite spectrum, competition, and technology neutrality (ITU, 33). The framework then takes the premise that regulatory friction is a performance variable, too: Long equipment-approval processes, fragmented equipment licences and high administrative fees can delay the deployment as much as a technical bottleneck.

Table 2. Proposed Multi-Layer Framework for Remote and Rural Satellite Connectivity

Layer	Core components	Primary function	Key decision variables	References (Author & Year)
Space	GEO/MEO/LEO satellites, beams, ISLs	Non-terrestrial capacity and geographic reach	Latency, capacity, coverage, weather, congestion, cost	Kodheli et al. (2021)
Transport	Gateways, fibre, microwave, mobile core, routing	End-to-end backhaul and path diversity	Gateway diversity, route resilience, peering, redundancy	Kodheli et al. (2021); Stiri et al. (2026)
Local access	4G/5G, Wi-Fi, FWA, LPWAN, D2D	Affordable distribution to users/devices	User density, terrain, mobility, device ecosystem	Lin et al. (2021); ITU (2025)
Edge & service	Caching, local compute, security, app gateways	Reduce backhaul load and preserve service continuity	Cache hit rate, application priority, local autonomy	Chen et al. (2024); Hu (2024)
Energy	Solar, batteries, power conditioning, backup	Maintain operation where grid supply is weak	State of charge, autonomy hours, load shedding, lifecycle	ITU (2025)
Governance	Licensing, spectrum, pricing, ownership, skills	Make service legal, affordable, secure and sustainable	Tariff, SLA, competition, data protection, local capacity	ITU (2025); McMahon et al. (2025)
Cross-layer orchestration	Telemetry, policy engine, SDN, analytics	Select links/resources by service objective	Availability, latency, cost, energy, security, priority	Kodheli et al. (2021); Mahboob & Liu (2024)

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Source: Author's framework, informed by ITU, 3

The six operational layers are connected via the cross-layer orchestration. A policy engine receives the telemetry from satellite links, terrestrial links, local access points, batteries, application servers, and service queues. It then chooses paths based on weighted criteria, such as availability, latency, energy, cost, capacity, security, and service priority. For instance, video for telemedicine might be given to a path with low latency, with software updates sent over a network that is more expensive to use in bulk but has a slower speed, emergency messages could be transmitted by satellite and terrestrial paths, and non-critical traffic could be limited during periods of low battery level. The orchestration model is consistent with the growing trend of software-defined and programmable satellite networks outlined in recent satellite research (Kodheli et al., 99).

Image 2: Proposed Multi-Layer Satellite Connectivity Framework for Remote and Rural Areas

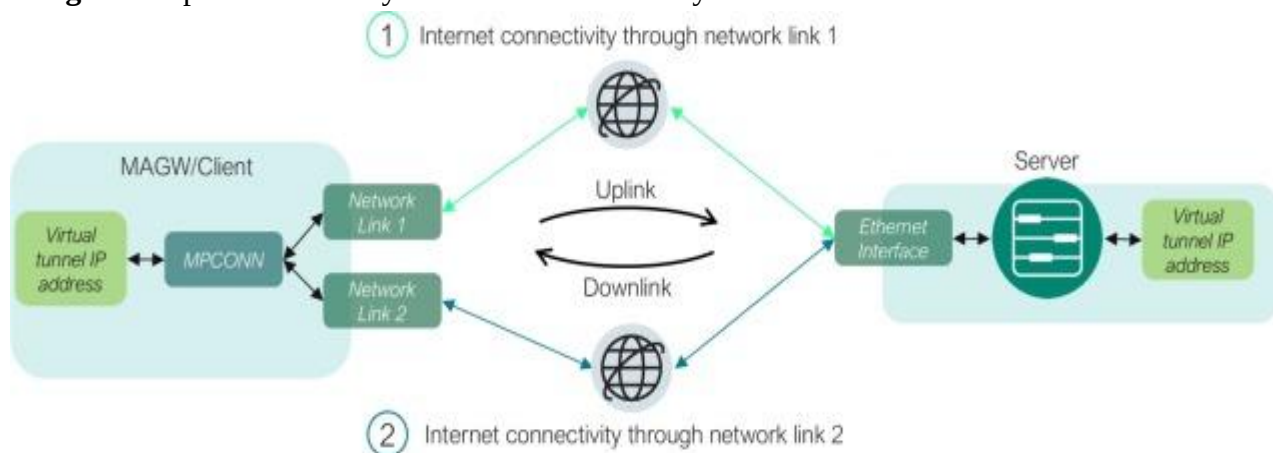


Table 2 provides a summary of the framework as an engineering and governance stack. The key limitation is that no layer can be optimized without taking other layers into account. A space link that relies on the unreliable power in the villages is not a high performance service. A tariff that is beyond local buying power is not an inclusive tariff. An inexpensive system that leaves the remote management unsecured is not sustainable. For cross-layer evaluation, then, it is necessary to state the contribution to performance and the risk of dependency of each layer for the deployment.

This framework also provides multi-connectivity per user or gateway. Why this is useful can be seen from recent empirically-based research by the authors on integrated terrestrial and satellite communication in rural areas, where the terrestrial service may be interrupted if there are not enough infrastructure units, while the satellite-only service can be limited in uplink capacity or latency for more demanding services. A 2025 rural multi-connectivity study found that multi-connectivity of 5G and satellite performed the required latencies, downlink and uplink thresholds much more consistently across the range of use cases tested than 5G or satellite alone (Multi-connectivity study, 2025, article 101260). The design lesson here is that it is not necessary to have two active links but critical sites and aggregation points should be capable of path diversity. The access strategy may be

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more specialized for the low-data-rate rural sensing scenario. Agricultural sensors, water systems, environmental stations, vehicles, and livestock trackers can be connected through a satellite IoT network without the need to create a dense terrestrial network. Cioni et al. demonstrate that satellite IoT is especially promising for distant geographies where terrestrial transmission is not possible and that the low-orbit satellites offer a helpful latency versus coverage balance (Cioni et al., 1720), but with the notable exceptions of power, standardization, terminal complexity, and spectrum design. In the framework, these sensors are allocated to a limited bandwidth service class and isolated from the high throughput human broadband to result in efficient allocation of scarce resources. The architecture has been designed to be vendor agnostic. It can be deployed using commercial LEO broadband, traditional GEO capacity, a regional satellite operator, an MNO partner, community Wi-Fi or any mix of these providers. Vendor neutrality makes for better negotiating power and less lock-in. It also facilitates migration as 3GPP NTN capabilities come to the fore. Technical interface between layers should thus be open IP networking, standards-based authentication, interoperable monitoring, and portable service policies wherever possible. Proprietary performance enhancements are allowed, but should not make it difficult to switch providers or connect a second connectivity path.

Performance, Deployment, and Socio-Economic Evaluation

One should consider evaluating the rural satellite framework based on the outcomes of the service, not the advertised speed. These are the fundamental technical measures: latency, throughput, jitter, packet loss, availability, congestion sensitivity, uplink capability, handover continuity and recovery time. These metrics interact. In telemedicine, high downlink is not enough to make up for unstable uplink, low average latency is not a good enough time if handovers create long breaks and excellent satellite performance is not enough if community Wi-Fi is congested. End-to-end testing, therefore, needs to be measured from the user device to the local access network and satellite path to the application endpoint. This requirement is backed by research which has a field orientation and focuses on operational rather than laboratory only conditions for performance assessment.

These are all strongly affected by the orbit characteristics. While the distance may not affect throughput, it does create a physical latency floor that can make highly interactive apps feel slow even if throughput is good, and which cannot be compensated for by GEO zone feature propagation. Based on the large-scale measurement work conducted recently by GEO (Merlach et al., 2026, article 112244), it has been noted that at least about 550ms of round trip delay should be expected before any additional queuing or processing is considered. LEO systems are capable of significantly reducing propagation delay, but also cause frequent movement of satellites and handovers. Thus, the performance objective should be application satisfaction, not orbit preference. High latency connections are appropriate for bulk software downloads, caching of educational content and periodic

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transfers of sensor data, while low latency connections are suitable for interactive voice, cloud and remote control.

Total cost of ownership (TCO) should be considered for economic evaluation, instead of the terminal price. Includes user equipment, mounting, local radio equipment, solar panels/batteries, generator (if applicable), installation travel, spectrum or licensing fees, satellite subscription, local support, spare parts, security updates, and replacement throughout the life of the project. Logistics and technician travel can be a major factor on maintenance costs in very remote communities. A shared village system can thus be more successful than an individual subscription, even though the shared gateway could be more expensive in the beginning. Households can buy lower-cost Wi-Fi or cellular equipment that they already have and public investment focused on common infrastructure.

Social and sectoral impact should also be assessed for the network. Previous satellite options have been compared, and LEO deployment in remote Indigenous communities in northern Canada has been reported as being faster, more reliable and cost effective, as well as having greater online participation. Meanwhile, researchers are finding problems with affordability, reliability, proprietary terminals, and lack of local technical support (McMahon et al., article 102912). The significance of this evidence is that it demonstrates that enhancing physical connectivity may not effectively address institutional and capability gaps while closing one of the digital divide.

Table 3 illustrates the relationship between representative rural applications and performance and architecture decisions. The values should not be viewed as standards; they are a range for planning purposes. These are designed to make the design teams consider how little capacity in the low latency link they should be willing to give to which traffic, and why. This service differentiation is very important when the cost of satellite capacity is high or when access to the community is shared which leads to a busy hour.

Table 3. Rural Use-Case Requirements and Recommended Connectivity Strategy

Use case	Typical traffic profile	Critical requirement	Recommended framework path
Telemedicine consultation	Two-way HD video + records	Low jitter, stable uplink, high availability	LEO/5G preferred; GEO or secondary path for fallback; QoS priority
Digital classroom	Video, content downloads, assessments	Moderate latency, high downlink capacity	Shared satellite backhaul + Wi-Fi; strong local caching
Precision agriculture	Sensors + periodic images/video	Wide coverage, mixed narrowband/broadband	Satellite IoT for sensors + LEO/GEO backhaul for media

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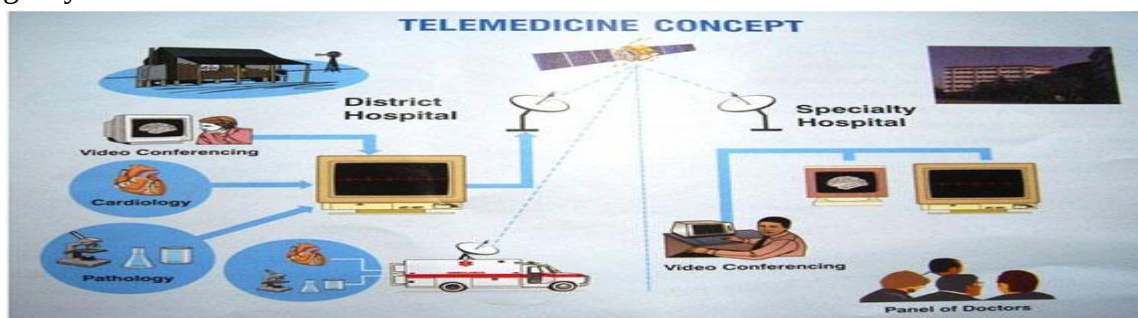
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Emergency communications	Voice, alerts, messaging, situational data	Availability and rapid restoration	Dual-path TN/NTN; D2D for basic reach; battery reserve
E-government/community kiosk	Web apps, authentication, file transfer	Consistency, security, affordability	Shared village terminal + local access + encrypted gateway
Remote enterprise/farm	Cloud, payments, logistics, video	Reliable broadband and uplink	Dedicated or pooled LEO; GEO backup where justified

Source: Research synthesis based on Stiri et al., 20

Deployments should be done in stages. Phase one: Geographic and demand mapping – population clusters, roads, schools, clinics, businesses, farms, government facilities, existing towers, fibre points, power assets, emergency sites. Phase two involves propagation and energy survey: determine obstruction, rainfall environment, wind loading, solar availability, grounding, and battery requirements. The architecture selection phase involves identifying the locations of the dedicated broadband terminals, the villages with a shared backhaul, the locations of the sensors requiring IoT, and where terrestrial fibre or microwave should continue as the dominant architecture. Phase 4 is Pilot operation including end-to-end measurements. Scale-up after adoption, maintenance workload, tariff response and service reliability have been observed in phase five. Cybersecurity is an element of the service continuity. Rural locations with satellites can be physically unsupervised, and can have a heavy dependency on remote management, making device hardening, certificate-based authentication, secure firmware updates, network segmentation, encrypted management channels and access logging even more important. The cross-layer orchestrator should consider security state as an input for determining path selection: if a gateway is compromised or out of date, it should not be a trusted routing element only because its signal is strong. Also, at remote locations, unnecessary Internet exposure should be minimized by employing zero-trust access, VPNs, and application-level controls.

Image 3: Applications of Satellite Connectivity in Rural Healthcare, Education, Agriculture, and Emergency Services



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The distinction should be made between the satellite segment and the local access segment. Users often blame the satellite service for weak Wi-Fi signals, overloaded access points or device issues. Satellite signal quality, backhaul capacity, local radio utilization, queue depth, application delay and power status should therefore be monitored separately in a monitoring platform. This multi-layered telemetry reduces troubleshooting time and makes SLA's more meaningful. It also delivers the data necessary to determine if the village would benefit from extra wireless capacity, another Wi-Fi hotspot, a new antenna location, or improved energy storage. The system is particularly helpful in public-service facilities. Edge caching can be used to store large educational documents in advance; medical centers can queue up bandwidth for teleconsultation and transfer medical records at the time of lower usage rates; centers of agricultural knowledge can integrate IoT sensor aggregation with high resolution pictures which are transferred periodically, and local governments can keep the digital service kiosks, even though the households can not afford the individual subscription yet. Plans can include public sites as anchor tenants to ensure a minimum demand that creates positive economics for community backhaul, while providing some social benefit immediately.

Challenges

The first big problem is spectrum coexistence. Satellite systems are multi-band and have to share resources with terrestrial services, other satellite systems and national spectrum allocation. The challenge of direct-to-cell is further complicated by the possibility of satellite and mobile systems operating bands adjacent to or overlapping the bands that are available in nearby locations over a broad area. Cooperation between mobile and satellite network operators is highlighted as critical for the successful deployment of NTN, while spectrum coordination and regulatory approval are identified as key challenges for NTN deployments by the GSMA. The Broadband Commission also notes the need to carefully manage interference and spectrum use as D2D grows (Broadband Commission, 13). Rural policy should therefore ensure access and maintain technical coordination, interference protection, and transparent authorisation. The second challenge is terminal affordability and the dependence of the ecosystem. While the performance of broadband technology can be appealing, it may also come with a high initial investment in a proprietary terminal for lower income households, and the terminal may not be easily repaired locally. This can be mitigated by converting one terminal to many local connections, as is done in community aggregation. In the longer-term, mainstream cellular chipsets will be able to enable satellite functions, thereby further lowering the barriers to devices in the future. As Lin et al. point out, NTN standardization is continuing across the three core areas: terminals, radio, and core, as well as service procedures, leading towards a 'wider interoperable system' (Lin et al., 153). Future studies should quantify the benefits and costs reductions of standardized devices in rural contexts in real-world scenarios.

The third challenge is constellation and network viability. Significant satellite launch, replacement, collision avoidance and mitigation of space debris are needed for large LEO systems. Questions have

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also been raised as to the life cycle emissions of large constellations versus terrestrial alternatives when examining the environment. This does not rule out the social value of connecting isolated communities but rather the term “sustainability” should be expanded to encompass impacts of ground energy and space-system. Rural planners need to evaluate technologies based on resources and emissions per meaningful connection per user, and regulators should mandate responsible debris elimination and spectrum utilization.

Conclusion

This paper has suggested a multi-layer approach to improve satellite connectivity coverage in remote and rural areas, which views the connection as a whole socio-technical system, not just a radio link. The framework integrates six operational layers in space, transport, local access, edge and service, energy, and governance by orchestrating them across layers. At its heart, its message is that the best rural architecture is a hybrid approach, bringing together the GEO, MEO and LEO resources and supporting them with fibre, microwave, 4G/5G, wi-fi, fixed wireless and satellite IoT as appropriate for each service. Local terrestrial distribution is crucial for low cost and high user density, and satellite systems are most useful when they mitigate the geographic cost penalty of terrestrial construction, contribute resilience and offer fast backhaul.

Also the analysis indicates that meaningful connectivity goes beyond coverage. Technical success or failure and social sustainability depend on affordable terminals and tariffs, reliable renewable energy, transparency and predictability of regulation, local technical capacity, cybersecurity, community participation and measurable service outcomes. Recent activities conducted by ITU, 3GPP NTN research, satellite-Internet surveys and rural field studies have all indicated that integration of the terrestrial and satellite networks is necessary and will go deeper than isolated network silos. This is the next frontier for researchers, however: cross-layer experimentation that gauges how seamlessly applications run, in terms of energy, cost and inclusion. The real challenge for both policymakers and operators is to create flexible, interoperable and multi-provider architectures that can adapt themselves to futureproof the industry with growing standardisation of NTN and direct-to-device ecosystems.

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