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6G for Bridging the Digital Divide: Wireless Connectivity to Remote Areas

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Abstract—In telecommunications, network service accessibility as a requirement is closely related to equitably serving the population residing at locations that can most appropriately be described as remote. Remote connectivity, however, would have benefited from a more inclusive consideration in the existing generations of mobile communications. To remedy this, sustainability and its social impact are being positioned as key drivers of sixth generation's (6G) research and standardization activities. In particular, there has been a conscious attempt to understand the demands of remote wireless connectivity, which has led to a better understanding of the challenges that lie ahead. In this perspective, this article overviews the key challenges associated with constraints on network design and deployment to be addressed for providing broadband connectivity to rural areas, and proposes novel approaches and solutions for bridging the digital divide in those regions.

Index Terms—6G; remote areas; digital divide; network service accessibility; wireless networks.

I. INTRODUCTION

In 2018, 55% of the global population lived in urban areas. Further, 67% of the total world's population had a mobile subscription, but only 3.9 billion people were using Internet, leaving 3.7 billion unconnected, with many of those living in remote or rural areas [1]. People in these regions are not part of the information era and this digital segregation imposes several restrictions to their daily lives and prospects. Children growing up without access to the latest communication technologies and online learning tools are unlikely to be competitive in the job and commercial markets. Unreliable Internet connections also make it difficult for people living in remote areas to benefit from online commerce and engage in the digital world,

thereby compounding already existing social and economic inequalities.

However, rural areas are now becoming more and more attractive as the new coronavirus (COVID-19) pandemic has shown, since it has reshaped our living preferences and pushed many people to work remotely from wherever makes them most comfortable [2]. Such agglomerations where people live and work are referred to as "oases" in this paper. Wireless connectivity in rural areas is expected to have a significant economic impact too. The use of technology in farms or fisheries will open new opportunities for local communities (e.g., indigenous population in the US). Technology will also provide better education, increased digital social engagement, and efficient health systems to those living in the most remote zones (e.g., urban-rural divide in China and India).

Despite these premises, advances in the communication standards towards provisioning of wireless broadband connectivity to remote regions have been, so far, relegated to the very bottom, if not entirely ignored. In these regards, despite being in its initial stages, the 6th generation (6G) of wireless networks is building upon the issues left open by the previous generations [3], and will be developed by taking into account the peculiarities of the remote and rural sector, with the objective of providing connectivity for all and reach digital inclusion [4]. Specifically, the research community should ensure that this critical market segment is not overlooked in favor of the more appealing research areas such as artificial intelligence (AI), machine learning (ML), Terahertz communications, 3D augmented reality (AR) and virtual reality (VR), and haptics.

Boosting remote connectivity can start by addressing spectrum availability issues. Licensed spectrum in sub-1 GHz bands, in fact, is a costly resource, and may require new frequency reuse strategy in remote regions because of their unique requirements. Judicious utilization of unlicensed bands may help reduce the overall cost, while advanced spectrum sharing models and enhanced co-existence schemes are two other powerful solutions to improve network coverage in these areas. Innovative business and regulatory models may be suitable to encourage new players, such as community-based micro-operators, to build and operate the local networks. Flexible and pluralistic spectrum licensing could be the way forward to boost the remote market.

Another issue is that remote areas may not have ample connectivity to the power sources (e.g., sub-Saharan Africa). Hence, it is imperative that 6G solutions be designed as self-

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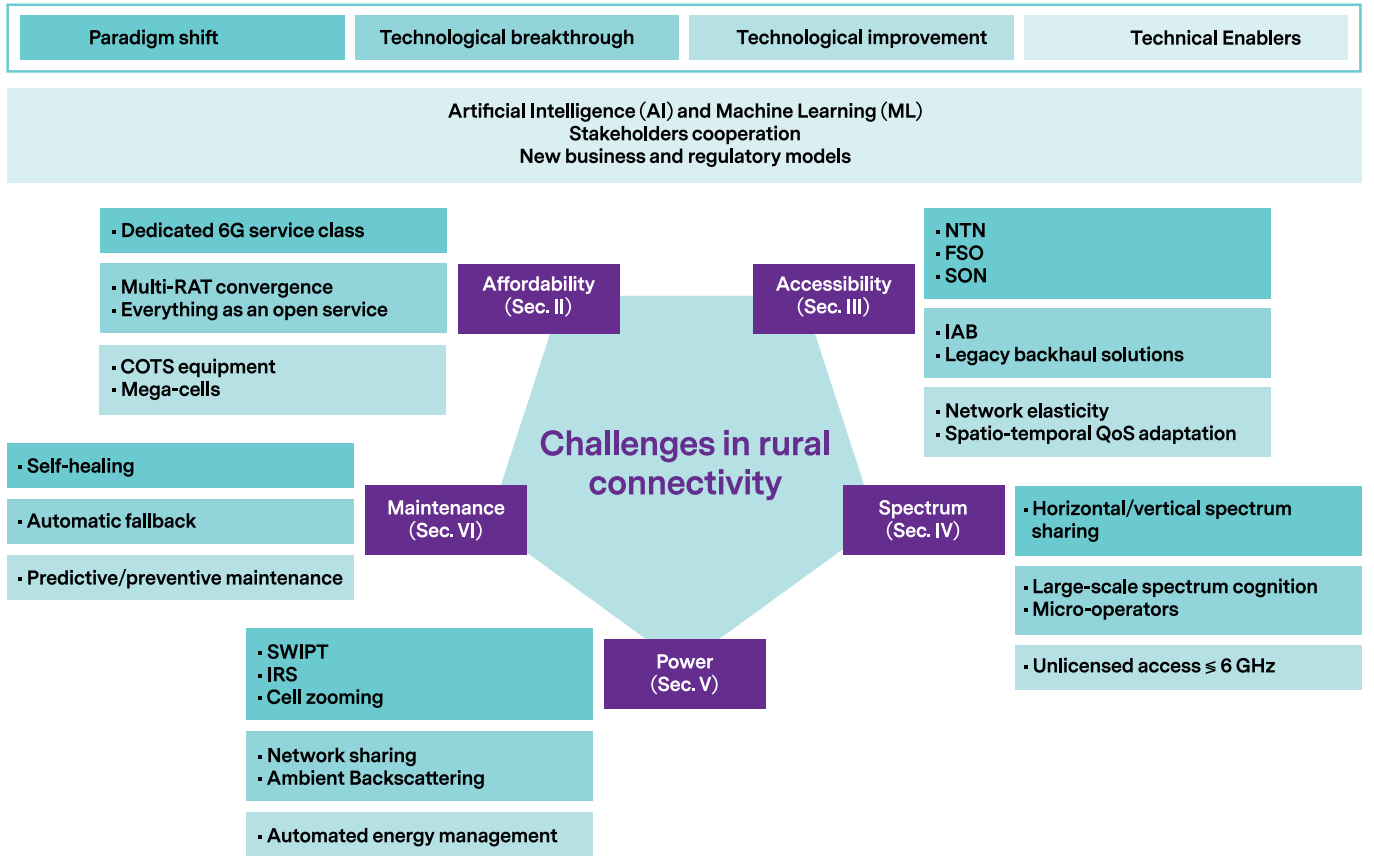


Fig. 1: A summary of the challenges for providing wireless connectivity to remote areas with proposed solutions.

reliant in terms of power/energy requirements, so as to improve return of investment (RoI) for remote areas, and/or with the ability to scavenge from the surrounding, possibly scarce, resources. Governments can assuage this situation to an extent by making it attractive for the profit-wary service providers to deploy solutions in remote areas. Revised government policies and appropriate business models should be jointly explored as they have direct implications on the technology requirements. Environmentally-friendly thinking should also be included throughout the chain from mining to manufacturing and recycling. Moreover, the abundant renewable sources need to be integrated into power systems at all scales for sustainable energy provisioning.

Remote maintenance of network infrastructures is also very important since it might be difficult to access remote areas due to harsh weather and terrain, or lack of transport connectivity (e.g., in Arctic regions). Suitable specifications for fault tolerance and fallback mechanisms need therefore to be incorporated.

Based on the above introduction, the fundamental challenges in remote areas are low return on investment, inaccessibility that hinders deployment and regular maintenance of network infrastructures, and lack of favorable spectrum and critical infrastructure such as backhaul and power grid, respectively. Along these lines, the contributions of this article are three-fold. First, we introduce trending technologies that future 6G networks should embrace from the early design and specification stages, to build a global connectivity for

all. Second, we highlight the challenges that hinder progress in the development of solutions for remote areas. Notably, we grouped them into five categories: affordability (Sec. II), accessibility (Sec. III), spectrum (Sec. IV), power (Sec. V), and maintenance (Sec. VI). Third, we map those challenges into promising technologies for bringing global connectivity to beyond 5G networks. This includes the evolution of existing 5G innovations, as well as some new research ideas that will emerge within the next decade. A summary of these rural-specific challenges and possible solutions is shown in Fig. 1, while the main insights are provided in the following sections. We deliberately skip a detailed literature survey, because a clear and comprehensive review is provided in [4].

II. AFFORDABLE SERVICE PROVISIONING IN REMOTE REGIONS

Among the biggest impediments to connecting the unconnected part of the world are the high costs involved and the prevailing low income of the target population. Fortunately, there are many affordable emerging alternatives in 6G which may bring new possibilities, as listed in this section.

A. Dedicated Remote-Centred Connectivity Layer

Besides 5G's typical service pillars, 6G should introduce a fourth service grade with basic connectivity requirements [4]. However, this remote mode cannot be just a plain version of the urban 6G, since it has to be tailored to the specificities of the remote locations. Some demands relevant to remote

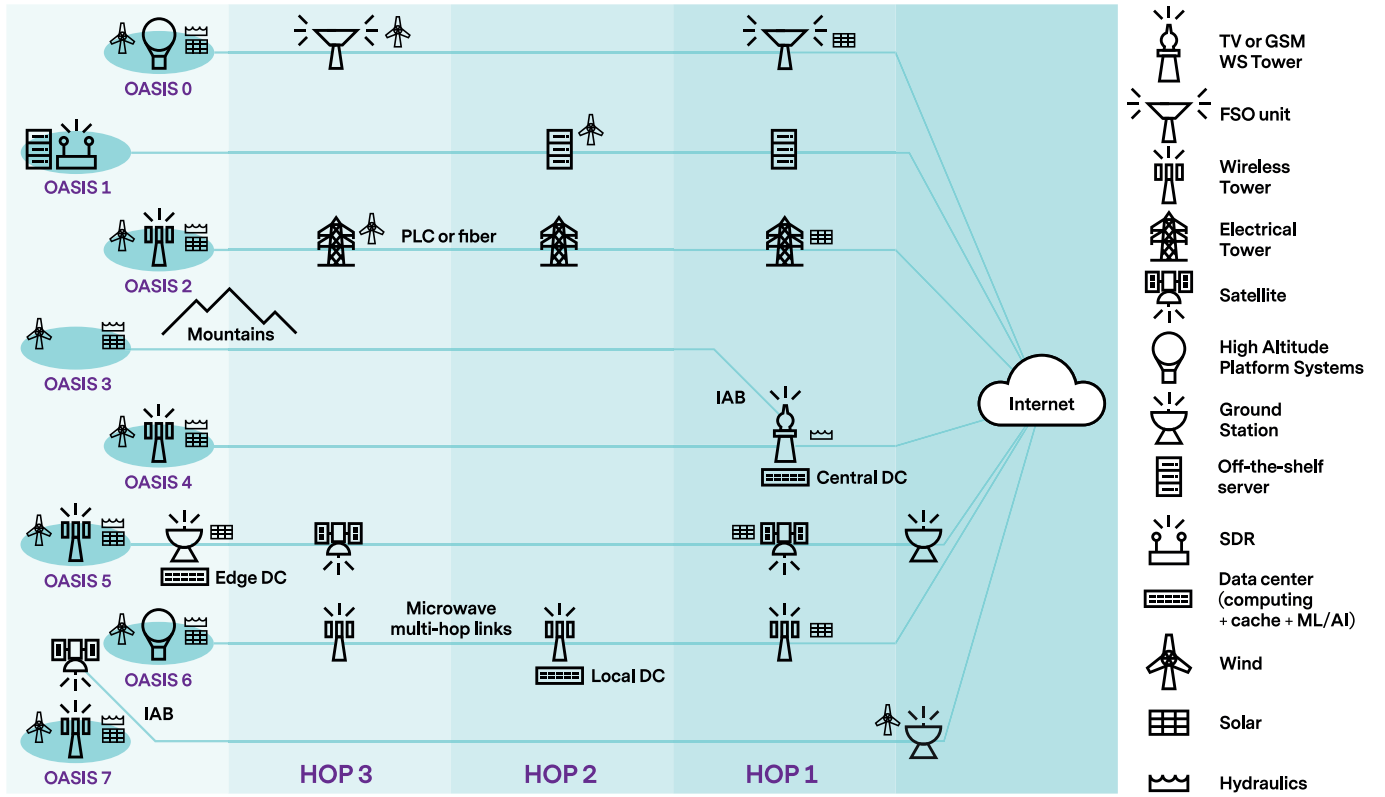


Fig. 2: Backhaul connectivity in rural areas.

connectivity scenarios like coverage and cost effectiveness need to be expanded, whereas the new service class needs more relaxed constraints in terms of some conventional 5G performance metrics like throughput and latency. This novel service class should have its dedicated slice, and be endowed with specific and moderate levels of edge and caching capabilities: the involved data can then be processed on edge, local or central data centers for better scalability, as illustrated in Fig. 2. Accordingly, such connectivity services can be charged at reduced prices.

B. Multiple Radio Access Technologies (RATs) Interworking

Local access in remote areas can be designed to aggregate multiple and heterogeneous RATs. At the same time, digitalization in remote areas calls for large coverage solutions (e.g., TV or GSM white spaces (WSs)), referred to as mega-cells, to increase the number of users within a base station and reduce the network deployment and management costs, albeit at some performance trade offs and with revised power limits.

Compared to 5G-like multi-RAT implementations, the availability of Terahertz and optical spectrum solutions in 6G will increase the heterogeneity and scale of the network, and open new opportunities for improving network performance [3]. In particular, visible light communications (VLCs) can boost the throughput indoor (i.e., where people spend 90% of their time), fronthaul, and underwater environments (see Fig. 3) while serving the intuitive goal of illumination, making it a cost-efficient technology.

C. Low-Cost Networking and End-User Devices

One way to reduce cost is the exploitation of legacy infrastructure. TV stations can be shared with mobile network operators (MNOs) to provide both tower and electricity. The latest developments in wireless communications can be applied in outdoor power line communication (PLC) to provide high data rate connectivity over the high- and medium-voltage power lines, increasing the capability of the backhaul networks in remote areas. Existing base stations and the already-installed fibers alongside roads or embedded inside electrical cables can also serve as a backhaul solution for connectivity in rural regions. End-user devices and modems should also be affordable and usable everywhere, i.e., when people move or travel to different places under harsh conditions. Therefore, the possibility to use commercial off-the-shelf (COTS) equipment at both the user's and network's sides is important, and integration with appropriate software stacks is welcome to reduce capital and operational expenditures (capex and opex). For example, in December 2020, Facebook's SuperCell platform, integrating high-altitude towers with COTS radios, was deployed to improve the RoI for rural area network coverage. While one SuperCell can reduce costs of ownership up to 33% compared to many equivalent macrocells, on the downside this prototype is power-hungry and presents a single point of failure for a large region.

D. Adoption of Open/Virtualized/Cloud-Native Solutions

The remote infrastructure is likely to be deployed by small Internet service providers (ISPs) and the cost of specialized hardware equipment is an issue to be overcome. Open source

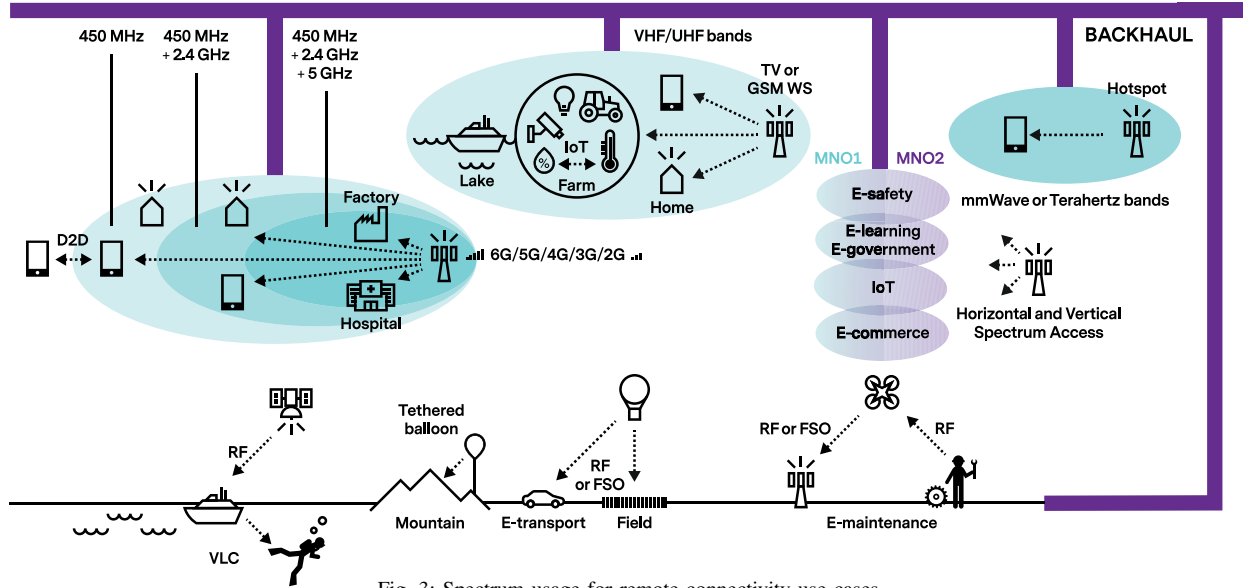


Fig. 3: Spectrum usage for remote connectivity use cases.

approaches allow MNOs to choose common hardware from any vendor and implement the radio access network (RAN) and core functionalities using software defined radio (SDR) and software defined networking (SDN) frameworks. Moreover, virtualized and cloudified network functions may reduce infrastructure, maintenance and upgrade costs [5]. These solutions are especially interesting for new players building the remote network from scratch, to foster the inter-operability and cost-effectiveness of hardware and software. However, current 5G studies have not yet clarified whether virtualized equipment can be deployed at low cost, a critical requirement for rural network operators with limited access to economic resources.

III. IMPROVING SERVICE ACCESSIBILITY IN REMOTE AREAS

In order to provide long-lived broadband connectivity, a minimum service quality must be continuously guaranteed. In this perspective, this section reviews potential solutions to promote resilient service accessibility in rural areas.

A. Multi-Hop Network Elasticity

The access network has, over generations, become multi-hop to provide flexibility in the architecture design, despite some increase in complexity. Given the typical geographic, topographic, and demographic constraints of present scenarios, performance levels (e.g., coverage, latency, and bandwidth) of individual hops can be made adaptive. The idea is to extend performance elasticity beyond just the air interface to include other hops in the RAN. The same approach can be brought to backhaul connections (see Fig. 2). Similarly, rural cell boundaries experiencing poor coverage can reap the elasticity benefits through the use of device-to-device (D2D) communications as depicted in Fig. 3.

Network protocols should be extended to include spatial- (e.g., location-based) besides temporal-quality adaptation to handle variations in channel quality over time.

B. Non-Terrestrial Networks

Network densification in rural areas is complicated by the heterogeneous terrain that may be encountered when installing fibers between cellular stations. To solve this issue, unlike current two-dimensional 5G networks, 6G envisions the deployment of non-terrestrial networks (NTNs) in 3D through air/spaceborne platforms like unmanned aerial vehicles (UAVs), high altitude platform stations (HAPSs), and satellites (e.g., Low Earth Orbit (LEO) constellations for last-mile connectivity) [6]. NTNs can offer a robust standalone networking solution to preserve connectivity in the absence of other already-deployed network infrastructures, or when terrestrial towers are out of service, e.g., after natural disasters [7]. Potential beneficiaries of this trend are shown in Fig. 3, including inter-regional transport, farm-lands, ships, mountainous areas, and remote maintenance facilities. The evolution towards NTNs will be favored by architectural advancements in the aerial/space industry (e.g., through solid-state lithium batteries and Gallium Nitride technologies), new spectrum developments (e.g., by transitioning to millimeter wave (mmWave), Terahertz and optical bands), and novel antenna designs (e.g., through reconfigurable phased/inflatable/fractal antennas realized with metasurface material). Despite these premises, however, there are still various challenges to be addressed, including those related to latency, coverage and energy constraints. For example, emerging LEO satellite initiatives like Starlink by SpaceX can provide global coverage and low-latency services once operational. Nevertheless, how to deal with end-of-life disposal of satellites and constellation management is yet to be addressed.

C. Wireless Backhaul

Service accessibility in rural areas involves prohibitive deployment expenditures for network operators and requires high-capacity backhaul connections for several different use cases. Fig. 2 provides a comprehensive overview of potential backhaul solutions envisioned in this paper to promote remote

connectivity. On one side, laying more fiber links substantially boosts broadband access in those areas, but at the expense of increased costs. PLC connections, on the other side, provide ease of reach at lower costs making use of ubiquitous wired infrastructures as a physical medium for data transmission, but some inherent challenges related to harsh channel conditions are still to be overcome. Fig. 2 illustrates also how emerging long-range wireless technologies, such as TV and GSM WS systems, are capable of delivering the intended service over longer distances with less power while penetrating through difficult terrain like mountains and lakes. NTN, as foreseen in 6G, could also provide a remote-ready, low-cost (yet robust), and long-range backhaul alternative to complement conventional technologies in remote areas.

Another recent trend is building cost-effective backhaul using software-defined technology to connect the unconnected communities (e.g., Oasis 1 in Fig. 2). Recently, the research community has also investigated integrated access and backhaul (IAB) as a solution to replace fiber-like infrastructures with self-configuring relays operating through wireless backhaul [8]. For example, the TV WS tower in Fig. 2 may use the TV spectrum holes to provide both access to Oasis 3 and connection to the backhaul link for Oasis 4. IAB has lower complexity compared to fiber-like networks and facilitates site installation in rural areas where cable buildout is difficult and costly. As a case study, in 2020 Huawei's RuralStar Pro prototype, an IAB-based solar-powered lightweight base station, was deployed in a mountainous village of China. The site installation was 80% faster than a traditional network, and improved the LTE coverage by more than 80% with only 100 W power consumption. While, in 5G, wireless backhaul is typically realized at mmWaves, the huge capacity of 6G-specific technologies, e.g., Terahertz, could be exploited to better multiplex the access and backhaul data within the same bands, thereby removing the need for additional hardware and/or spectrum licence costs.

Nowadays, free space optical (FSO) links are also being considered as a powerful alternative to increase network footprint in isolated areas with challenging terrains. However, FSO units are very sensitive to optical misalignment. For instance, the HOP1 FSO unit depicted in Fig. 2 should be permanently and perfectly aligned with the FSO unit installed in the HOP3 location. In-depth research on spherical receivers and beam scanning is hence needed to improve the capability of intercepting laser lights emanating from multiple angles.

D. Physical-Layer Solutions for Front/Mid/Backhaul

Even though wireless backhauling can reduce deployment costs, service accessibility in rural regions still requires a minimum number of fiber infrastructures to be already deployed. Fiber capacity can hence be increased if existing wavelength division multiplexing networks are migrated to elastic optical networks (EONs) by technology upgrades at nodes; the outdated technology of urban regions may then be reused to establish connectivity in under-served rural regions without significant investment.

Besides backhaul, midhaul and fronthaul should also be improved by AI/ML-based solutions providing cognitive capabilities for prudent use of available licensed and unlicensed

spectrum [9]. This is especially useful in remote areas where the sparse distribution of users may result in spectrum holes. The unlicensed spectrum, in particular, can promote better RoI for service delivery and improve network elasticity, as will be discussed in Sec. IV-A. New possibilities including evolved multiple access schemes and waveforms, like non-orthogonal multiple access (NOMA), should be investigated; this technology is particularly interesting for Internet of Things (IoT) services where some sensors are close to and some far away from a base station [10]. AI/ML can be exploited to control physical and link layers for smooth and context-aware modulation and coding schemes (MCSs) transitions, even though this approach would need to be lightweight to reduce cost and maintenance, and optimized for the intended market segment.

E. Self-Organizing Networks (SONs)

To explicitly address the problem of network outages (e.g., due to backhaul failure), which are very common in remote locations, 6G should transition towards SONs implementing network slicing, dynamic spectrum management, edge computing, and zero-touch automation functionalities. This approach provides extra degrees of freedom for combating service interruptions, and improves network robustness. In this context, AI/ML can help both the radio access and backhaul networks to self-organize and self-configure themselves, e.g., to discover each other, coordinate, and manage the signaling and data traffic [9].

IV. TOWARDS A FLEXIBLE USE OF SPECTRUM IN REMOTE AREAS

We now present some promising solutions to address spectrum availability issues, which currently pose a serious impediment to broadband connectivity in remote areas.

A. Cognitive Radio Networks Using Unlicensed Bands

One of the major barriers for network deployment in rural areas is spectrum licensing, since participation in spectrum auction is hindered to small ISPs. Indeed, 6G may evolve towards fully autonomous standalone networks that uniquely operate in unlicensed bands, for example where giant operators are not interested in providing their service. In these regards, the unlicensed access variants of 5G mainly operate in the (already crowded) low/mid bands, and do not integrate 6G-specific bands, thus complicating network operations. The massive connectivity demands of rural vertical industries (e.g., farming, mining, etc.) will further exacerbate this issue.

In this perspective, 6G should consider several other frequencies for unlicensed operations, e.g., in the 90–100 GHz and Terahertz bands. Moreover, existing synchronization and control mechanisms like listen-before-talk (LBT) should mature towards more distributed intelligence-empowered algorithms to avoid misleading spectrum occupancy, and better orchestrate network operations. Further, endowing 6G mobile radios with large-scale cognition capabilities, along with autonomous and intelligent tuning of radio parameters, will allow ISPs to instantaneously obtain an accurate spectrum occupancy map, and be informed about vacant spectrum opportunities in

a given area. Such an approach will also provide protection against unauthorized transmissions and unpredictable propagation conditions to new entrants.

B. Spectrum Co-Existence

Sub-6 GHz frequencies remain critical for remote connectivity thanks to their favorable propagation properties and wide reach, confirmed by many successful rural/remote broadband initiatives worldwide (e.g., UHF/VHF TV WSs in Africa, CDMA 450 MHz in Ecuador, WiFi 2.4 and 5 GHz in Asia). In these crowded bands, spectrum re-farming and inter/intra-operator spectrum sharing can increase spectrum availability [11]. Nevertheless, coverage gaps and low throughput in the legacy bands call for expanding the operational bandwidth of 5G systems over different spectra, combining frequencies above and below 6 GHz besides the optical spectrum. Using advanced carrier aggregation techniques in 6G systems, the resource scheduling unit can choose the optimal frequency combination(s) according to service requirements and spectrum characteristics. The proposed model offers a scalable bandwidth that maintains service continuity in case of connectivity loss in those spectrum bands that are more sensitive to surrounding effects. Likewise, multi connectivity (as discussed in Sec. II-B) provides diversity, improved system resilience, and situation awareness by establishing multiple links from separate sources to one destination. This aggregation can be achieved at various protocol and/or architecture levels ranging from the radio link up to the core network, allowing effortless deployment of elastic networks in areas difficult to access.

C. Regional Licenses and Micro-Operators

Deployment of terrestrial networks for remote areas is challenging due to harsh terrain and lack of infrastructure and personnel. Network operators would then rather roam their services from telecommunication providers already operating in those areas than building their own infrastructure. However, such an approach may entail the need for advanced horizontal (between operators of the same priorities) and vertical (when stakeholders of various priorities coexist) spectrum/infrastructure sharing frameworks. Solutions like license shared access (LSA, in Europe) and spectrum access system (SAS, in the US) are mature examples of such an approach with two tiers and three tiers of users, respectively. This can evolve to include n tiers of users belonging to m different MNOs. An example of a four-tiered access is provided in Fig. 3. From the top, we find the E-safety services with the highest priority, a tier-2 layer devoted to E-learning sessions and E-government transactions, a middle-priority tier-3 layer for IoT use cases that generate sporadic traffic, and a final lower-priority tier-4 layer that uses the remainder of the available spectrum (e.g., for E-commerce services). Such solutions, however, need to be supported by innovative business and regulatory models to motivate new market entrants (e.g., micro-operators) to offer competitive and affordable services in remote zones [12].

V. POWERING IN A GREEN AND EFFICIENT WAY

Power supply is among the highest expenses of MNOs and a major bottleneck for ensuring robust connectivity in remote

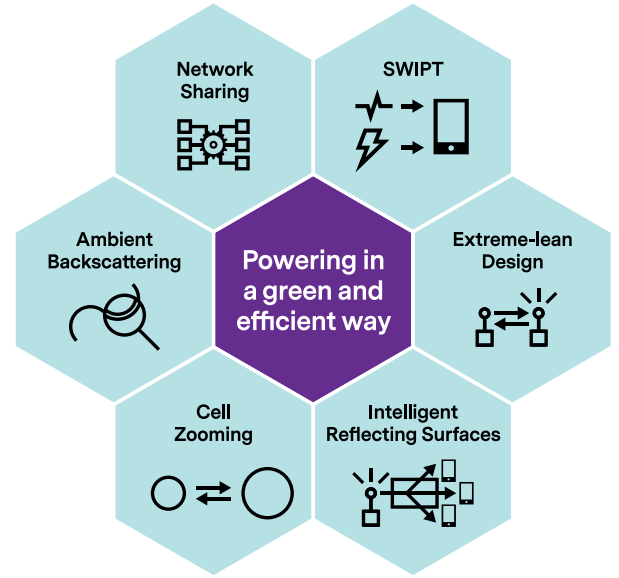


Fig. 4: Key enablers for efficient and green powering of rural areas.

areas. MNOs' reliable powering can be improved following (a combination of) these solutions, as summarized in Fig. 4.

A. Efficient and Optimal Energy Usage

Energy efficiency while guaranteeing affordable yet robust connectivity for residents remains a key requirement for 6G remote solutions. Endowing rural networks with energy metering capabilities at the component level is a driver to support autonomous energy management systems, while software-enabled renewable-powered units will help attain significant power.

Techniques like cell zooming relying on power control and adaptive coverage, that were deliberately left out of early 5G standards development, can also enhance RoI for front/mid/backhaul layouts, e.g., by adaptively zooming out/switching off base stations deployed where the population density is particularly low. Multi-connectivity schemes can also harness cell zooming at cell edge and shadowed locations for expanded coverage and capacity.

B. Network Sharing

Telecom operators and stakeholders (e.g., regional content providers, manufacturers, governmental authorities, etc.) should coordinate a joint network development process right from the early 6G standardization stages. Network design shall foresee different levels of sharing, ranging from infrastructure/network to multi-tenant resource sharing. In particular, the different players should cooperate to avoid deploying separate power plants and hardware for those services offered in the same rural area, thus saving precious (already limited) economic resources for other types of expenses. For network sharing agreements to be a success, 6G needs to guarantee full competition, independent control, and secure services.

C. Technological Breakthroughs

The simultaneous wireless information and power transfer (SWIPT) paradigm enables energy-constrained nodes to scav-

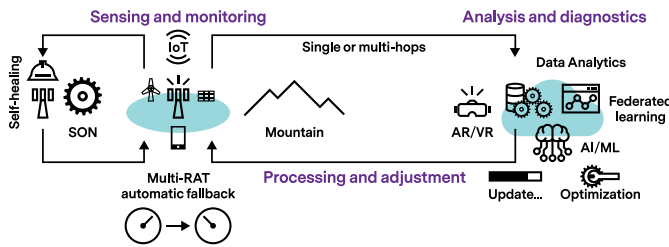


Fig. 5: A workflow for cost-efficient maintenance operations in remote areas.

enge energy from information signals. Incorporated in 6G, this technology can foster cheap manufacturing of battery-free sensors for rural services with intermittent traffic (e.g., agriculture). On one side, time-switching-based SWIPT, which is technically less complex than power switching, can potentially provide sufficient throughput to sparsely populated regions. Information bits can be conveyed through backscattering ambient signals for short-range scenarios. At the same time, SWIPT platforms can be installed in rural locations (e.g., on flying platforms) to charge low-power network elements starved of energy. The low levels of harvested energy, however, are still impeding the integration of advanced power-hungry functions in wireless-powered networks, thus calling for further research [13].

Another revolutionary element of the 6G ecosystem promoting energy-efficient wireless operations is the use of intelligent reflecting surfaces (IRSs), equipped with a large number of passive elements smartly coordinated to reflect any incident signal to its intended destination without necessitating radio frequency (RF) chains. On one side, passive beamforming may result in significant power loss over long distance, preventing standalone coverage in remote areas. In turn, IRSs, combined with existing infrastructures, can alter the electromagnetic environment experienced by the users, and favorably relay the traffic in underconnected regions, e.g., at the network edge, thus achieving higher overall network performance with substantial energy savings [14].

VI. INTELLIGENT AND AFFORDABLE MAINTENANCE

Hard-to-reach areas increase the complexity of maintenance in commercial 4G/5G networks, which is further exacerbated by the lack of qualified personnel residing in those areas. In this section we present innovative ideas to enable intelligent and cost-effective maintenance in 6G networks deployed in rural regions, as depicted in Fig. 5.

A. Network Intelligence and Automation

In the next decade, 6G is expected to leverage the power of collective intelligence by gathering huge volumes of data to prevent network malfunction and self-optimize [9]. This will minimize the need for on-site intervention in remote facilities and truly operate the network in an autonomous fashion. Nevertheless, such services will increase the need for centralized data processing in rural locations, which may become a bottleneck in large-scale scenarios. A promising approach is to design distributed learning strategies capable of offloading complex computation tasks into decentralized

environments with abundant energy supply. Federated learning may further simplify network automation by processing learning models (e.g., on cheap hardware and/or flying SDR platforms, as recommended for rural connectivity) instead of training data [9].

B. Proactive Outage Detection

AR and VR environments can remotely simulate real scenarios where a radio component runs under typical remote/rural conditions. Outcomes of these simulations can be combined with both external historical information of similar components, and internal contextual data gathered using pervasive intelligence, to predict node failures. This will help 6G networks build solid and automatic backup plans (e.g., system updates or operational parameter optimization) for hard-to-reach areas where on-site repair activities could be impractical [15].

C. Self-Healing Capabilities

Intermittent power availability and battery-constrained equipment in rural locations can lead to connectivity failures. Reflecting panels, e.g., IRSs, mounted on aerial platforms are able to achieve panoramic signal reflection from the sky and temporarily replace the front/backhaul for remote nodes. Further, they can direct RF energy towards low-power devices like farming IoT sensors for energy harvesting. Automatic fallback can also be scheduled to downgrade the connectivity to another technology under poor network conditions, e.g., by implementing appropriate multi-connectivity schemes as described in Sec. II-B. All these capabilities will benefit from the strong support of 6G collective intelligence [9].

VII. CONCLUSIONS

The problem of providing connectivity to rural areas will be a pillar of future 6G standardization activities. In this article we discuss the challenges and possible approaches to addressing the needs of the remote areas, as summarized in Table I. It is argued that optimally integrating NTN and FSO technologies can provide low-cost broadband solutions in extremely harsh environments, and can be the next disruptive technology for 6G remote connectivity. Integration of outdated technologies should also be provisioned so that they may be used to service the remote areas. Such provisions should extend to integrate COTS solutions to fully benefit from cost advantage gains. Spectrum, regulatory, and standardization issues are also discussed to support remote area connectivity. We also expect forthcoming 6G to largely embrace multidisciplinary features, i.e., pervasive intelligence, stakeholders cooperation and flexible regulations, as key enablers for inclusive connectivity. These approaches, directly or indirectly, address the very fundamental challenge of RoI in deploying remote connectivity solutions. For this reason, the discussion in this article repeatedly alludes to capex/opex savings innovations which can be facilitated by appropriate technical, policy, and regulatory mechanisms in 6G.

While the support of existing cellular deployments may already provide preliminary coverage, resilience, and flexibility in rural regions, it is yet to be studied how standalone deployments could support remote connectivity where integration

TABLE I: Open research questions for catering to remote regions in 6G.

Challenge	Potential Solutions	Future Research Directions
Affordability (Sec. II)	Dedicated 6G service class Multi-RAT convergence COTS equipment Everything as an open service Mega-cells	Define corresponding requirements and relevant key performance indicators (KPIs) Seamless resource orchestration over heterogeneous RF and optical bands Obsolescence concerns and need for anticipated replacement plans Inter-operability and cost-effectiveness concerns New guidelines for safety and power limits
Accessibility (Sec. III)	Network elasticity Legacy backhaul solutions Spatio-temporal QoS adaptation IAB NTN FSO SON	Flexible and automated resource orchestration Integration with emerging backhaul solutions (e.g. IAB, NTN, FSO) to reduce costs Intelligent tuning of encoding parameters to reduce complexity Balanced resource multiplexing between access and backhaul Complicated placement in 3D space and limited energy concerns Sensitivity to optical misalignment Evolving towards proactive self-coordinated 6G SONs using collective intelligence
Spectrum (Sec. IV)	Unlicensed access ≤ 6 GHz Large-scale spectrum cognition Micro-operators Horizontal/vertical spectrum sharing	Evolution towards collective intelligence-empowered control Sharing limited local information/models instead of complex data Innovative business and regulatory models encouraging new local entrants Need for rich environmental awareness for interference-free coexistence
Power (Sec. V)	Network sharing Automated energy management Ambient Backscattering Cell zooming SWIPT IRS	Full competition, independent control and secure services in multi-tenant networks Component-centric energy metering capabilities with pervasive intelligence Short transmission range Need to achieve a complex level of data-driven coordination Low levels of harvested energy Channel estimation overhead and deployment complexity in 3D air-ground networks
Maintenance (Sec. VI)	Predictive/preventive maintenance Self-healing Automatic fallback	Need for real-time computation offloading mechanisms Based on emerging technologies still maturing (e.g., IRS, UAV, energy harvesting) Preserving seamless and uninterrupted services during fallback

with existing communication technologies is impractical, e.g., on top of mountains, on the ocean, or in the air space.

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