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

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Abstract—In telecommunications, network sustainability as a requirement is closely related to equitably serving the population residing at locations that can most appropriately be described as remote. The first four generations of mobile communication ignored the remote connectivity requirements, and the fifth generation is addressing it as an afterthought. However, sustainability and its social impact are being positioned as key drivers of sixth generation’s (6G) 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 sustainability; 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. 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 connection also hinders people from remote areas to benefit from online commerce and engage in the digital world, thereby compounding already existing social and economic inequalities.

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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. Hence, the use of technology in farms and mines will increase the productivity and open new opportunities for local communities. Technology will also provide better education, higher quality entertainment, increased digital social engagement, enhanced business opportunities, higher income, and efficient health systems to those living in the most remote zones.

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. The fundamental challenges 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. In these regards, despite being in its initial stages, the 6th generation (6G) of wireless networks is building upon the leftover from 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)/virtual reality (VR), and haptics.

Boosting remote connectivity can start by addressing spectrum availability issues. Licenced spectrum in sub-1 GHz, in fact, is a cumbersome and costly resource, and may require new frequency reuse strategy in remote regions because of their unique requirements. Utilization of locally unexploited frequencies and unlicensed bands judiciously may help in reducing the overall cost, thereby making remote connectivity a viable business opportunity. Advanced horizontal and vertical spectrum sharing models, along with enhanced co-existence schemes, are two other powerful solutions to improve signal reach in these areas. Innovative business and regulator models may be suitable, to encourage new players, such as community-based micro-operators, to build and operate the local networks. Local, 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. Hence, it is imperative that 6G solutions for remote areas are designed as self-reliant in terms of their power/energy requirements, and/or with the capability to scavenge from the surrounding, possibly scarce, resources. Governments can assure 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 parallelly explored as they have direct implications on the technology requirements. Environmentally-friendly thinking should also be included throughout the chain of energy consumed 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 and incorporation of some degrees of self-healing capability is also very important since it might be difficult to access remote areas due to a difficult terrain, harsh weather, or lack of transport-connectivity. Suitable specifications for fault tolerance and fallback mechanisms need therefore to be incorporated.

Based on the above introduction, the objective of this article is two-fold: (i) highlight the challenges that hinder progress in the development and deployment of solutions for catering to the remote areas, and (ii) suggest novel approaches to address those challenges. In particular, the paper targets the 6G mobile standard, such that these important issues are considered into the design process from the very beginning. We deliberately skip a detailed literature survey, because a clear and comprehensive review is provided in [4]. We focus, rather, on discussing the requirements and the corresponding challenges, and proposing novel approaches to address some of those issues.

A summary of these challenges and possible solutions is shown in Fig. 1. The rest of the article is organized as follows. Sec. II discusses the question of how future 6G can deliver affordable connectivity to remote users. Sec. III provides a range of promising technical solutions capable of facilitating access to broadband connectivity in remote locations. Sec. IV promotes the use of a variety of dynamic spectrum access schemes and suggests how they can evolve to meet the surging needs in the unconnected areas. Sec. V presents approaches for integrating infrastructure sharing, renewable sources, and emerging energy-efficient technologies to boost optimal and environmentally friendly power provision. Sec. VI presents innovative ways to simplify maintenance operations in hard-to-reach zones. Finally, the conclusions are summarized in Sec. VII.

### II. Affordable Service Provisioning in Remote Segments

One of the biggest impediments to connecting the unconnected part of the world is 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 enumerated in this section.

**Dedicated remote-centred connectivity layer.** Besides 5G’s typical service pillars (i.e., eMBB, ULRRC, and mMTC), 6G should introduce a fourth service grade with basic connectivity target key performance indicators (KPIs). 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 sector. Some KPIs relevant to remote 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 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.

**Multiple radio access technologies (RATs) interworking.** Local access in remote areas can be designed to aggregate multiple and heterogeneous RATs. Remote streams can then be split over one or more RATs, thus allowing flexibility and providing the highest performance possible at minimal cost in everyday life and work. At the same time, digitalization in remote areas calls for large coverage solutions (e.g., TV or GSM white spaces (WSs)) to increase the number of users within a base station and helps reduce the network deployment and management costs, albeit at some performance trade-offs.

Radio frequency (RF) solutions can be complemented by the emerging optical wireless communications (OWCs). In particular, short range visible light communications (VLCs) category operating over the visible spectrum can boost the throughput in indoor, fronthaul and underwater environments (see Fig. 3) while serving the intuitive goal of illumination making it a cost-efficient technology.

**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 voltages 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 off-the-shelf 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).

**Adoption of open, virtualized and 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 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, this field still requires further research and development work before commercial deployment.

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.

**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 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 static-(e.g., location-based) besides temporal-quality adaptation to handle variations in channel quality over time.

**Wireless backhaul solutions.** 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 boost 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 and connected loads are still to be overcome. Fig. 2 illustrates how, even though the use of conventional microwave and satellite links can fulfill the performance requirements of hard-to-reach zones, 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.

Another recent trend is building efficient cost-effective backhaul links using software-defined technology embedded into off-the-shelf multi-vendor hardware to connect the unconnected remote 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 easier-to-deploy relays operating through wireless backhaul using part of the access link radio resources [6]. 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 as compared to fiber-like networks and facilitates site installation in rural areas where cable buildout is difficult and costly. The potential of the IAB paradigm is magnified when wireless backhaul is realized at millimeter waves (mmWaves), thus exploiting a much larger bandwidth than in sub-6-GHz systems. Moreover, mmWave IAB enables multiplexing the access and backhaul data within the same bands, thereby removing the need for additional hardware and/or spectrum license costs.

Nowadays, free space optical (FSO) links are being considered as a powerful full-duplex and license-free 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 in spherical receivers and beam scanning is hence needed to improve the capability of intercepting laser lights emanating from multiple angles.

**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 upgradation 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 [7]. This is especially useful in remote areas where the sparse distribution of users may result in spectrum holes. The unlicensed spectrum, in particular, can provide significant cost-savings for service delivery and improve network elasticity. New possibilities including evolved multiple access schemes and waveforms, like non-orthogonal multiple access (NOMA) for mMTC, 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 [8]. AI/ML can be also 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.

**Non-terrestrial network solutions.** 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, 6G envisions the deployment of non-terrestrial networks (NTNs) where air/spaceborne platforms like unmanned aerial vehicles (UAVs), high altitude platform stations (HAPSs), and satellites, provide ubiquitous global connectivity when terrestrial infrastructures are unavailable [9]. Potential beneficiaries of this trend are shown in
Fig. 3, including inter-regional transport, farmlands, 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 mmWave 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 that need to be addressed, including those related to latency and coverage constraints. NTNs can also provide remote-ready, low-cost (yet robust), and long-range backhaul solutions for terrestrial devices with no wired backhaul.

**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.

**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.

**Leveraging cognitive radio networks.** One of the major barriers for network deployment in rural areas is spectrum licensing, since participation in spectrum auction is typically difficult, from an economic point of view, for small ISPs. In this perspective, new licensing schemes can prosper the cognitive radio approach, allowing local ISPs to deploy networks in areas where large operators are not interested in providing their service [10]. Spectrum awareness mechanisms, e.g., geolocation database and spectrum sensing, can be used to inform network providers about vacant spectrum in a given area, as well as providing protection against unauthorized transmissions and unpredictable propagation conditions. For instance, Fig. 3 shows how TV and GSM WS towers can expand the connectivity beyond the rural households to reach more distant locations like farms and wilderness areas.

**Spectrum co-existence.** Sub-6 GHz frequencies remain critical for remote connectivity thanks to their favourable propagation properties and wide reach. In these crowded bands, spectrum re-farming and inter/intra-operator spectrum sharing can considerably increase spectrum availability [10]. Nevertheless, coverage gaps and low throughput in the legacy bands call for advanced multi-connectivity schemes to combine frequencies above and below 6 GHz. Using advanced carrier aggregation techniques in 6G systems, the resource scheduling unit can choose the optimal frequency combination(s) according to service requirements, device capabilities, and network conditions. 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 relief, atmospheric effects, and water absorption: for example Fig. 3 illustrates a scenario in which vital facilities in rural communities enjoy permanent connectivity using the lower bands in case of communication failure on the higher bands. Likewise, multi-connectivity 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 deployments of elastic networks in areas difficult to access.

**Utilizing unlicensed bands.** A combination of licensed and unlicensed bands has been acknowledged by many stan-
dardization organizations to improve network throughput and capacity in unserved/under-served rural areas, as depicted in Fig. 3. While the FCC has recently released 1.2 GHz in the precious 6 GHz bands to expand the unlicensed spectrum, the huge bandwidth available at millimeter- and terahertz-wave bands will further support uplink and downlink split, in addition to hybrid spectrum sharing solutions that can adaptively orchestrate network operations in the licensed and unlicensed bands. High frequencies require line of sight (LOS) for proper communication, complicating harmonious operation with lower bands. Accordingly, time-frequency synchronization, as well as control procedures and listening mechanisms, like listen-before-talk (LBT), need to evolve towards more cooperative and distributed protocols to avoid misleading spectrum occupancy. The management of uncoordinated competing users in unlicensed bands will emerge as important issue, and it needs to be addressed in 6G networks.

**Regional licenses and micro-operators.** Deployment of terrestrial networks for remote areas is challenging due to terrain, 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, which are responsible for last-mile service delivery and infrastructure management) to offer competitive and affordable services in remote zones [11].

**V. POWERING IN A GREEN AND EFFICIENT WAY**

Power supply is among the highest expenses of MNOs and a major bottleneck for ensuring reliable connectivity in remote areas. MNOs’ profitability and reliable powering can be improved following (a combination of) these solutions, as summarized in Fig. 4.

**Infrastructure sharing.** Local communication/power operators, as well as various stockholders such as companies, manufacturers, governmental authorities and standardization bodies, should build an integrated design which entails a joint network development process right from the installation phase. In particular, the different players should cooperate to avoid deploying several power plants for different use cases, thus saving precious (already limited) economic resources for other types of expenses.

**Efficient and optimal energy usage.** The 6G remote area solutions should be energy efficient and allow base and relay stations to minimize power consumption while guaranteeing affordable yet sufficient service for residents [12]. In particular, energy efficiency should target IoT sensors’ design and deployment, since the increasing use of a massive number of IoT devices, e.g., to boost farming and other activities such as environmental monitoring, is expected to significantly increase in the near future.

At the moment, these efforts have been made after the standardization work was completed, but 6G should include efficient use of energy during the standardization process itself. Techniques like cell zooming relying on power control and adaptive coverage can be reused at various network levels for flexible, energy-saving front/mid/backhaul layouts. AI/ML techniques can be very helpful in these scenarios. For example, the traffic load statistics on each node can be monitored to choose the optimal cell sleeping and on/off switching strategies to deliver increased power efficiency in all the involved steps of communication.

**Technological breakthroughs.** In addition to obvious energy sources such as solar, wind, and hydraulics, energy harvesting through the ambient resources (e.g., electromagnetic signals, vibration, movement, sound, and heat) could provide a viable efficient solution by enabling energy-constrained nodes to scavenge the energy while simultaneous wireless information and power transfer [13].

Another recent advancement 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 any RF chain. Although still in its infancy, this technology offers significant advantages in making the propagation conditions in harsh remote areas more favorable with substantial energy savings [14].
VI. INTELLIGENT AND AFFORDABLE MAINTENANCE

Operations, administration and management (OAM) functionalities and dedicated maintenance for each network component are of paramount importance to overall system performance and user experience in traditional commercial 4G/5G networks. This comes at the expense of complicated and costly tasks, especially in hard-to-reach areas. In this section we present innovative ideas to enable intelligent and cost-effective maintenance in 6G network deployed in rural regions.

Network status sensing and diagnosing. Traditionally, the OAM system is adopted for network status monitoring with a major drawback, i.e. manual post-processing and reporting time delay due to huge amounts of gathered data. To enable an intelligent and predictive maintenance, network diagnostics relying on AI-based techniques is advised [15]. With the development of edge computing technologies, multi-level sensing can be employed to achieve near-real time processing and multi-dimensional information collection within a tolerable reporting interval. For instance, processing operations related to short-term network status could be mostly done at the edge node to ensure fast access to this vital information in rural zones.

Network layout planning and maintenance. As mentioned in the previous sections, the network in remote areas is mainly composed of cost-effective nodes along the path from the access to the core parts (e.g., radio, centralized and distributed units, IAB-donors and relays) that need to be organized in either single or multiple hops. In this situation, the whole system will be harmed if one of these nodes experiences an accidental failure. To enhance the resilience of such networks, more flexible and intelligent network layout maintenance is required. More precisely, using evolved techniques such as SONs (see Sec. III), the link among each couple of nodes within the network can be permanently controlled and dynamically substituted or restored in case of an outage (see Fig. 5). Additionally, since a big part of the next generation mobile network is virtualized, appropriate tools or even a dedicated server may be needed for automatic software updates monitoring, periodic backups and scheduled maintenance to avoid or at least minimize the need for on-site intervention in those remote facilities. Automatic fallback mechanisms can also be scheduled to downgrade the connectivity to another technology under bad network conditions, e.g., by implementing appropriate multi-connectivity schemes, as described in Sec. IV.

Network performance optimization. Network optimization in rural areas should take into account remote-specific requirements and constraints. For example, access to the edge resources, which are finite and costly and can be rapidly exhausted, should be optimized taking into consideration the intended services, terminal capabilities, and charging policy of the network and its operator(s).

A summary of the maintenance life cycle in remote and rural areas is shown in Fig. 5. In particular, after intelligently building and processing relevant system information data sets, maintenance and repair activities (e.g. system updates or operational parameters optimization) can be performed remotely and safely using 3D virtual environments such as AR and VR.

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. It is argued that such service should be optimized for providing a minimum fallback capability, while still providing full support for spatio-temporal service scalability and graceful quality degradation. We also give insights on the constraints on network design and deployment for rural connectivity solutions. We claim that optimally integrating NTN and FSO technologies along the path from the end-point to the core element using open software built on the top of off-the-shelf hardware can provide low-cost broadband solutions in extremely harsh and inaccessible environments, and can be the next disruptive technology for 6G remote connectivity. Integration of outdated technology should also be provisioned so that they may be innovatively used to service the remote areas. Such provisions should extend to integrate open and off-the-shelf solutions to fully benefit from cost advantage gains. Spectrum, regulatory, and standardization issues are also discussed because of their importance to achieve the goal of remote area connectivity. It is fair to say that including remote connectivity requirements in the 6G standardization process will lead to a more balanced and universal social as well as digital equality.

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