INVITED PAPER

Exploring the Boundaries of Connected Systems: Communications for Hard-to-Reach Areas and Extreme Conditions

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ABSTRACT | Cellular communication standards have been established to ensure connectivity across most urban environments, complemented by deployment hardware and facilities tailored for city life. At the same time, numerous initiatives seek to broaden connectivity to rural and developing areas. However, with nearly half the global population still offline, there is an urgent need to drive research toward enhancing connectivity in areas and conditions that deviate from the norm. This article delves into innovative communication solutions not only for hard-to-reach and extreme environments but also introduces “hard-to-serve” areas as a crucial, yet underexplored, category within the broader spectrum of connectivity challenges. We explore the latest advancements in communication systems designed for environments subject to extreme temperatures, harsh weather, excessive dust, or even disasters such as fires. Our exploration spans the entire communication stack, covering communications on isolated islands, sparsely populated regions, mountainous terrains, and even underwater and underground settings. We highlight system architectures, hardware, materials, algorithms, and other pivotal technologies that promise to connect these challenging areas. Through case studies, we explore the application of 5G for innovative research, long range (LoRa) for audio messages and emails, LoRa wireless connections, free-space optics, communications in underwater and underground scenarios,

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delay-tolerant networks, satellite links, and the strategic use of shared spectrum and TV white space (TVWS) to improve mobile connectivity in secluded and remote regions. These studies also touch on prevalent challenges such as power outages, regulatory gaps, technological availability, and human resource constraints, where we introduce the concept of peri-urban hard-to-serve areas where populations might struggle with affordability or lack the skills for traditional connectivity solutions. This article provides an exhaustive summary of our research, showcasing how 6G and future networks will play a crucial role in delivering connectivity to areas that are hard-to-reach, hard-to-serve, or subject to extreme conditions (ECs).

KEYWORDS | 5G and 6G networks; digital divide; extreme communication; free-space optic (FSO); remote area connectivity; TV white space (TVWS).

NOMENCLATURE

3GPP	3rd Generation Partnership Project.
5G-NR	5G new radio.
5G-RedCap	5G new radio with reduced capabilities.
ADC	Analog-to-digital converter.
ACLR	Adjacent channel leakage ratio.
ACRA	Advanced coding for remote areas.
ACK	Acknowledgment.
AI	Artificial intelligence.
API	Application programming interface.
AR	Augmented reality.
ARA	Agriculture and Rural Communities.
AraRAN	ARA radio access network.
AW2S	Advanced Wireless Solutions and Services.
BATMAN-ADV	Better approach to mobile ad hoc networking advanced.
BLER	Block error rate.
BS	Base station.
CBRS	Citizen Band Radio Service.
CBSD	Citizen Broadband Service Device.
CISAR	Centro Italiano di Sperimentazione Attivita ed Radiantistiche.
COTS	Commercial off-the-shelf.
CPE	Customer premises equipment.
CPU	Central process unit.
CQI	Channel quality indicator.
CSI	Channel state information.
CU	Central unit.
DAC	Digital-to-analog converter.
DPD	Digital predistortion.
DSA	Dynamic spectrum access.
DU	Distributed unit.
EC	Extreme condition.
EIRP	Equivalent isotropic radiated power.
eMBB	Enhanced mobile broadband.
eMTC	Enhanced machine-type communication.
FCC	Federal Communications Commission.
FDD	Frequency-division duplexing.
FDU	Fiber distribution unit.
FEC	Forward error correction.
FlexNOW	Flexible nonorthogonal waveform.
FPGA	Field-programmable gate array.
FSA	Fragmented spectrum allocation.
FSO	Free-space optic.
FSOC	Free-space optical communication.
FTTH	Fiber to the home.
FWA	Fixed wireless access.
GAA	Generalized authorized access.
GFDM	Generalized frequency-division multiplexing.
GPS	Global positioning system.
GSM	Global system for mobile communication.
HAPS	High-altitude platform station.
HTRA	Hard-to-reach area.
ICASA	Independent Communications Authority of South Africa.
ICN	Information-centric network.
ICTP	International Centre for Theoretical Physics.
IoT	Internet of Things.
IP	Internet protocol.
IQ	In-phase and quadrature.
IR2A	Intrareceiver for remote areas.
ISM	Industrial, scientific, and medical.
ISP	Internet service provider.
ISU	Iowa State University.
ITU	International Telecommunication Union.
KPI	Key performance indicator.
LDPC	Low-density parity check.
LEO	Low Earth orbit.
LiFePO4	Lithium iron phosphate.
LoRa	Long range.
LoRaWAN	Long-range wide area network.
LTE	Long-term evolution.
MAC	Medium access control.
MBIE	Ministry of Business, Innovation and Employment.
MBS	Multicast and broadcast services.
MCS	Modulation coding scheme.
MEC	Mobile edge computing.
MIMO	Multiple-input–multiple-output.
MIMORA	MIMO for remote areas.
MNO	Mobile network operator.
mMTC	Massive machine-type communication.
NB-IoT	Narrowband Internet of Things.
NREN	National Research and Education Network.
NTIA	National Telecommunications and Information Administration.
NTN	Nonterrestrial network.
Ofcom	Office of Communications.
OOBE	Out-of-band emission.
O-RAN	Open radio access network.
OWC	Optical wireless communication.
PAL	Priority Access License.
PAPR	Peak-to-average power ratio.
PAWR	Platform for Advanced Wireless Research.

PDU	Power distribution unit.
PEST	Political, economic, social, and technological.
PHY	Physical.
PoE	Power over Ethernet.
QAM	Quadrature amplitude modulation.
QoE	Quality of experience.
QoS	Quality of service.
RAN	Radio access network.
RF	Radio frequency.
RFSoC	RF system-on-chip.
RRH	Remote radio head.
RoF	Radio over fiber.
RoI	Return of investment.
RSL	Received signal level.
RU	Radio unit.
SAS	Spectrum allocation service.
SDN	Software-defined network.
SDR	Software-defined radio.
SFP+	Enhanced small form-factor pluggable.
SNR	Signal-to-noise ratio.
TCP	Transmission control protocol.
TDD	Time-division duplex.
TED	Technology, entertainment, and design.
TR-STC	Time reversal space–time code.
TSG-RAN	Technical Specification Groups on Radio Access Networks.
TSG-SA	Technical Specification Groups on Services and Systems Aspects.
TVWS	TV white space.
UAV	Unmanned aerial vehicle.
UDP	User datagram protocol.
UE	User equipment.
UGV	Unmanned ground vehicle.
UHF	Ultrahigh frequency.
UK	United Kingdom.
VoIP	Voice over Internet protocol.
VPN	Virtual private network.
VR	Virtual reality.
VSAT	Very small aperture terminal.
V2X	Vehicle-to-everything.
Wi-Fi	Wireless fidelity.
WiLDNet	Wi-Fi-based long-distance network.
XR	Extended reality.

I. INTRODUCTION

If we observe the development of communication system technologies, we will find that there has been a significant improvement in the QoS delivered by recent communications infrastructure [1], [2]. However, the ongoing trend also shows that this improvement, though rapid, is effective only within the stringent limits of technology, harsh conditions, and economic policies [2], [3], [4]. As the technological evolution of communication systems has grown from 1G to 5G in terms of cellular networks or as we have seen data rate growth from 6 Mb/s over just about 10 km to tens of gigabits per second over thousands of kilometers in the optical fiber space, urban communities tend to experience state-of-the-art services offered by these improvements [5]. However, in rural area and HTRA, the deployment of communication infrastructure faces additional economic and technical challenges, leaving them unserved or underserved [6], [7].

This connectivity gap in remote and rural areas results in a digital divide [8], [9], [10], keeping a large number of people apart from the information age and impacting their productivity in the manufacturing, healthcare, transport, agribusiness, mining, and logistics sectors. Communication system designs (hardware, electronics, algorithms, and deployments) are usually subject to operational conditions such as the availability of line of sight (LOS), operation within restricted environmental ranges, and affordability. What happens outside these operational and economic limits? What is the state-of-the-art and the trend of communication systems outside major urban areas, in remote rural communities, and under extremely harsh environmental conditions? We aim to explore answers to these questions in this article as we discuss communications for HTRA and EC.

A. Communications for HTRAs and ECs

The rapid expansion of communications networks has created various opportunities for users in different areas and under varying conditions. However, this expansion is met with two main challenges: reaching or serving remote communities and HTRA, and serving in EC. In this section, an effort is made to differentiate between communications for HTRA and EC. Communication for HTRA focuses on the design of communication systems to reach underserved areas such as rural areas, remote locations, tunnels and underground areas, hilly and mountainous areas, and far-reaching areas such as the Arctic. Designs for HTRA communications also entail situation-based restrictions such as emergencies and natural disasters that might inadvertently make some places hard to reach. On the other hand, communications for EC focus on the design of communication systems to provide connectivity under ECs and hostile environments such as deep underwater, outer space, high altitudes, extreme dust, and extreme temperatures. As summarized in Table 1, although both paradigms are usually considered differently in the literature, the challenges that they pose significantly overlap. This overlap occurs because, in some cases, HTRA experiences prevalent EC, such as the Arctic, underwater areas, and underground facilities, or remote villages experience extreme weather conditions.

B. Background Works and Article Contributions

The study of communications in HTRA and EC has recently surged with frameworks proposed to provide connectivity in otherwise unreachable and unconnected areas. In most studies, reaching unconnected areas has been

Table 1 HTRA Versus EC Communications

Parameter	Hard-to-Reach Area Communications	Extreme Conditions Communications
Environment	Geographically isolated or under-served areas with limited infrastructure [2]–[4].	Harsh and extreme environments (e.g., deep underwater, outer space, high altitudes, extreme temperatures) [11], [12].
Bandwidth and Data Rates	Lower bandwidth, typically sufficient for basic services like voice and text. However, bridging the digital divide requires increased data rates for better experience [13], [14].	Higher bandwidth for data-intensive applications (e.g., video feeds, scientific data). Requires technical solution to address distortions under extreme weather conditions [15].
Latency	Tolerant of higher latency due to less data-intensive applications. Requires low latency for recent teleoperation services aimed at rural communities [16]. [13], [17].	Often requires low latency for real-time control and feedback due to the nature of applications [16], [18].
Energy Efficiency vs Availability	Energy is available but emphasis on efficiency is to conserve resources and ensure longevity [13], [19].	Energy is mostly limited. Requires energy-efficient systems due to power constraints in EC locations [20], [21].
Communication Protocols	May use standard protocols for basic connectivity.	Often requires specialized communication protocols for overcoming unique challenges.
Hardware Durability	Designed for long durability for limited maintenance due to limited resources in rural areas.	Requires ruggedized hardware to withstand ECs [22], [23].
System Reliability	Moderate considerations as communication system is designed to keep remote areas connected.	Critical considerations as ECs might disrupt communication systems -hence requires redundancies to address disruptions [24]–[26].
Application Focus	Focus on basic services, community development, and bridging the digital divide [27]–[29].	Often used for scientific research, exploration, and data collection in remote locations [30]–[33].

treated holistically based on generic challenges such as factors that predominantly affect the areas. Kumar et al. [34] presented a specific discussion for HTRA connectivity in rural India. The analysis in this study focused on the technologies applicable to address the connectivity issue and the strengths and weaknesses of the technologies. The study proposes a reduction in the cost of deploying networks and an improvement in service adoption rates to address connectivity. With advances in cellular communication, 6G has been proposed to provide connectivity in HTRA. However, the cost of backhaul deployment was presented in [35] and [36] as a major limitation for providing 6G connectivity to rural areas.

The research in [35] also provides insights into the prospective paths to bridge the digital divide between not-connected, underconnected, connected, and hyper-connected areas. In [13] and [37], coverage, cost, and reliability were identified as key components required to close the digital gap. While Zhang et al. [13] identified applications and opportunities for future rural wireless communications such as residential welfare, digital agriculture, and transportation, and made a strong case for bridging the digital divide based on this application, the study focused more on the data provider approach to create awareness of the problem and proposed a provide-driven data solution to address the issues with digital connectivity in rural Canada. However, these studies did not discuss the technologies, spectrum, or social factors that affect the rural connectivity.

In the study of [38], 6G technology is proposed in an architecture to provide extreme communication parameters within the scope of EC. The study highlighted the limitations of current 5G to address current technological trends such as XR/VR, digital twins, or 3-D communications and discusses how extreme communications requirements can be fulfilled in 6G. Maja et al. [39] took a different approach by discussing indicators for smart rural villages, which identifies connectivity as a key requirement for industry 4.0 in rural areas. Other related works, such as [40], [41], and [42], focus on technologies that could be used to address HTRA and EC, including the use of CubeSat communications and its technologies such as the Internet of Space Things, and low-power LoRa networks. The review in [7] proposes a big communication (BigCom) framework to address connectivity issues. The authors provide suggestions to key stakeholders, including governments, network operators, and content providers. Although the work in [7] identified the need for political, economic, social, technological, legal, and environment (PESTEL), no analysis was conducted in the survey.

Although the aforementioned studies provide an excellent review on the state of rural connectivity, the perspectives are based on reviews of literature or studies limited to a particular region. In this study, we push the knowledge body in connectivity in HTRA and EC by providing harmonized analytical insights from experts who have deployed the technology in various parts of the globe. In addition, previous works have discussed the challenges facing HTRA and EC based on arbitrary selection of factors that could impact connectivity in such areas. Discussions with respect to technological factors and political factors were treated in isolation of a standard framework, whereas, in this work, we provide a comprehensive PEST analysis that presents an interrelated discussion of how political and legal factors, economic and business factors, and social and technological factors affect EC and HTRA. A summary of key contributions in this work is given as follows.

1) We identify and examine the current challenges facing connectivity for all, particularly in terms of communications in HTRA (remote, rural, and hard-to-serve) areas and communications under EC. Using the PEST analytical tool, we demonstrate how communications in HTRA and EC are limited by PEST factors.
2) We discuss the state-of-the-art at the boundaries of connected systems by showcasing key technologies such as the use of long-distance Wi-Fi, TVWS communications, spectrum sharing, and studies on the effect of conditions on communication as it pertains to HTRA and EC communications.
3) We present a vision that identifies the role of future generation networks in communications for HTRA and EC. Beyond conventional cellular networks, such as 5G and the expected 6G solutions, we expand this role by considering the deployments of rural-focused terrestrial networks, the use of nonterrestrial networks, and recent solutions using FSOCs to provide a high-data-rate backhaul for communications in HTRA and EC.
4) We identify key regulatory issues facing EC and HTRA communications, discussing how licensed and unlicensed spectrum can support HTRA and EC.
5) Finally, we conduct extensive experiments and studies at the boundaries of connectivity. This is provided as case studies that showcase various solution deployments in HTRA and EC across the globe. The case studies offer insights into the key technologies used to provide connectivity to these areas and, more importantly, present a review of how these leading technologies perform in the areas, lessons learned, and future directions in the deployment of technical solutions for connectivity in HTRA and EC.

The rest of this article is structured as follows. Section II introduces the challenges that limit connectivity for all and sheds light on communications in the poorest nations/regions in the world and obstacles that significantly affect access to basic communication resources. Section III highlights the key regulatory issues affecting HTRA and EC, also presenting possible regulatory changes to foster better communication in these areas. Sections IV and V provide an overview of the concepts, technologies, and current solutions and techniques used in the deployment of communications for HTRA and EC. In Section VI, a critical examination is offered regarding the role of future generation networks in bridging the digital divide. Section VII encompasses various studies in EC and HTRA, implementation details, analysis, and discussion on how current innovations could improve the state-of-the-art. Section VIII presents the conclusions that summarize the current boundaries of connectivity and the contributions of this work in terms of economic and technical models to help connect the unconnected.

II. CURRENT CHALLENGES THAT LIMIT CONNECTIVITY FOR ALL

It is necessary to provide people in HTRA with connectivity solutions as this will promote new opportunities for those in such communities. Connectivity will provide access to applications that would support better education, improved social engagement via digital social media tools, improved health care systems, better entertainment, and general improved quality of life. In addition, with the shift in work culture due to COVID-19, if provided with the above average connectivity solutions, persons in such local areas can work remotely, which would indirectly improve their quality of life and also boost the economy in such communities. In essence, in the current digital era, universal access to the Internet is seen as one of the basic necessities, along with access to clean water, roads, schools, and so on [9], but, currently, this is achieved only for those who can afford its cost. In Finland, for example, access to digital connectivity is now a legal right and all service providers must supply a digital broadband service, regardless of location. On the contrary, the poorest nations and regions of the world, where obstacles to socioeconomic development are the most severe, are disproportionately and severely impacted by a lack of access to the basic Internet services. Despite the overwhelming arguments that emphasize the need for connectivity in these areas, this disproportionate deprivation still remains rampant. In this section, we use the PEST analysis tool, summarized in Fig. 1, to identify the key challenges that limit connectivity for all.

A. Political and Legislative Challenges to Connectivity

Political interventions have been seen as necessary to ensure the adoption and integration of telecommunication solutions. Strong political support not only encourages an improved economic case for integration of such technologies but could also offer regulatory reliefs that would make investing in telecommunications an attractive option. The implementation of supportive regulations, intervention policies, and governmental initiatives has been some of the effective ways that political factors have driven (or hindered) the spread of telecommunication solutions. These initiatives could directly support the growth of communications in HTRA and EC or indirectly hinder such growth. For example, a policy that disburses more funds in urban centers leads to improved quality of life in those areas, which inadvertently could lead to migration, and the need to put in more funds in such areas while indirectly leaving the rural areas underdeveloped [43]. Such seemingly benign initiatives would result in boosting the economy of the developed urban centers, while the same migration would significantly weaken the economy of the rural underdeveloped areas. As a result, the urban centers, with improved economy, are empowered more to drive future developments while depriving the rural areas, thereby increasing the digital divide between both regions.

B. Economic and Business Challenges

The main barriers to economic growth and social benefits identified by the World Bank include the cost of services and the lack of access to terrestrial and wireless networks. There is a general consensus on the impact of these challenges, especially the cost. In [44], it is noted that broadband is still too expensive in developing countries, where it costs more than 100% of the average monthly income, compared to 1.5% in developed countries. This presents a picture of the fundamental economic challenge in rural developing areas, for the realization of future Internet services that will offer appropriate access to all parts of society [9].

In practice, the economic challenges are not isolated from regulatory policies. One regulatory policy that directly limits cellular deployments in rural regions is the fact that operators acquire spectrum for both urban and rural areas but often prioritize deployments in urban areas where investments are profitable. Although regulators often have “universal service” rules aimed to provide coverage in rural areas, there have been many loopholes in their enforcement, thereby leaving persons in rural areas deprived. Therefore, some countries have realized the need to license spectrum in smaller geographical chunks, to allow regional initiatives, businesses, and local operators to establish commercially sustainable small networks.

Another limitation, related to this, is the de facto standard business model of flat rate pricing (independent of data volumes) to cellular customers applied by large operators in many countries today. The profitability of a rural BS in these models is no longer measured by the amount of traffic it serves, but rather by how many new subscriptions its installation will render (i.e., how many people reside in its potential coverage area). With these business models, essentially no new rural BSs are commercially justified.

In [45], members of the Internet Research Task Force’s “Global Access to the Internet for All” Research Group provide a global classification and a summary of the essential features of various alternative network deployments that have emerged in recent years, intending to deliver Internet services in locations where mass market network deployments do not exist or are insufficient. In summary, the only solution for these unsatisfied potential users is to directly undertake the building of the infrastructure required to obtain access to the Internet, typically forming groups to share the corresponding cost.

C. Social Challenges

By considering social factors as those primarily influenced by the cultural norms, traditional beliefs, or habitual patterns of a people, social challenges affecting technology in HTRA and EC can be examined from two perspectives: as individual persons and as a community. The first aspect concerns how social factors, such as habits, influence the way individuals in these areas use technology. Second, when considering society as a whole, the promotion or use of technology faces challenges in adoption based on societal trends.

In terms of individual, the adoption or growth of wireless communications technology in local communities is influenced by how the features of the technology impact their daily practices. In communities where people are well-educated and informed about the benefits of such technology for their businesses, productivity, and social lives, it is easier for the technology to being adopted. However, in many remote communities, individuals are often less educated about these benefits and may be unaware of the significance such technology could bring to their quality of life or their businesses. Therefore, in such remote areas, there could be more reluctance in supporting the adoption of wireless communications systems, given the significant upfront cost. In addition, the close-knit nature of rural communities usually results in a widespread generic acceptance or collective resistance to change since individuals rely on interpersonal communications and established practices. This collective mindset underscores the need for nuanced approaches to overcome resistance and foster acceptance.

The scenario presented in [46] and [47], where the adoption of 5G technology was inaccurately linked to the spread of coronavirus, exemplifies the complex challenges technology adoption faces in the face of social myths. The research in [46] highlighted the urgent need for public health interventions, such as health education strategies, to debunk the myths associating 5G with the COVID-19 pandemic in Sub-Saharan Africa. The prevalence of such myths among a significant portion of the adult population underscores the broader issue of how deeply ingrained beliefs and misinformation can impede technological progress in regions such as HTRA and EC. These examples serve as a stark reminder of the role social factors that play in either hampering or facilitating the adoption of new technologies. Addressing these social barriers effectively requires tailored strategies that not only consider local values and community dynamics but also employ effective communication to break down myths and foster a receptive environment for technological advancements in rural areas.

This approach highlights the interconnectedness of social challenges and the adoption of technology, pointing

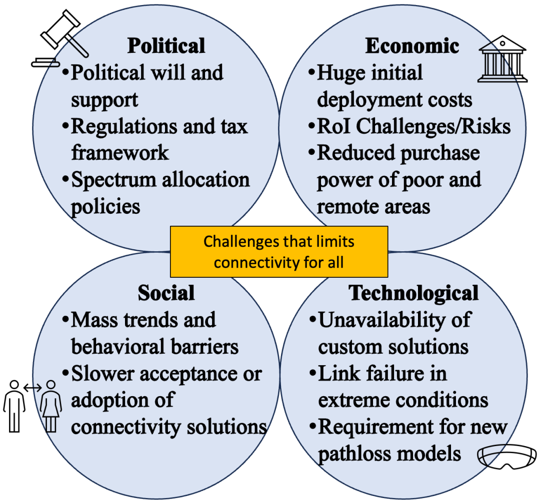


Fig. 1. ***PEST challenges that limit connectivity [36], [48], [49].***

toward the necessity of adopting multifaceted strategies that resonate with local communities' values and beliefs to ensure successful implementation and acceptance of new technologies.

D. Technology Challenges

Deploying connected systems to HTRA and EC presents significant technological challenges, necessitating innovative solutions that often (unfortunately) entail high costs. This discussion is organized around two principal types of solutions: 1) link-based solutions, aimed at establishing connections between communication points, and 2) end-to-end solutions, designed to offer a seamless communication pathway from source to destination. In this section, we delve into these two approaches in greater detail.

1) Challenges in Link-Based Solutions: Link-based solutions are crucial for establishing robust connections in various environments, from urban and peri-urban settings to the most challenging remote areas. These solutions span a broad spectrum of technologies, including LEO satellites, the IoT platforms (e.g., SIGFOX, NB-IoT, and LoRaWAN), classical wireless (Wi-Fi, Bluetooth, and Zigbee), and innovative approaches such as OWC [50]. OWC (including FSOC) emerges as a promising concept, addressing various challenges within 5G and the IoT communication systems by offering supplementary technology that supports massive connectivity through high throughput, low latency, and reduced power consumption [51]. On the cutting edge of experimental research, FSOC can benefit from techniques such as mode division multiplexing for extreme communication speeds [52], [53] as well as modal diversity, for improved resilience [54], [55]. Each technology faces unique challenges, particularly when deployed in ECs or to cover vast, underserved areas.

Environmental factors, such as rain, fog, snow, dust, and sand, significantly affect the performance of communication technologies, especially those operating at higher frequencies, such as 5G millimeter-wave (mmWave) channels and FSO links [56], [57]. The attenuation caused by these environmental conditions can degrade signal quality, necessitating strategies to mitigate their impact, including the use of elevated antennas or selecting frequencies less susceptible to atmospheric losses.

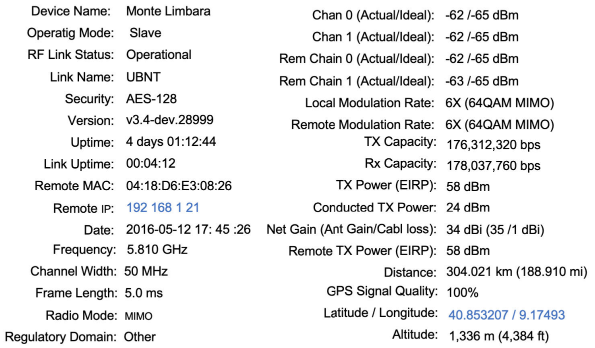
Moreover, the deployment of communication devices outdoors introduces additional challenges. Temperature variations, for instance, can significantly influence the reliability of LoRa communications, demonstrating the need for careful planning with respect to the environmental conditions [58]. The strategic use of highly elevated antenna systems, such as those on TV towers, offers a way to enhance network reach and maintain capacity over extensive distances, which is particularly relevant for creating ultra-large cells in 5G and future 6G networks [59].

Addressing these link-based challenges requires a multifaceted approach, combining technology selection, environmental consideration, and innovative deployment strategies to ensure reliable connectivity across varied and often difficult terrains.

2) Challenges in End-to-End-Based Solutions: End-to-end solutions focus on ensuring seamless connectivity from source to destination, overcoming the limitations of traditional network protocols and architectures in the face of unreliable links. The development of technologies, such as opportunistic networks [60], disruption-tolerant networks [61], and ICN-based solutions, aims to create more adaptable and resilient communication systems. ICN, in particular, addresses the inefficiencies of IP address-based networking by emphasizing content-centric operations [62], with research such as [63] exploring the integration of ICN principles with LoRa to offer comprehensive networking solutions.

An interesting aspect of end-to-end solutions is their ability to adapt to the dynamic nature of network environments and user demands. This includes efficiently managing data delivery across potentially unreliable links and ensuring data integrity and security in diverse conditions. The foundation of these solutions lies in the naming of content, name-based routing, intermediate caching, and self-certification of content, which together facilitate a more efficient and secure data exchange.

Moreover, the architecture of end-to-end solutions often incorporates advanced network protocols and strategies to enhance connectivity in remote and rural areas. Innovative network designs, such as those proposed in [64], leverage cognitive radio approaches and advanced PHY and MAC layers to exploit underutilized spectrum bands such as TVWS, providing high-speed connectivity at significant distances from BSs. These approaches exemplify how end-to-end solutions can address the comprehensive requirements of network connectivity, ensuring not only



Device Name: Monte Limbara
Operatig Mode: Slave
RF Link Status: Operational
Link Name: UBNT
Security: AES-128
Version: v3.4-dev.28999
Uptime: 4 days 01:12:44
Link Uptime: 00:04:12
Remote MAC: 04:18:D6:E3:08:26
Remote IP: 192 168 1 21
Date: 2016-05-12 17: 45 :26
Frequency: 5.810 GHz
Channel Width: 50 MHz
Frame Length: 5.0 ms
Radio Mode: MIMO
Regulatory Domain: Other

Chan 0 (Actual/Ideal): -62 /-65 dBm
Chan 1 (Actual/Ideal): -62 /-65 dBm
Rem Chain 0 (Actual/Ideal): -62 /-65 dBm
Rem Chain 1 (Actual/Ideal): -63 /-65 dBm
Local Modulation Rate: 6X (64QAM MIMO)
Remote Modulation Rate: 6X (64QAM MIMO)
TX Capacity: 176,312,320 bps
Rx Capacity: 178,037,760 bps
TX Power (EIRP): 58 dBm
Conducted TX Power: 24 dBm
Net Gain (Ant Gain/Cabl loss): 34 dBi (35 /1 dBi)
Remote TX Power (EIRP): 58 dBm
Distance: 304.021 km (188.910 mi)
GPS Signal Quality: 100%
Latitude / Longitude: 40.853207 / 9.17493
Altitude: 1,336 m (4,384 ft)

Fig. 2. ***Screenshot of the parameters of the 304-km link between Amiata and Limbara. Dual-polarization antennas implemented MIMO, thus achieving a combined throughput of 355 Mb/s.***

the establishment of robust links but also the seamless integration of these links into a coherent, resilient network infrastructure.

By focusing on the distinct aspects of link-based and end-to-end challenges separately, we can appreciate the complexities and innovative solutions required to establish and maintain effective communication networks in diverse and challenging environments.

III. REGULATION ISSUES FOR HTRAS AND EXTREME COMMUNICATIONS

Access to the wireless communication spectrum is a pivotal aspect, governed by the ITU and various national regulatory bodies to control this invaluable resource. This framework requires obtaining licenses for specific frequency bands, a process often marked by significant expense and time, creating substantial barriers to entry.

Radio amateurs have been fortunate to gain access to certain frequency bands for experimental and noncommercial purposes. For example, in May 2016, a temporary permit was granted by the Italian spectrum regulator for a 50-MHz bandwidth experiment on a 5-GHz carrier. This initiative, led by a team from CISAR, ICTP, and Ubiquiti engineers, showcased a long-distance broadband experiment achieving 176 Mb/s in one direction and 178 Mb/s in the other over a 304-km path between Mount Amiata in Tuscany and Mount Limbara in Sardinia. The total throughput of 355 Mb/s was made possible using 64 QAM and MIMO with 1.2-m parabolic dishes at each location, as shown in Fig. 2. The elevation of both mountains facilitated clearing the first Fresnel zone over the sea [65].

Spectrum usage for noncommunication purposes in ISM applications enjoys less stringent regulatory requirements. A significant decision by the FCC to permit the use of some ISM frequencies also for communication, subject to power and spectrum-sharing restrictions, has led to the global proliferation of Wi-Fi and similar technologies in unlicensed bands. This has profoundly impacted remote areas, where traditional services are scarce, but small businesses and organizations can utilize these frequencies to offer affordable connectivity, commonly in the form of long-range Wi-Fi links, Wi-Fi mesh networks, and TVWS. Unfortunately, the deployment of TVWS has been limited by regulatory inconsistencies across different regions. The allocation of the 6-GHz band remains a contentious issue between proponents of licensed versus unlicensed usage.

FSO technology operates without licensing, focusing primarily on regulations regarding safety limits to prevent eye and skin damage. This attribute has rendered it an appealing option for achieving high-speed communication over shorter distances, typically up to a few kilometers at gigabit speeds. Despite its advantages, the deployment of FSOC systems in HTRA remains limited due to their high cost, a consequence of not being mass-produced compared to radio-based systems. Efforts to develop cost-effective, open-source FSOC solutions are currently in progress, aiming to make this unlicensed technology more accessible for widespread use [66].

For countries with vast landmasses such as Brazil and India, and large developing regions such as Africa, employing licensed bands for wireless connectivity poses significant challenges. Utilizing ISM bands for unlicensed wireless communications faces limitations due to power constraints, congestion, and uncoordinated access techniques. A promising solution is the exploitation of TVWS.

In Brazil, recent regulatory advancements permit local ISPs to use vacant TV channels for connectivity services. While specific regulations for TVWS are under development, current guidelines impose strict power limitations on devices. Unlike the FCC, Brazilian regulations do not limit EIRP, capping instead the BS and UE at 1 W (30 dBm) of peak conducted power delivered to the transmitting antenna per TV channel. This allows ISPs to employ directional antennas for targeted coverage and encourages the development of multicarrier waveforms with low PAPR to enhance reach. Protecting incumbent users necessitates stringent OOBE and ACLR controls and flexible frequency selection to avoid RF filtering complications. The integration of new waveforms with effective DPD schemes and a geolocation database ensures incumbent protection and system adaptability, allowing frequency adjustments in response to incumbent detection. In Brazil, this protective measure is augmented by mandatory spectrum sensing by BS and UE to detect unauthorized broadcasts, enhancing secondary network performance and primary network security, and serving as a monitoring tool for regulatory authorities.

The following (and to a limited extent, Section IV) provides further detail on specific regulatory cases, including progressive shared spectrum mechanisms such as CBRS in the U.S. and UK Ofcom shared spectrum bands, and other initiatives such as the delegation of authority to civic, community, tribal, and indigenous groups. These efforts aim to make spectrum resources more accessible to unserved and underserved communities for self-provisioning, especially in rural and remote areas with low population densities.

A. United States—Citizen Broadband Radio Service

Introduced by the FCC in 2015, CBRS [67] is a three-tier spectrum-sharing framework operating in the 3.5-GHz band, specifically from 3.55 to 3.7 GHz. This band overlaps with the 3GPP n77 band (3.3–4.2 GHz) [68] and is traditionally used for naval radar operations, primarily along the U.S. coastlines. Inland, the spectrum is made available through a novel three-tiered access system to maximize its utility.

The first tier, incumbent access, reserves spectrum use for the U.S. Government and naval activities, maintaining priority access. The second tier, PAL, involves auctioned frequency bands allocated for specific geographic locations and time periods, ensuring guaranteed access for commercial users such as industries and campus networks. The third tier, GAA, offers shared spectrum access managed through a national database and an SAS. Approved SAS administrators, including companies such as Google and Federated Wireless, play a crucial role in protecting PAL operations and allocating channels in 10-MHz segments to CBSDs. The SAS sets critical parameters, such as maximum EIRP, channel frequency, bandwidth, and licensing duration, and maintains operational records of CBSDs.

CBRS's GAA tier represents a dynamic shared access model, enabling communities, civic groups, and other entities to establish private network access using this radio spectrum across various locations, including rural and underserved areas. Unlike TVWS, CBRS benefits from being within a standard 3GPP band (n78) [68], ensuring a broader availability and affordability of BS and UE modems for deployment.

B. UK—Shared and Local Spectrum Access

In 2019, Ofcom introduced new shared access licenses [69] for several sub-6-GHz bands, including FDD paired frequencies in the 1800-MHz band, TDD bands at 2300 MHz, and the 3GPP n77 band from 3.3 to 4.2 GHz, offering 400 MHz of spectrum. Concurrently, "local access licenses" were announced, allowing access to allocated spectrum in areas where the incumbent cellular operator/MNO are not utilizing their purchased spectrum. This approach adopts a "use-it-or-share-it" strategy, as opposed to a "use-it-or-lose-it" model.

Applications for these shared bands are processed directly through Ofcom, which allocates spectrum based on requests within several days. With 400 MHz available in the n77 band, the channel bandwidths from 10 to 100 MHz can be allocated. For instance, the n77 band allows BS transmit powers up to 24-dBm (EIRP) and antenna heights not exceeding 10 m. It is anticipated that the management of shared spectrum bands will eventually transition to online databases, facilitating true DSA.

The utilization of the n77 band, and the overlapping n78 3GPP band, for spectrum sharing is gaining momentum across the EU. Germany already operates shared n78 bands, with France, Denmark, and The Netherlands considering n77 and n78 frequencies for spectrum sharing.

C. Indigenous Communities and Rights of Spectrum Access

In countries such as the United States and Canada, tribal communities have a unique form of access to the radio spectrum on their lands, granted administratively by the national government instead of through auctions [70], [71]. This arrangement provides these often rural and underserved communities the opportunity to utilize specific frequency bands for FWA broadband or cellular/mobile networks. When these allocations include favored 3GPP bands, such as the 2.5-GHz bands currently deployed in some locations, it increases the likelihood of accessing affordable BS and UE equipment.

Further discussions and consultations are underway about granting tribal communities full sovereignty over the spectrum on their lands. This move is seen by some as essential for fostering innovation and closing the digital divide within these communities [72]. However, this approach introduces engineering challenges, as RF energy cannot be confined to tribal or national borders.

In Aotearoa New Zealand, the MBIE has taken a groundbreaking step by allocating 5G spectrum bands to Māori [73], spanning the entire nation rather than being confined to traditional lands or specific locations. This allocation, part of the 3.5-GHz band, stems from historical Treaty of Waitangi claims and negotiations, aiming at equitable resource distribution for the benefit of Māori and the nationās economic future.

This initiative represents a significant move toward affirming the rights of indigenous communities by granting them control over natural resources. The allocation allows for the development of shared spectrum networks, potentially operating both in rural areas and nationwide. Since the first formal 5G spectrum allocation in 2022 within the n78 (3.5-GHz band) [68], the Tū Ātea: Māori Spectrum and Telecommunications Service has made substantial progress. It focuses on connecting people, especially in unserved and rural areas, demonstrating the impact of empowering communities to manage and utilize spectrum resources effectively.

IV. TYPICAL TECHNOLOGIES FOR COMMUNICATIONS IN HTRAs

Achieving connectivity in HTRA often requires innovative and hybrid solutions due to a variety of challenges. Under the assumption that fiber or copper connections are not available, these challenges range from unreliable or slow GSM services, which may be attributed to insufficient backhaul capacity, to the high costs associated with more advanced Cellular technologies that disproportionately affect residents of rural, urban, and peri-urban areas. This section explores the most common technologies that offer viable solutions to these challenges, providing insights into their application, benefits, and limitations.

A. Wi-Fi-Based Connectivity

Wi-Fi, based on the IEEE 802.11 protocol, has significantly contributed to providing last-mile connectivity, particularly in urban environments. With over 42 billion cumulative Wi-Fi shipments throughout its lifespan, Wi-Fi presents a globally accessible, cost-effective solution. Efforts to adapt the 802.11 protocol for long-distance applications, termed WiLDNet, address the inherent limitations of the original 802.11 MAC protocol, which is not suited for LoRa due to its requirement for an ACK for each packet transmitted. Given that the propagation speed of radio waves is 300 km/ms, a transmitter on a 300-km link must wait 2 ms for the ACK, leaving the channel idle and significantly reducing throughput. To overcome these limitations, modifications were made to standard Wi-Fi network cards, notably the elimination of per-packet ACK and the introduction of an adaptive loss-recovery mechanism employing FEC and bulk ACKs [74]. Real-world deployments have demonstrated a 2–5 fold increase in TCP or UDP throughput, significantly lowering loss rates compared to traditional 802.11 protocols. WiLDNet can also be adjusted to meet specific end-to-end performance metrics such as throughput, delay, and loss.

An illustrative example of long Wi-Fi connectivity's viability is the link between El Aguila and Platillon Mountains in Venezuela, which spans 380 km (discussed in Section VII). This connection achieved a throughput of 3 Mb/s in each direction, serving as a precedent for subsequent deployments [75]. The adoption of more efficient protocols for long-distance Wi-Fi using standard hardware has been embraced by various vendors, each developing proprietary versions to stay competitive while incorporating technological enhancements such as improved modulation techniques, broader bandwidths, dual polarization, MIMO technologies, and GPS for synchronization to mitigate self-interference. For instance, in Malawi, the Nstreme protocol on Mikrotik hardware was deployed to link hospitals with the local NREN, lowering costs and enhancing network scalability [75]. Other long Wi-Fi initiatives include connecting rural schools in Ghana and the Philippines to the Internet using WiLDNet, and in Southern India, where WiLDNet linked eye-care centers in impoverished villages with a major eye hospital in Theni. This adaptation of established Wi-Fi technology for remote access has effectively bridged connectivity gaps. Policy-wise, most countries permit Wi-Fi links in ISM bands without the need for a license.

An additional strategy for enhancing connectivity in HTRA includes the deployment of Wi-Fi mesh networks. These networks utilize multiple Wi-Fi access points to create a large, interconnected network that can efficiently route data across vast areas, providing robust and flexible connectivity options, especially in environments where traditional Wi-Fi setups are limited by obstacles. Further details on this are provided in some case studies.

B. Free-Space Optical Communications

A possible application of FSO communication is to increase the capacity of existing microwave infrastructure. FSO systems can be installed on existing high sites in hybrid configurations for reliability [76]. FSO can also provide ad hoc support in the event of natural disasters by offering high-capacity emergency links, allowing people to continue using their mobile devices to contact the outside world, while the damaged infrastructure is repaired.

There are a number of commercially available FSO systems with a diverse range of data rates and distances, as shown in [51, Fig. 2]. Data rates of up to 10 Gb/s are now relatively common (likely due to the prevalence of off-the-shelf fiber Ethernet hardware at those rates), covering ranges of several kilometers. Presumably, some systems employ wavelength- or polarization-division multiplexing to achieve data rates higher than 10 Gb/s. The Taraa (a part of Google X) system has been demonstrated at 20 Gb/s over 20 km. Regrettably, commercial FSO systems are generally not cost-effective enough to justify their use for rural connectivity. There have been some low-cost open-source attempts, such as Koruza [77], which can sustain 1 Gb/s over approximately 300 m.

When lasers propagate through the air, the transmitted beam undergoes fading due to attenuation and atmospheric turbulence [54]. FSO systems typically utilize 850- or 1550-nm wavelengths. The longer range systems use 1550 nm because of their "eye-safe" nature. The transmit power can be significantly increased compared to shorter wavelengths to overcome attenuation and, to some extent, turbulence without the system exceeding regulatory safety limits.

Turbulence presents a significant challenge, primarily because of its random nature. This has led to numerous studies aiming to better model and correct for turbulence-induced errors on the FSO channel. One strategy is to use structured light, where the laser beam wavefront is tailored to be more resilient to turbulence [55], [78]. However, to date, the best solutions to this problem are adaptive optics and digital signal processing, neither of which are cost-effective as they require bespoke hardware. A particular challenge posed by turbulence-induced fading is deep fading, where the received signal falls below a usable threshold. Fountain codes offer a potential solution to this issue [79].

C. TV White Space

TVWS, one of the first regulated shared spectrum bands, was introduced around 2010. Formal regulator processes and licensing facilitated its deployment in countries, including UK [80], the United States [81], India [82], Kenya [83], and Malawi [84], among others. These networks, primarily aimed at rural and unserved areas, represented a significant shift toward utilizing unused spectrum in remote locations where traditional mobile/cellular services were economically unfeasible due to high installation costs and low potential returns.

The irony in many rural settings is the abundance of unused spectrum, contrasted with the absence of service provision by major operators. This scenario often persists unless interventions such as government co-funding or regulator support come into play, examples being the UK's Shared Rural Network project [85] and various NTIA funding initiatives in the United States [86]. TVWS emerged as a solution, offering clear and legal spectrum access for private network deployment without dependency on national carriers.

Despite the engineering feasibility of TVWS networks, their wider adoption has been hampered by the costs associated with proprietary hardware and their operation outside of 3GPP frequency bands [68], which could have leveraged more affordable and mass-produced equipment. Early applications in the United States [81] and UK [69] since 2011 have included backhaul/midhaul connectivity and point-to-multipoint networks for FWA, yet the high equipment costs and lack of integration with traditional mobile networks limited TVWS's full potential realization.

In developing countries, the underutilization of spectrum has been scientifically documented, leading to initiatives that map spectrum usage and argue for TVWS allocations for wireless links. Pilot projects with temporary TVWS licenses have taken place in several countries, including Malawi [87], Mozambique, Tanzania, South Africa, and Colombia, highlighting the need for an open database for TVWS deployments—a common requirement in industrialized countries.

Among vendors offering TVWS equipment, we have Harmonics [88], Adaptrum [89], Carlson Technologies [90], Nominet [91], Red Technologies [92], and WiFrost [93]. Carlson and Adaptrum are no longer offering TVWS devices. Newer developments in TVWS are discussed in the ARA wireless living lab and the 5G-RANGE network in Section VII.

D. Toward DSA

TVWS is a particular case of dynamically sharing the spectrum among several users on a real-time occupancy base. The next significant step is moving toward DSA in other frequency bands as well.

In recent years, the transition to DSA has predominantly been viewed as a challenge to be addressed by cognitive radio technologies. This involves both BSs and future UEs actively monitoring radio spectrum usage to enable short-term and opportunistic access to any available spectrum not in use at that time, which could be utilized by a local SDR. Although the process of spectrum sensing and measurement is considerably advanced, the integration of DSA strategies and hardware/software has not yet been realized in commercial or national regulatory systems. Consequently, the implementation of DSA management systems remains a prospective opportunity. However, it is anticipated that we will witness this in the very near future. SDR and RF signal sampling technology have become widely accessible. For instance, the RFSoC SDR device from AMD enables the sampling of multiple channels at rates of 10 GS/s and 14-bit resolution. This provides DAC and ADC channels for MIMO radios and DPD calculations and now facilitates cognitive radio operations through real-time spectrum monitoring up to 5 GHz with current technology [94]. With the introduction of AI to aid spectrum management, DSA is expected to emerge within the next few years.

Conclusively, it is important to acknowledge the contributions of the Dynamic Spectrum Alliance organization [95] in the shared spectrum narrative. As a cross-industry and independent body operating in numerous countries, its mission is specifically to promote market adoption of DSA. This organization aims to leverage spectrum sharing and DSA methodologies to provide enhanced support for connecting the world's 4 billion underserved individuals.

V. KEY CONSIDERATIONS FOR ECs

ECs are characterized by scenarios where standard communication technologies or channels are either significantly disrupted or rendered inoperative. Such conditions encompass environments subjected to extreme temperatures (both low and high), excessive dirt and dust, and areas prone to instability. In these contexts, the demand for reliable connectivity escalates, given its pivotal role in ensuring the safety and navigation of individuals through hazardous conditions.

To establish resilient wireless communications amidst severe weather and adverse environmental conditions, adaptability and robustness are imperative. The presence of heavy rain, fog, snow, and drastic temperature variations can severely impair wireless links, causing signal degradation [11]. Modern advancements, such as 5G-NR, herald the advent of CSI estimation in nonactive channels, a significant leap from the limited capabilities of earlier systems, thereby enhancing the feasibility of environment-aware wireless communications [96].

Wireless mesh networks, inherently designed for reliability through multiple routing paths and redundancy, are not immune to the adverse effects of harsh weather, which can reduce link capacities. The deployment of optimization models that recalibrate routing and adjust traffic demand is crucial in mitigating partial link failures and maintaining network performance under strenuous conditions [97].

Addressing the challenges posed by ECs requires a focus on hardware resilience, design considerations, and the mitigation of environmental and catastrophic risks, such as fires, which threaten to compromise communication infrastructure. This discussion foregrounds the exploration of KPIs pertinent to extreme communications, emphasizing the indispensability of technological innovations and redundancy mechanisms in adapting electronic performance to harsh environments.

Central to the discourse on extreme communications is the reliance on sophisticated hardware and technological solutions. Antennas engineered to endure harsh weather conditions, for example, are vital for maintaining signal integrity. Satellite communications emerge as a key player by providing less weather-impacted connectivity from space. The progression toward 6G-enabled devices marks a significant stride in infrastructure enhancement, coupled with AI-driven network management systems that dynamically adjust to fluctuating weather conditions, thus preserving communication fluidity during extreme weather episodes. Furthermore, the immunity of fiber-optic cables against severe weather conditions underscores their value in the 6G framework, enabling high-speed data transmissions.

In confronting hardware failures and channel disruptions, redundancy strategies are paramount. The incorporation of backup power solutions, such as generators and batteries, alongside dual-path and diversity routing techniques, ensures uninterrupted data flow, even in the event of primary channel failures. Redundant infrastructure components—including switches, routers, and servers—fortify the network against hardware malfunctions. Cloud computing extends a layer of resilience by facilitating data storage and access across multiple locations, whereas geographic diversification bolsters network availability under extreme weather conditions. Proactive network monitoring for early disruption detection and the deployment of distributed antenna systems round off the comprehensive suite of measures designed to navigate the challenges of extreme communication environments.

A. Extreme Communications Versus ECs

Communications systems are being designed to push performance indicators to extreme limits [98]. This development has stretched the boundary of communications systems toward providing extremely high data rates or extremely low latency. Extreme communications focus on the design of systems to achieve such extreme performances in scenarios such as extreme massive MIMO for 6G with the use of metasurfaces [99], ultrahigh data rates for holographic applications, and ultralow latency for teleoperation [100]. While these applications address needs in advanced sectors such as V2X, teleoperation, and industry 4.0, ECs could significantly alter communication channel conditions, potentially leading to reduced QoS or a complete denial of service. Communications for ECs aim to maintain a required QoS irrespective of prevailing conditions, which includes the use of communication hardware in extremely low (and high) temperatures, extreme dust and dirt conditions, and extremely unstable areas. For these challenges, delay or disruption-tolerant networks and the required technologies (electronic) for ECs are necessary. In addition, suffice to mention, the possibility of "in-x" local networks with star-like topologies and satellite or high-speed optical backhauls with redundancies would support disruptions, failures, or electronic performance changes in ECs.

B. Reliable Connectivity for ECs

Environmental conditions play a key role in the design of communications systems. Although most designs do not account for deteriorating or adverse weather conditions and the performance or QoS of the communication systems significantly varies based on prevailing environmental conditions. This correlation becomes a major concern as key facilities currently depend on the performance of communication networks and disruptions would significantly affect industry operations, transportation, and ad hoc services such as emergency response units. To guarantee these services irrespective of condition-based disruptions, the introduction of ad hoc networks, multisensor networks, and terrestrial mobile networks [101] has been proposed. However, more recently, developments to address such scenarios are centered around reconfigurable intelligent surfaces (RISs) and intelligent sensing and communication (ISAC) systems. RISs improve the reliability of communication networks by providing alternate "LOS-like" communication channel where the primary LOS of the communication network has been disrupted [102]. This alternate communication path maintains the QoS and can be used to provide reliable connectivity in the presence of conditional disruptions. A second key technology in this space is the use of ISAC, which, by simultaneously sending information to the receiver and observing the channel state, could provide higher spectral efficiency at reduced hardware cost. ISAC also holds the potential to retune system configuration by optimizing the network with respect to time-, code-, frequency-, and spatial-domain resources, to dynamically modify the beamforming gain of massive antennas while maintaining the system QoS.

VI. RECENT ADVANCES TOWARD HTRA AND EC

In what follows, we discuss recent advances in provision of communication services in HTRA and EC. This section discusses rural-focused innovations applied to agriculture farms as solutions robust against impact of weather while catering to the uniquely sparse distribution of households in country sides. It also includes discussions on nonterrestrial networks and future opportunities by HTRA and EC communications in rural communities.

A. Rural-Focused Broadband Technology Innovation

1) Rural-Focused Terrestrial Networks: The sparse distribution of agricultural farms, small cities/communities, and independent households in rural regions necessitates rural-focused broadband technologies. For example, an agricultural farm or a rural city may be tens or even hundreds of kilometers away from the nearest Internet backbone. Connecting such remote locations with fibers is often not economically viable, and there is a need for long-distance, high-capacity wireless backhaul solutions that can provide robust broadband middle-mile services to these areas at an affordable cost [103].

Although microwave wireless backhauls have been utilized in rural areas, they lack the capacity required for next-generation broadband services envisioned for 5G and 6G. To achieve high-capacity wireless backhaul, exploration of solutions at higher frequency bands, ranging from mmWave bands to FSO communication bands (e.g., 194 THz), is necessary due to the availability of more spectrum for wideband communications.

However, there is an inherent tradeoff between capacity and robustness, with higher frequency wireless backhaul links being more susceptible to weather impacts [104]. Thus, there is a pressing need to develop solutions that simultaneously offer high capacity and robustness in long-distance wireless backhauls. A promising approach is to exploit *temporal, spatial, and spectral diversity* within and across individual backhaul links. By leveraging the *temporal* variation and diversity of wireless channels, along with techniques such as packet retransmissions and FEC, communication reliability can be improved.

To utilize *spatial* diversity across wireless backhaul links with different endpoints, point-to-point backhaul links can be organized into mesh networks. In these networks, nodes are spatially distributed across large geographic areas (e.g., tens or hundreds of kilometers in diameter), enabling the use of varying weather impacts on spatially distributed links to enhance communication robustness by routing data traffic across these links and paths. By deploying backhaul links of different operation frequencies between every two nodes in the backhaul mesh, *spectral* diversity can be leveraged to optimize the overall communication capacity and robustness between nodes.

Transforming the aforementioned temporal, spatial, and spectral diversities into field-deployable solutions for robust, high-capacity wireless backhaul communications in rural regions present significant research opportunities across the network stack. For example, to enable agile adaptation to link dynamics while optimally using available communication capacity across different links and paths, RaptorQ [105] fountain code can be leveraged to provide low-overhead, FEC-based liquid data transport for real-time, robust communications across wireless backhaul mesh networks [106].

In addition to the need for long-distance, high-capacity wireless backhaul, rural regions also present unique requirements for wireless access networks. While the relatively denser user distribution in rural cities and communities may benefit from cellular systems operating at higher frequency bands, such as the 5G midband and mmWave bands, the sparse distribution of individual households in vast rural areas calls for cellular systems operating at lower frequency bands (e.g., the TVWS band) with massive MIMO and beamforming capabilities. Operating at lower frequencies enables larger cell radii and reduces costs by decreasing the number of BSs needed to cover a given geographic area. Massive MIMO and beamforming improve spectrum use efficiency and communication capacity by directing beams toward sparsely distributed users and also help increase cell radius.

Another distinctive aspect of rural wireless communication is the seasonal, on-demand use of ground, and aerial vehicles on agricultural farms, necessitating on-demand provisioning of spectrum and communication infrastructures. This enables high-throughput, real-time wireless communications for precision agriculture [103] and offers opportunities for dynamic spectrum sharing.

2) Nonterrestrial Networks: Along with rural-focused terrestrial wireless backhaul and access networks discussed above, NTN using spaceborne satellites (e.g., LEO satellite communications) and airborne HAPSs is expected to play crucial roles in connecting regions of extremely low user density (e.g., 1–6 users per square mile) [107]. In particular, NTN's wide service coverage and reduced vulnerability of spaceborne/airborne vehicles to PHY attacks and natural disasters help enable unique use cases [108].

1) *Service ubiquity and global connectivity:* Reducing the digital divide by providing direct access connectivity for handsets, homes, public/private/nonprofit organizations, and the IoT devices.
2) *Service continuity and resiliency:* Combining NTNs with terrestrial networks to provide service continuity for moving terrestrial platforms (e.g., trains, cars, and trucks), maritime platforms (e.g., maritime vessels), airborne platforms (e.g., aircraft), as well as for emergency networks in remote areas or after a disaster (e.g., earthquakes and floods).
3) *Service scalability:* Leveraging the large coverage areas of NTNs to provide MBS for public safety, massive software updates, group communications, live broadcasts, ad hoc multicast/broadcast streaming, and so on.

To realize these use cases, we need to address NTN challenges associated with the motion of satellites (e.g., dynamic cell patterns, delay variations, and Doppler), high altitude of satellites and large propagation delays, large beam size and delay differences for UEs at different locations within a beam coverage area, seamless hand over between NTNs and terrestrial networks, and so on [108]. These and related topics have been studied by the 3GPP [108], [109], whose work started with study items on NTN in Releases 15 and 16. The necessary features for NTN support have been specified as part of the 3GPP Release 17. More specifically, the Release 17 normative work on NTN in the 3GPP TSG-RAN and TSG-SA was completed in June 2022. The standard covers 3GPP-defined satellite access networks based on the 5G-NR protocols and the 4G NB-IoT and eMTC protocols, all operating in FR1 bands. The 5G-NR-based satellite access aims at serving handheld devices with eMBB services, whereas the NB-IoT and eMTC-based satellite access aims at providing

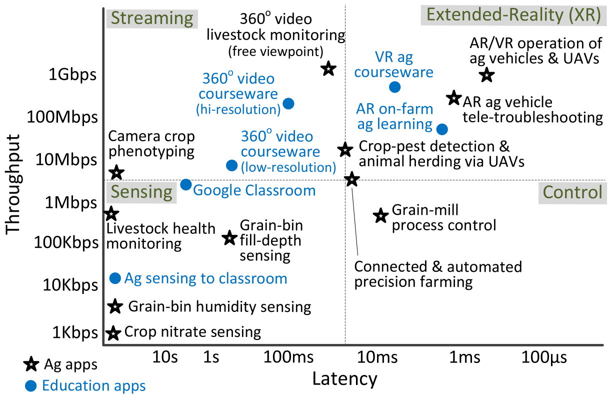


Fig. 3. ***Example applications in smart agriculture and rural education [103].***

machine-type communications to the IoT devices for applications in agriculture, transport, logistics, security, and so on. To support new scenarios covering deployments in frequency bands above 10 GHz and to introduce several enhancements for 5G-NR NTN and IoT NTN, normative work is being carried out as part of Release 18 [108], [109].

3) Future Opportunities of HTRA and EC Solutions in Rural Communities: The terrestrial and nonterrestrial networks previously discussed present a broad spectrum of applications across various fields, including agriculture, education, public safety, transportation, manufacturing, renewable energy, and telehealth. Fig. 3 illustrates potential applications in smart agriculture and rural education, showcasing the impact of wireless networks with varying communication throughput and latency characteristics.

High-throughput and low-latency wireless networks are poised to enable XR-based remote operation of UGVs and UAVs in smart agriculture, alongside AR-/VR-based educational initiatives. Low-latency wireless networks will facilitate precision farming through the collaborative use of UGVs and UAVs. High-throughput wireless networks are essential for at-scale, continuous agricultural phenotyping through a network of field-deployed cameras, while low-throughput, pervasive wireless networks will support monitoring of livestock health, crop nitrate levels, and grain-bin humidity.

Similar sensing and control, streaming, and XR applications are anticipated in other sectors, such as XR-based remote operation of ground and aerial robots in disaster response, connected and automated vehicles in transportation, real-time sensing and control in advanced manufacturing, and XR-based remote mental health consulting services for rural communities.

The diversity of applications within rural wireless networks introduces varied system criticalities, promoting a cycle of research, prototyping, demonstration, deployment, and application maturation of increasing criticality across both research and practical implementations. Concurrently, the core communication services shared across these domains (e.g., ultrareliable, low-latency wireless for safety-critical control and AR/VR) enable the research and innovation community to focus on specific fields such as agriculture and education. This focused approach helps in the development and maturation of rural wireless systems that can be subsequently adapted or expanded to additional domains.

B. Beyond 5G and 6G Developments for Connectivity in Remote Areas

Recently, the 3GPP [110] has presented the 5G-NR Release 17 [111], introducing new functionalities aimed at closing the connectivity gap in remote and rural areas. These features include the following:

1) 5G-RedCap devices;
2) 5G-NR over NTN;
3) support for uncrewed aerial systems;
4) the IoT over NTN;
5) UE power saving enhancements for 5G-NR;
6) enhancement of RAN slicing for 5G-NR;
7) 5G-NR slicing QoE;
8) coverage and positioning enhancements;
9) enhanced support of nonpublic networks;
10) support for edge computing in 5G core.

The 5G-RedCap, also known as 5G-NR Light [112], will enable devices with simplified PHY and MAC layers to achieve improved energy consumption and coverage, facilitating the deployment of IoT over 5G in remote and rural areas. The reduced cost of 5G-RedCap devices will also contribute to lowering the barrier to technological adoption in low-income regions. The integration of 5G-RedCap over NTN, combined with support for uncrewed aerial systems, will leverage satellites, HAPSs, and drones to extend coverage over large areas, providing direct-to-device connectivity in unserved or underserved areas. The implementation of IoT over NTN will enhance the applicability of 5G networks in remote and rural areas, facilitating the deployment of IoT devices for agriculture, mining, and environmental monitoring. UE power saving for 5G-NR represents a significant advancement, as many devices in remote and rural areas lack easy access to power sources. Enhancements in RAN slicing for 5G-NR and 5G-NR slicing QoE will enable operators to tailor network slices to meet the specific needs of remote and rural applications, such as extensive coverage and increased robustness. Coverage and positioning enhancements will improve services in remote locations, supporting autonomous machines in agriculture and mining industries. Enhanced support for nonpublic networks will permit local providers, associations, or even individual users to establish private 5G networks, catering to diverse application scenarios in remote and rural areas. Finally, the introduction of edge computing support by the 5G Core will facilitate the deployment of latency-sensitive applications at the MEC, close to the

Fig. 4. *Network of autonomous cellular BSs (no roads, no wired (fiber) backhaul, and no electricity grid) connect today the indigenous Sami people in their summer villages in the valleys of Arctic Sweden. Left: map with an indication of the region. Middle: summer impression (photograph: Jon Anders Svonni). Right: winter impression (photograph: Håkan Enoksson).*

end user, ensuring acceptable QoE even with the inherent delays in remote area networks or NTN.

Beyond the enhancements introduced by 3GPP Release 17, researchers globally are envisioning the 6G network [113], which is expected to support novel functionalities beyond mere communications, such as positioning, mapping, imaging, and sensing. These new features will be offered as services for future applications. Although the precise specifications for 6G networks have not yet been standardized, various proposals from research initiatives worldwide suggest that the next mobile network generation will encompass a wide array of new RANs, tailored for low-cost and long-range scenarios pertinent to this discussion. Innovative spectrum access methods, including TVWS, DSA, and FSA, are under consideration for standardization within 6G networks, facilitating the deployment of secondary mobile networks in uncovered and underserved regions. Several new enabling technologies are proposed to support these approaches, such as nonorthogonal waveforms with minimal OOBE without RF filters, low PAPR signaling, highly efficient waveforms based on faster-than-Nyquist signaling, cell-free MIMO, cognitive radio powered by AI techniques, and advanced spectrum sensing. Although research on 6G networks is still in its nascent stages, it is evident that the forthcoming generation of mobile networks could represent a definitive solution for bridging the digital divide across all scenarios.

VII. CASE STUDIES

In this section, we present case studies on the deployment of connectivity solutions in both HTRAs and ECs. The regions discussed as part of the case studies include remote, rural, and even peri-urban connectivity in the United States, Brazil, Venezuela, South Africa, Malawi, Scotland, and extreme Arctic weather conditions in Sweden. These case studies introduce practical deployments for connectivity solutions in HTRA and EC and discuss the key challenges faced in connecting such areas, as well as the effects of the deployed solutions. Here, we also introduce the idea that "hard-to-serve" areas can be viewed as a subset of HTRA. In these cases, despite the potential availability of conventional connectivity methods such as the different types of cellular technologies or FTTH, factors, such as affordability or ease-of-use (e.g., digital literacy constraints), make these areas essentially hard to reach.

A. Connecting Indigenous People and Tourists in Arctic Sweden

The first case study illustrating many of the aforementioned aspects is taken from the North of Sweden. Fig. 4 illustrates this remote and pristine mountainous region, situated along the Kungsleden trail, which is one of the most famous long-distance hiking trails in Sweden. Besides tourists, hikers, and visitors to small mountain lodges, the region is known to be inhabited, seasonally, by indigenous Sami communities, who have summer camps in the valleys with about 50 cabins.

Overall, there are 300–400 active and part-time residents in the area (from reindeer herding Sami businesses, tourism and accommodation companies, and aviation companies to police/mountain rescue, nature conservation, and research). In addition, over 50 000 annual visitors spend an average of one week in the area.

Yet, ever since the advent of mobile cellular telephony in the 1980s, this region has been forgotten by the national

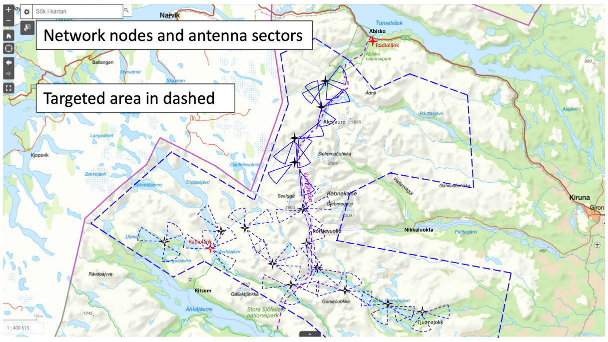


Fig. 5. *Arctic network map.*

operators [114]. In the valleys, there is no mobile coverage from any of the national operators, neither from Sweden nor from Norway.

The harsh environment, with long dark winters, a five-week polar night, and temperatures far below 0 °C for months, makes this area particularly challenging for cellular infrastructure deployment.

In 2018, as part of the national project #fulltäckning [115], the first off-grid BS was installed near the top of a mountain near Lake Alesjaure. The BS was placed in a container equipped with solar panels and batteries to provide power. Backhaul transmission was sourced from the main MNO 4G network and connected to its own core network through a VPN tunnel. The BS (which provided 2G and 4G connections) had three antenna directions, and initially, its low output power (0.2 W) kept energy consumption low and maintained good coverage through its high-altitude location and its high-gain antennas (23-dBi gain). Calls were reliably connected up to 12 km from the BS and users reported functional coverage up to 20 km from the BS.

This first installation marked the start of a developing network in the area in the years since. Today, it covers approximately 50 km of the Kungsleden trail between Abiskojaure and Sälka (a significant portion of the most popular stretch of the trail). Having been in a testing stage for years, a commercial operation is planned from 2024, by MNOs providing services. Further extensions in other mountain areas are planned in the coming years.

For many reasons, the provision of mobile network coverage in the area is a challenge. There are no roads that allow easy installation and maintenance, there is no access to a (fiber) backhaul network, and there is no fixed electrical grid in the vicinity of the BS locations.

The current state of the network is illustrated in Fig. 5. Up to 15 BSs are operational or planned. These stations are all robust and autonomous radio cabins with integrated antennas, placed at high positions for maximum coverage, and with a simple mounting concept (mostly directly anchored into the bedrock). Their power supply is provided through a combination of solar panels and fuel cells and, at some sites, through wind turbines, for green sustainable power supply all year round. Solar power is not feasible during the months of complete darkness at these latitudes in the winter.

Refueling of the tanks needs to be done twice per season: once in midwinter and once by the end of the spring/winter. A battery bank equipped with LiFePO4 batteries is designed to provide power for several days of operation, thus providing a backup for scenarios where the power supply would fail.

Today's pico-BSs (4G and 2G) in combination with high-gain antennas provide good coverage. In a recent update, output power has been increased to 5 W per LTE sector, allowing for improved coverage. In a fully loaded communication regime, a BS dissipates 250 W of power.

In early 2023, the network owners were the first to ever be allowed to locally use the spectral block frequencies that years back were acquired by a national operator (who then did not use its license in this area). This pioneering event illustrates that the seeming exclusivity of the nationwide auctioned licenses in this kind of region can successfully be challenged. The network's adaptable technology is offered to mobile operators, public safety, and other entities with communication/site needs. They can be made available based on roaming or with their own network codes for the BSs.

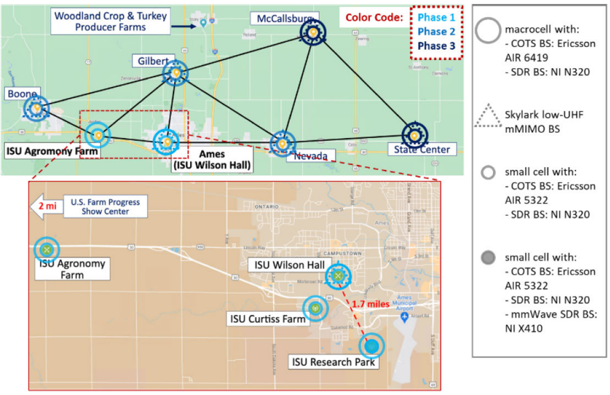


Fig. 6. ***ARA deployment in central Iowa, United States [116].***

We expect that the network now has reached a critical tipping point beyond which MNOs will be interested to accept invitations to provide services and profitability will be reached so that further investments and extensions can materialize.

B. ARA Wireless Living Lab

To enable rural-focused broadband research, education, and innovation, the ARA wireless living lab has been established as the U.S. PAWR in rural broadband [103], [116]. ARA embraces the unique community, application, economic, and operational contexts of rural wireless systems, and it features first-of-its-kind deployment of advanced wireless access and backhaul platforms in real-world agriculture and rural settings [116].

Fig. 6 shows the ARA deployment in central Iowa, United States. The top subfigure shows the long-distance, high-capacity wireless backhaul mesh network *AraHaul* spanning the City of Ames, where ISU resides, and surrounding agriculture farms and rural towns, with each AraHaul site equipped with heterogeneous platforms of the ARA wireless access network AraRAN. The bottom subfigure shows the additional AraRAN sites in the City of Ames.

As summarized in Table 2, AraRAN includes both SDR and COTS platforms that operate at frequencies ranging from low-UHF to mmWave bands. AraHaul consists of long-distance, high-capacity free-space optical, mmWave, and microwave terrestrial wireless backhaul links, as well as LEO satellite communications links. ARA enables a wide range of research in advanced rural wireless and

Table 2 Heterogeneous Radio Platforms in ARA [116]

	Radio Platforms	Frequency Range	Bandwidth
AraRAN	Skylark mMIMO	470–710 MHz	up to 40 MHz
	NI X410	1 MHz–7.2 GHz	400 MHz
	InterDigital	26.5–29.5 GHz	500 MHz
	NI N320	3–6000 MHz	200 MHz
	NI B210	70–6000 MHz	56 MHz
	Ericsson FR1	3.4–3.6 GHz	200 MHz
	Ericsson FR2	24.25–27.50 GHz	325 MHz
AraHaul	Aviat 11 GHz	10.6–11.5 GHz	100 MHz
	Aviat 80 GHz	71–86 GHz	2 GHz
	AraOptical	194THz	5 GHz
	LEO satcom	12–40 GHz	2 GHz

applications, with examples shown in Table 3. In what follows, we use the Skylark massive MIMO access network platform and the Aviat Networks wireless backhaul platform to illustrate the ARA living lab capabilities and enabled rural wireless research. Sections VII-B1 and VII-B2 provide some detail on the various subsystems.

1) TVWS Massive MIMO Platform in ARA: To enable research and innovation in high-capacity rural wireless networks with large cell radii, ARA deploys the Faros V2 BS and UEs from Skylark Wireless [117]. Currently, it has deployed one BS and 23 UEs in rural and agriculture settings. The deployment provides connectivity to crop and livestock agricultural farms around the City of Ames, Iowa, and the UE deployment features both fixed locations in farms and City of Ames as well as mobile platforms such as agriculture vehicles and robots, public safety vehicles, and city buses. Three more Skylark BSs and up to 60 additional UEs will be deployed by spring 2024 [118].

The Skylark Faros V2 BS follows the O-RAN-type architecture, which disaggregates the RAN functions into CU, DU, and RU, as shown in Fig. 8. The detailed design is given as follows [118].

1) Faros CU is an Intel-based CPU running Ubuntu 20.04 with a dedicated FPGA network interface card to accelerate the PHY layer application. The CU runs the main services responsible for executing the PHY and MAC. The FPGA card has four SFP+ interfaces, one of which is for uplink, while three interfaces are for downlink that can connect to three DUs.
2) Faros DU has an FPGA module responsible for clocking and synchronization of the radios on the RUs. Each DU can connect up to six RUs. The DU also has a reference radio that is used for communicating pilots to and from the radios on the RUs for reciprocity calibration and monitoring. The CSI from these pilots along with the uplink pilots from UEs is used in estimating the downlink channel. The reference radio has two channels and is connected to two omnidirectional antennas.
3) Faros RU consist of seven radio modules, each having two radio channels. Each radio is connected to one polarization of a dual-polarized antenna resulting in a total of 14 antenna ports. Each RU connects to a PDU for powering up the radios and to an FDU that connects it to the DU.
4) Faros UEs is the client radio that connects to the Faros BS. The UE radio also has two channels and connects to a directional dual-polarized antenna at fixed locations and two omnidirectional antennas at mobile locations. The UE is powered through a 1-Gb/s PoE port on the UE.

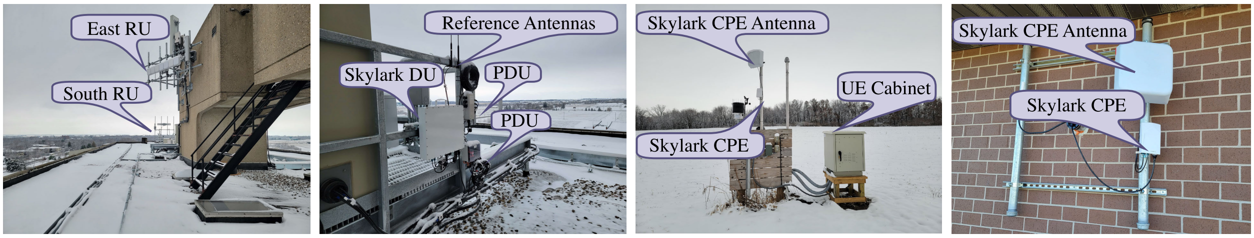
Table 3 Example Research Enabled by ARA [116]

Domain	Research area
Modeling	• Real-world rural wireless channel characterization • Physical dynamics and mobility characterization
Architecture	• Long-distance, high-capacity wireless backhaul • Cellular networks with massive MIMO and Device-to-Device (D2D) links • Mobile networking of agricultural vehicles and robots • Integrated wireless access and backhaul • Integrated wireless, fiber, and edge computing
Technology & Service	• Ultra Reliable Low Latency Communications • Massive MIMO, beamforming, and beam tracking • Fixed and mobile mmWave networking • massive Machine Type Communications (mMTC) • Dynamic spectrum sharing • Green wireless networking
Application	• AR/VR based teleoperation of vehicles and robots • Real-time collaborative machine learning • AR/VR-based crop phenotyping • Animal health monitoring and education

The BS is deployed on the rooftop of the Wilson residence hall at ISU. The CU is inside the cabinet on the rooftop, while the DU is mounted outside the cabinet on a metal platform. There are a total of three RUs covering three sectors of 120°. Since each RU has 14 antenna elements, the total number of antennas are 42. The deployment on the rooftop of Wilson Hall is shown in Fig. 7(a) and (b). Fig. 7(c) and (d) shows the UEs deployed in the field.

The Faros V2 system allows for capturing real-time CSI data over the air, and Fig. 9 shows the impact of weather on rural TVWS massive MIMO channels. Raw CSI data are collected before and during snow, as well as before and during rain, and the IQ samples of uplink pilots from the UEs are used to analyze the correlation of channels between each antenna pair. We can see that there is a higher degree of correlation between the channels before snow than during snow and before rain than during rain. This shows that the channels become more uncorrelated when it is snowing or raining. The parameter r shows the number of channel pairs whose correlation is greater than 0.5. It is observed that the number is higher before snow/rain. The decrease in channel correlation during snow/rain is due to the additional randomness introduced by snow/rain as a result of spatial diversity and randomness in snow flakes/raindrops. This decrease in channel correlation and increase in channel diversity can allow massive MIMO to help compensate for the additional path loss introduced by snow/rain [118].

2) Wireless Backhaul Platform in ARA: AraHaul employs a set of heterogeneous high-throughput wireless platforms, ranging from microwave and mmWave to FSOCs. The specific spectrum bands and communication capacity-range regions of AraHaul are summarized in Table 4.



(a) (b) (c) (d)

Fig. 7. ***Field deployment of Skylark Faros V2 system [118]. Note: CPE. (a) Skylark East and South RUs. (b) Skylark DU, FDU, and PDU. (c) Skylark CPE at Curtiss Farm. (d) Skylark CPE at city water tower.***

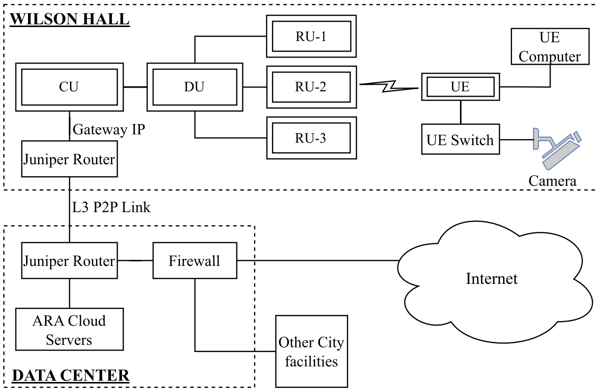


Fig. 8. ***Skylark deployment architecture [118].***

Table 4 AraHaul Wireless Link Capacity [104]

Platform	Frequency Range	Max. Bandwidth	Link Capacity
Aviat 11 GHz	10.6–11.5 GHz	100 MHz	1 Gbps
Aviat 80 GHz	71–86 GHz	2 GHz	10 Gbps
AraOptical	191.7–194.8 THz	80 GHz	160 Gbps

The long-distance microwave and mmWave point-to-point communication platforms from the Aviat Networks [119] represent the state-of-the-art in wireless backhaul communication, and it offers programmability, SDN support, and rich APIs for sensing wireless channel behavior (e.g., path loss and interference). The long-distance FSOC platform, called AraOptical [120], has been developed by the ARA project team, and it offers whole-stack programmability as well as high capacity, adaptability, and robustness.

Currently, ARA has completed the design and implementation of one AraHaul link, which is between the ISU Agronomy Farm site (monopole deployment) and ISU Wilson Hall site (rooftop deployment), as shown in Fig. 10. The distance between two sites is 6.31 mi. Additional AraHaul links will be deployed in 2024 and 2025, ultimately forming the envisioned mesh topology in Fig. 6.

Fig. 11 illustrates the building blocks of the AraHaul nodes at Agronomy Farm and Wilson Hall. The microwave and mmWave wireless backhaul links are set up using the advanced WTM 4811 radios from Aviat Networks, which represent the state-of-the-art in long-distance point-to-point wireless communications. WTM 4811 is a single box, single antenna, and multiband radio, which operates at both 11-GHz (microwave) and 80-GHz (mmWave) bands. It can support up to 1 and 10 Gb/s at the microwave and mmWave bands, respectively. These two carriers can function independently or collaboratively, offering enhanced

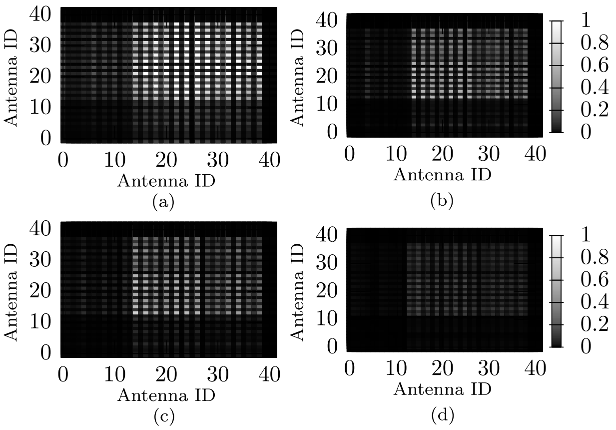
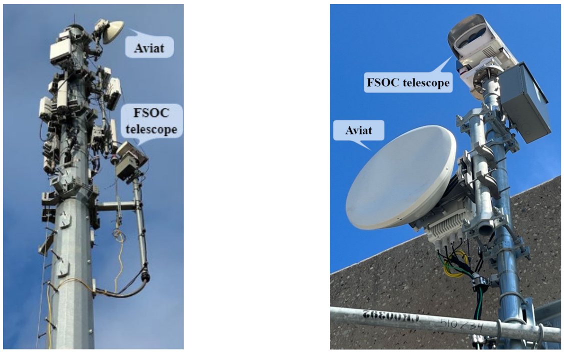


Fig. 9. ***Impact of snow and rain on low-UHF massive MIMO channel correlation [118]. (a) Before snow ($r = 191$). (b) During snow ($r = 40$). (c) Before rain ($r = 22$). (d) During rain ($r = 0$).***



(a) (b)

Fig. 10. ***Aviat dish antennas and FSOC telescopes of AraHaul [104]. (a) Agronomy Farm site. (b) Wilson Hall site.***

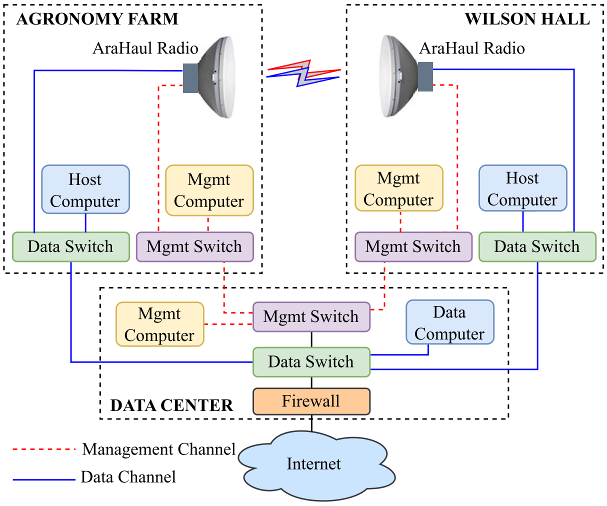


Fig. 11. ***AraHaul hardware and network architecture [104].***

flexibility in data and management traffic transmission through link adaptation.

Using the deployed microwave and mmWave wireless backhaul link, Zu et al. [104] have conducted experimental studies on the link capacity, as well as the impact of the weather conditions on various performance metrics such as RSL and link throughput. More specifically, measurement data were collected for three different link configurations (summarized in Table 5) for a duration of 6 h in a round-robin manner. The AraHaul link was running under each configuration for 15 min, during which RSL values were reported by the Aviat radios, and link throughput was measured using *iPerf* with UDP packets. Weather data were collected by the weather sensors for the same time duration.

Fig. 12 plots the measurement results of three different wireless link configurations during a 6-h period before, during, and after the rain in Ames, Iowa. It is clearly observed that the microwave link at 11 GHz is able to maintain steady RSL and throughput over the entire duration. In contrast, the mmWave link at 80 GHz is more susceptible to weather conditions, and the weather impact is more salient when a higher bandwidth and/or a higher order modulation scheme are used, as evidenced by 80-GHz Config #2's down time (hence no RSL measurement) and zero throughput around rain.

The aforementioned results demonstrate the tradeoff between communication capacity and weather resiliency across wireless links at different frequency bands, as well as the criticality of optimally controlling the operation modes (e.g., channel bandwidth and modulation schemes) of higher frequency wireless links.

Table 5 AraHaul Link Configurations in the Experiment

Config #	Carrier	Bandwidth	Modulation	Tx Power	Ant Gain	Beamwidth
11 GHz	10.6–11.5 GHz	100 MHz	4096 QAM	26 dBm	33.6 dBi	3.2 °
80 GHz #1	71–86 GHz	1 GHz	16 QAM	14.5 dBm	50 dBi	0.5 °
80 GHz #2	71–86 GHz	2 GHz	32 QAM	13 dBm	50 dBi	0.5 °

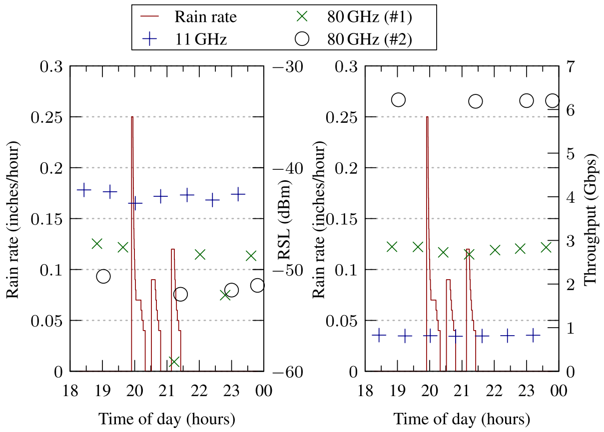


Fig. 12. ***Behaviors of AraHaul links over a distance of 6.31 mi (or 10.15 km) during a 6-h time period with varying rain rates. Three groups of results are plotted: 11 GHz ("+" points), 80 GHz Config #1 ("×" points), and Config #2 ("○" points). Details of the configurations are listed in Table 5. Rain conditions were reported by the Lufft WS100 disdrometer, RSL data were reported by the Aviat WTM 4811 radio, and link throughput was measured by* iPerf *[104].***

C. Peri-Urban Divide in South Africa

In this section, we will delve into the intricate facets of the digital divide in South Africa, with a specific focus on peri-urban regions [10]. It is commonly assumed that the digital divide exists primarily in remote or geographically challenging areas, but this assumption is not the whole truth. When we factor in elements such as poverty, education, digital literacy, and societal relevance, the landscape becomes significantly more complex. What we might consider "hard-to-reach" areas could be just across the road from extremely affluent neighborhoods. First, we will paint a broad picture and then zoom in on some intriguing deployments pertaining to this use case.

Internet usage in Africa, a continent with a population of 1.46 billion, accounting for 18% of the global population, is on the rise annually. Nevertheless, it remains substantially lower compared to the rest of the world. According to statistics from the ITU [121], in 2022, mobile network coverage reached 92% of the African population, with 50% of that coverage provided by 4G/LTE, in contrast to the global 4G average of 88%. A significant urban–rural divide is evident in Africa: 40% of the urban population in Africa uses the Internet (this is 64% of African Internet users), whereas only 23% in rural areas have access.

In Africa, 61% of the adult population owns a mobile phone, compared to the global average of 73%, and above 90% in the Americas and Europe [122]. Gender disparity in mobile phone ownership in Africa is striking, with a parity index of 0.76, signifying that females aged 10 and above are 24% less likely to own a mobile phone than their male counterparts—the highest gender disparity in the world. In comparison, the Americas and Europe have achieved gender parity, defined as a value between 0.98 and 1.02. It is worth noting that these statistics pertain to mobile phones, which encompass nonsmart devices. Conventional Internet access necessitates a smartphone or similar computing device.

A 2018 survey conducted in South Africa revealed that 60% of adults owned a smartphone, 33% owned a nonsmart mobile phone, and the remaining portion had no mobile phone at all [123]. It has been found that in South Africa, seven out of ten use their smartphones to access the Internet [124].

Affordability emerges as a prominent factor in device ownership. Multiple surveys have reinforced this notion. In 2020, 35% of South African respondents without smartphones cited affordability as the primary barrier to mobile Internet use, followed by "lack of relevance" at 20% and "lack of digital literacy and skills" at 17% [125]. Notably, these last two reasons may be intertwined, as individuals with limited digital literacy might fail to recognize the utility of the Internet. This combination of factors often outweighs the affordability challenge. A related survey [126] revealed that approximately 30% of respondents claimed they had "no necessity" for a smartphone, while 40% cited affordability as the main reason for not owning one. In addition, 15% considered smartphones "too complicated."

These reasons, although not immediately intuitive, significantly contribute to the digital divide, where digital literacy is sometimes taken for granted, particularly in an era of user-friendly touchscreens and mature interfaces. We will not delve further into the complex topic of whether the issue lies with de facto digital literacy or perhaps the limited availability of Internet content and apps in African languages? A parting statistic is on this topic; in 2021, Africa hosted only 2.3% of GitHub's active developers, compared to, for instance, North America, which had 31% of the contributions [127].

Many of the statistics presented here align with low and lower middle-income global averages, which is not surprising considering Africa's economic challenges [128]. The continent has an average GDP per capita of about \$2100, whereas the European Union boasts an average of \$37 500.

At the time of writing, the most affordable nonsmart mobile phone in South Africa costs around 200 Rand (\$10) through a popular online retailer. Smartphones can be purchased for approximately \$30, equivalent to two or three days' wages at minimum wage in the country. Based on these numbers, *device* affordability may not be the primary issue. Let us now turn our attention to the cost of mobile data.

The Broadband Commission suggests that an affordable percentage of monthly income allocated to Internet connectivity (whether mobile or fixed data) is 2%. The global average in 2022 was 1.5%, comfortably below this benchmark. Unfortunately, in Africa, the average cost of 2 GB of mobile data stands at 5% of the average household income. Focusing on South Africa, at the time of writing, a single 1-GB data bundle (valid for 30 days) from one of the major mobile networks costs 85 Rand (equivalent to 8 cents/MB), just under half a day's wage. For the cost of a loaf of bread (12 Rand), one can purchase a 50-MB bundle (24 cents/MB). How much data is required for "reasonable" Internet access, encompassing common activities such as YouTube and social media? Globally, in 2022, the average mobile data usage per smartphone was 15.9 GB [129], with North America and Western Europe averaging around 20 GB. In Sub-Saharan Africa, the average was only 4.7 GB.

Consider a monthly data requirement of 15 GB, priced at 529 Rand (0.034 cents/MB)—similar to the cost of the smartphone mentioned earlier. Intriguingly, for 559 Rand/month, users can subscribe to unlimited fixed 4G or 5G (depending on coverage) on a contract basis. This appears to be an attractive option until we realize that many households can only afford small data bundles as a percentage of their monthly income. Tragically, the cost per MB for the less fortunate is disproportionately high.

Several creative solutions have emerged in South Africa to address the challenge of Internet connectivity. Many of these solutions are centered around the use of off-the-shelf Wi-Fi hardware, which is both low cost and license-free. Below is a summary of several such cases.

Mankosi, a rural community in the Eastern Cape, is home to around 6000 residents. It developed one of South Africa's first rural, cooperative-owned, and operated ISP, known as the Zenzeleni Networks project, in collaboration with the University of the Western Cape [130]. Previously, the local community, situated about 60 km from the nearest city, Mthatha, expended up to 22% of their income on costly data and airtime. The Zenzeleni project provides affordable telecommunication services via solar-powered wireless community networks, enabling residents access to low-cost, uncapped Wi-Fi for 25 Rand/month—substantially more affordable than the prevailing rates in South Africa. The mesh network comprises interconnected, low-energy devices dispersed across the area. Having received a license exemption from the ICASA, the community only pays for backhaul Internet connectivity, available at wholesale prices. This enables services and voice calls to be accessed at a fraction of the standard costs, with the collected funds being utilized for community projects. This initiative has also empowered locals, some of whom have become network technicians.

A similar example can be found in Olievenhoutsbosch, a peri-urban township settlement in Centurion, South Africa, with around 26 000 households and an average household income of 2450 Rand. Unlike the rural Mankosi, Olievenhoutsbosch is located just a short drive (across the highway) from affluent housing estates with extensive infrastructure and fiber-optic connectivity [see Fig. 13(a)]. The average household in Olievenhoutsbosch can afford a monthly 350-MB data bundle from mobile service

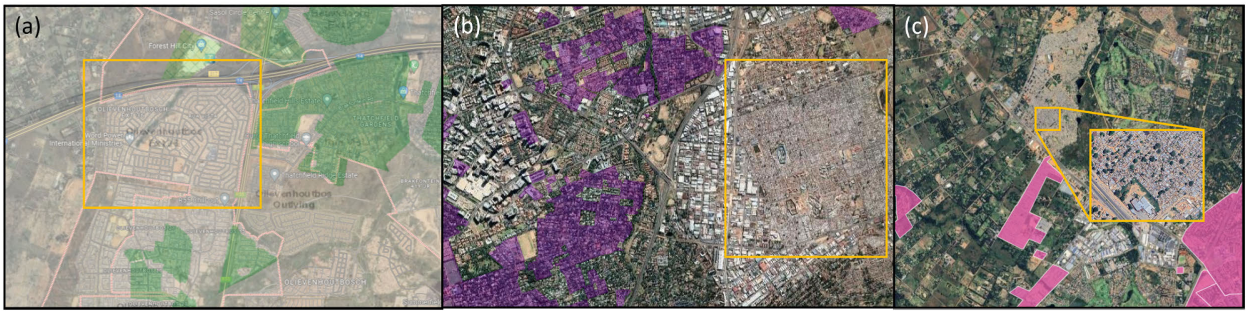


Fig. 13. ***Satellite images of three different low-income areas near Johannesburg, South Africa. (a) Olievenhoutsbosch. (b) Alexandra. (c) Cosmo City. The color overlays are nearby FTTH networks.***

providers, as per the aforementioned 2% benchmark. For smartphone owners relying on such a data bundle, caution is needed regarding automatic updates and apps such as YouTube, given that the Facebook app alone consumes about 60 MB. An unlucky user might use up these data in 5 min on a good connection where the app defaults to a high-definition stream.

RIOT Network is a South African start-up aiming to address this "unfair" data price scaling issue similarly by sharing backhaul from nearby locations and dividing the cost [131]. They have a network in Olievenhoutsbosch and sell uncapped Internet access using their system for 90 rupees/month. Their CROWDNet solution is a bespoke wireless mesh network, conceived, designed, and manufactured in South Africa. Each compact node can be installed by trained community members and is capable of linking with nearby nodes, connecting and sharing available GSM connectivity (such as 4G or 5G), and providing a local Wi-Fi hotspot.

Differing from the previously mentioned systems, iNethi, introduced in September 2018 in Ocean View, Cape Town (population 13 500 with 3000 households), is a community-owned platform providing free local cloud hosting, chat, and social networking services, in addition to conventional Internet connectivity [132]. The system caches valuable educational content such as Wikipedia and TED talks, minimizing Internet backhaul requirements. For content not hosted locally, users can acquire low-cost vouchers at 20 rupees ($1) per gigabyte. Upon connection, users are greeted with a landing splash page exhibiting infographics on various subjects, including COVID-19 during the pandemic period.

The iNethi network deploys LibreMesh access points and incorporates BATMAN-ADV and BMX6 mesh protocols to ensure scalable routing. The underlying transport network operates on Wi-Fi and TVWS.

All three of these systems leverage Wi-Fi as a transport network, typically utilizing mesh networks. Although this is a logical design pattern, it can be labor-intensive and expensive to deploy, with substantial impact only truly realized when there is a significant user base. A modified deployment approach might involve initially employing long-range, high-speed wireless point-to-point links to connect high-impact sites, such as schools or community centers in low-income areas. This would offer immediate impact by providing Internet connectivity to, for instance, hundreds of students, and serving as a central launchpad for a conventional community mesh network.

FSO systems may be a suitable technology for these point-to-point links as they generally support superior speeds to radio-based technology and have a range of a few kilometers [51], [54]. Essentially, this approach would transport a fiber connection from the outskirts of a low-income area, creating a "fiber, before the fiber" access point inside the area, under the assumption that service providers will eventually deploy conventional infrastructure. Unfortunately, existing commercial FSO systems are carrier or military grade hardware and are not affordable in this context; however, there have been several interesting demonstrations of very low-cost FSO systems that make use of off-the-shelf, repurposed fiber hardware [66], [133].

This approach could prove effective in developing nations such as South Africa, where well-connected, high-income areas often neighbor low-income areas with sparse connectivity. A case in point is illustrated in Fig. 13(b), presenting a satellite image where Alexandra (a township housing over 180 000 residents, many residing in informal, makeshift dwellings made of corrugated iron) is located just across the highway from Sandton (Johannesburg's wealthiest area and central business district). A similar case is shown in Fig. 13(c), where there is fiber very near an informal settlement, but the time horizon for deployment of fiber to that settlement is likely to be distant.

D. Providing Rural and Remote Area Connectivity in Brazil

In Brazil, there is a huge connectivity contrast between urban and rural areas. While coverage in cities is typically around 90%, only 23% of the area exploited for agribusiness is covered by 2G, 3G, or 4G networks according to a recent study from the Brazilian federal government [134]. This report also estimated that the agribusiness vertical in

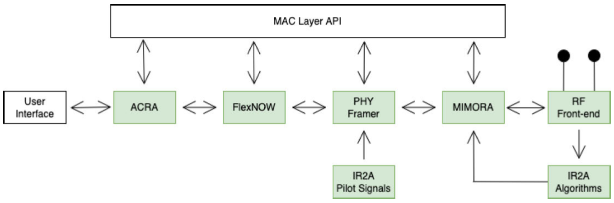


Fig. 14. ***Simplified block diagram of the 5G-RANGE PHY layer.***

Brazil could improve its productivity by $20 billion per year if the area covered by mobile networks is improved from 23% to 90%. In terms of social impact, Ziegler and Segura [135] have identified that up to 13 million people (≈6.4% of the total population) are living in underserved or uncovered areas in Brazil. Hence, connectivity in remote and rural areas can bring positive social, environmental, and economic impacts for Brazilian society.

The main challenges that hinder the use of today's technologies to deploy mobile networks in rural areas are: 1) high cost of spectrum licenses that increases the time frame for the RoI; 2) limited coverage and throughput provided by technologies designed and tailored for urban areas; and 3) high cost and complexity of the equipment that needs to be deployed in remote areas.

The development of new digital communication techniques introduced during the concept and design of 5G networks brought new solutions that can be used to overcome these challenges [136]. New waveforms with very low OOBE can be used to exploit unlicensed TVWS, reducing the cost of spectrum exploitation [137]. Powerful FEC schemes, such as polar codes and LDPC [138], together with MIMO techniques for diversity and spatial multiplexing [139] can increase the network coverage even with limited transmit power. Use of SDR [140] implementation approach and RoF allows operators to run the band-base processing in the cloud, deploying simple RRH in remote areas. These solutions have been combined to conceive a new mobile network architecture that can be integrated in future standards to close the connectivity gap in remote and rural areas. Following, we present the main aspects of this network.

1) 5G-RANGE Network: The 5G-RANGE network is composed of innovative PHY and MAC layers with new functions to support the remote area applications. Fig. 14 presents the main blocks of the 5G-RANGE PHY layer, where the innovative blocks are highlighted.

All FEC functions are implemented by the ACRA block. LDPC and polar codes have been considered. The evaluation of these two codes has shown that they present a similar BLER performance, but polar codes are more flexible in terms of code length and code rates if proper rate matching is used. Therefore, polar code has been selected for both control and data channels. FlexNOW is responsible for the waveform processing. Since the 5G-RANGE is designed to operate using TVWS, the waveform must present low OOBE and high spectrum efficiency. Among the available waveforms, GFDM has been selected because its flexibility allows for other waveforms to be covered within a single framework. The PHY layer Framer is used to multiplex the necessary control and reference pilots in the frame, which are provided by the IR2A pilot signals. Also, the PHY layer Framer block is used by the MAC layer to allocate time–frequency resources for multiple users. MIMORA is the block responsible for implement the MIMO techniques in the 5G-RANGE network. Two different techniques can be employed depending on the channel conditions for each user. For users with high SNR and good channel conditions, the MIMORA block employs space multiplexing MIMO to improve the channel capacity, providing higher data rates. For users with low SNR and challenging channel conditions, the MIMORA block employs TR-STC [141] to provide diversity and improve the system robustness. The MAC block performs all functions for resource allocation, MCS control based on the CQI received from each user, and channel allocation. The MAC layer is responsible for all cognitive functions for TVWS exploitation as well. Spectrum sensing in the PHY is performed by the IR2A block when defined by the MAC layer.

2) Prototype Network: The 5G-RANGE network was implemented using SDR over the GNU-Radio platform [142]. All the PHY and MAC layer blocks have been developed using C/C++ to run in real time. The prototypes can allocate up to 24 MHz of TVWS channels and provide up to 100 Mb/s of throughput. Fig. 15 shows a picture of the 5G-RANGE BS.

This prototype BS was used to perform field tests in Santa Rita do Sapucaí, Brazil. A mobile unit was installed in a vehicle for the coverage and throughput evaluation. Fig. 16 shows a picture of the setup used for the field test. The prototype network was able to provide 100 Mb/s

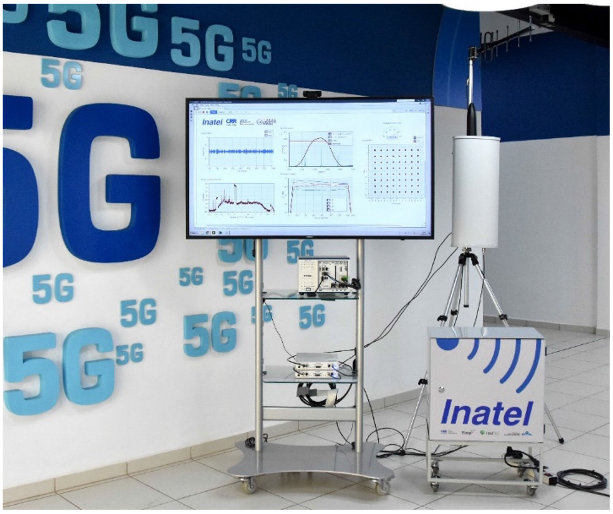


Fig. 15. ***Prototype of the 5G-RANGE BS.***

Fig. 16. ***Setup used for the 5G-RANGE field tests.***

at 50.6 km from the BS using 24 MHz in the UHF band. Hence, all the requirements for the remote and rural areas' mobile networks in Brazil have been addressed by the 5G-RANGE network.

From the development of the initiatives in Brazil, it is clear that, in order to provide connectivity in uncovered or underserved areas, a more flexible RAN is essential. New spectrum exploitation techniques based on shared unlicensed access, innovative robust nonorthogonal waveforms with low OOBE integrated with nonorthogonal multiple access, and adaptive MIMO techniques that can shift from diversity gain to spatial multiplexing gain according to the channel quality are some of the features that future mobile networks for remote areas must incorporate.

E. Wireless Data in the Venezuelan Andes

In the early 1990s, rural areas of Venezuela lacked telephone services, as the government prioritized access to the electrical grid over telecommunications infrastructure. The Telecommunications Laboratory, Universidad de los Andes, Mérida, Venezuela, embarked on a project to investigate the application of wireless technologies for providing data connectivity to educational and health institutions [143]. Initial experiments utilized packet radio technology within the 140–148-MHz amateur radio band at speeds of 9600 b/s, later transitioning to the UHF band to achieve up to 56 kb/s using the KA9Q TCP/IP software package by Phil Karn. This phase encountered limitations due to the dependency on frequencies licensed exclusively for amateur radio use.

The regulatory landscape shifted when the Venezuelan telecom authority permitted the use of the ISM bands for telecommunications, mirroring FCC's policies. This development presented a significant opportunity.

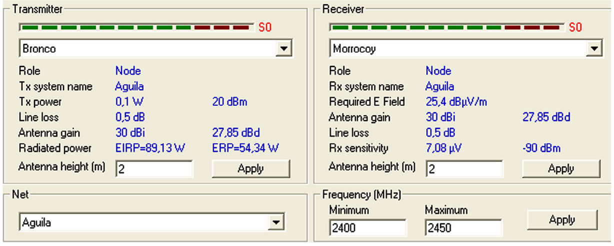
The project subsequently adopted spread spectrum technology within the 915-MHz band, utilizing Agere desktop cards that were meant for local connectivity and had small indoor patch antennas. Adopting custom-built ten-element Yagi antennas allowed to reach a long distance. One of the first significant achievements was establishing a 10-km link to La Aguada, a mountain situated at 3400-m elevation, where a repeater provided extensive LOS coverage over Mérida.

Following the reallocation of the 915-MHz band for cellular use, the project transitioned to the 2.4-GHz band, accommodating the use of smaller antennas. A pivotal development was the installation of a corner reflector antenna at La Aguada, significantly expanding coverage over Mérida and its vicinity. The university's Internet service, supplied through a VSAT antenna atop the Telecommunications Laboratory, was extended to remote educational facilities and many of the university's dispersed sites. Support from Fundacite Merida, a governmental scientific organization, facilitated the creation of the Red Teleinformática del Estado Merida network. This initiative linked schools, hospitals, and community centers using repeaters positioned at strategic locations, including a link spanning 70 km. In 1998, the introduction of a multisectoral antenna at La Aguada and the adoption of FDD techniques enhanced the network's throughput to 10 Mb/s in each direction.

In 2002, a partnership between the Universidad de los Andes and the University of Bremen was formed to gather environmental data from a high-altitude shelter at 4800 m. The 2.4-GHz band was unsuitable for this wireless link due to its utilization as the intermediate frequency of a 270-GHz receiver. This challenge was overcome by deploying an Alvarion 5.8-GHz bridge across a 15-km path, which proved reliable over several years, thanks to effective heat dissipation provided by substantial heat sink fins, as shown in Fig. 17.

Encouraged by these achievements, the project explored the feasibility of long-distance wireless communication using cost-effective, low-power Wi-Fi radios. Key to this exploration was the identification of geographical conditions conducive to such communication. The Andes Mountains and adjacent flat terrains presented an ideal setting. A collaborative effort with the ICTP in 2006 facilitated further experimentation using repurposed satellite dishes and the 2.4-GHz frequency supported by the affordable Linksys WRT54G router.

Fig. 17. ***Alvarion transceiver with massive heat sink fins.***



Bronco
Role: Node
Tx system name: Aguila
Tx power: 0,1 W 20 dBm
Line loss: 0,5 dB
Antenna gain: 30 dBi 27,85 dBd
Radiated power: EIRP=89,13 W ERP=54,34 W
Antenna height (m): 2

Morrocoy
Role: Node
Rx system name: Aguila
Required E Field: 25,4 dBµV/m
Antenna gain: 30 dBi 27,85 dBd
Line loss: 0,5 dB
Rx sensitivity: 7,08 µV -90 dBm
Antenna height (m): 2

Net: Aguila

Frequency (MHz)
Minimum: 2400
Maximum: 2450

Fig. 18. ***Radio mobile simulation parameters for the 280-km path between Pico del Aguila and El Baúl.***

Utilizing the Radio Mobile simulation tool [144], which implements the irregular terrain model [145], an unobstructed 280-km link was found between Pico del Aguila and El Baul. The subsequent site survey revealed the presence of an obstacle near Pico del Aguila, but an alternative site within the area, which had a clear LOS, was identified. The new simulation confirmed the feasibility of this link with a transmitting power of 100 mW and 30-dBi antennas at both ends, as illustrated in Fig. 18.

Confident of the existence of LOS, one team with a 2.7-m antenna went to Pico del Aguila, while another one, equipped with a 2.4-m antenna, went to El Baul. Coarse alignment was done using compasses, followed by a precise one using a signal generator and a spectrum analyzer. However, the propagation delay over the 280-km distance exceeded the ACK timer allocation, so it was necessary to increase the ACK expiration time in the Open WRT firmware to allow packet transfer, after which a steady link with approximately 65-kb/s throughput was obtained.

A subsequent experiment over a 380-km path utilized commercial 30-dBi antennas (1.5 m diameter) and wireless routers provided by the TIER group of Berkeley University [74], which implement a time duplexing protocol, thus eliminating the need of per-packet ACK, allowed us to achieve a bidirectional 6-Mb/s throughput (3 Mb/s in each direction). This link, whose profile is detailed in Fig. 19, remains the world's longest terrestrial wireless connections using modified Wi-Fi technology [146], demonstrating the potential for high-throughput, long-distance wireless connectivity using affordable technology. Of course, under anomalous propagation conditions, leading to the formation of sporadic tropospheric ducts, much longer distances have been reported [147].

F. Connecting Health-Maintaining Organizations in Malawi

The number of medical practitioners in Malawi is very small, so one way to make more efficient use of this scarce resource is by installing an efficient communication network through which local expertise could be shared.

To this end, a project was designed at the ICTP with the aim of connecting the Medical College, Blantyre, with the Mangochi Hospital and a number of other health-maintaining institutions, some of which are staffed only by paramedics.

The idea was to leverage existing communication towers to install low-cost broadband radios and antennas that would support data communications and videoconferencing, vital for medical applications [75].

After careful planning using digital elevation maps, a backbone was envisaged that started at the Medical College, with a 7-km link to Mpingwe, then a 55-km link to Zomba Peak, at 2000-m elevation, and from there a 100-km link to Mangochi tower, near the hospital. All of these links had an unencumbered LOS with complete clearance of the first Fresnel zone.

To improve reliability, a completely redundant backbone was planned, each link fit with eight radio transceivers (four at each end), four antennas with dual-polarization feeds (equivalent to four vertical plus four horizontal-polarization antennas in each link). The radios were installed into four wireless routers (two radios per router), housed in weather-resistant enclosures. This provided two independent transmission paths, one with each polarization, served by two simultaneous transmitters and receivers at each end. FDD was used instead of TDD, which entailed a thorough frequency planning exercise in the 5-GHz band to avoid interference from the high-power transmission frequencies into the receiver's front end. The wireless network was installed between July 25 and August 12, 2008. The end-to-end throughput over the 167-km backbone with two repeaters was 40 Mb/s, enough to cover the demands of data transfer, VoIP, and medical videoconferencing among the different sites.

The hardware installed at Mpingwe is shown in Fig. 20 as an example; a similar configuration was deployed at Zomba tower.

In Zomba tower, two additional access points operating at 2.4 GHz were installed to provide connectivity to Zomba City.

In a separate intervention, after the initial deployment, another link was installed at the Mangochi tower to provide connectivity to the remote Saint Martin hospital, 17 km away, so that local personnel could interact with the professors at the Medical College, Blantyre.

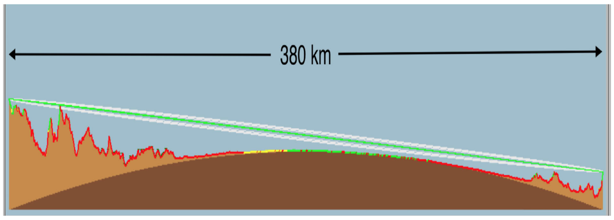


Fig. 19. ***Terrain profile of the LOS 380-km link in the Venezuelan Andes. The white lines represent the first Fresnel zone boundaries, red is the terrain profile envelope, and brown is the Earth's curvature.***

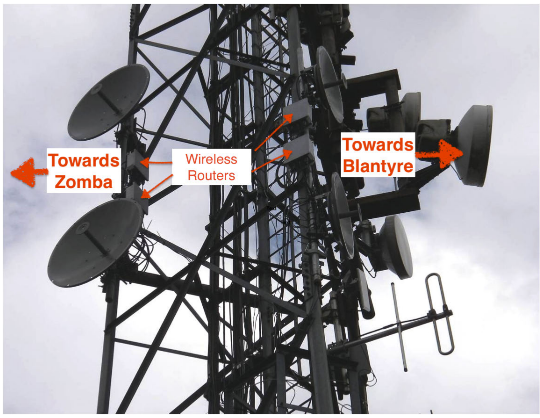


Fig. 20. *Mpingwe repeater. On the left side of the tower, the two antennas pointing toward Zomba Peak, and in between them, the two enclosures containing the wireless routers. On the front side of the tower, the two smaller diameter antennas pointing toward Blantyre. The connection between the two arms of the repeater is done by means of a switch located in the shelter at the base of the tower.*

G. Orkney Islands in Scotland—Self-Provision Mobile/Cellular Using Shared Spectrum

Located off the coast of the UK's most northerly tip, the Orkney Islands are remote and exposed to the elements of the North Sea. This archipelago consists of 70 islands with 20 inhabited with 22 000 inhabitants across an area that is 80 km from north to south and near 40 km from east to west. These characteristics make it difficult to build and operate traditional telecommunications infrastructure and low population density in most locations (except perhaps the main island town of Kirkwall) means that the return on investment is not there for cellular operator/MNO to provide full coverage across the area. In fact, in 2023, Orkney is ranked 96th for public cellular/mobile coverage in the UK out of 96 areas. It is worth noting that despite the rural communications challenges, Orkney can boast a very stable, skilled, and growing population and has been recently voted the best place to live in the UK. Established rural industries, such as renewable energy, agriculture, and aquaculture, complement traditional incomes from tourism, oil and gas industry, and shipping. To support this thriving community, the local government, i.e., Orkney Islands Council, operates and delivers essential services such as health and community care, education, inter-island and mainland ferry services, and general environment management. Therefore, good mobile/cellular and broadband facilities are very important for the sustainability of the economy.

Orkney therefore represents a stark example of a rural community who cannot wait several years for government funding interventions or the evolution of new business models for national service providers. Here, we review on the outcomes of the UK Government's co-funded project called *5G New Thinking*, which built private 5G networks in rural and unserved areas in Orkney. A key aim was to demonstrate that communities and civic groups can be supported to economically build and operate such networks. The positive outcomes of the project support the argument that future intervention funding for mobile/cellular deployment in rural areas should also target direct funding support for communities and local councils to support this type of self-provision. It is then proposed that this will complement and provide an alternative to the more usual approach of funding to incumbent cellular/mobile operators, who often do not have the capacity to work in rural areas, and even with intervention funding may not be able to build sustainable business models given their operational restrictions in very remote locations, and QoS and uptime operational requirements (such as the five 9 s of 99.999%) for a national network service provision.

1) 5G New Thinking Project, 2017–2022: This project involved a number of industry, academic, and civic partners working with a number of rural communities to devise different approaches to help solve the rural connectivity challenge. The project was led by Cisco Systems Ltd., with key partners, including the University of Strathclyde, CloudNet IT Solutions Ltd., Orkney Islands Council, the University of Glasgow, Faroese Telecom, Federated Wireless, BBC R&D, and Neutral Wireless Ltd. The 5G New Thinking project built upon know-how and experience of an earlier project, *5GRuralFirst*, from 2017 to 2019 [148] and from 2020 to 2022 developed a 4G/5G testbed network that was built across two remote island groups in Orkney, as shown in Fig. 21. The testbed explored a range of issues and challenges related to the provision of digital connectivity in hard-to-reach rural areas, encompassing technical aspects of building neutral host networks for roaming/

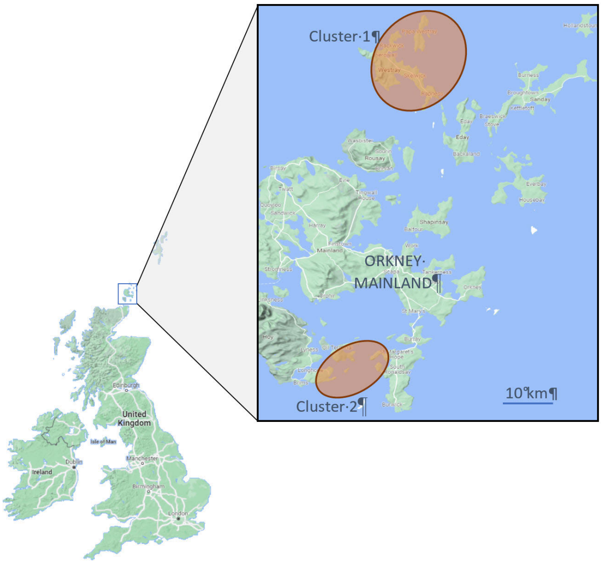


Fig. 21. *Orkney Islands in the North of Scotland.*

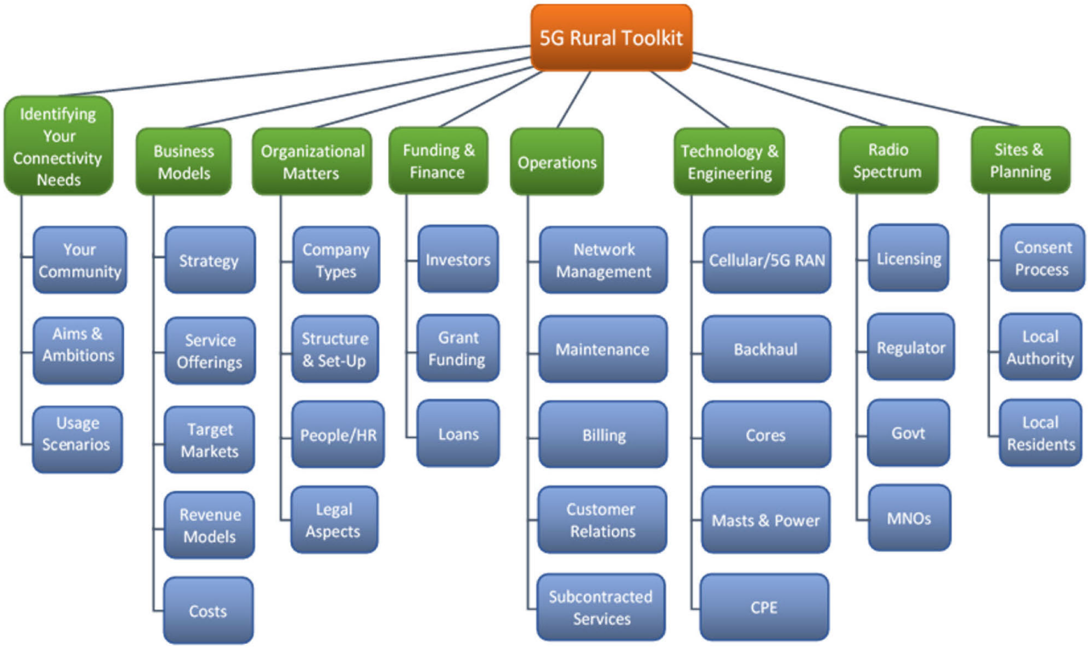


Fig. 22. ***Organization of the 5G new thinking rural toolkit [149].***

integration with mobile/cellular providers, and business models for community-owned and operated networks, spectrum access, mast site access and planning consent, and so on.

One of the key outputs of the project was a *5G New Thinking Rural Toolkit* [149] that not only aimed to integrate the results and learning from the project but also now provides a step-by-step experience and learning guide for other interested rural communities to consider whether or not they would or should take the same challenge of self-provisioning. The toolkit is the culmination of many years' work and experience by private, public, and academic consortium members and is openly available and implemented on a Media Wiki platform with free access [149]. The outputs of the project, and therefore the key topics covered by the toolkit, are summarized in Fig. 22. The toolkit also provides interactive tools for cost/feasibility analysis and guidance accessing spectrum in local and shared access spectrum bands in the UK.

2) Orkney Private Network Locations: The 5GNT Orkney testbed provided coverage across two "clusters," as shown in Fig. 21. Cluster 1 encompasses two remote islands in the north of Orkney; Cluster 2 encompasses three remote islands in the south of Orkney. Both clusters have poor (or no) fixed broadband connectivity and poor (or no) mobile/cellular data coverage in 4G (and often GSM/2G).

The overall aim was to create a network that has a good level of high-quality LTE macro coverage "everywhere," with smaller areas of 5G coverage delivered via 5G-NR radios. This, in turn, enables 4G and 5G connectivity to mobile phones in premises, roads, and countryside throughout the clusters, and 4G and 5G FWA to home and businesses also.

Cluster 1 (see Fig. 21) provides coverage in two islands that lie in the northwest of Orkney:

1) Westray, with an estimated population of 620 people living in 248 premises;
2) Papa Westray, with an estimated population of 90 people living in 72 premises.

Papa Westray is a small community, which has limited services. It is served by a small foot passenger vessel, which is there to provide community access (including doctor/National Health Service nurses, and school pupil transport) daily to and from the island. Flights to/from these islands are up to three times per day, using a shared small airplane shuttle service, also linking other islands.

Cluster 2 (see Fig. 21) provides coverage in three islands that lie in the southwest of Orkney:

1) South Walls, with an estimated population of 230 people living in 151 premises;
2) Hoy, with an estimated population of 190 people living in 128 premises;
3) Flotta, with an estimated population of 90 people living in 75 premises.

Hoy, measuring 143 km^2, is the largest island after the Orkney mainland. A natural causeway, the Ayre, links to the much smaller island of South Walls. The northern part of Hoy is a birdlife reserve and one of the most visited islands by tourists. Flotta is a small island lying adjacent to Hoy, has a large oil terminal providing employment, and also relies on agriculture as another main source of income. Therefore, in both clusters, the provision of good connectivity is very important for business and commerce

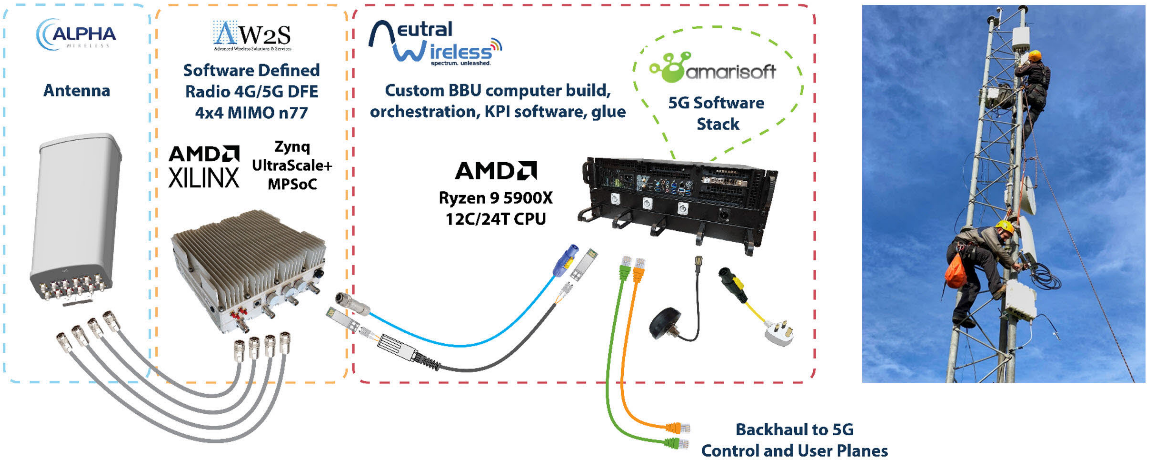


Fig. 23. ***Main components of the 4G/5G radios used for 5G new thinking: antenna, RU, baseband unit and backhaul/core connections, and Cloudnet IT Solutions Ltd. mounting radio heads and antennas on the masts.***

and community requirements of education, health and well-being, and general network connectivity.

3) Network Planning and Design: The 5G New Thinking Rural Toolkit (online at [149] and summarized in Fig. 22) reviews the end-to-end design process and key topics to all of the key topics and considerations to build the networks. The design and implementation of the network were carried out in two separate stages: 1) the *design stage* and 2) the *implementation stage*. The design stage involved decisions related to all aspects of the network, encompassing overall requirements and expectations, the RAN and spectrum licensing, mast site locations and construction, the backhaul network (microwave and fiber), electrical power supply, communications rooms/cabinets, and so on. The implementation stage involved building and constructing the network, followed by testing and then operation working with the communities on various use cases. Fig. 23 shows the civil works installation of one of the masts and associated cabinets and backhaul connections.

The design stage involved decisions being made regarding numerous aspects of the network. It was essentially iterative in nature, taking the broad requirements of the network and the desired coverage as a starting point. The first step involved identifying potential mast site locations, based mainly on some preliminary studies of the terrain coupled with local knowledge of the area and landowners. The next step involved running RF coverage simulations from each of these potential sites and essentially working out the best combination of sites that would be likely to achieve the desired coverage most efficiently. This involved various factors having to be repeatedly considered in an iterative manner. For example, what RF bands would be used and how easy would it be to acquire spectrum licenses? How easy would it be to provide backhaul connectivity to the site? Where would the electrical power come from? How easy would it be to access the site and transport equipment to it? Is the landowner known, and if so, is he/she likely to be amenable to discussions and negotiations on allowing the site to be used for our purpose? Is planning consent required, and if so, how likely is it that such consent will be granted? The outcome of this stage was a provisional list of suitable mast sites, which was used as the basis for carrying out the high-level network design.

The high-level network design involved the specification of decisions, such as RF bands and transmit power levels for each BS, the backhaul approach for each BS site (e.g., fiber and microwave), data throughput capacities, mast heights, and the approach to security. Once a high-level design was arrived at, a low-level (detailed) design was created. This expressed the various design choices and design parameters in detail, including network configuration and IP addressing parameters. In addition, a bill of materials was created, along with an implementation plan.

4) Network Build and Deployment: The implementation of the network involved various activities: preparing the mast sites; procuring masts, radio equipment, cabinets, backhaul, and electrical power; and installing and configuring the various network elements—switches, routers, firewalls, 5G cores, and so on. The networking equipment was all procured, tested, assembled, and configured prior to installation in the lab, and then, delivery, build, and operation of the networks on Orkney were progressed by the on-island engineering partners.

While this is a seemingly structured step-by-step flow, without local knowledge, relationships, and guidance, one key learning from the project was that it is just not possible for external parties/companies to progress at any level of efficiency or reasonable cost without local support and skills. On the 5G New Thinking Project, one lynch pin of the project was the leadership of an on-island technology company, *CloudNet IT Solutions Ltd*. Not only did they have local knowledge and relationships and operated FWA and other communications services, but they also had expertise around masts, cabinet deployments, fiber backhaul, as well as the capacity to configure and deploy 4G and 5G systems. With a 7-h door-to-door journey from the nearest project partner in Scotland's largest city, Glasgow, local expertise was a critical factor in this project being a success.

5) Final Network Designs and Implementation: The final network design consisted of three 4G/5G BSs in cluster 1 and four in cluster 2. The radios deployed over the years on Orkney for the 5GRUralFirst and 5G New Thinking operated in T&D bands in 3GPP bands 28 (700 MHz), band 42 (3.5 GHz), and most notably on the n77 UK shared spectrum band (3.8–4.2 GHz) with TDD operation and up to 100-MHz channels. Backhaul connections were via microwave links and fiber where available; 4G/5G radios were SDR implementations and Split 8, with antenna, RUs, and baseband units illustrated in Fig. 23. The team from on-island industry partner CloudNet Solutions Ltd. can be seen installing antennas and RUs on the masts at one of the cluster sites in Fig. 23. The radios were bespoke and customer designed and system engineered by partners Neutral Wireless Ltd., working with EU partners, Alpha Wireless (antenna), Amarisoft (5G software stack), and AW2S (RF units).

Working with the communities, use case tests and demonstrations were progressed for health and well-being support, agri-tech applications, renewable energy monitoring (IoT), and providing wider area coverage to residents via mobile connectivity FWA for homes, businesses, and community premises. As part of the project, we were able to demonstrate the engineering principles of neutral host and roaming; however, the business aspects around agreements with national network providers were not closed in the lifetime of the project. Therefore, 4G/5G networks were very much standalone, and services such as voice were only via over-the-top apps such as WhatsApp, and no emergency service calling provision was available [150].

Two-key learning from the Orkney rural connectivity project was: 1) the importance of local knowledge, local skills, and a good and trusting relationship with the communities and 2) the realization that building the technology is challenging, but achievable—however, alongside this technology, there needs to be a business model for sustainability. More information is available in the toolkit [149] on the various business and network sustainability models considered, such as partnerships, cooperatives, and anchor partners.

H. Key Findings and Vision

Given the various case studies, across diverse geographical locations, that have been presented in this section, here we discuss major findings as well as key solutions to address the challenge with connectivity for all. Currently, commercial service providers find it difficult to recover the required investment in a reasonable amount of time when the population density is very low. Therefore, noncommercial organizations have led efforts to service those areas. Unlicensed frequencies have therefore been the preferred choice, with long-distance Wi-Fi the dominant technology, as highlighted in the Venezuela and Malawi case study. TVWS technology is well suited for sparsely populated regions, but the stringent requirements to protect the incumbents and the associated high equipment cost have so far limited its deployment. This could change with the newer solutions described in the ARA and the Brazil case studies that address the frequency agility and OOBEs or leveraging MIMORA. The use of optical frequencies, addressed in the ARA case study, can also help but is limited by the high attenuation in the presence of fog and the high cost of the currently available equipment. The alternative is for noncommercial entities to obtain special permits to use licensed spectrum in regions not yet served by commercial operators, as described in the Arctic region and the South African case studies. The Orkney case study delves into the use of 5G for remote regions and demonstrates the importance of community involvement. The increasing availability and reduced cost of satellite networks are poised to offer an attractive solution for serving remote areas.

To provide connectivity for all, a common theme across the various case studies in the UK, Brazil, Venezuela, Sweden, the United States, South Africa, and Malawi is the availability and affordability of spectrum. The allocation of large chunks of spectrum to nation-wide operators limits its availability for more local/focused operators. In addition, when available, the process required to acquire such spectrum is quite cumbersome. There is a need to investigate and optimize the spectrum acquisition process in terms of technology, regulation, and economics. Balanced regulatory models are required to ensure a more agile process in acquiring necessary spectrum for serving local areas. The development and adoption of spectrum solutions, such as dynamic shared spectrum access, self-organizing networks, and cognitive radios, need progress in both technologies and policies.

Another generic requirement is the need for HTRA/EC-specific equipment designed to minimize operational expenditure (OpEx). Given the low population density and reduced economic viability of these areas, reducing OpEx is fundamental to supporting the adoption of leading communication technologies in HTRA and EC. Two key aspects of this reduction are energy and human resources. Equipment for serving these areas should intelligently optimize energy use by the adoption of integrated sensing and communication (ISAC) solutions such that radio sense usage dynamically reduces energy consumption by powering down high-frequency radios in times/periods of low network traffic. In terms of human resources, networks to serve HTRA and EC are required to be designed to minimize the need for maintenance through the use of automation and remote monitoring technologies enabling operators to provide quicker interventions to make service more reliable at reduced cost.

Together, these case studies have demonstrated the need for wireless technology innovations specifically targeting HTRAs and ECs, and such innovations span antennas, RF circuits, and the whole network stack from the PHY layer to link, network, transport, and application layers. Innovations are also needed for effective deployment and operation, conducive business models and public policies, as well as workforce development and ecosystem building. These real-world insights demonstrate the need for treating HTRAs and ECs as unique focus areas for next-generation wireless systems study and development, and the emergence of rural-focused wireless research, education, and innovation platforms such as the ARA [103] wireless living lab also enables broad public–private partners across academia, industry, government, and communities to closely collaborate in driving technology innovation and adoption.

VIII. CONCLUSION

The unequivocal need for connectivity has led to significant advances in the theory and practice of communication systems. A majority of these solutions exist within specific or confined operating parameters. This article goes beyond conventional discussions to address the state of connectivity at the very boundaries of connected systems, focusing on HTRAs and ECs. We present a critical analysis of the challenges in deploying communication solutions in HTRAs and ECs, identifying PEST factors that are unique to such areas. In addition, this work includes various case studies that discuss and provide the vision for the future of connectivity for hard-to-reach (and in some cases hard-to-serve, due to nontechnical reasons) areas and ECs in key locations across the globe, including the Arctic, South Africa, Malawi in Africa, Brazil, Venezuela in South America, and rural farms in Iowa, United States. By analyzing the state of communications in HTRAs and ECs across such a broad spectrum of locations, this article provides novel insights into the complexities at the boundaries of connectivity. The authors hope that the insights herein will provide a vision toward solutions that could address these challenges and ultimately lead to a fully connected world.

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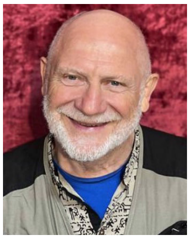

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