ARA: A Wireless Living Lab Vision for Smart and Connected Rural Communities

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ABSTRACT

The rural US includes 72% of the nation's land and 46 million people, and it serves as major sources of food and energy for the nation. Thus rural prosperity is essential to US wellbeing. As a foundation for next-generation rural economy and communities, broadband connectivity is a key driver of rural prosperity. Yet 39% of the rural US lacks broadband access, and most agriculture (ag) farms are not connected at all. To address the rural broadband challenge, we will develop the *ARA* rural wireless living lab. ARA will not only serve as a first-of-its-kind, real-world wireless experimental infrastructure for smart and connected rural communities, it will also provide the living lab processes, activities, and organizations to engage the broad wireless and application communities in the research, education, innovation, and pilot of affordable, high-capacity rural broadband solutions. Through this visioning article, we illustrate the community, application, economic, and operational contexts of rural wireless, the design of ARA, ARA-enabled research, and how ARA is expected to make rural broadband as affordable as urban broadband today. This article is also a call-to-action for the broad wireless and application communities to participate in the ARA living lab activities and to join the ARA Consortium of public-private partners in shaping the future of advanced wireless, rural broadband, and rural communities in general.

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CCS CONCEPTS

• **Networks** → **Network measurement**.

KEYWORDS

Wireless living lab, rural broadband, smart and connected rural communities, NSF PAWR

1 RURAL WIRELESS LIVING LAB VISION

The rural US includes 72% of the nation's land and 46 million people, and it serves as a major source of food and energy for the nation. Thus rural prosperity is essential to US wellbeing. As a foundation for rural economy and quality of life, rural broadband is a key driver [3, 12, 14]. Yet 39% of the rural US lacks broadband access, and most ag farms are not connected at all [12, 14]. . To address the rural broadband gap, wireless networks are essential building blocks, as they incur lower cost than fiber networks in connecting regions of lower population density and, for emerging rural industries such as digital and precision agriculture, wireless networks are the only means to connect mobile ground vehicles (e.g., combines and tractors) and unmanned-aerial-vehicles (UAVs) [2, 10]. On the other hand, just as rural electrification has required rural-focused technology innovations (e.g., higher-voltage distribution networks) and community capacity building (e.g., through electric cooperatives) [13], *rural broadband requires rethinking wireless systems design to embrace the community, application, economic, and operational contexts of rural wireless systems, and it requires not only wireless innovation but also rural application innovation and community capacity building.*

Most people in rural US live in communities such as rural cities, towns, or villages, while some people live in independent houses scattered around the outskirts of communities or in the remote countryside. Rural communities are usually separated from one another by unpopulated regions such as ag farms and forests which often stretch tens of miles if not more. Some rural communities have access to fiber networks, but many do not. Unpopulated rural regions usually do not have broadband access at all, even though they are the heartland of emerging industries such as digital and precision agriculture [12, 14]. Therefore, *terrestrial wireless* *networks of long-distance, high-throughput links* are expected to serve as effective, low-cost *wireless backhaul networks* for connecting remote rural communities, ag farms, and countryside houses to the closest fiber end-points. Within rural communities and ag farms, different *wireless access networks* such as cellular networks with D2D links, ad hoc networks, and delay-tolerant networks can be used to support different applications. Emerging wireless communication techniques such as massive MIMO can be used to connect independent houses scattered at the outskirts of rural communities. *High-throughput, low-earth-orbit satellite networks* such as Starlink [6] and OneWeb [7] are also expected to serve as wireless backhaul and/or access networks for rural communities, ag farms, and countryside houses.

Once deployed, these rural wireless systems will enable a wide range of *smart and connected rural communities applications* in domains such as agriculture, education, public safety, transportation, manufacturing, renewable energy, and telehealth. For instance, Figure 1 shows example applications in smart agriculture and rural education that will be enabled by wireless networks of different communication throughput and latency properties. High-throughput, low-latency wireless will enable AR/VR-based remote operation of unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs) in smart agriculture, as well as AR/VR-based K-20 ag education; low-latency wireless will enable precision farming via collaborative UGVs and UAVs; high-throughput wireless will enable at-scale, continuous ag phenotyping via a large number of field-deployed cameras; and low-throughput, pervasive wireless will enable livestock health, crop nitrate, and grain-bin humidity sensing. Similar types of sensing and control (SC), streaming (ST), and mixed-reality (MR) applications are expected to be enabled in other domains, for instance, AR/VR-based remote operation of ground and aerial robots in disaster response, connected and automated vehicles in transportation, real-time sensing and control in advanced

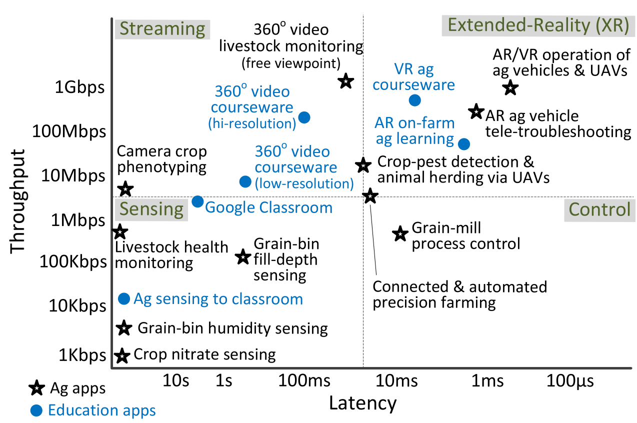

Figure 1: Example applications in smart agriculture and rural education.

manufacturing, and AR/VR-based remote mental health consulting services to rural communities. The *diversity* of rural wireless applications offers diversity in systems criticality, which facilitates spiral research, prototyping, demonstration, deployment, and maturation of applications of increasing criticality and across research and production uses. In the meantime, the *shared fundamental communication services* (e.g., ultra-reliable, low-latency wireless for safety-critical control and AR/VR) across application domains allow us to focus on select domains such as agriculture and education to develop and mature rural wireless systems which can then be replicated/extended to other domains.

To realize the aforementioned application vision which in turn will help stimulate the research, development, and piloting of advanced rural wireless systems, we shall engage the *application research, innovation, and user communities* to develop and deploy the envisioned rural wireless applications, and we shall also engage the *rural wireless operations communities* in deploying the underlying wireless infrastructures. For affordable broadband access, it is expected that *rural community organizations* such as rural cities and cooperatives will actively participate in the deployment and operation of wireless infrastructures [4]. Therefore, rural wireless systems are expected to be deployed in community infrastructures such as water towers and grain bins, in addition to commercial wireless towers, and the rural wireless design shall capture such operational context.

ARA: Wireless Living Lab for Smart and Connected Rural Communities. To enable the aforementioned research, development, and applications of rural wireless systems and as a part of the National Science Foundation Platforms for Advanced Wireless Research (PAWR) program, we will develop the wireless living lab ARA[1]. Figure 2 demonstrates the ARA vision of the wireless living lab for smart and connected rural communities. At the foundation of ARA is the deployment of advanced wireless platforms in real-world agriculture and rural settings, capturing the systems and environmental properties as well as the application and community contexts of rural broadband. For instance, ARA features the future of precision agriculture in both crop and livestock farms, involving automated ground vehicles as well as cameras and nanosensors. With unique wireless platforms ranging from low-UHF massive MIMO (mMIMO) to mmWave wireless access and long-distance backhaul, free-space optical, and low-earth-orbit (LEO) satellite communications, employing both software-defined-radio (SDR) and programmable commercial-off-the-shelf (COTS) platforms, effectively leveraging mainstream wireless software platforms such as SD-RAN, a production-quality, open-source

[1]Here *ARA* stands for Agriculture and Rural Communities. In astronomy, Ara is a southern constellation of stars.

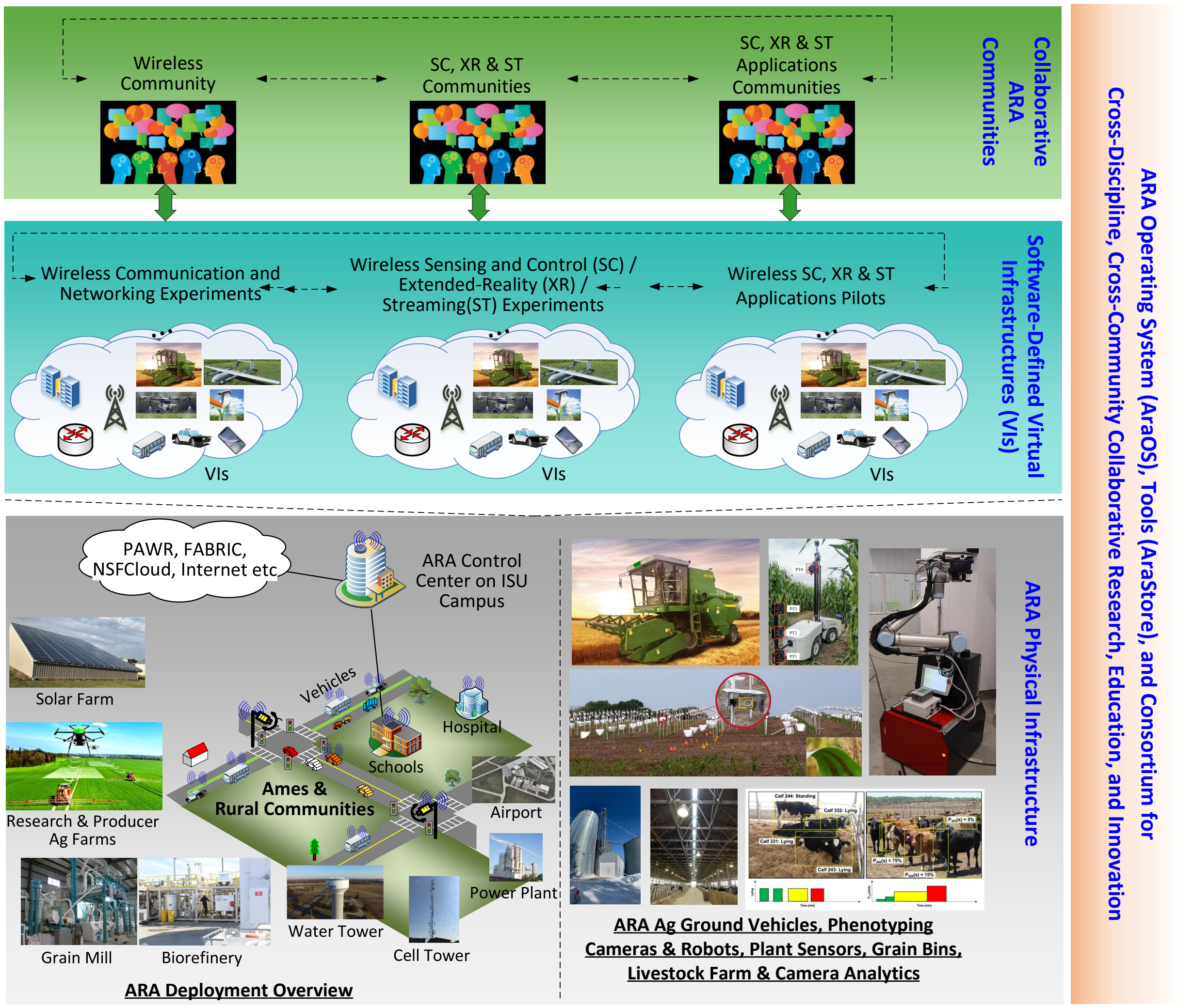

Figure 2: ARA: wireless living lab for smart and connected rural communities.

implementation of the O-RAN wireless architecture, and with a contiguous coverage of over 600 square miles of rural areas, ARA serves as an at-scale, deeply-programmable infrastructure for rural wireless research in real-world settings.

Transforming the physical infrastructure into a research instrument supporting rigorous scientific studies and application trials, the software system of ARA — AraSoft — will enable reproducible, convenient experimentation and facilitates cross-discipline, cross-community collaborations. In particular, with AraSoft, the ARA physical infrastructure will be transformed into software-defined virtual infrastructures which support research in wireless communications and networking, applications technologies such as sensing and control, extended reality (XR), and streaming, as well as their integration with field application pilots.

Collectively, the ARA hardware and software systems will enable cross-discipline, cross-community collaboration in research, education, and innovation, thus enabling the forging of the *ARA Consortium* of public-private partners in advanced wireless systems and applications. These collaborations are expected to generate not only the scientific and technological foundations of advanced wireless but also provide the pathways for its real-world adoption. We expect these collaborations to serve as a model for research, prototyping, pilot deployment, and adoption of advanced wireless technologies in smart and connected rural communities.

2 ARA DESIGN AND RESEARCH VISION

ARA deployment. Figure 3 shows the system architecture of ARA. ARA will deploy advanced wireless as well as edge and cloud equipment across the Iowa State University (ISU) campus, City of Ames (where ISU resides), and surrounding research and producer farms as well as rural communities in *central Iowa*, spanning a rural area with diameter over 60km

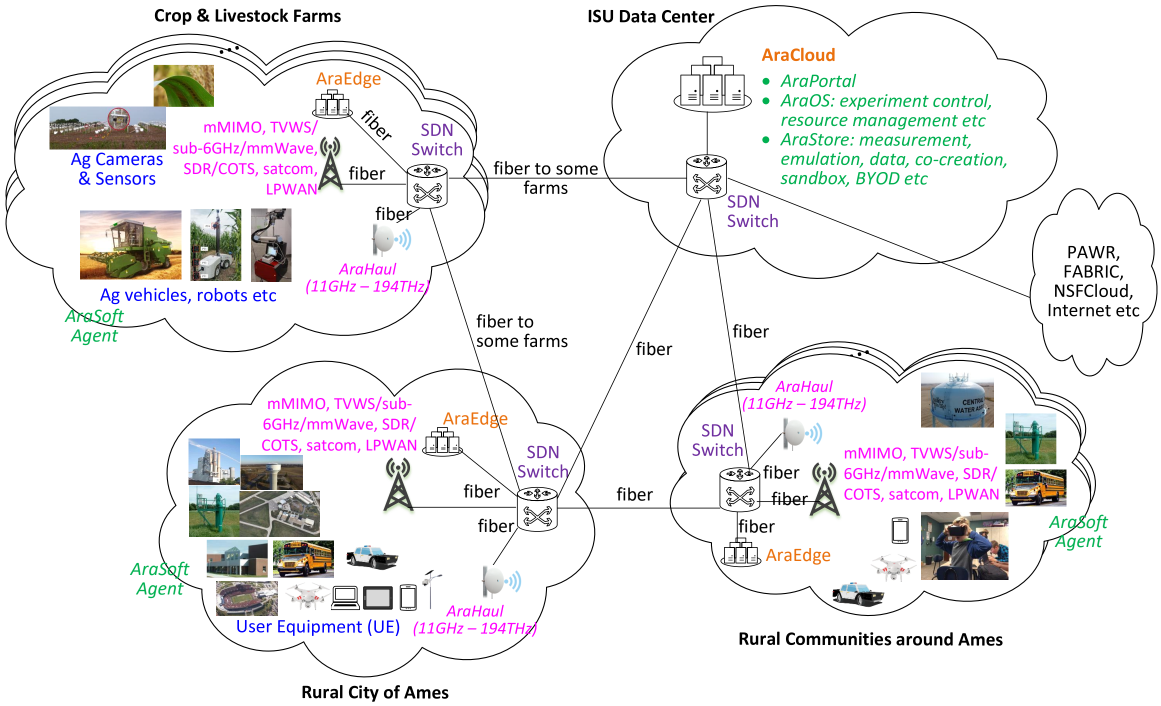

Figure 3: ARA system architecture.

(i.e., 37.5 miles). The ARA cloud computing and storage resources will be deployed in the ISU data center, and edge resources will be deployed in a distributed manner across ARA farms and communities to enable low-latency wireless applications. The ARA deployment will be connected, through dark-fiber/VLANs, to the other PAWR sites as well as the NSF FABRIC and NSFCloud infrastructures. As shown in Figure 4, the ARA ag farms and communities will be interconnected through the *AraHaul*, a multi-modal, long-distance,

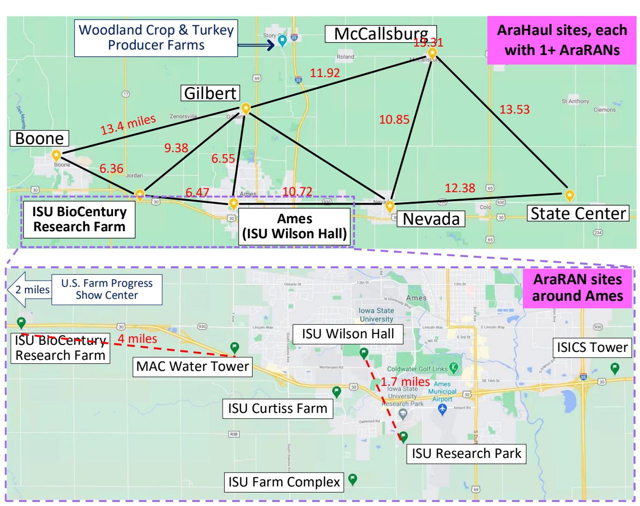

Figure 4: AraHaul and AraRAN deployment plan.

and high-throughput wireless backhaul infrastructure spanning six rural cities and one ag farm. Within the ag farms and rural cities, the *AraRAN* wireless access infrastructure will be deployed to provide high-capacity, low-latency connectivity to user equipment (UE) such as ag ground vehicles and robots, phenotyping cameras and sensors, police cars, school buses, and students' laptops. Some farms and communities are also interconnected with *fiber networks*, which facilitate ARA management and enable experiments involving both fiber and wireless networks. ARA will deploy LEO satellite communication user terminals on select ag farms and in the city of Ames, to serve as wireless backhaul or access links.

Research enabled. AraHaul will employ a rich set of heterogeneous high-throughput wireless platforms, ranging from optical to mmWave, microwave, and LEO satellite communications. The AraHaul platforms operate at different spectrum bands and provide different capacity-range regions as follows:

- AraOptical: 194THz, 80+Gbps over 15km
- Aviat Networks WTM 4800: 71-76 & 80-86GHz, 20Gbps over 15km
- Aviat Networks WTM 4200: 11GHz, 2.5Gbps over 20km
- Aviat Networks WTM 4811: 11, 71-76 & 80-86GHz, 2.5-20Gbps over 15km
- LEO satellite communication terminal: 12-18G/26.5-40GHz, 100Mbps across planet

The AraOptical long-distance free-space optical communication platform will be developed by the ARA project team, and it offers whole-stack programmability as well as high capacity, adaptability, and robustness. The long-distance mmWave and microwave point-to-point communication platforms from the Aviat Networks 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). Besides the LEO satellite communication terminals, AraHaul forms a terrestrial mesh spanning 60km in diameter, with link distance ranging from 9km to 24km. Accordingly, AraHaul enables research in multi-modal, long-distance, high-throughput wireless backhaul communications, for instance, leveraging the spatial, temporal, and spectral channel diversity for robust high-capacity communication and real-time bandwidth aggregation.

AraRAN will employ the Skylark low-UHF massive MIMO (mMIMO) SDR platform to enable whole-stack mMIMO research in the TVWS band and the public safety band. In collaboration with Skylark, ARA will also introduce programmable, high-performance mMIMO COTS network stack to the research community, thus offering the performance of production-grade COTS implementation and the programmability of research platforms at the same time. AraRAN also features SDR and COTS platforms in the sub-7.2GHz band and mmWave band. The AraRAN deployment of these platforms enables research such as bandwidth aggregation, channel aggregation, and channel bonding which are expected to lay the foundation for high-throughput, universal, and affordable rural broadband, as we will discuss in detail in Section 3.

ARA platforms cover a wide spectrum range. For instance, the ARA SDR platforms cover the following spectrum range from mmWave to low-UHF:

- mmWave: 24.25-27.5 / 26.5-29.5GHz, with 500MHz real-time bandwidth
- sub-7.2GHz with heterogeneous platforms:
  - Skylark low-UHF mMIMO: 470 – 806MHz, with 40+MHz real-time bandwidth
  - USRP X410: 1MHZ – 7.2GHz, with 400MHz real-time bandwidth
  - USRP N320: 3MHz – 6GHz, with 200MHz real-time bandwidth
  - USRP X310: 10MHz – 6GHz, with 160MHz real-time bandwidth
  - USRP B210: 70MHz – 6GHz, with up to 56MHz real-time bandwidth

The ARA COTS platforms cover the following spectrum range from optical to low-UHF:

- AraHaul: 194THz, 71-76 & 80-86GHz, 11GHz
- AraRAN base stations & UEs: mmWave, microwave, low-UHF
- LEO satellite user terminals: 26.5-40GHz, 12-18GHz
- Keysight N6841A RF sensor: 20MHz - 6GHz; up to 20MHz bandwidth

The wide spectrum coverage of ARA enables research in spectrum sensing, channel bonding and aggregation, bandwidth aggregation, and so on.

Besides enabling research in wireless communication itself, ARA enables energy efficiency research for wireless networks by deploying intelligent power control and metering hardware and software across the ARA infrastructure. The deployment of AraEdge and AraCloud compute servers also enable research in advanced wireless applications such as AR/VR-based, human-on-the-loop automated agriculture. AraSoft also provides different levels of ARA access (e.g., bare-metal, virtual machine, and container access), and it offers automation tools for different user communities such as the wireless, networked control, AR/VR, and streaming, as well as agriculture and education communities.

Figure 5 summarizes a subset of the ARA features and the enabled research. We expect many more research use cases to be invented by the communities thanks to the programmability and flexibility of ARA. Compared with other PAWR platforms (i.e., Powder, COSMOS, and AERPAW), ARA pushes wireless to the far, rural edge while maintaining high-capacity and low-cost.

3 A VISION OF AFFORDABLE RURAL BROADBAND ENABLED BY ARA

Embodying the fundamental systems and environmental properties of rural broadband and employing novel wireless research platforms, ARA enables research in innovative architectures and technologies for low-cost middle-mile and last-mile connectivity in rural regions. Addressing the key barriers to rural broadband penetration and the key elements of rural broadband cost in a comprehensive manner, the living lab approach of ARA also enables research and innovation in agriculture, education, and other domains of smart and connected rural communities, and it enables cross-discipline, cross-community collaborations to drive the research, development, and deployment of affordable, high-throughput rural broadband solutions. Table 1 illustrates the operation region of the individual ARA technologies as well as ARA as integrative rural wireless platform.

In what follows, we elaborate on how ARA-enabled technologies and initiatives are expected to reduce the rural broadband cost by up to an order of magnitude, thus holding the potential of making broadband services in rural regions as affordable as those in urban regions today.

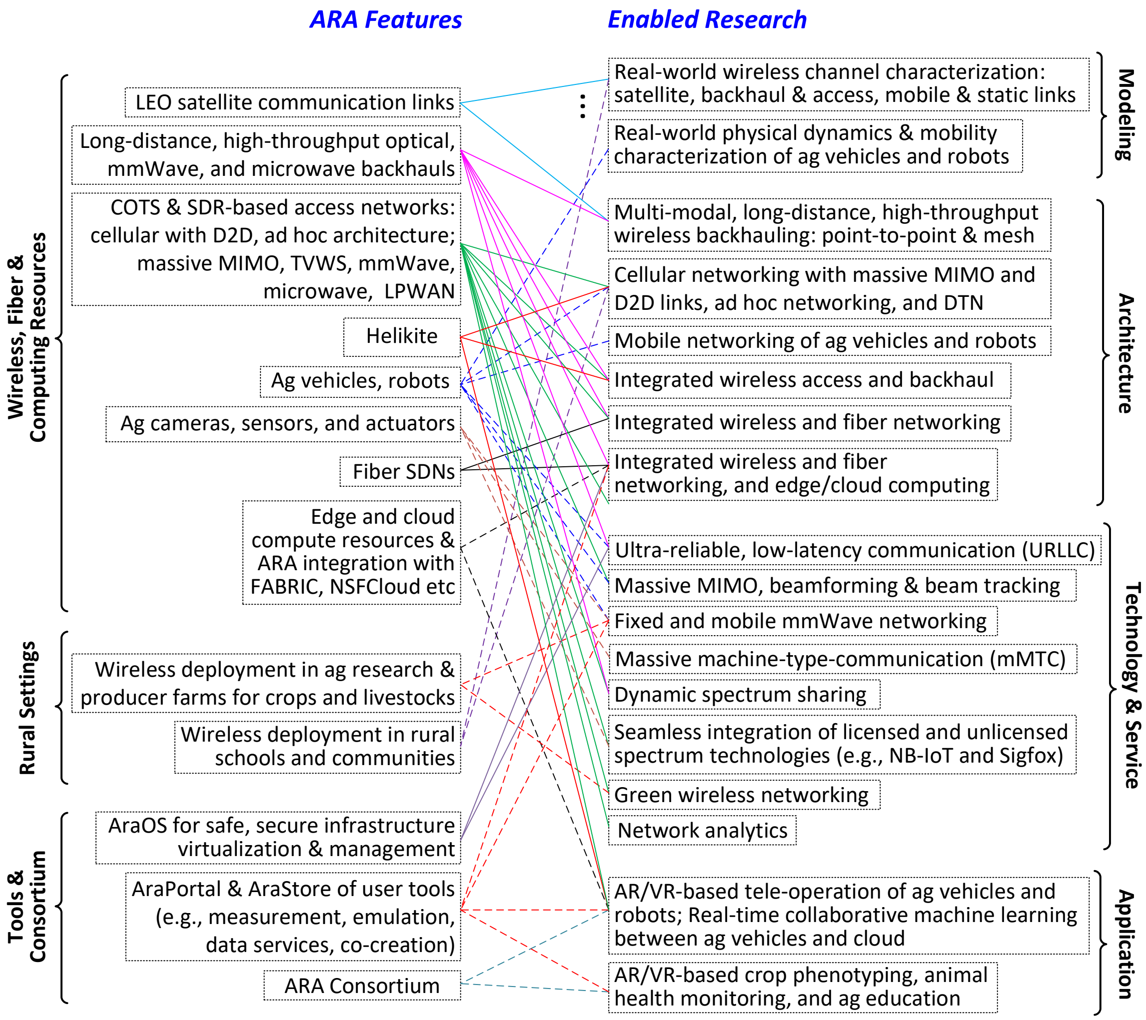

Figure 5: Examples of research areas enabled by ARA.

Technology	Cost/Bit	Bandwidth per User/Link	Distance to Gateway
AraHaul: AraOptical	Low	100Gbps+	15km+, 60km+ (with mesh)
AraHaul: mmWave	Low	10Gbps+	15km+, 60km+ (with mesh)
AraHaul: microwave	Low	1Gbps+	15km+, 60km+ (with mesh)
LEO Satcom	Medium	up to 100Mbps+	60km+
AraRAN: low-UHF mMIMO	Low	up to 100Mbps+	up to 10km+
AraRAN: mid-band	Medium	up to 600Mbps+	up to 4km+
AraRAN: mmWave	Medium	up to 2Gbps+	up to 400m+
ARA	Low	100Mbps+	60km+

Table 1: ARA operation region.

3.1 Holistic Approach to Affordable Rural Broadband

To enable pervasive broadband services for smart and connected rural communities, we need to address all of the three key barriers to rural broadband penetration: *affordability* of broadband services, *skills and awareness* of rural broadband users, *local adoption and use* of broadband for applications and services of significance to rural regions [8]. We also need to keep in mind the interdependencies between affordability, skills and awareness, and local adoption and use. For instance, the development and use of broadband applications in smart agriculture and rural education by and for the rural workforce and residents will increase broadband demand per service area, which in turn will reduce the amortized cost of serving individual users and use cases in rural regions and thus improve the affordability of broadband services. In addition, in finding strategies to reduce rural broadband cost, we need to pay attention to both the capital cost (CapEx) and operational cost (OpEx), which typically account for 54% and 46% of the total rural broadband cost respectively today [11]. With the above guidelines in mind, the ARA wireless living lab enables the development of a holistic approach to addressing rural broadband cost as follows.

CapEx reduction. Through its multi-modal, long-distance, and high-throughput AraHaul deployment, ARA will enable research and development of long-distance, high-throughput wireless middle-mile solutions; through its AraRAN deployment of COTS and SDR-based access networks, ARA will enable research and development of high-throughput wireless last-mile solutions that, with technologies such as massive MIMO, are suitable for sparse user distributions in rural regions. As we will discuss in detail in Section 3.2, compared with existing broadband solutions, these middle-mile and last-mile solutions can reduce rural broadband CapEx by a factor up to 10 or more today, and even more CapEx reduction is expected over time. Given that the typical population density in rural regions and urban regions are 10-42 people and 283 people per square mile respectively [1], *the CapEx reduction enabled by ARA is expected to make the per-person CapEx of broadband services in rural regions comparable to that in urban regions today.*

OpEx reduction. For affordable broadband, it is expected that rural communities such as rural cities, schools, cooperatives, and farmers will actively participate in the deployment and operation of broadband infrastructures [4]. Aligned with this economic and operational context, the ARA deployment extensively uses community infrastructures such as water towers. In addition, ARA-enabled research in rural network analytics and management automation and ARA-enabled training and outreach activities are expected to empower and engage rural communities in the deployment, operation, and use of broadband infrastructures, which is expected to help maximize community resource utilization and reduce broadband OpEx. ARA-enabled research in dynamic spectrum sharing and the relatively more availability of wireless spectrum in rural regions are also expected to reduce spectrum access cost for rural community wireless networks.

Demand incubation. By engaging the application technology and end-user communities of rural broadband, the living lab approach of ARA will enable cross-discipline, cross-community collaborations for the research and innovation in agriculture, education, telehealth, and other domains of smart and connected rural communities. This will help address the "skills and awareness" and "local adoption and use" barriers of rural broadband, which in turn will increase broadband demand from rural communities and thus further reduce the amortized per-user cost of broadband investment. The active participation of rural communities and industries in broadband use and application innovation will help develop rural innovation capacities and communities, which are essential to the long-term rural prosperity as well as the associated demand for rural broadband services.

Collectively, the above CapEx and OpEx reductions and demand incubation are expected to significantly reduce rural broadband cost (e.g., by an order of magnitude) and thus stimulate pervasive broadband deployment.

3.2 Broadband CapEx Reduction by ARA-enabled Solutions

Middle-mile CapEx reduction. The multi-modal AraHaul platform will enable low-cost middle-mile solutions for connecting rural communities to their nearest wired gateways. For instance, with the AraOptical radio and its RF backup costing about $12K and $3K respectively, each AraHaul platform costs about $15K today. By engaging rural communities to deploy the AraHaul platforms over their existing tall infrastructures (e.g, water towers and grain bins), the installation can be completed within about $5K. With a point-to-point communication range of more than 10 miles in typical rural settings (e.g., Iowa), the cost of AraHaul-based solutions will be about ($15K+$5K)/10 = *$2K per mile*. In comparison, if we were to connect a remote rural community to the nearest wired gateway using fibers, the cost would be *$10K-$20K per mile* depending on factors such as rurality and topography [5].

Therefore, AraHaul-based solutions *reduce the middle-mile CapEx by a factor of 5-10 today*. Over time, the cost of AraHaul platforms will keep decreasing; on the other hand, the cost of fiber deployment is expected to remain or even increase, since a major component of the fiber deployment cost is labor. Accordingly, the *cost reduction enabled by AraHaul platforms is expected to further increase over time.*

Last-mile CapEx reduction. The AraRAN high-throughput wireless access networks will enable low-cost last-mile solutions within rural communities. For instance, massive MIMO used in AraRAN enables high spectrum efficiency and user throughput. The beamforming capability of massive MIMO also enables larger inter-cell distance and makes massive MIMO a promising technology for rural broadband. Frenger et al. [9] have shown that, with 64-element antenna arrays operating at 2GHz spectrum, massive MIMO base stations can enable about 8 times increase in inter-cell-site distance (and thus 64 times reduction in spatial density of cell sites), as compared with cellular networks without massive MIMO. With low-UHF massive MIMO platforms such as those featured in ARA, the inter-cell-site distance can be increased even further.

Assuming a cell radius of 4 miles [9], a population density of 10-42 people per square mile in rural regions [1], and an average household size of 4 people, a massive MIMO base station can cover 125–527 homes. Assuming a base station costs about $120K (e.g., a typical Ericsson 5G base station) and the associated tower infrastructure costs $30K [5], the CapEx of AraRAN is about *$284.7-$1.2K per home* in rural communities depending on population density. In comparison, if we were to use fiber-to-the-home solutions within rural communities, the typical cost would be *$4K-$12K* per home depending on factors such as population density and soil conditions [5].

Therefore, compared with existing cellular and fiber networks, AraRAN-based solutions *reduce the last-mile CapEx by a factor of up to 64 and 10–14 today*, respectively. Over time, the cost of AraRAN-based solutions will keep decreasing, especially considering the future of software-driven wireless evolution and the increasing use of open-source platforms. The adoption of AraRANs in ag farms and other rural locations (e.g., wind and solar farms) will significantly increase user equipment density, thus further reducing the per-user cost of broadband investment. Accordingly, the *cost reduction enabled by AraRAN is expected to further increase over time.*

4 CALL TO ACTION

Through its unique rural deployment in research and producer farms, grain mills, biorefineries, and rural communities and school districts, by including ag vehicles, robots, and portable wireless infrastructures (e.g., helikite), and by using state-of-the-art LEO satcom radios, long-distance, high-throughput wireless backhaul radios as well as SDRs and COTS wireless access equipment, ARA will serve as a *first-of-its-kind, real-world wireless experimental infrastructure for smart and connected rural communities.* By supporting fundamental communication services (e.g., ultra-reliable, low-latency wireless for safety-critical control and AR/VR) that are *shared* across rural and urban applications (e.g., transportation), ARA enables field investigations of research questions that are of generic interest to rural and urban communities but are difficult to conduct in urban settings in early phases of the exploration. For instance, wireless-networked, safety-critical teleoperation of ground and aerial vehicles are better field-tested in open ag farms before their field tests/deployments in complex, crowded urban environments.

The ARA wireless living lab vision is to empower the broad wireless and application communities to pursue ARA-enabled research, education, and innovation activities that hold the potential to not only address the rural broadband challenge but also leverage rural wireless as an opportunity to advance wireless research as well as rural innovation and community development. We welcome you to participate in the ARA living lab activities and to join the ARA Consortium of public-private partners from academia, industry, government, and communities in shaping the future of advanced wireless, rural broadband, and rural communities in general. We welcome you to check out www.arawireless.org for the latest ARA activities and progress.

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