WIRELESS TECHNOLOGIES for RURAL FARMING COMMUNITIES

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EXECUTIVE SUMMARY

Conversations about rural broadband access tend to focus on connections to homes and businesses, but precision agriculture increasingly requires reliable connectivity to the farm office and the field. In the field, farmers rely on wireless connectivity—such as fixed wireless and mobile cellular—to make real-time strategic and logistical decisions about their land, crops, animals, equipment, and farm facilities.

Connected sensors in the field collect the accurate, timely data that farmers can use to optimize their practices and conserve resources. Sensors in the ground can measure the moisture of soil to improve irrigation systems and reduce water consumption. Weather sensors can predict frost and storm patterns to reduce the risk of crop loss. Many sensors connect to mobile applications, allowing farmers to access the data when they need it, wherever they are, as long as they have mobile connectivity.

This white paper examines wireless technologies capable of providing broadband connectivity with an emphasis on rural farming communities. Other wireless technologies that are useful for extending broadband connectivity and for special applications, especially in agriculture, are also examined.

To provide access to rural households that are unserved or underserved by wired technology, cellular LTE and 5G are the quickest options for connectivity. Most rural areas have some amount of availability of cellular service, but it may not be sufficient. In areas where 5G is available, speeds can be competitive with wired technologies. Wireless internet service providers (WISPs) offer comparable services but may have limited-service areas.

Localities should consider engaging with existing wireless service providers to encourage expansion of existing service areas and capabilities. We provide some suggestions as to the form that engagement might take.

In areas where neither wired nor wireless service is available, it is feasible to provide high-speed wireless connectivity using some combination of Citizens Broadband Radio Service (CBRS) and Wi-Fi, among other technologies. There is more expense involved in these approaches, but they can offer significant benefits when other options are exhausted.

INTRODUCTION

Access to affordable, reliable, high-speed broadband is essential to full participation in modern life. A broadband connection, and the skills to make use of it, enable people to access health care and other essential services, obtain an education, build careers, and conduct business.

The most reliable and highest-speed connectivity is via wired networks such as fiber. However, in much of rural America, low population density does not result in sufficient return on investment (ROI) for commercial providers of wired network services to deploy infrastructure without sufficient grants and loans to help defray the cost of capital expenditures. In these cases, wireless technologies may be employed to provide high-speed service in areas that may not see wired services in the foreseeable future.

For the purposes of this study, **broadband** is considered data speeds of **100 Mbps down and 20 Mbps up or better.**

Modern wireless technologies can provide network connectivity and speeds that compete with wired services in the best instances and in others provide usable connectivity that still qualifies as "broadband." The selection of wireless technologies is varied in capability and costs. One of the advantages of wireless connectivity is that the deployment of one technology or service is not a significant impediment to deployment of different or newer technologies and services. This is due primarily to the reduced infrastructure requirements of wireless.

This report covers some of the currently available wireless technologies that can provide alternatives to wired connectivity in locations where wired technology may not be available, with an emphasis on rural and agricultural areas.

WIRELESS TECHNOLOGY CAPABILITIES and TRADE-OFFS

A wired network connection is the desired goal for everyone, assuming the data bandwidth is sufficiently high. When that is impractical, wireless is the alternative.

Infrastructure costs associated with wired technology are significant. In 2022, the cost for fiber installation ranged from **$35,000** to **$80,000** per mile; the variance depends on contractors and terrain. And the fiber installation is only one of the infrastructure costs associated with providing wired network access: The timeline for planning and installation of wired network connections, including dealing with rights-of-way issues for installing fiber either above or below ground, can be costly and time consuming.

Wireless solutions have an advantage: 90 percent of the infrastructure is in a single location, namely the base station and its antenna support, usually a tower of some sort. Once installed and running, a wireless base station can provide service to tens or hundreds of users immediately. A new tower installation is still expensive and takes time to plan and construct, but a wireless system has the advantage, unlike a wired network, that as population in a service area grows, new users can be added immediately without the need for additional infrastructure and cost. In many developing countries, we are observing explosions of cellular wireless broadband services due to the lower cost of deployment, the speed of deployment, and the high ROI.

Wireless systems face the challenge of access to radio spectrum to provide services. Much of the available spectrum is licensed, including cellular spectrum, with licenses costing commercial providers billions of dollars to cover all or parts of the United States. Likewise, spectrum for WISPs (wireless internet service providers) is licensed, but not as expensive, as licenses are more localized. The cost, and availability, of spectrum can be a challenge for new service providers. This is an expense wired providers do not incur.

There are some slivers of unlicensed spectrum that are available for wireless systems. The most commonly used is the spectrum for Wi-Fi at 2.4 GHz, which, because of the ubiquity of Wi-Fi home routers and Wi-Fi capability on cell phones, is often crowded. However, in rural areas where population density is low, this may not be the case. Newer Wi-Fi spectrum at 5 GHz and 6 GHz is becoming available, so there are more opportunities to deploy larger systems. The biggest challenges for this unlicensed spectrum are the technical restrictions, particularly the limitations on transmitter power. The Federal Communications Commission (FCC) rules provide severe restrictions on the amount of transmitter power and antenna gain which limits the range of these systems.

CBRS at 3.5 GHz is a relatively new, (almost) license-free service that is intended to provide broadband data capabilities. There are license-free options to use this spectrum, but technical requirements that are designed to avoid interference among users mean that operations of these systems are more complicated and hence incur additional expense. However, as more CBRS systems are deployed, costs will come down and the complexity will become more manageable, providing more opportunities for new services.

Site selection, approval, and construction for a wireless base station or access point can be expensive and time consuming. But one of the advantages of wireless infrastructure such as a tower is that it can support multiple service providers. The vertical space on these supports can be separated by provider, with multiple services sharing the same structure. This reduces costs and deployment time for all.

A challenge for wireless providers is that at each base station or access point there is a need for a wired connection to the network, preferably fiber. This limits the siting of wireless towers somewhat, since if existing wired infrastructure is not easily available for connection, the cost of running cable or fiber can be significant. The expense of a fiber run to the tower site can be offset, however, by leasing to multiple service providers. In some instances, microwave backhaul links can be used to provide that connectivity to the wired network, but these links add another component of complexity to the system and potential reliability issues.

Often the tower infrastructure is the highest cost of entry into a market for wireless service providers. Most commercial towers are erected and owned by third parties who then rent space to service providers. However, these tower companies face infrastructure costs and ROI concerns like those of wired infrastructure companies. These economic realities present an opportunity for creative approaches utilizing public-private cooperative ventures to create tower infrastructure or other vertical assets that service providers can then utilize to provide network access to underserved communities. Local and state governments should be encouraged to engage with tower and service providers to enable new services and create cooperative opportunities that benefit residents and businesses.

One metric of system performance that wired networks usually excel in, when compared with wireless networks, is reliability. Wired networks tend to be extremely reliable, as they are closed systems with static infrastructure. Typical wired systems strive for "five 9s" of reliability—meaning that the infrastructure is working 99.999 percent of the time. That equates to roughly five minutes of downtime in a year. Wireless system reliability is typically in the range of 99 percent to 99.9 percent availability, meaning their downtime per year is higher.

Wireless systems depend on radio wave propagation to get signals from one location (the base station) to another (the end user). The propagation of radio waves can suffer from several impairments that result in reduced reliability. Many are transitory, some are seasonal, and others are permanent.

Permanent types of impairments are typically things that cause complete blockage of the signal path from the tower to the end user. These are usually terrain (hills, ridges, and mountains), dense vegetation (forests) or man-made structures (buildings, bridges, etc.). At the higher frequencies used for cellular and wireless networks, these obstructions usually cause complete loss of signal if they completely block the optical line of sight to the signal source. In these cases, there is little that can be done to mitigate the signal loss other than locating another base station that is unobstructed or a repeater that is within unobstructed range of both ends of the obstructed link.

Blockage by vegetation is not always a fatal impairment to a radio link. Depending on the density and length of the signal path through the vegetation, and the frequency of operation of the wireless signal, the signal path may still function successfully. However, the attenuation, or reduction in signal strength, due to dry vegetation is significantly less than that due to wet vegetation. So even if a signal link functions successfully in dry weather, rain may well cause the link to degrade significantly or fail completely. It will usually recover once the vegetation dries out, but such a link will have poor reliability due to those outages. Vegetative losses can also be seasonal. Deciduous trees' leaves fall during autumn and winter, allowing a signal path to operate quite reliably. But with spring and the flowering of new leaves, signal losses increase and produce unreliability of the signal link, which is exacerbated by wet weather.

Despite the challenges wireless technologies may entail, they do have the advantage of being able to turn on connectivity to large swaths of users quickly in comparison to wired services. Infrastructure costs can also be less than those for wired services, although not insignificant. Wireless excels at being the "last-mile" solution when fiber is available relatively close to an unserved area but extending fiber to individual users is not economical. The key to deploying a reliable and successful wireless solution is a well-engineered system.

As stated at the beginning of this section, the desired goal is to connect each end user to a wired, broadband data connection. However, when a wired connection or high bandwidth is unavailable or uneconomical, wireless solutions are the viable alternative.

The one capability for which wireless systems have superiority over wired systems is for mobile communications. Most of us experience that with our mobile cell phones. Wired data systems tie our computers and phones to a single fixed location. Agriculture is a business that is conducted over large expanses of territory. Farmers need data and voice communications wherever they are working. Only wireless can provide that mobility. Whether the task is making a phone call, downloading drone or sensor data, or uploading planning information for crop treatments, the field is their office and where their information is needed. This is where wireless is essential.

WIRELESS TECHNOLOGIES for BROADBAND

In this section we describe and discuss the most prevalent wireless technologies used to provide broadband connectivity, including those that can support precision agriculture applications in the field.

In general, wireless access systems that provide broadband connectivity, especially in tandem with a high-capacity, wired connection to the home/office, can be categorized into one of two types: fixed wireless access (FWA) and mobile access systems.

Multiple broadband wireless technologies can be used to implement both fixed wireless access and mobile access systems. The following section discusses typical technologies that are used to implement such systems. Some of the technologies discussed are capable of providing long-range, wide-area coverage, while others are intended for short-range, localized coverage. Data rates also vary, but all are capable of providing the minimum required to qualify as "broadband."

FIXED WIRELESS ACCESS

LTE

LTE stands for "Long-Term Evolution" and is commonly used in connection with 4G, the fourth-generation global wireless communication standard that was first defined in 2008. LTE is not technically the same as 4G, but almost all 4G networks now run on LTE. LTE defined cellular access networks with high spectral efficiency, high peak data rates, and short round-trip times as well as flexibility in frequency and bandwidth. While many people associate LTE cellular with mobile communications, it is also being used more for fixed wireless access with the major cellular carriers promoting fixed access especially for rural customers.

With the introduction of 5G, is 4G LTE obsolete? In short, no. Although a new generation of cellular technology usually comes along about every decade, the life span and usability of each generation of cellular technology is much longer. For instance, 3G technology was commercially introduced in 1991, but the last 3G networks in the US were not turned off until 2022. The current 4G LTE systems will coexist with 5G networks, probably for the next decade.

Depending on the provider, LTE service may be using multiple frequency bands from 600 MHz to 2.7 GHz in the United States. The lower frequency bands provider longer ranges and greater building penetration. The higher bands usually have wider bandwidths and so can provide higher data rates, although this is not an absolute.

WiMAX

Worldwide Interoperability for Microwave Access (WiMAX) is a family of wireless broadband communication standards. They enable delivery of "last-mile" broadband access as an alternative to cable and DSL. WiMAX is a competitor to LTE, and the latest WiMAX standard release is compatible and interoperable with some forms of LTE. The latest versions of WiMAX can provide up to 1 GB/s data rates to fixed stations.

There are no uniform, global spectrum allocations for WiMAX, and the technology has suffered for it. The largest segment available in the United States was around 2.5 GHz and licensed primarily to Sprint Nextel and Clearwire, which was acquired by Sprint (now T-Mobile) in 2012. Sprint terminated its WiMAX network in 2016. The cellular operators almost universally support LTE, so WiMAX systems are less plentiful. The two known WiMAX network owners in the United States are AT&T Alaska and DigitalBridge, both launched in 2007.

CBRS

Citizens Broadband Radio Service (CBRS) is a new radio service that operates only in the United States using 150 MHz of spectrum from 3.55 to 3.7 GHz which the Federal Communications Commission (FCC) **allocated in 2015**. CBRS has tiered access based on priority: lower-priority users may not interfere with higher-priority users. Incumbent users such as the U.S. Navy have the highest priority. Next are Priority Access Licenses (PAL), which are licensed by the FCC. Up to seven PALs may be licenses in any given county. Lastly are General Authorized Access (GAA) users, who are unlicensed but must still meet the FCC technical requirements.

All current CBRS systems use LTE technology. As such, they are compatible with existing cellular devices and modems. CBRS systems will be deployed by cellular and other providers to provide additional capacity for their existing networks and to provide fixed wireless access for customers. If user devices (cell phones, hotspots, cellular modems) are compatible, all that is required is an appropriate SIM card for operation on a CBRS LTE system.

CBRS can be used to create private LTE networks. Like those deployed by cellular providers, private entities can create their own private LTE network to cover a school district, factory, farm, or other area using CBRS equipment, either indoors or outdoors. Again, with compatible equipment, a SIM card is all that is required to deploy end-user devices. Many cell phones today have the capability of using multiple SIMs, and there are even eSIMs (electronic SIMs that do not require a physical card). With such devices, a phone may operate on both a commercial cellular network and a private CBRS network simultaneously.

Equipment costs for a private CBRS system are currently high. Access points (APs) can cost $3,000 to $6,000, excluding installation, plus ongoing expenses for wideband connectivity and other administrative costs. As CBRS becomes more widespread, costs should come down, as is typical with all electronic technologies.

CBRS systems are more complicated to deploy and operate than Wi-Fi networks. But they do offer the possibility of longer range, less congestion, and **more security and privacy**.

SATELLITE

In the past couple of decades, the cost to launch satellite communications networks for internet access to individual users has come down to a point where it is economically feasible. Geostationary satellites offer the advantage of reliable service if a clear view of the geostationary arc (roughly SE to S to SW) is available at the customer site. Since the satellite appears fixed in the sky from the customer's view, the antenna needs only to be aimed once and fixed. One of the drawbacks of geostationary satellites is the latency of the data. Latency is a measure of the delay in a network. Geostationary satellites typically have a latency of approximately 550 milliseconds. This makes pseudo real-time applications such as Voice Over Internet Protocol (VOIP) work poorly due to audio and video delays.

In recent years, new generations of low Earth orbit (LEO) satellites, such as Starlink and Amazon's Project Kuiper (in development), are being deployed to provide internet access. These solutions are extremely attractive due to the lack of need for local infrastructure. They can provide high data rates and moderate latency.

Satellite internet access is not without its potential pitfalls. Besides the latency issues already mentioned, precipitation (rain and snow) can significantly degrade satellite signals, causing periodic outages. A clear line of sight (LOS) to the satellite is required for best operation. For geostationary satellites, this is usually relatively straightforward to provide, since the pointing direction to the satellite is fixed. For LEO satellites, the antenna must track the satellite as it crosses the sky with changing azimuth and elevation from the user's terminal. If at any point the path to the satellite is obstructed by terrain, buildings, or vegetation, signal loss is quite likely. Thus, LEO satellites can experience periodic service outages, but they are usually short lived (minutes, typically).

TABLE 1: SATELLITE INTERNET PROVIDERS COMPARED

	HUGHESNET	STARLINK	VIASAT
MAX SPEEDS	25 MBPS DOWNLOAD, 3 MBPS UPLOAD	20-250 MBPS DOWNLOAD, 5-30 MBPS UPLOAD	12-150 MBPS DOWNLOAD, 3 MBPS UPLOAD
REGULAR MONTHLY RATE	$65-$175	$110-$135	$100-$400
CONTRACT	2 YEARS	NONE	2 YEARS
EQUIPMENT COSTS	$15 MONTHLY OR $350 ONE-TIME PURCHASE	$599 ONE-TIME PURCHASE (OR $2,500 FOR PREMIUM)	$15 MONTHLY OR $300 ONE-TIME PURCHASE
DATA ALLOWANCE	15-100 GB	1 TB	40-500 GB

Wi-Fi

Most people are familiar with Wi-Fi due to its almost ubiquitous use within homes, offices, and many public spaces. Wi-Fi, also referred to as 802.11 after the Institute of Electrical and Electronics Engineers (IEEE) specification that defines it, operates in unlicensed radio spectrum at 2.4 GHz, 5 GHz, and 6 GHz. There are some Wi-Fi systems that use the 915 MHz unlicensed spectrum (Wi-Fi HaLow), but they provide lower bandwidth for longer ranges than the commonly used 2.4 and 5 GHz Wi-Fi bands. For example, at 915 MHz, ranges of 1 to 3 km are typical, while at 2.4 GHz and 5 GHz, ranges are usually in the 100- to 200-m range, but the data rates at 915 MHz are 1 to 3 Mbps.

Wi-Fi can provide data rates of 100 to 300 Mbps on local connections (2.4 and 5 GHz), but the ultimate data rate that can be delivered is dependent on the wired connection from the Wi-Fi router to the internet. Wi-Fi is not compatible with LTE or other mobile networks due to technical specifications of the signals and different frequencies being used.

Due to the unlicensed nature of the Wi-Fi spectrum, there are limitations on its capabilities. One of the most significant limitations is that as part of the FCC rules, Wi-Fi devices must not interfere with any other device and likewise must accept interference from other devices. This is usually only an issue in heavily populated residential areas or offices where multiple separate Wi-Fi systems may be in use. In rural areas, this is rarely an issue since there are multiple channels that can be used, so nearby Wi-Fi routers can minimize or avoid interference by using different channels.

The other significant limitation of Wi-Fi systems is the radio frequency (RF) power output limitation required by the FCC. Because they are unlicensed devices, they are limited to a maximum radiated power of 1 watt. This is usually sufficient to provide coverage inside a typical residence or even a small office area. It may even provide coverage outside a building for several hundred feet. This is intentional, since Wi-Fi is intended for short-range access.

There are newer Wi-Fi systems (sometimes called Wi-Fi 6) that use multiple nodes that attach to a central router using mesh networking technology. This extends the coverage footprint of the Wi-Fi network to a much larger area. When appropriately placed, a mesh network may provide coverage over an area of several acres.

MOBILE ACCESS

Most users think of mobile operation (e.g., cell phones) when they think of 4G LTE since this was the first and most common application encountered. When cellular phones were initially developed, they provided only voice calls. With the development of second-generation cellular technology (2G), the capability of short text messaging was added to cell phone capabilities. With 3G technology, data communications capability was added, allowing access to the World Wide Web as well. Today's 4G LTE technology improves data rates and allows faster connections and more digital capabilities. With 4G, everything is data—voice, messaging, web browsing, streaming, etc. And it can all be done from a phone you carry in your pocket. If you are within reach of a cellular network, you have every capability a fixed wired connection has. The biggest difference between wired and wireless systems is speed. Wired networks can achieve data rates up to 1 Gbps, although that differs considerably between providers and locations, with most being much slower. Wireless capabilities vary among technology and providers, but 5G systems are usually capable of at least 50 Mbps downlink speeds.

4G LTE

4G LTE is the same as LTE, discussed in the previous section. The only limitations 4G LTE incurs are that data rates may be limited or connections may not be as reliable, depending on the coverage of the cellular network. In urban and suburban areas, this is rapidly becoming less common. But in rural areas with low population density, cellular networks still may not have as extensive coverage to provide reliable communications. But cellular is nevertheless the most ubiquitous mobile communications solution for most of the population, even in rural areas.

5G

Fifth-generation (5G) cellular technology is the next evolution in mobile wireless communications. 5G is a significant departure in technology and capabilities from 4G cellular technology. For most end users, the greatest improvement they will notice will be increased data rates, although this will be primarily in urban and suburban areas. As 5G technology rolls out across the country, the greater bandwidth and capacity it provides is making it possible for cellular providers to be able to offer faster mobile services as well as high-speed home internet (at least while network capacity allows). T-Mobile seems to be leveraging this capability the fastest in 2023. With the erection of new 5G base stations and towers, T-Mobile is pushing home internet service at very competitive prices and relatively high speeds.

MOBILE SATELLITE

There are some satellite services that are focused on providing connectivity for mobile users. These solutions are not designed for high-bandwidth applications but can provide useful data and voice communications in areas with no or unreliable terrestrial mobile service (e.g., cellular).

The Iridium satellite service launched in 1998 to provide worldwide communications from handheld phones, satellite messenger communications devices, and integrated transceivers. The system uses 66 satellites in near-polar orbits at a height of 485 miles to provide continuous service worldwide. The Iridium service requires dedicated handheld units or integrated transceivers for voice communications. Smaller devices are capable of data messaging and transmissions, but the data rates are low (2 to 10 kbps), and costs for service can be relatively high in comparison to terrestrial cellular service. The primary advantage of Iridium satellite service is providing communications capability in areas with few or no other viable options. The equipment is relatively compact and lightweight, so it makes a good, if relatively expensive, option for emergencies.

Another satellite option is Starlink Roam. This is not a true mobile connectivity service but a portable service. The terminal unit is not designed for operation while in motion but can be easily deployed while stopped. Starlink offers high-speed connectivity and can be deployed with Wi-Fi to provide high-speed connectivity in a small area within a few hundred feet of the terminal.

OTHER WIRELESS TECHNOLOGIES

The technologies discussed herein are primarily oriented toward providing high-speed network access to homes and workplaces where wired network connectivity is not available. In addition, there are several lower-bandwidth wireless technologies that can be utilized for rural applications.

Primary among these is LoRa (from "long range"). LoRa is a proprietary radio communication technique that provides long-distance connectivity using low power. LoRa and LoRaWAN (LoRa Wide Area Network) create a communication system that is ideal for relaying data and control messages that do not require large bandwidth and are power sensitive. LoRa is usually deployed in license-free spectrum, reducing the cost of deployment, and is designed to operate at very low power levels. A LoRaWAN network can typically provide data rates from **0.3 kbps to 50 kbps**. Many types of agricultural sensors have been developed using LoRa, such as soil-moisture sensors and intrusion detectors. These are compact and inexpensive, and they can run on batteries for months to years. The typical communications range is several kilometers. LoRa can be used for automation, smart energy, and location-based services.

Most people are familiar with Bluetooth technology because of wireless headsets and speakers commonly used with their cell phones. But Bluetooth has other uses as a short-range networking technology. Bluetooth operates in the same 2.4 GHz band commonly used by Wi-Fi and is capable of data rates of 1 to 3 Mbps. **The effective, reliable range between Bluetooth devices can span more than a kilometer down to less than a meter**. Range can be extended using mesh networking to provide greater coverage. Bluetooth devices can be used for remote control, sensing and activation, and data communications.

COMPARISONS of CAPABILITIES and COSTS

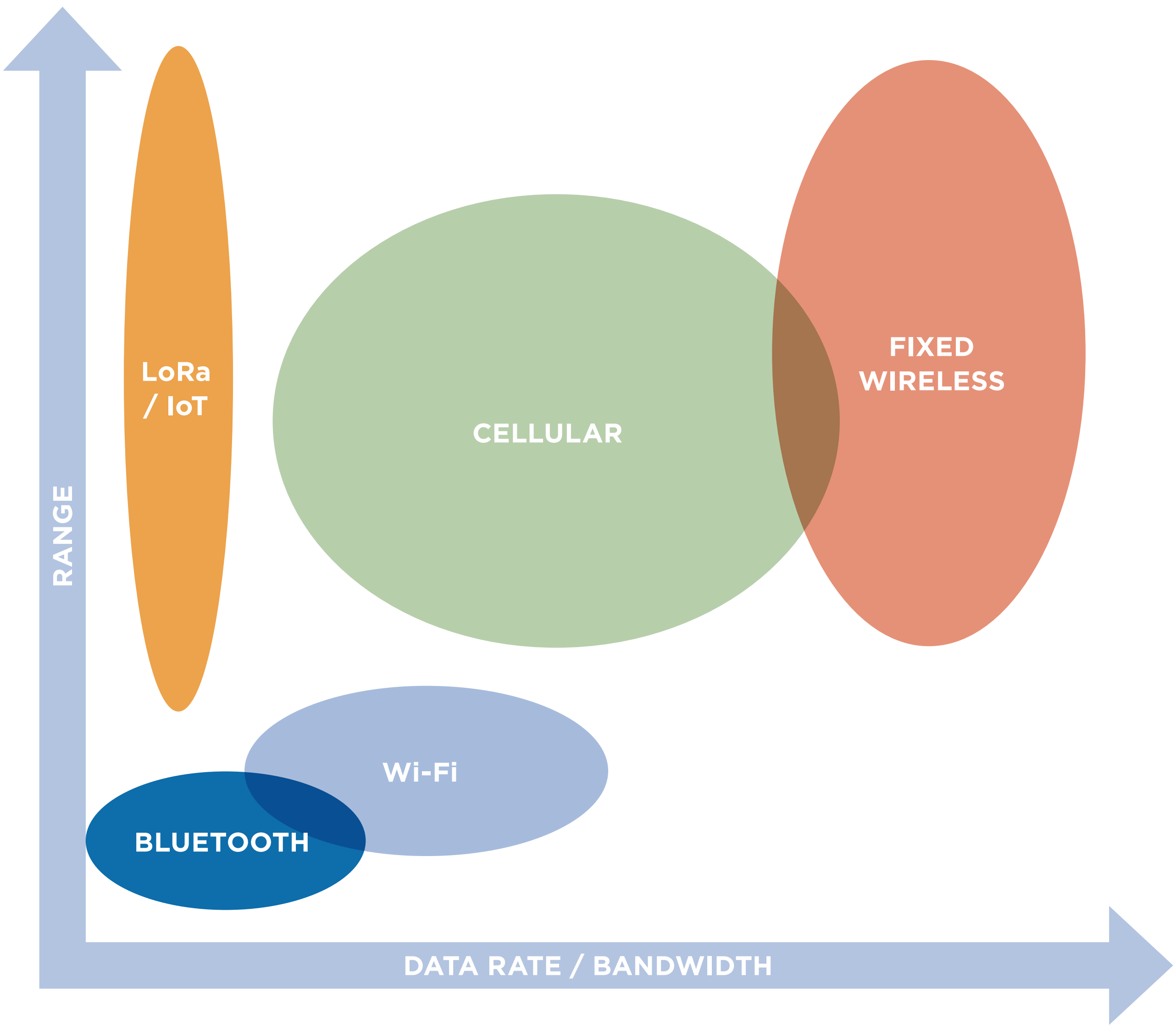

Figure 1: Relative trade-off between data rate and range for different classes of wireless technologies

Figure 1 is a qualitative comparison of the range and data rates of various wireless technologies. Exact values are dependent on a large number of factors and cannot be quantified with certainty. This graph provides a generalized comparison between technologies.

TABLE 2: COMPARISON OF WIRELESS TECHNOLOGIES' RANGE, DATA RATES, AND RELATIVE COST

TECHNOLOGY	TYPICAL RANGE	BANDWIDTH (DOWNLINK)	COST
4G LTE	25 MI (MAX)	35 MBPS TYPICAL	$$
5G		70 MBPS TYPICAL	$$
WIMAX (FIXED WIRELESS)	4-6 MI TYPICAL; UP TO 30 MI	30–40 MBPS	$$
WI-FI	150' INDOOR; 300' OUTDOOR	20 MBPS	$
LORA	3 MI (URBAN); 10 MI (RURAL)	27-253 KBPS	$
BLUETOOTH	.25 MI	125 KBPS–1 MBPS	$
CBRS	6–20 MI	20–200 MBPS	$$-$$$

Notes on Table 2:

1. Cost vary widely, particularly for commercial services, so definitive numbers are difficult to quote. Likewise, ranges and bandwidth are heavily dependent on network design and terrain.

2. 4G LTE, 5G, and WiMAX are commercial services that require extensive infrastructure investment. CBRS can be a commercial service, but private systems can also be deployed. The higher potential cost is reflected in the infrastructure cost of creating a private system.

3. Wi-Fi, LoRa, and Bluetooth are almost exclusively fielded by individuals or small groups. Their lower cost is reflective of not just lower equipment costs but also lower data rates and shorter ranges.

WIRELESS ACCESS MODELS for RURAL AREAS and AGRICULTURE

In order to meet the user's needs economically, it is important to fit the solution to the requirements. Home and office users have different needs than mobile users or remote sensors, in terms of data rate, latency, and reliability. In this section we first define three overall access models with differing requirements. Potential wireless technology solutions for those models are also identified.

Next, five use cases are identified for the use of wireless in rural areas and on the farm to aid agriculture. Each of these use cases can utilize several different wireless technologies.

TABLE 3: SUMMARY of WIRELESS ACCESS MODELS for RURAL AREAS and AGRICULTURE

ACCESS MODEL	REQUIREMENTS	TYPICAL SOLUTIONS
HOME/OFFICE ACCESS	HIGHEST POSSIBLE DATA RATES (100 MBPS MINIMUM DESIRED)	WISP PROVIDERS
	FIXED ACCESS	4G LTE/5G (WHERE AVAILABLE)
	24/7/365 AVAILABILITY	CBRS (PRIVATE OR COMMERCIAL)
		SATELLITE
SHORT-RANGE ACCESS	COVERAGE WITHIN HOME/OFFICE OR <1/2 MILE	WI-FI
	MODERATE TO HIGH DATA RATES (10–100 MBPS)	BLUETOOTH
	CONTINUOUS CONNECTIVITY NOT REQUIRED	
MEDIUM/ LONG-RANGE ACCESS	COVERAGE >1 MILE FROM HOME/ OFFICE	LORA (LOW DATA RATE)
	DATA RATE DEPENDENT ON APPLICATION	LTE/5G
	SENSORS/TEXT—LOW DATA RATE	CBRS
	LARGE DATA SETS (E.G., UAV DATA)—HIGH DATA RATE	SATELLITE

USE CASE 1

ALTERNATIVES to WIRED INFRASTRUCTURE

(Home/Office Access)

The most desirable solution for internet connectivity is a wired connection to the home or office, ideally via optical fiber. But in a situation where that is not feasible, wireless connections can be a viable alternative—although even terrestrial-based wireless systems require wired backhaul. The most common alternative is likely cellular 4G LTE connections. Depending on tower locations, the LTE network can provide data rates that will meet minimum broadband requirements. New 5G deployments can offer higher data rates (multi-Mbps) for usually similar prices to LTE. But 5G deployments to rural areas will not be completed for several years.

Other alternatives include WISP providers and CBRS/private LTE systems. These are generally small-business, localized providers. They may, however, be more economical than the large carriers and more willing to serve less densely populated areas.

The service provider bears the burden of building the infrastructure for the nodes, including running fiber to the tower. Users buy or rent the appropriate modem as well as pay for monthly service. Modem costs are typically $100 to $300, with monthly service rates of $50 to $200.

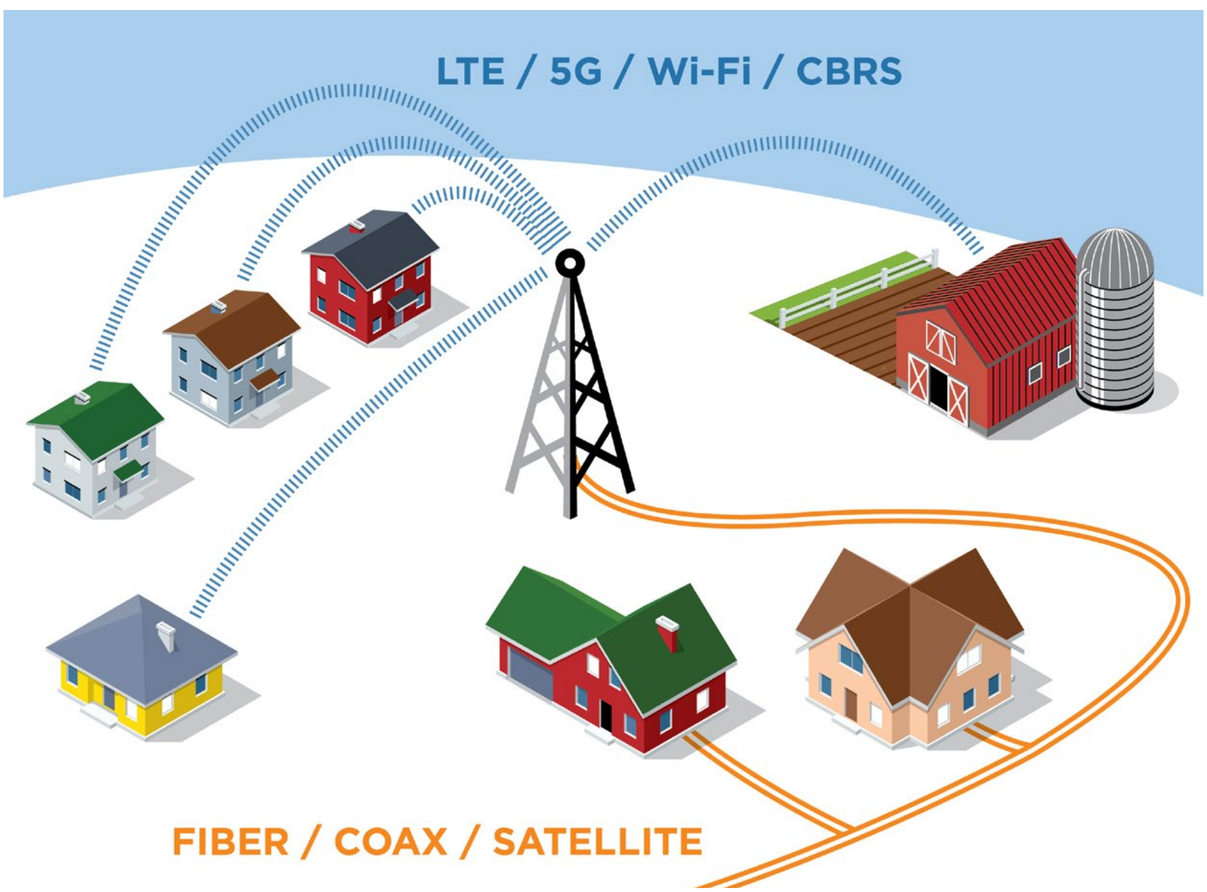

Figure 2: Wireless solutions to provide connectivity where wired connections are not available.

Ogle County, Illinois, is an example of a community using wireless to reduce the number of unserved users. Figure 3, below, is a map done by the State of Illinois showing unserved areas (all Fixed) in Ogle County, color coded by household density per square mile. The greatest concentration of unserved households is in the south-central/southwest portion of the county, with an additional high concentration of unserved households in the central northeast corner of the county.

Based on this map, we postulated a straw-man design for a four-tower CBRS system concentrating on the largest unserved areas. The predicted coverage for this system is shown in Figure 4. A comparison of the two maps shows that a significant portion of the unserved households could be covered with these four towers. We provide similar coverage predictions for all counties in the study area in Appendix B.

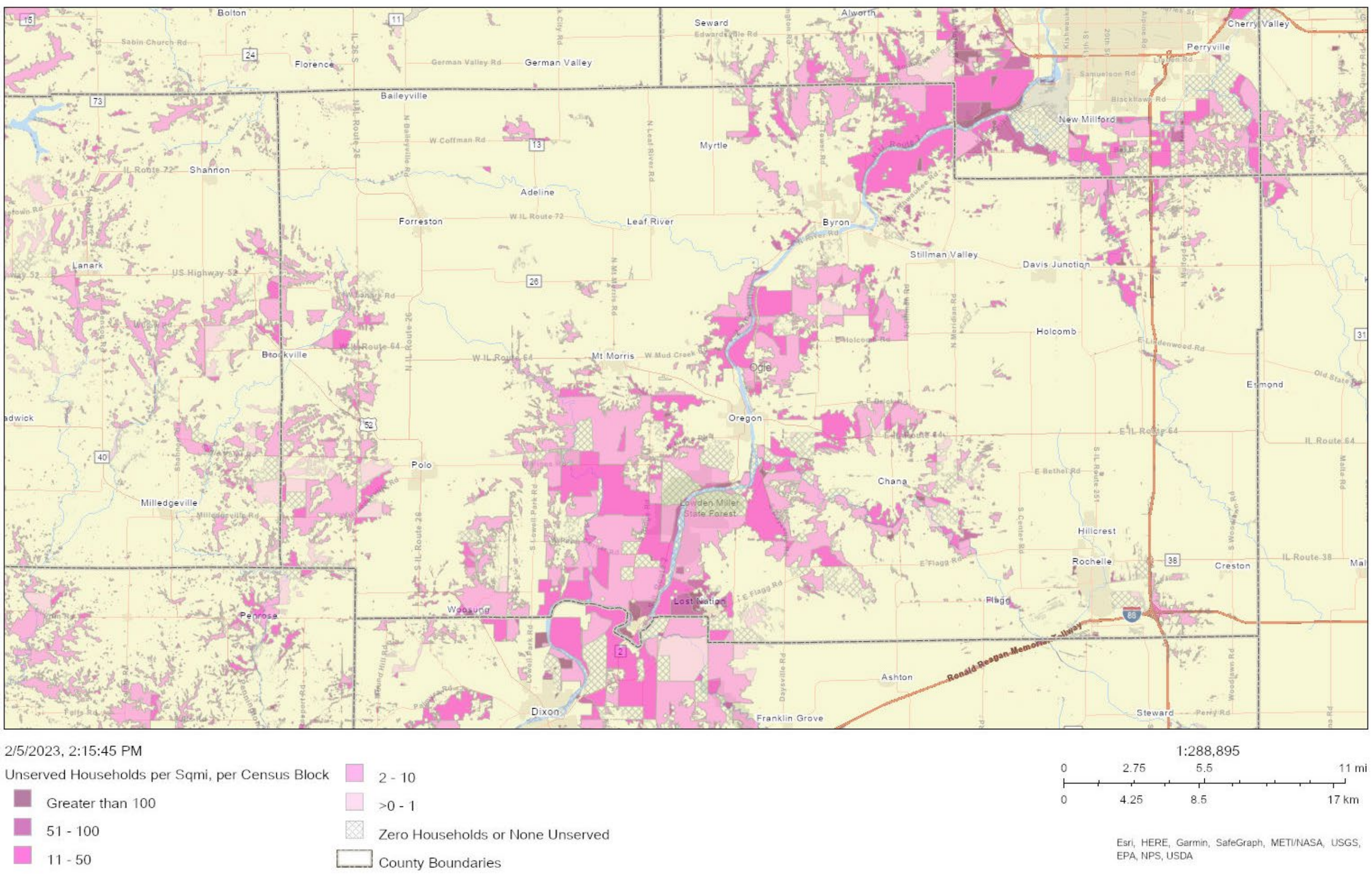

Figure 3: Unserved areas (All Fixed) of Ogle County showing density of households (courtesy of State of Illinois)

ToC

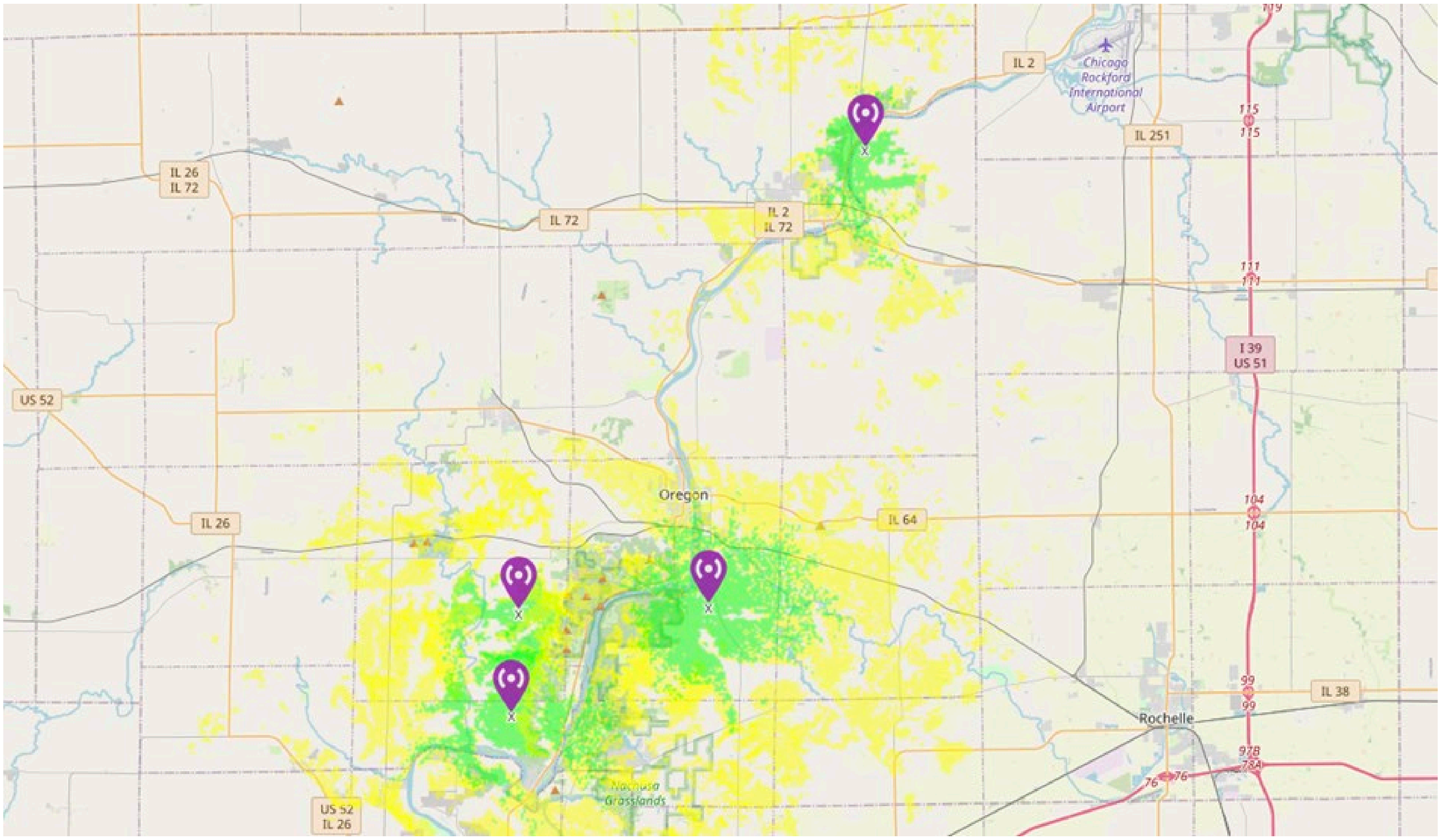

Figure 4: Simulation of CBRS coverage in Ogle County

USE CASE 2

EXTENDING CONNECTIVITY with MESH NETWORKS

(Home/Office Access)

In a situation where there may be wired connectivity on the edge of a small grouping of residences, connectivity may be extended to unconnected residences via Wi-Fi using the newest WiFi6 and WiFi7 routers with mesh networking. In mesh networking, multiple access points (APs) connect to one another to provide what appears to the end user to be a continuous network. One of the strengths of mesh networking is that there can be multiple paths to get from point A to point B in the network, so that if a link fails or is congested, there is an alternative path. The disadvantage of a mesh network is that all users are sharing the bandwidth of the wired connectivity point. Thus, during times of heavy usage, the effective bandwidth available to individual users is reduced.

For a private mesh system to operate, there must be a cooperative agreement between the users. The users with the high-data-rate fiber or coaxial connections will bear the brunt of the cost of the high-data-rate connection, but that presumably will be shared by the other users of the mesh network. All mesh users will need Wi-Fi AP devices to create the mesh. Mesh-capable APs typically cost $100 to $300, but we can expect to see prices drop as this technology becomes more widely used. Outdoor installation of APs is desired in order to increase range between mesh nodes and improve signal strength, which will increase data throughput.

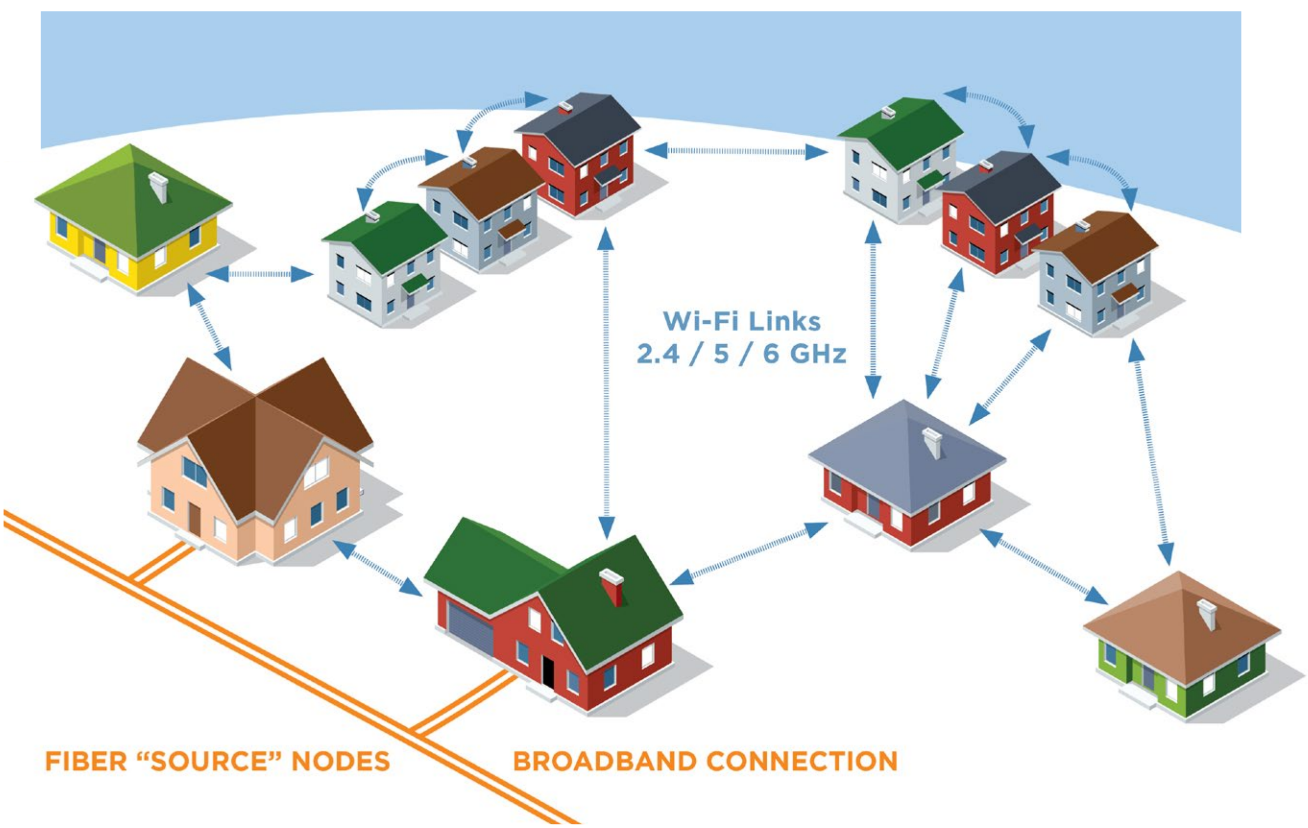

Figure 5: Mesh network to extend connectivity within a small area

ToC

USE CASE 3

EXTENDING THE REACH of a HOME/OFFICE CONNECTION

(Short-Range Access, Medium/Long-Range Access)

If a reliable network connection to a home or office is available, that connection can be accessed and shared with mobile devices that can operate within the local area. Wi-Fi is the most ubiquitous solution for extending home or office internet to mobile devices. Most Wi-Fi access points offer service within a relatively short range (~300'). But new Wi-Fi6 and Wi-Fi7 devices use mesh networking and with a few mesh nodes can provide network connectivity over tens of acres of space.

CBRS systems can be used to create private LTE networks that can provide localized, private, and secure network connectivity using existing mobile cellular devices. These systems are more complicated to deploy and operate than a Wi-Fi network, but they have the potential to offer a greater range.

Certain applications, such as sensors, do not require high bandwidth or low latency. These are also applications that may be power sensitive. For these instances, solutions such as LoRa and Bluetooth may provide economical possibilities that are also low powered.

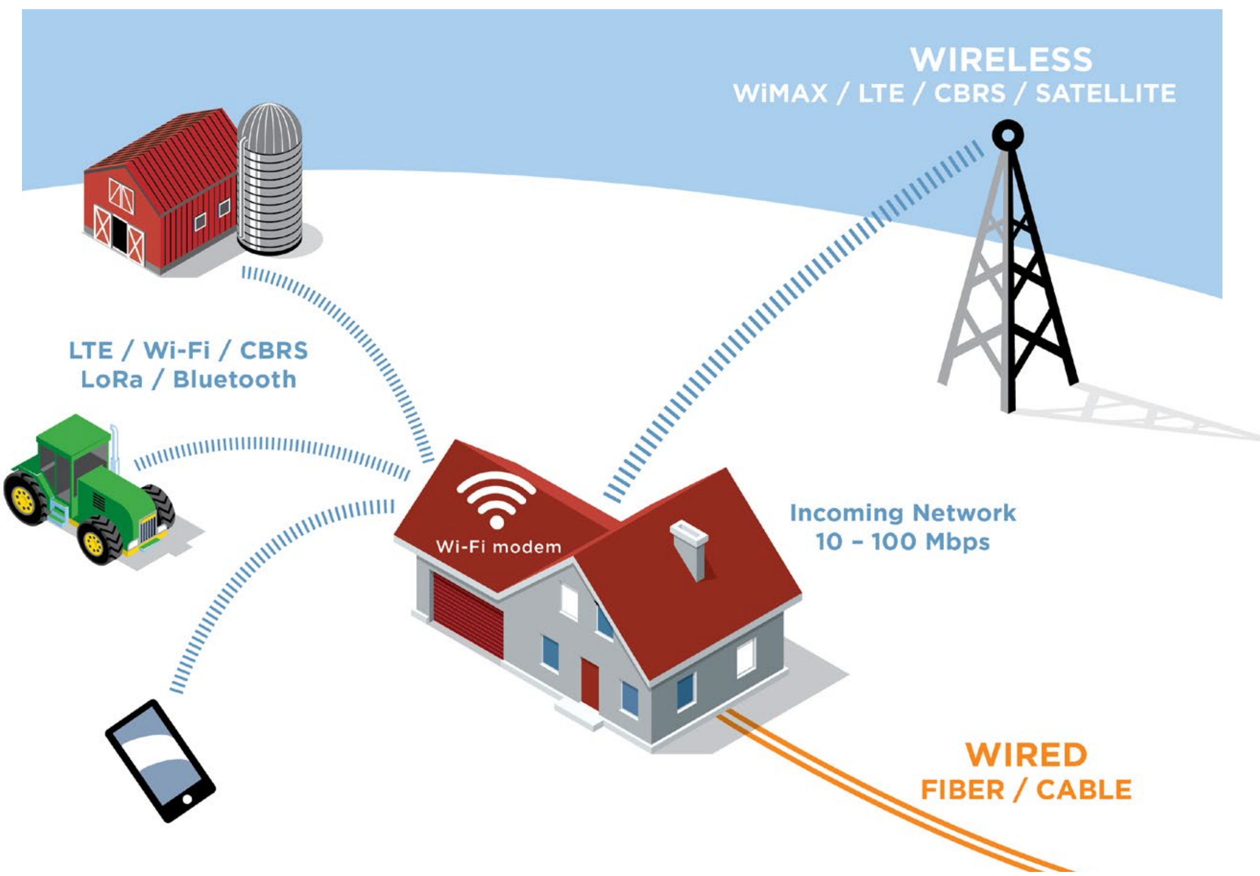

Figure 6: Extending connectivity beyond the house/office

USE CASE 4
MOBILE CONNECTIVITY on the FARM
(Medium/Long-Range Access)

The modern farm requires mobile network connectivity. Whether for vehicles, equipment, or remote sensors, there is a need for voice and data connectivity from the farmhouse to the barn and out to the edges of the fields. At the heart of the farm network is the broadband connection, usually at a fixed location. Extending that connectivity beyond the home or office are wireless networks. There are numerous solutions from commercial cellular carriers to private CBRS systems to provide that connectivity. Each farm's solution will be unique based on requirements, technology availability, and economics. The optimal solutions are not cookie cutter.

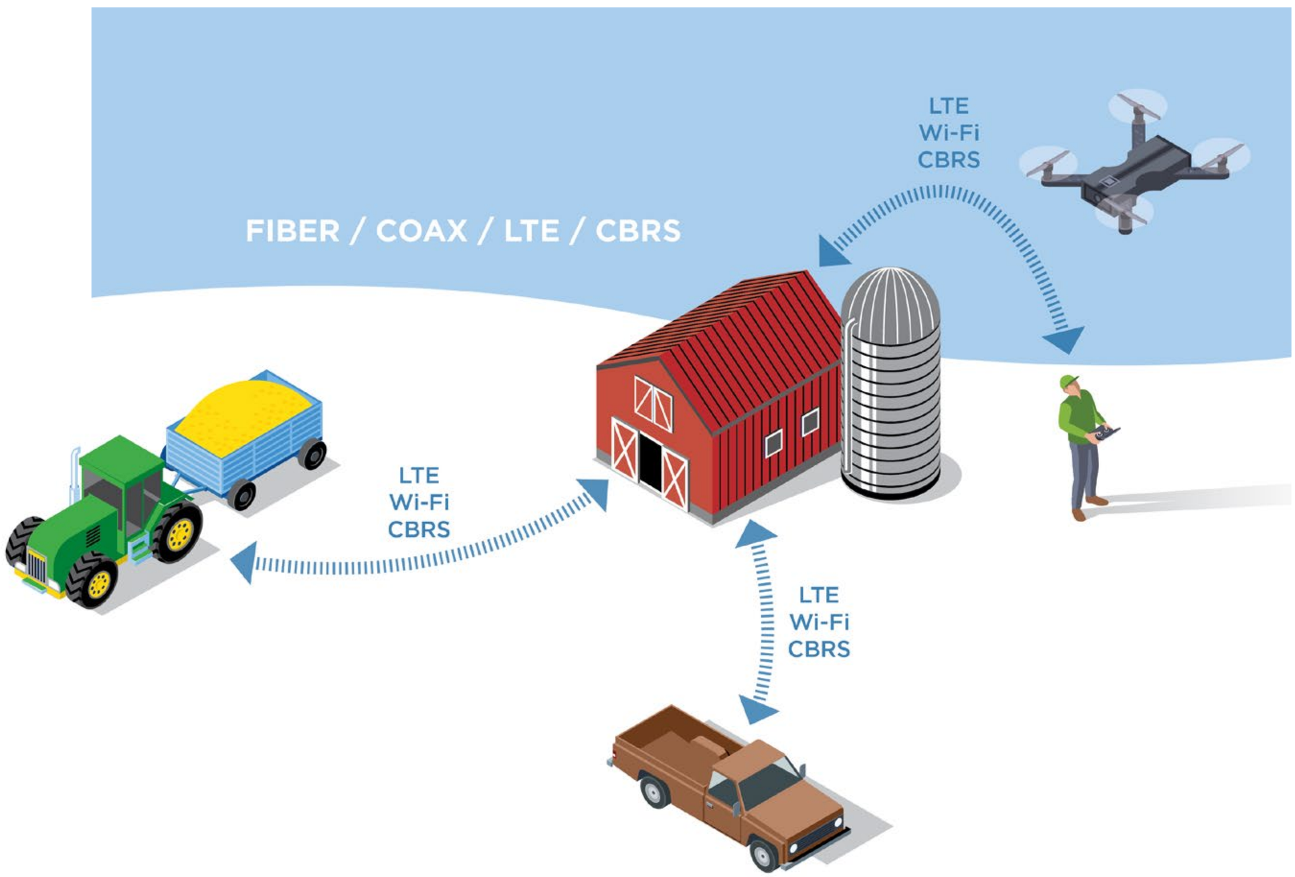

Figure 7: Wireless connectivity on the farm has numerous possibilities and will be unique depending on requirements and economics.

USE CASE 5

REMOTE SENSING on the FARM

(Medium/Long-Range Access)

Remote sensing is becoming a more widespread and important tool for farmers. From soil-moisture sensors to unmanned aerial vehicles (UAVs) for multispectral data collection to access and asset tracking, wireless sensor usage is increasing. All these applications require wireless connectivity for timely data collection to be turned into actionable intelligence for farmers. The bandwidth and latency requirements, however, vary by the types of data being collected. Soil-moisture sensors produce relatively small amounts of data (kilobytes, usually), and, due to the relatively slow rate of change of soil moisture, fast delivery is not required. At the other extreme, data collected by UAVs produce many megabytes of data. These data may require uploading for analysis out of the field, and the resulting information may require quick response times to be useful. In the first instance, low-data-rate solutions such as LoRa may be perfectly adequate. In the latter example, high-bandwidth, low-latency connectivity is required. This requires high bandwidth not only in the field but also at the connection to the larger internet.

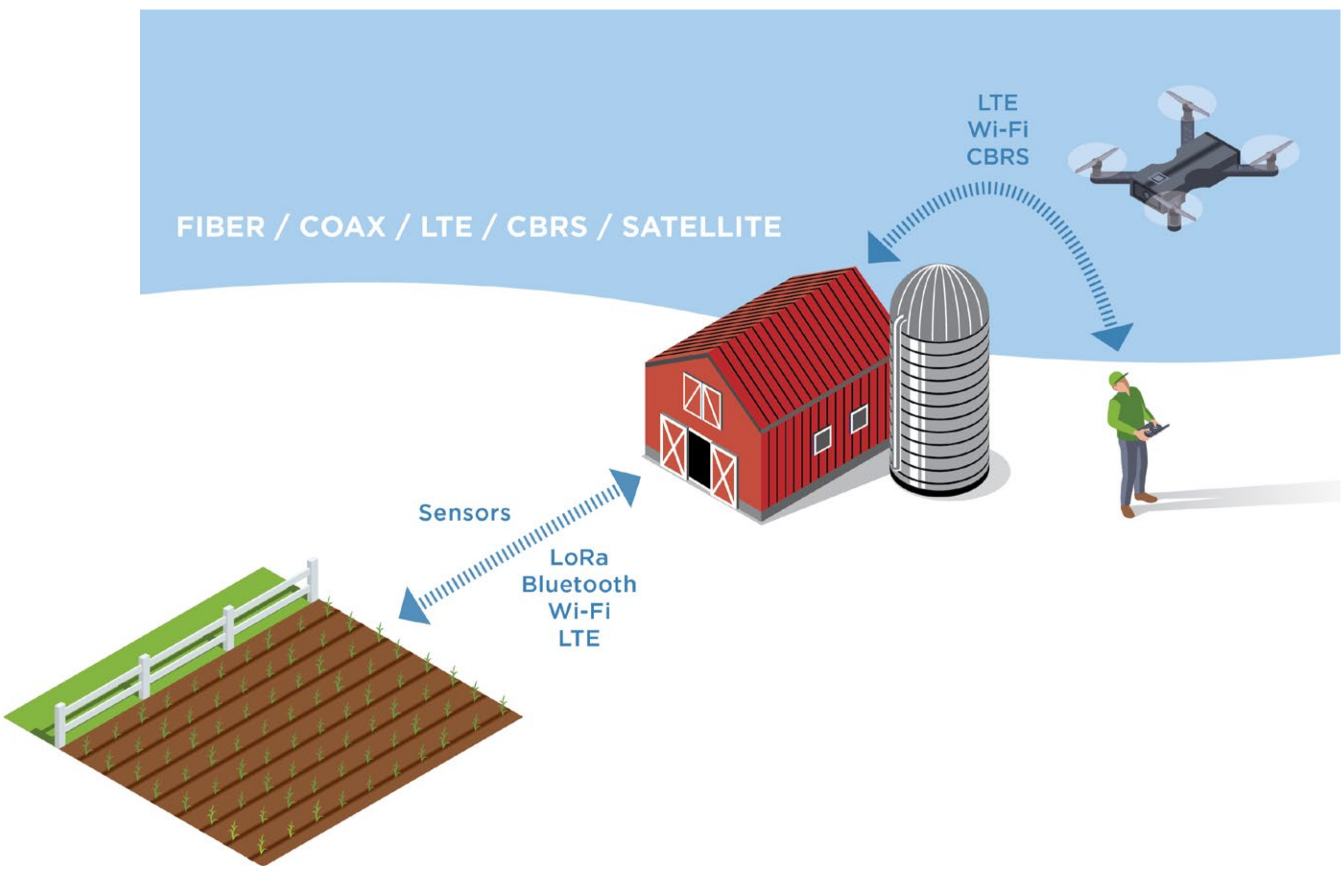

Figure 8: Examples of wireless connectivity used for remote sensing in agriculture.

STRATEGIES for IMPROVING WIRELESS CONNECTIVITY

Bringing or improving wireless connectivity to an area unserved or underserved by broadband is a matter of technology, policy, and economics. The technology part of the puzzle is the most straightforward. The policy and economics pieces are the most difficult. Each community will need to develop an approach to creating or expanding wireless connectivity that meets its unique needs, capabilities, and resources.

The most readily available broadband wireless service is cellular LTE and 5G, if available. Depending on coverage, data rates can reach 10+ Mbps up/100 Mbps down but usually cannot compete with fiber. Wireless Internet Service Providers (WISPs) can also offer comparable speeds and may even exceed LTE data rates. Many WISPs are smaller local companies, so their service area may be limited. Nevertheless, existing wireless providers offer the quickest route to providing service to areas underserved by broadband if they can be persuaded to expand their service areas and capabilities.

Below are strategies for planning coverage and developing partnerships with wireless connectivity providers. In essence, existing wireless connectivity providers (e.g., cellular companies and WISPs) with a presence in the area are the shortest, quickest path to expanding coverage. However, in some instances, developing new services or resources such as Wi-Fi, CBRS, LoRa, and Bluetooth, while not suitable by themselves to provide broadband connectivity, can be useful for extending coverage in some localities and for special applications in agriculture.

This is obviously a slower process, but by undertaking these steps, localities can speed the process:

1. Map out existing wireless services (cellular, WISP) serving the county. (Note: Some providers offer services in adjacent counties but may have spillover coverage at the county borders.)

2. Identify unserved and underserved areas, using broadband mapping resources, and develop priorities for development.

3. For areas that have some existing or nearby wireless service, engage with the providers about extending coverage to needed areas. Developing relationships with providers and encouraging extension of existing provider coverage may be the quickest path to providing connectivity to underserved communities.

4. Local government can function as an advocate for underserved communities by
    a. helping to identify areas for existing providers to expand their networks that will be economically viable;
    b. identifying existing infrastructure that can be leveraged for expanded facilities, e.g., vertical assets and fiber locations/sources; and
    c. addressing policy or regulatory issues that will complicate or delay deployment of new infrastructure.

5. In unserved areas where existing service providers either do not exist or cannot be enticed to expand their coverage, it may be necessary to develop new wireless capabilities. A government-owned and -operated system is a significant challenge and may not be desirable for several reasons. Unless the county has a strong existing information technology infrastructure, developing internet service provider (ISP) capabilities is a major challenge. In some states, there are laws preventing local governments from offering internet service in “competition” with commercial providers, regardless of whether those commercial providers are actually providing service.

6. Local governments can engage in public-private partnerships with commercial providers to bring internet coverage to unserved communities. These partnerships can include providing access to local government resources for vertical assets or siting, assisting with access to fiber connections including permitting and right-of-way negotiations. New commercial development can be leveraged to expand E911 coverage or other first-provider access, e.g., paging for fire departments, providing benefits to the service provider as well as the county.

7. Assemble a coalition of wireless and precision-agriculture experts that can assist local farmers to plan and deploy advanced wireless technology. Outside expertise will be needed early on, but over time, local coalition members should be able to mature in their knowledge and be able to serve as a resource for others.

GLOSSARY

Attenuation	The reduction of a signal due to blockage or passage through objects like vegetation or buildings
Backhaul	The connection between a wireless base station and the core network
Bluetooth	Short-range wireless data technology
CBRS	Citizens Broadband Radio Service
Data rate	A measure of the number of bits or bytes per second of data being transmitted or received
DSL	Digital Subscriber Line; a technology used to transmit digital data over telephone lines
Fixed access	Wireless data service to homes or other fixed locations
Geostationary arc	As viewed from earth, the location of satellites in geostationary orbit about the equator
IoT	Internet of Things
ISM	Industrial, Scientific, and Medical; unlicensed spectrum
LoRa	Long Range; wireless technology for low-power, low-data-rate, long-range communications
LoRaWAN	Low-power wide-area network using LoRa technology
LTE	Long-Term Evolution (i.e., 4G)
LTE Cat M1	Low-data-rate, machine-to-machine LTE
mmW	Millimeter Wave; microwave, high-bandwidth data
Mobility	Wireless service to non-fixed devices such as phones, vehicles, and sensors
Point-to-multipoint	A communications connection of one-to-many; usually describing fixed wireless data service
Point-to-point	A communications connection between two endpoints or nodes, often abbreviated P2P
Private LTE network	A communications network utilizing LTE technology but not operated by common carriers, e.g., cellular providers
Protocol (wireless)	Set of rules and techniques for wireless data communications
Satellite (communications)	Artificial object placed in outer space to provide communications for stations on earth
Spectrum	Specific radio frequencies used to provide wireless access
Wi-Fi	Unlicensed wireless local area network, usually 2.4/5 GHz
Wi-Fi HaLow	New Wi-Fi standard operating at 915 MHz at a lower data rate
WiMAX	Worldwide Interoperability for Microwave Access
WISP	Wireless Internet Service Provider

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APPENDIX A

TABLE 4: CBRS PRIORITY ACCESS LICENSES in ILLINOIS STUDY AREA

EDGAR COUNTY	- WATCH TV Company (dba WATCH Communications) - Mediacom LLC - Wetterhorn Wireless LLC
HANCOCK COUNTY	- AMG Technology Investment Group LLC - Windstream Services LLC - Wetterhorn Wireless LLC
McLEAN COUNTY	- WATCH TV Company (dba WATCH Communications) - Mediacom LLC - Wetterhorn Wireless LLC
OGLE COUNTY	- Mediacom LLC - AMG Technology Investment Group LLC - Wetterhorn Wireless LLC
SCHUYLER COUNTY	- United States Cellular Corporation - AMG Technology Investment Group LLC - Wetterhorn Wireless LLC

APPENDIX B

As part of this study, WRC undertook looking at the locations of current cell towers within each of the five counties in the study area. This data was collected from the cellmapper.net website, which uses crowdsourced data from cell phone users to record network availability. This data is assumed accurate as of April 2023. The wireless industry is constantly improving its coverage and availability, particularly with the rollout of 5G capability, so this information should be considered a snapshot in time.

These maps, along with other internet coverage predictions provided by the state of Illinois, help us to make a rough initial assessment of cellular coverage of the counties in the study. Based on this information, WRC created simulations based on the assumption of deploying new towers in areas of the county using CBRS technology to provide internet connectivity to areas with poor or nonexistent cellular service. These simulations are not intended to be a deployment plan, but rather a straw-man design to demonstrate the capabilities of adding more wireless resources within the county. The maps are based on CBRS technology predictions, but cellular and WISP providers may likely have greater coverage areas due to the lower frequencies used for those services.

There are also fixed-wireless providers that claim to service each of the counties. However, coverage maps and access points for these providers are not generally available, so we are unable to provide any significant insight into their capabilities. Reviewing what information may be available, it appears that at least some of the fixed-wireless providers operate primarily in adjacent counties with some spillover coverage along county boundaries adjacent to their primary service areas but allowing them to claim coverage in the counties in the study.

EDGAR COUNTY

TABLE 5: WIRELESS PROVIDERS in EDGAR COUNTY

CELLULAR PROVIDER	FIXED WIRELESS PROVIDER
T-Mobile	AgPro Wireless
AT&T	Rise Broadband
Verizon	Rising Wireless Cellular
	Verizon Wireless
	WATCH Communications

Some wireless providers may only serve portions of the county.

Figure 9: T-Mobile LTE cell sites in Edgar County, 1 cell site

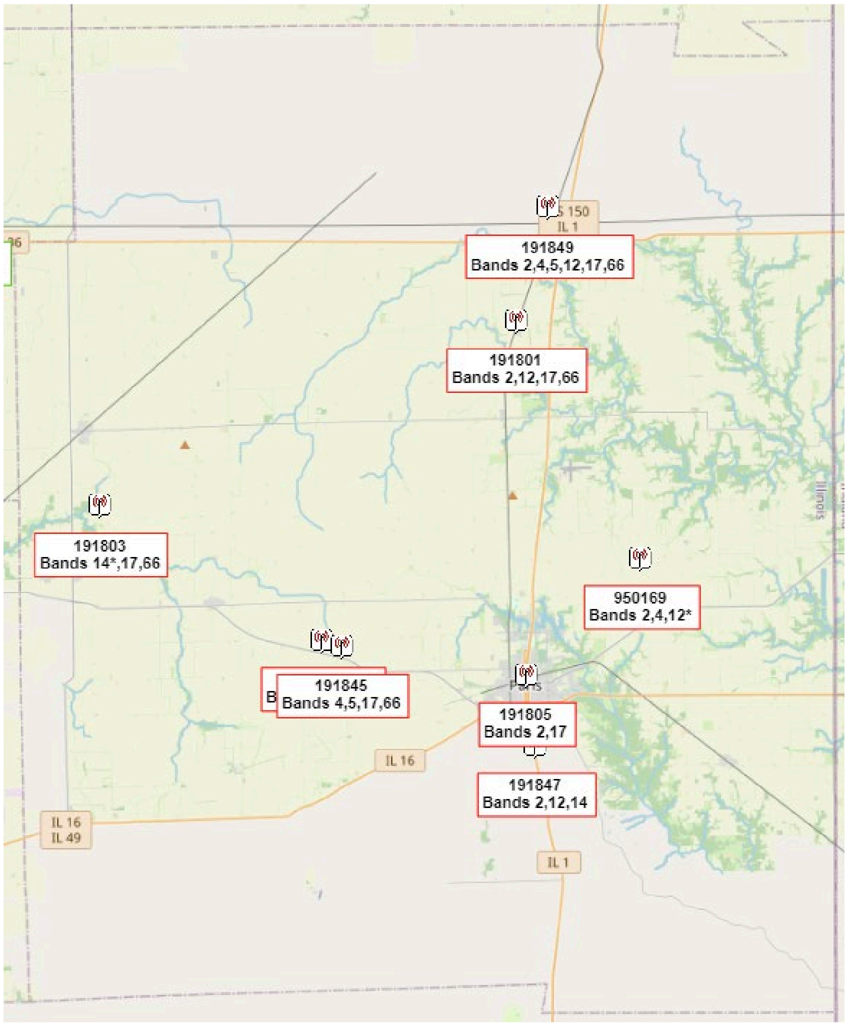


Figure 10: AT&T Mobility LTE cell sites in Edgar County, 8 cell sites

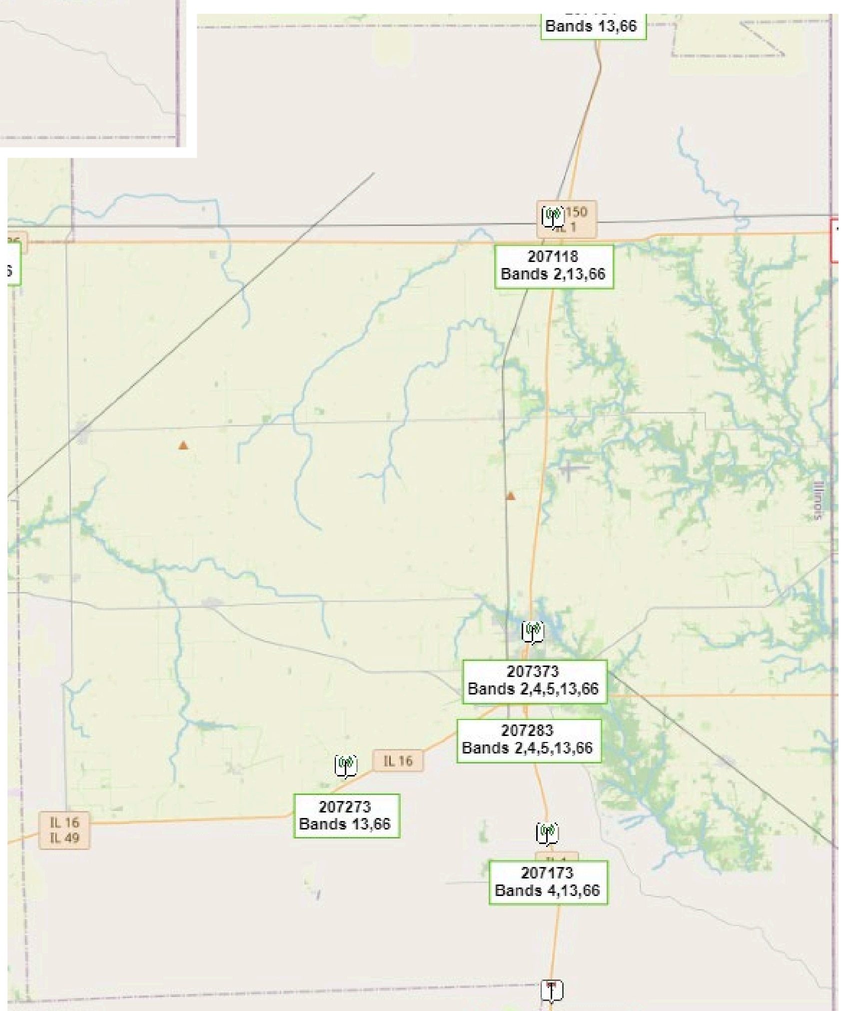


Figure 11: Verizon LTE cell sites in Edgar County, 6 cell sites

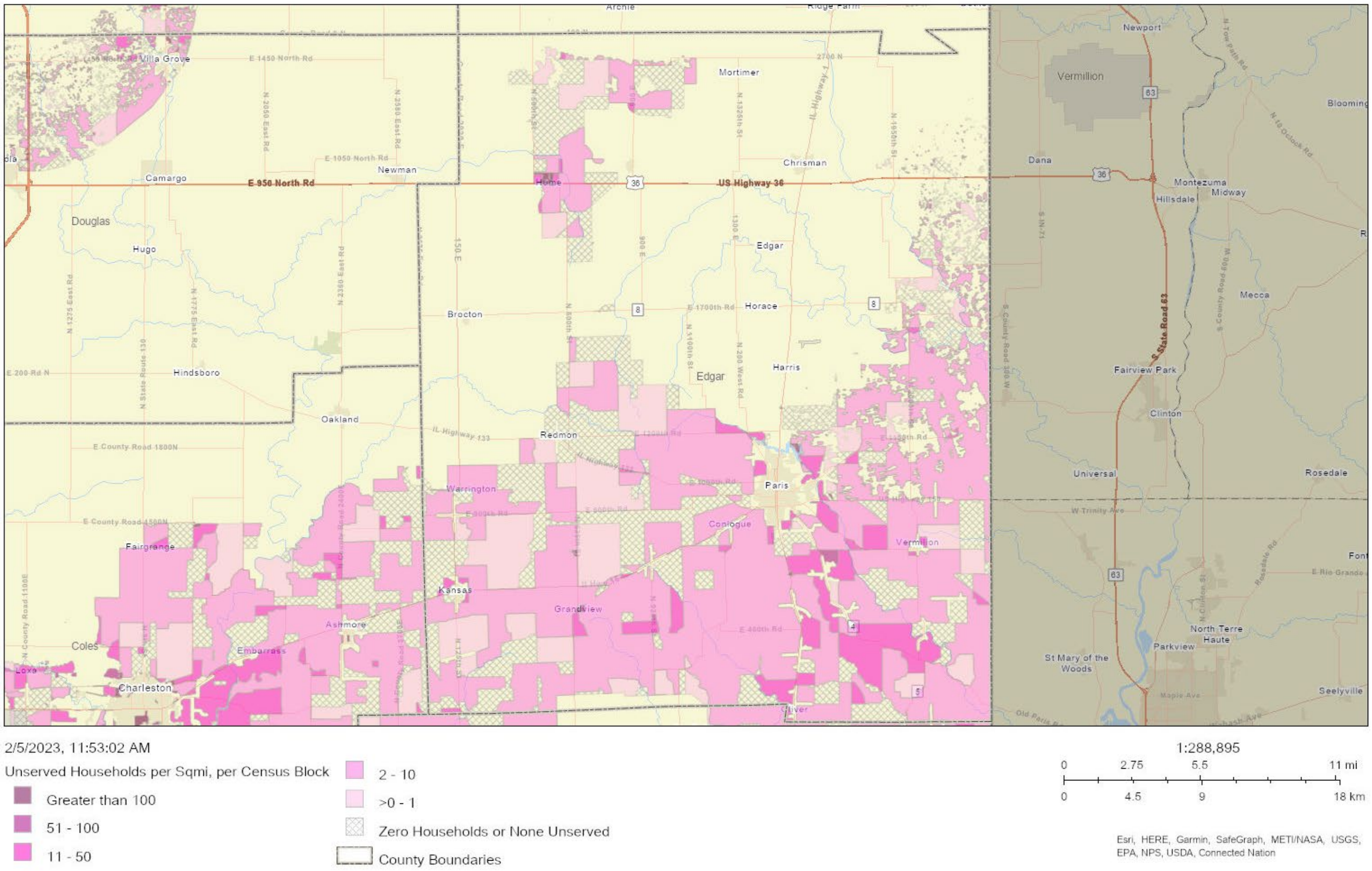


Figure 12: Unserved areas (All Fixed) in Edgar County showing density of households (courtesy of State of Illinois)

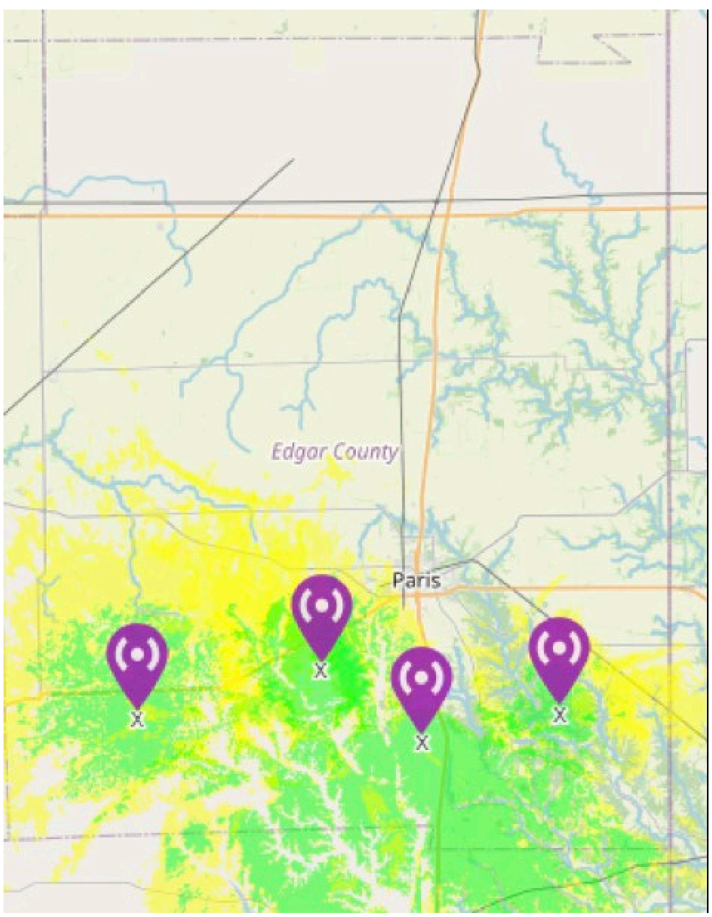


Figure 13: WRC Simulation of coverage in Edgar County with 4 CBRS towers

HANCOCK COUNTY

TABLE 6: WIRELESS PROVIDERS in HANCOCK COUNTY

CELLULAR PROVIDER	FIXED WIRELESS PROVIDER
T-Mobile	DerbyNet
AT&T	Netlink Residential
Verizon	Verizon Wireless
US Cellular	

Some wireless providers may only serve portions of the county.

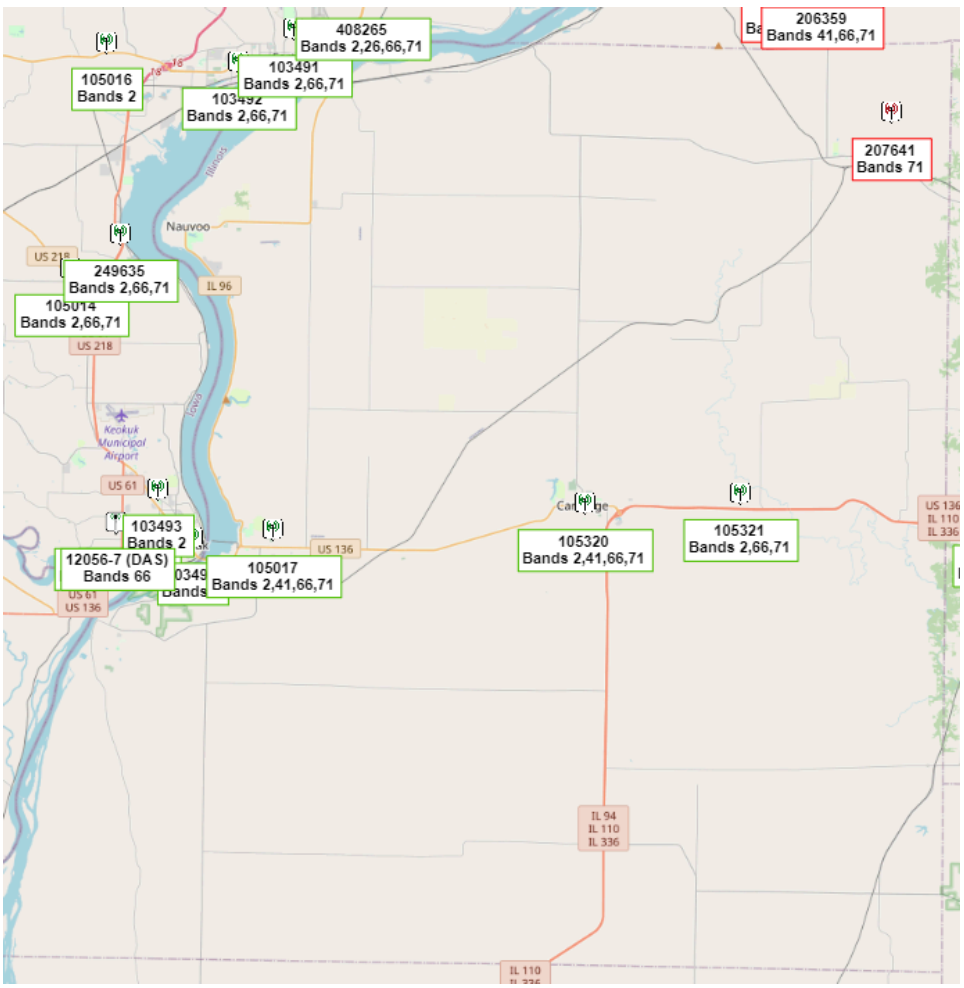


Figure 14: T-Mobile LTE cell sites in Hancock County, 4 cell sites

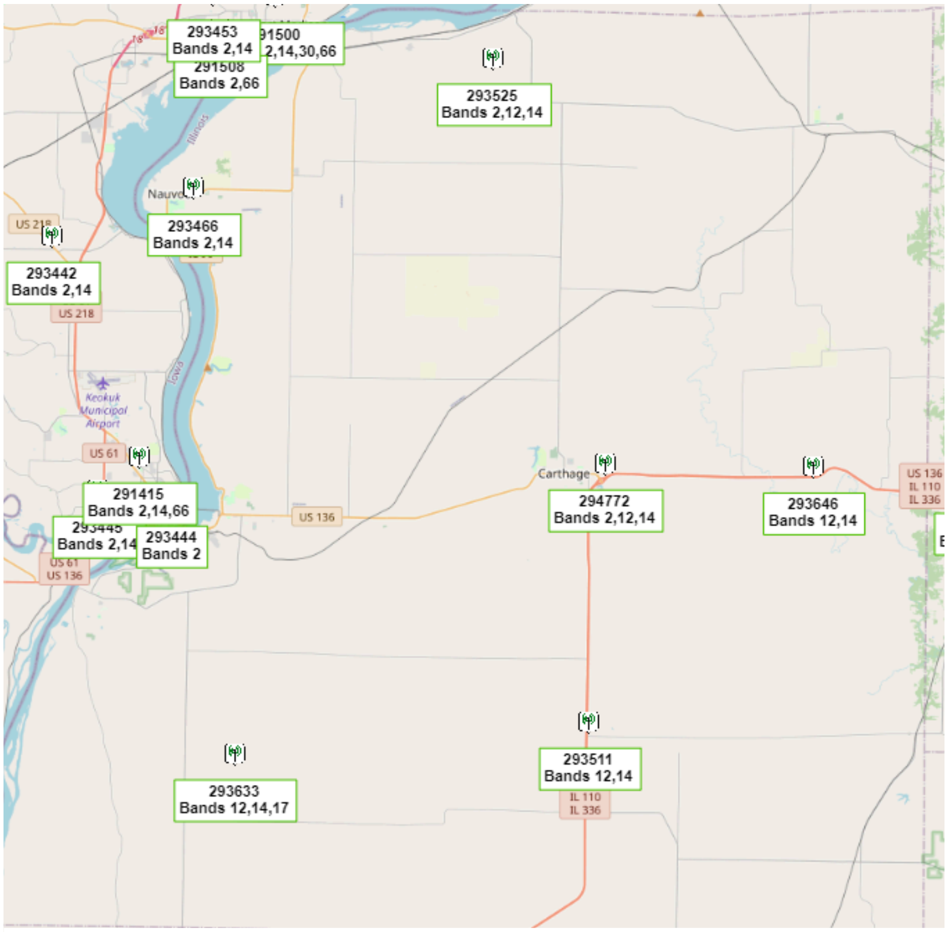


Figure 15: AT&T Mobility LTE cell sites in Hancock County, 6 cell sites

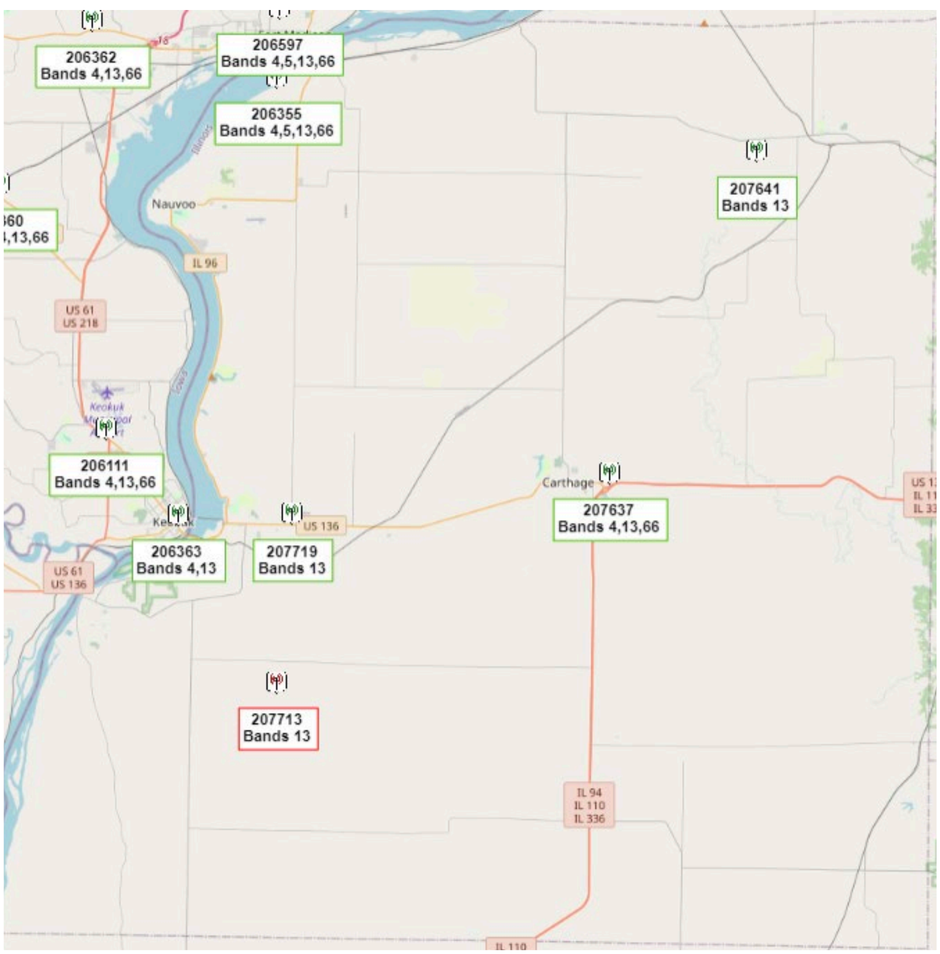


Figure 16: Verizon LTE cell sites in Hancock County, 5 cell sites

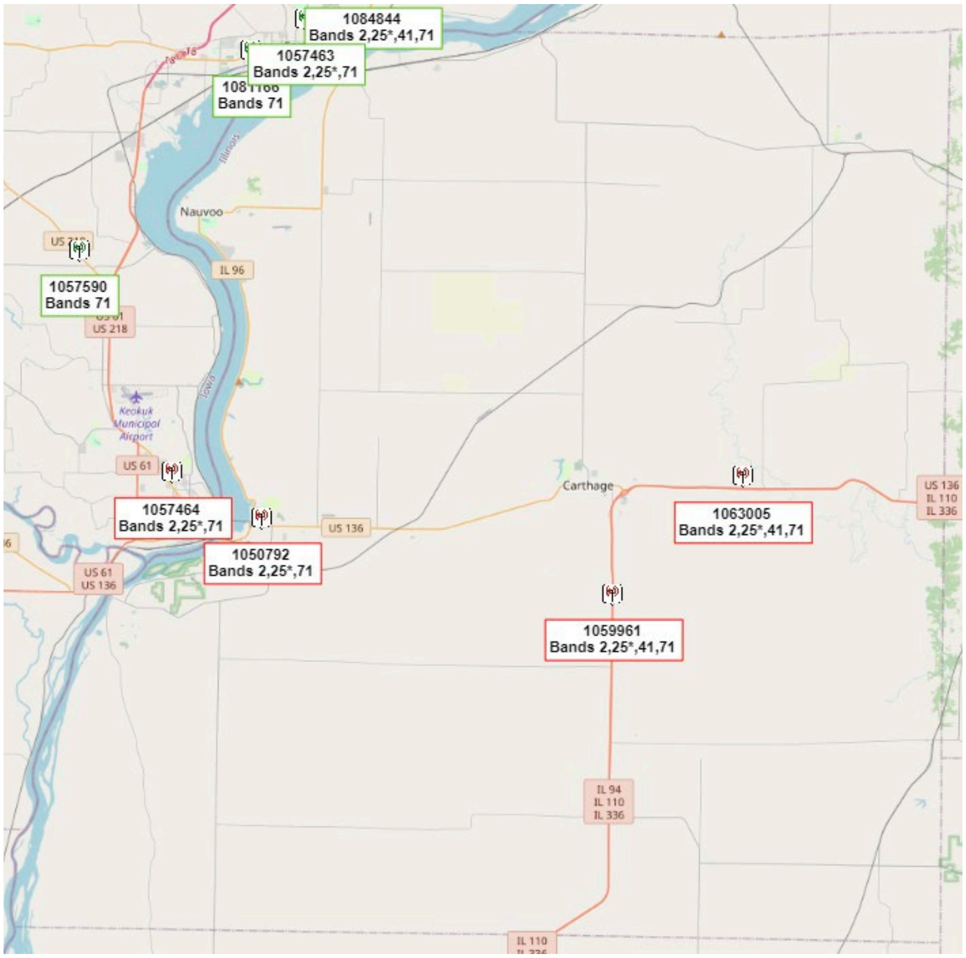
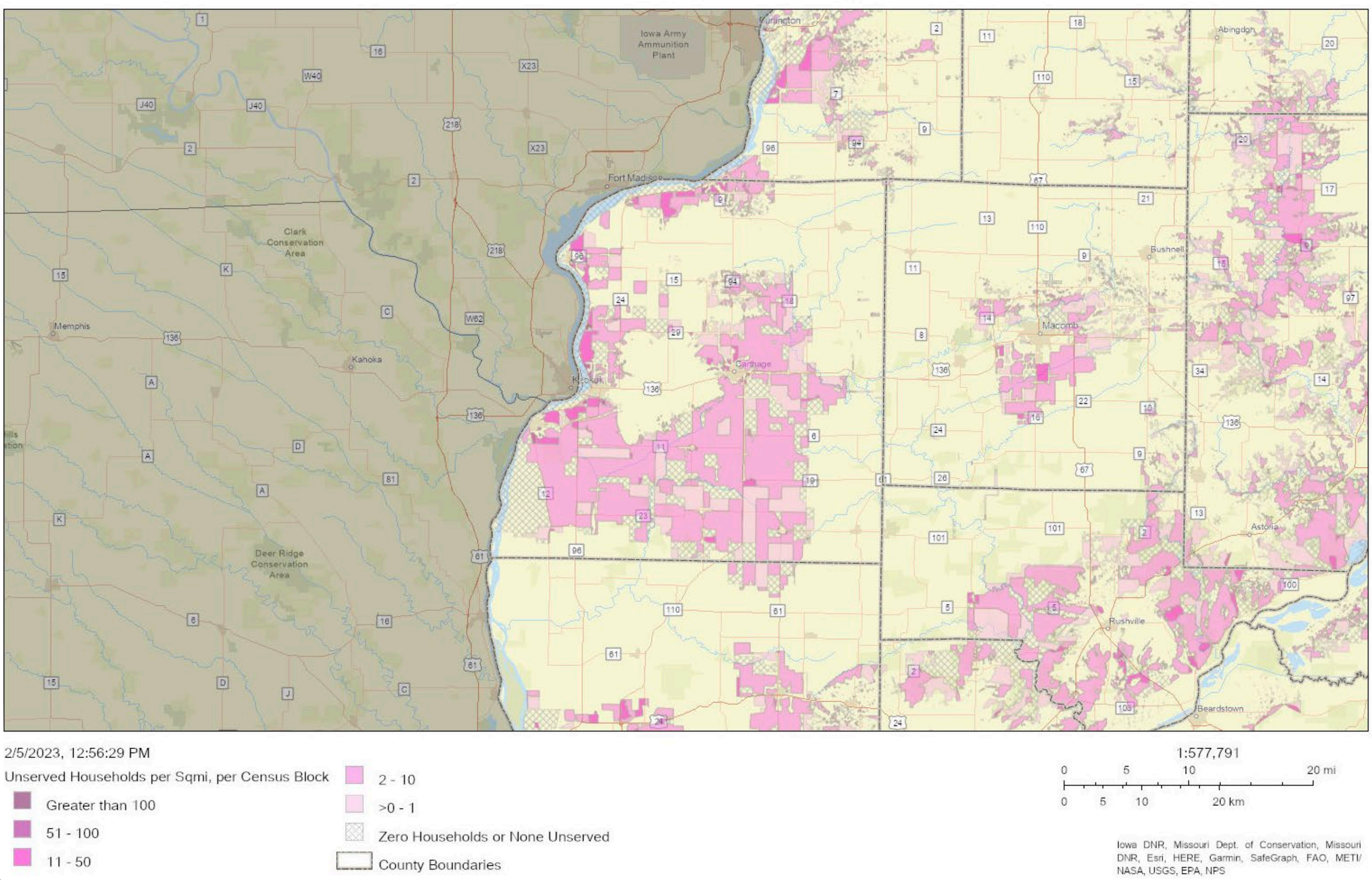


Figure 17: T-Mobile 5G cell sites in Hancock County, 2 cell sites

Figure 18: Unserved areas (All Fixed) in Hancock County showing density of households (courtesy of State of Illinois)



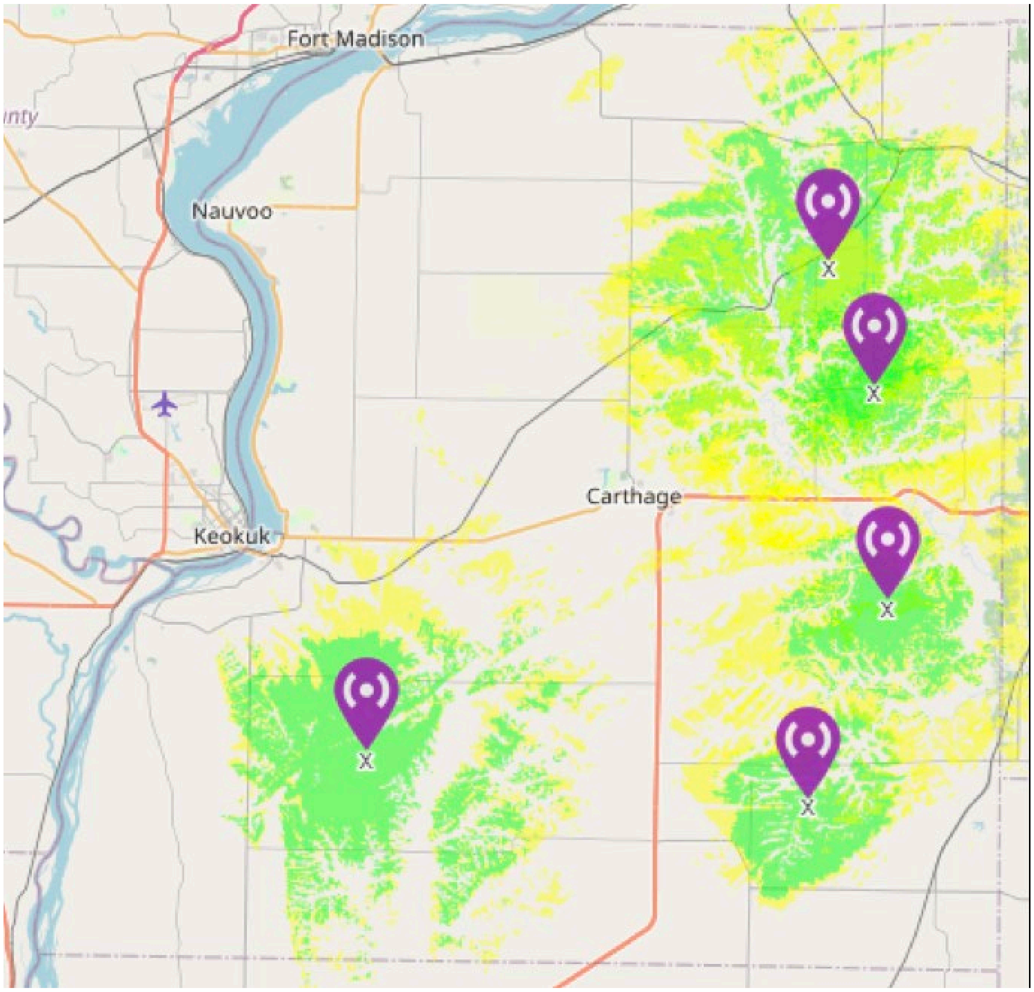


Figure 19: WRC simulation of coverage in Hancock County with 5 CBRS towers

McLEAN COUNTY

TABLE 7: WIRELESS PROVIDERS in McLEAN COUNTY

CELLULAR PROVIDER	FIXED WIRELESS PROVIDER
T-Mobile	New Wave Net Corp
AT&T	Nextlink Residential
Verizon	Rise Broadband
	Verizon Wireless
	WATCH Communications
	Wireless Data Net

Some wireless providers may only serve portions of the county.

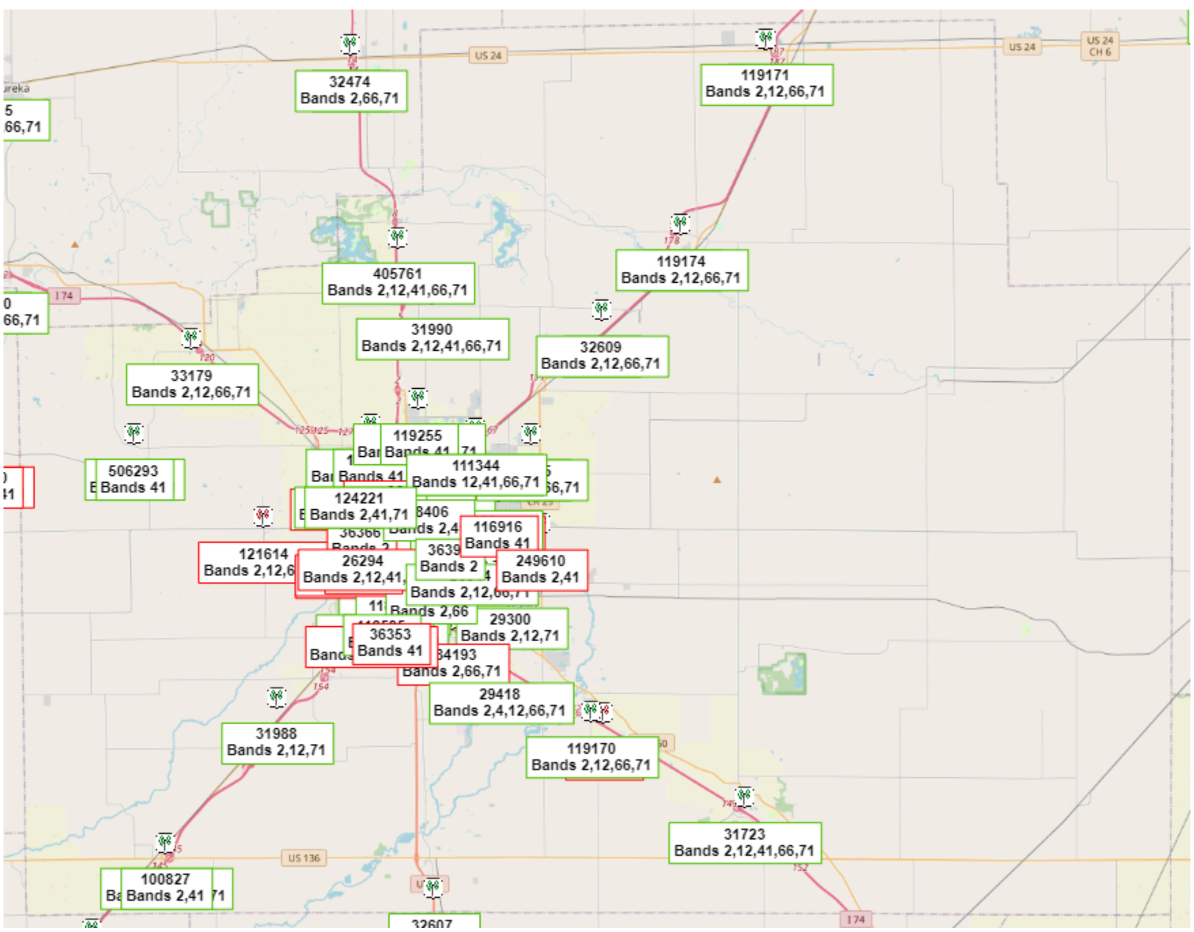


Figure 20: T-Mobile LTE cell sites in McLean County, 64 cell sites

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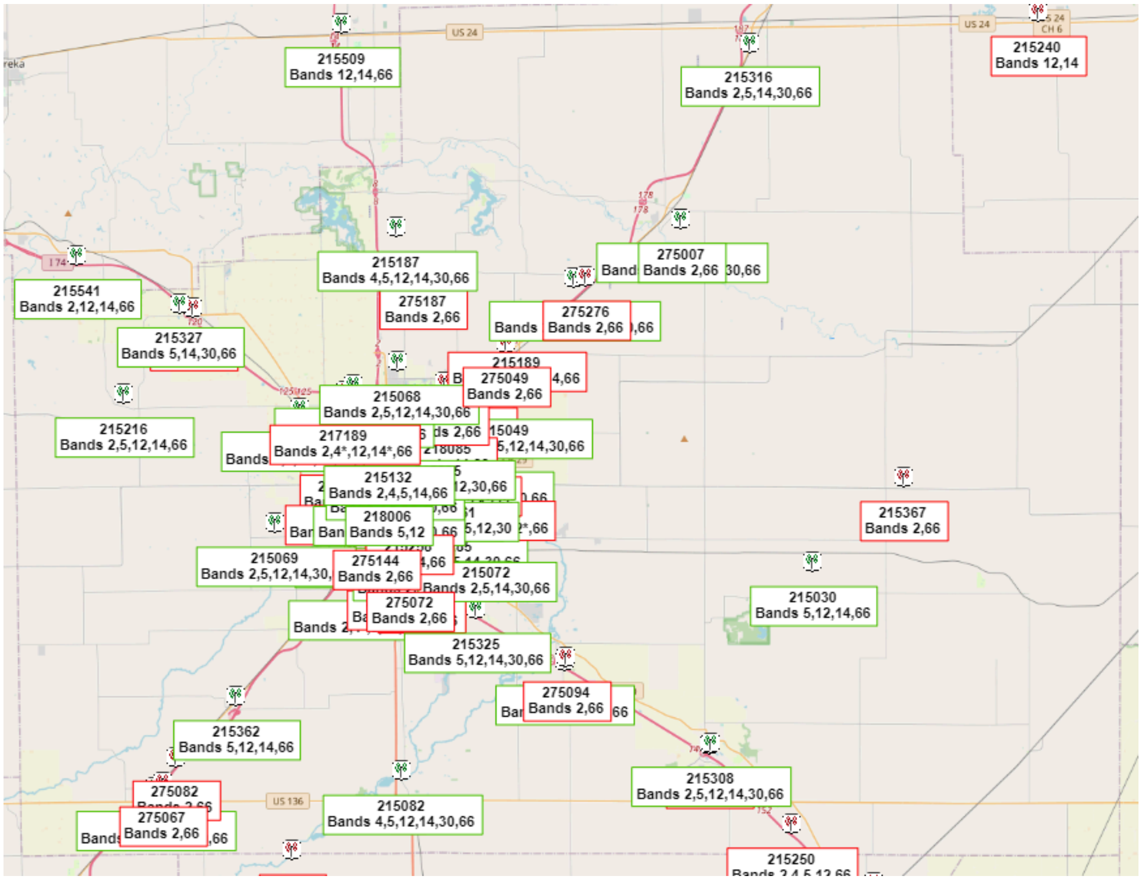

Figure 21:
AT&T Mobility LTE cell sites in McLean County, 80 cell sites

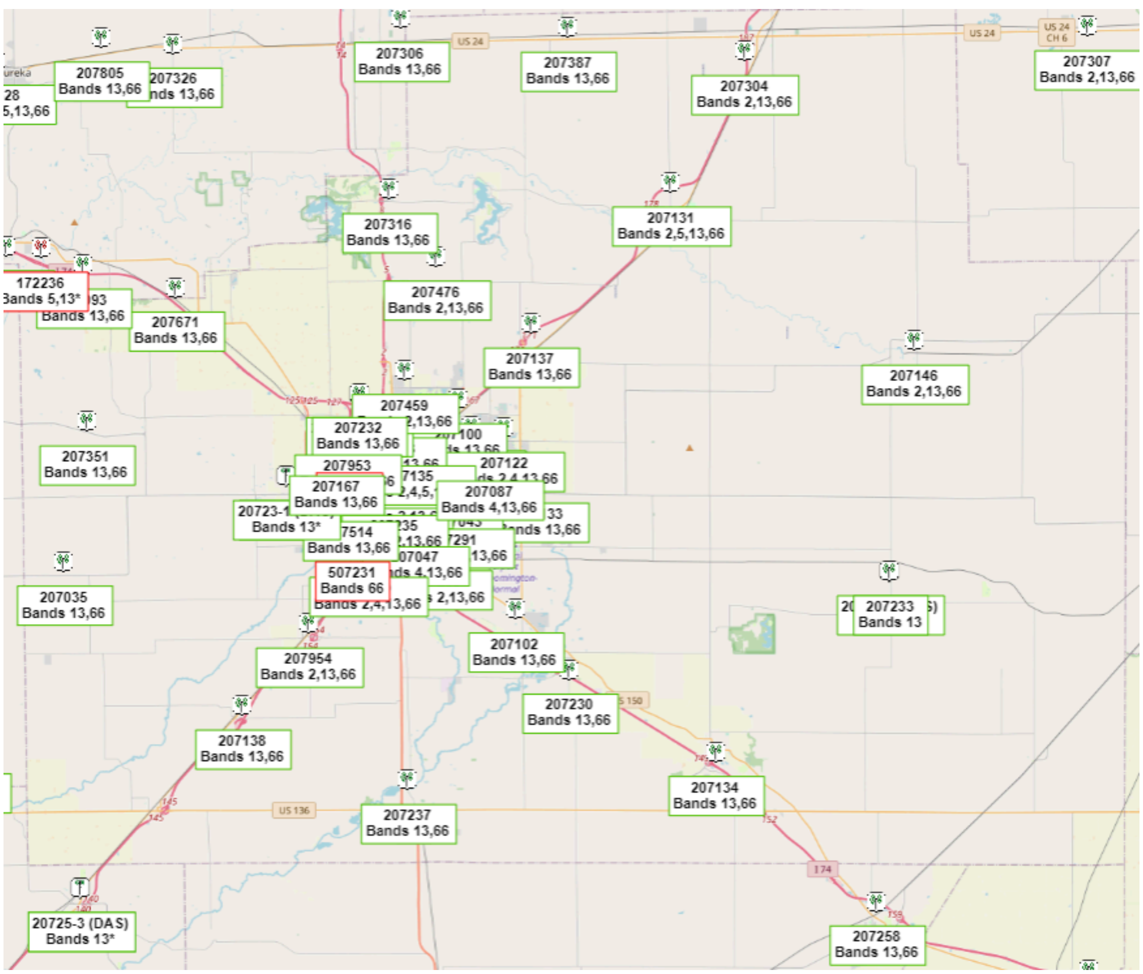

Figure 22:
Verizon LTE cell sites in McLean County, 47 cell sites

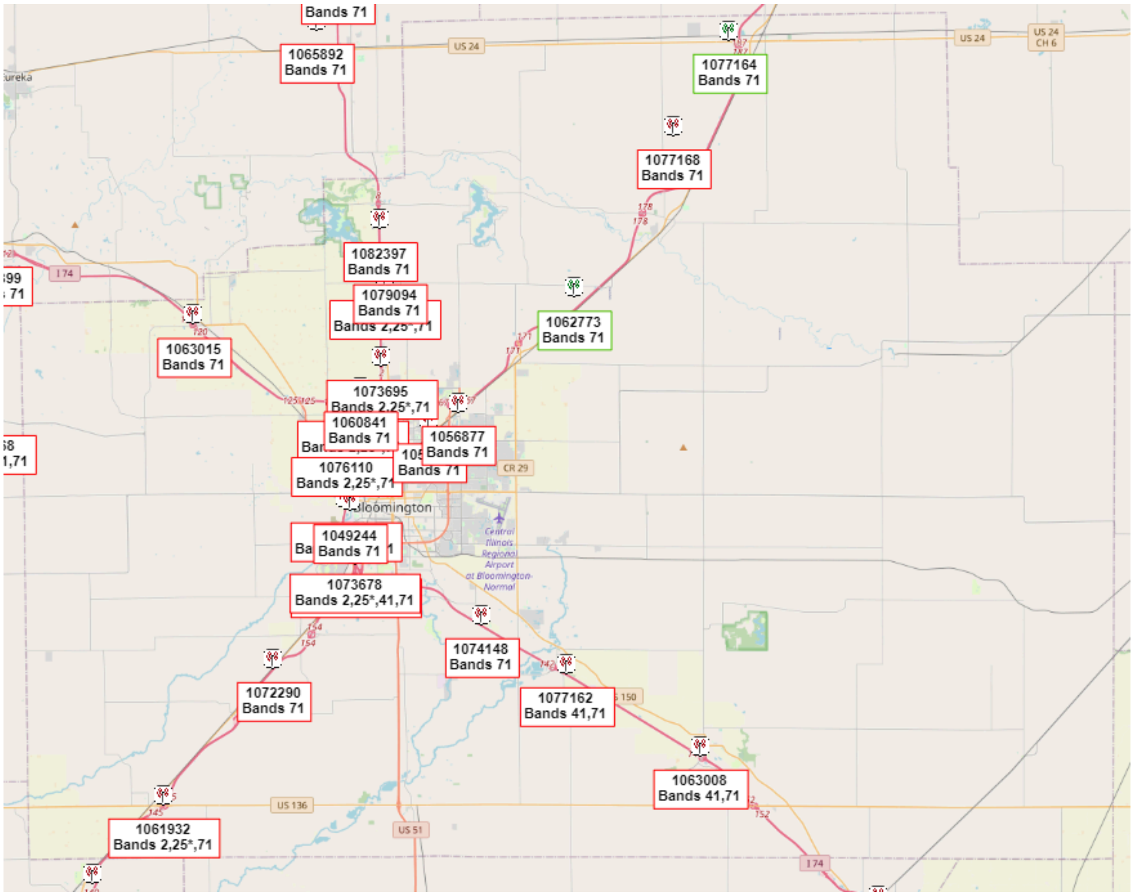

Figure 23:
T-Mobile 5G cell sites in McLean County, 24 cell sites

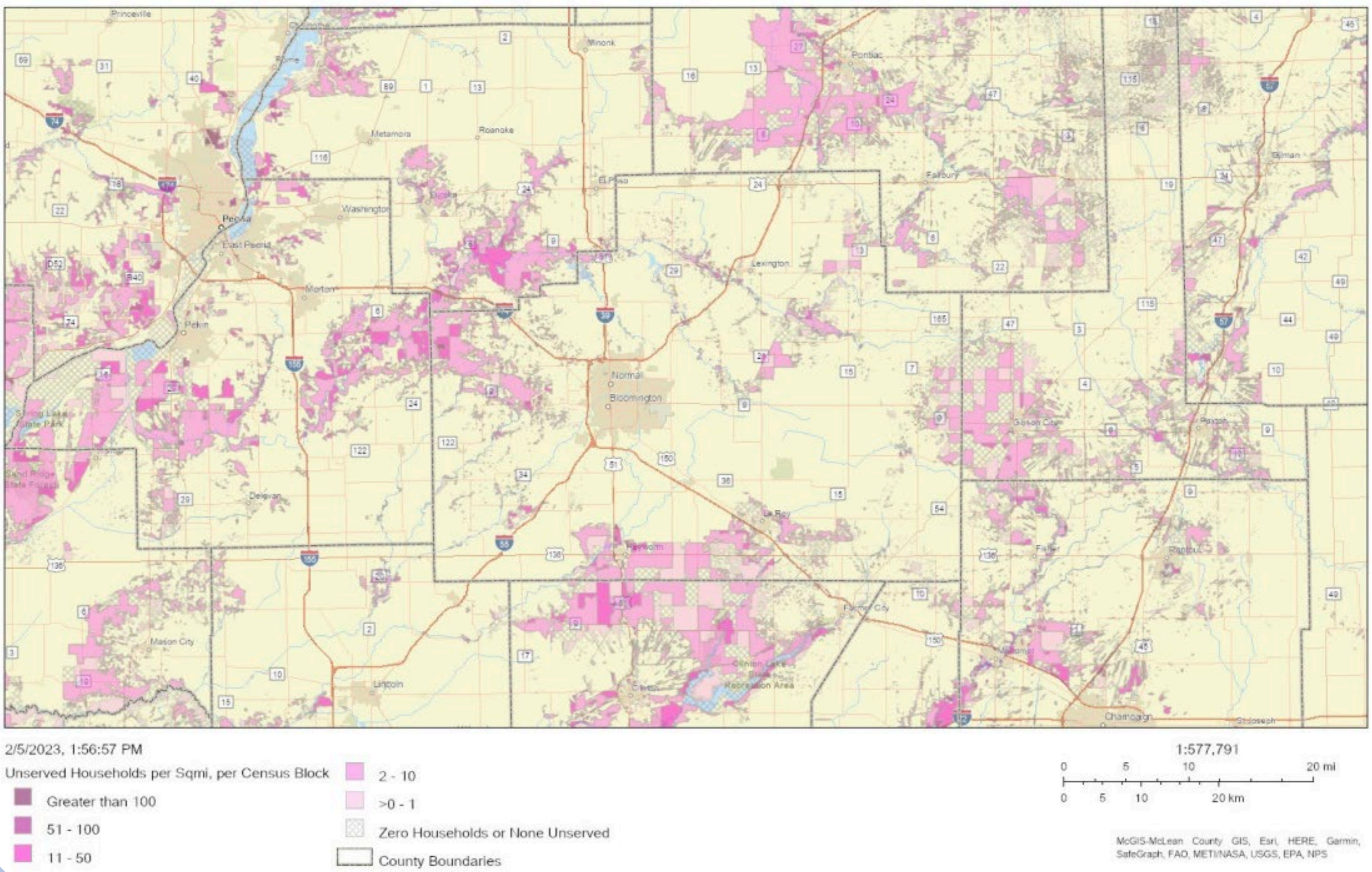

Figure 24:
Unserved areas (All Fixed) in McLean County showing density of households (courtesy of State of Illinois)

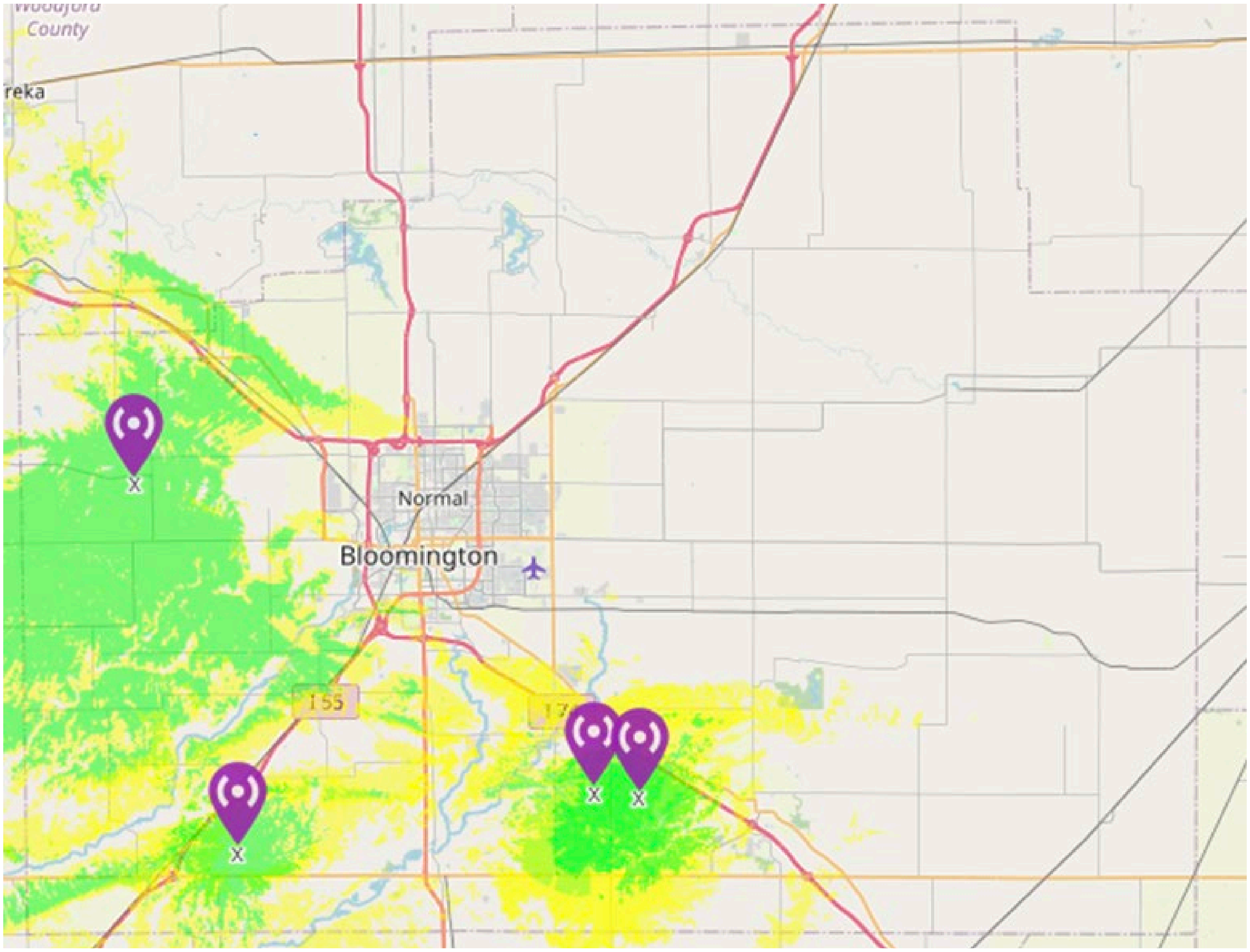

Figure 25: WRC simulation of coverage in McLean County with 5 CBRS towers

OGLE COUNTY

TABLE 8: WIRELESS PROVIDERS in OGLE COUNTY

CELLULAR PROVIDER	FIXED WIRELESS PROVIDER
T-Mobile	AirCell
AT&T	e-vergent
Verizon	JCWIFI
US Cellular	KWISP
	LR Communications
	Next-Level Technology Partners
	Rise Broadband
	Sonic Spectrum
	Verizon Wireless

Some wireless providers may only serve portions of the county.

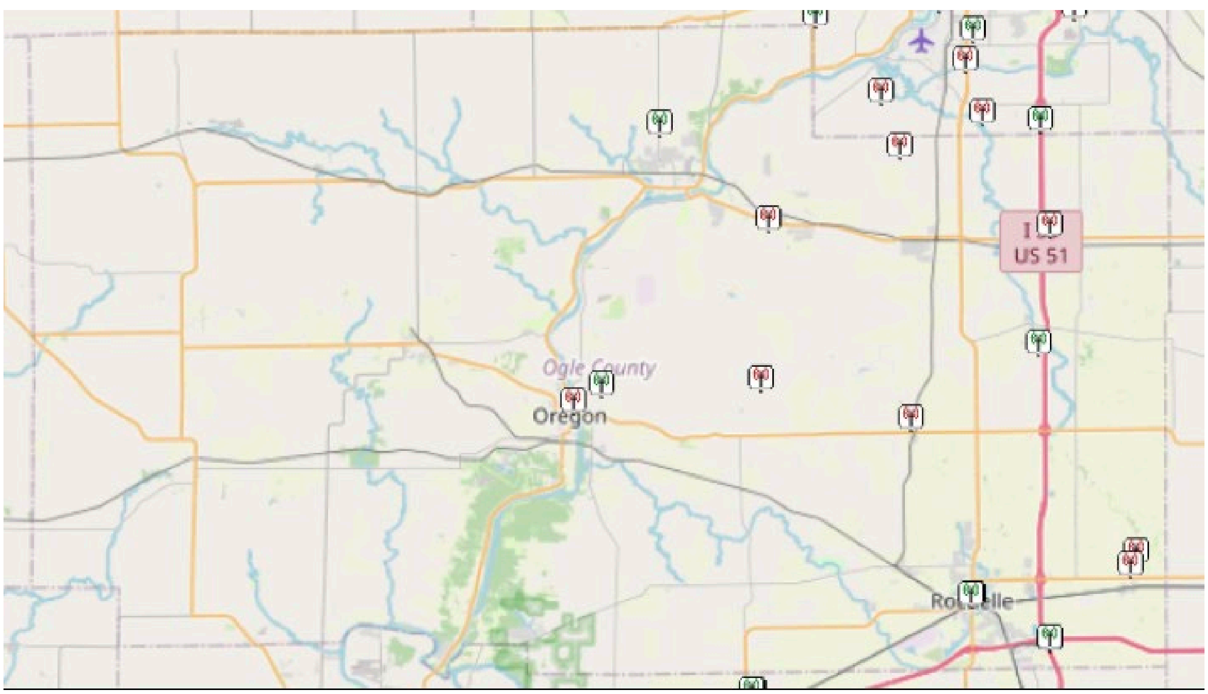

Figure 26: T-Mobile LTE cell sites in Ogle County, 11 cell sites

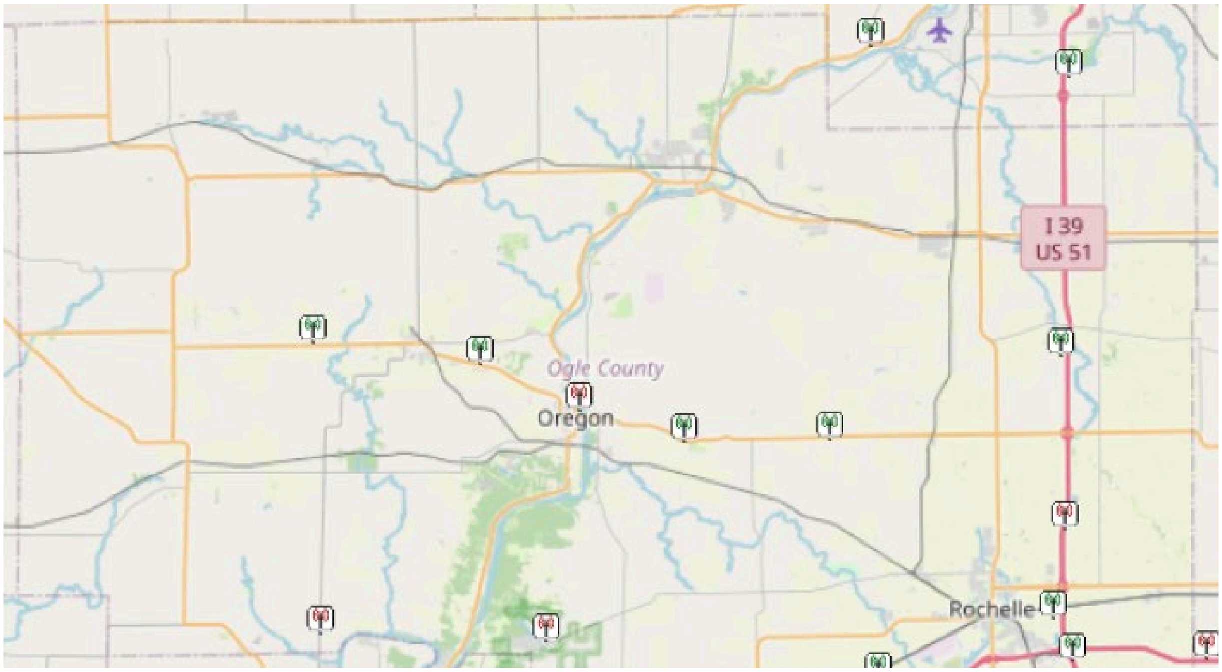

Figure 27: AT&T Mobility LTE cell sites in Ogle County, 12 cell sites

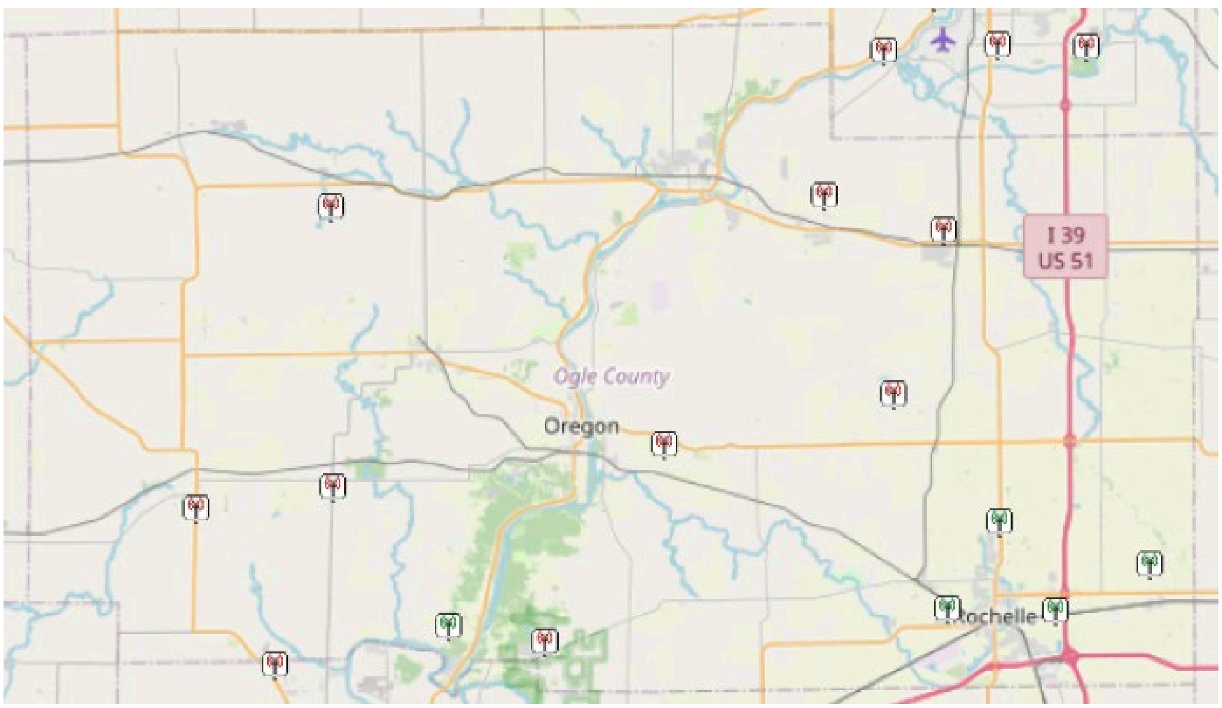

Figure 28: Verizon LTE cell sites in Ogle County, 12 cell sites

Figure 29: T-Mobile 5G cell sites in Ogle County, 9 cell sites

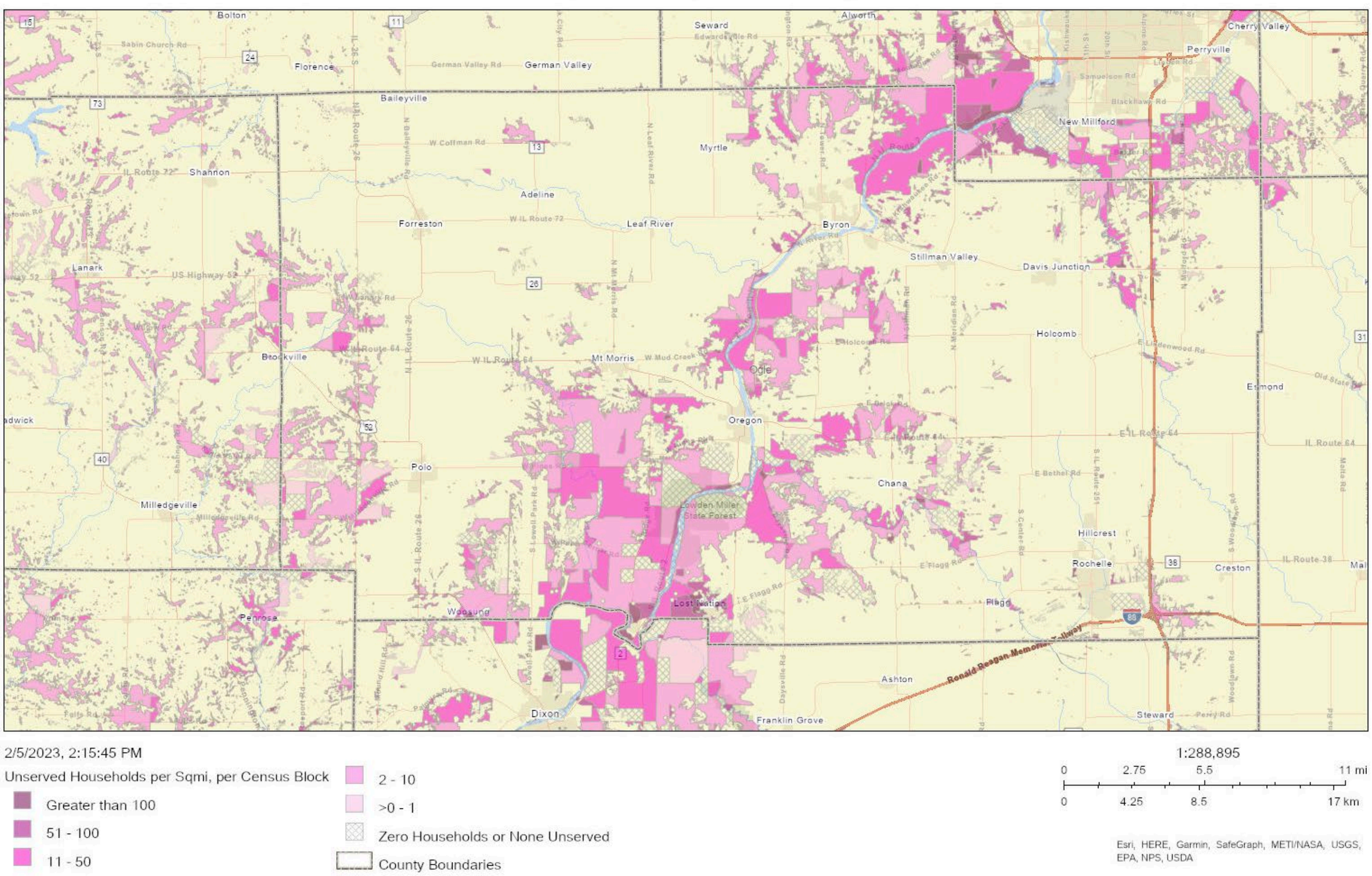

Figure 30: Unserved areas (All Fixed) in Ogle County showing density of households (courtesy of State of Illinois)

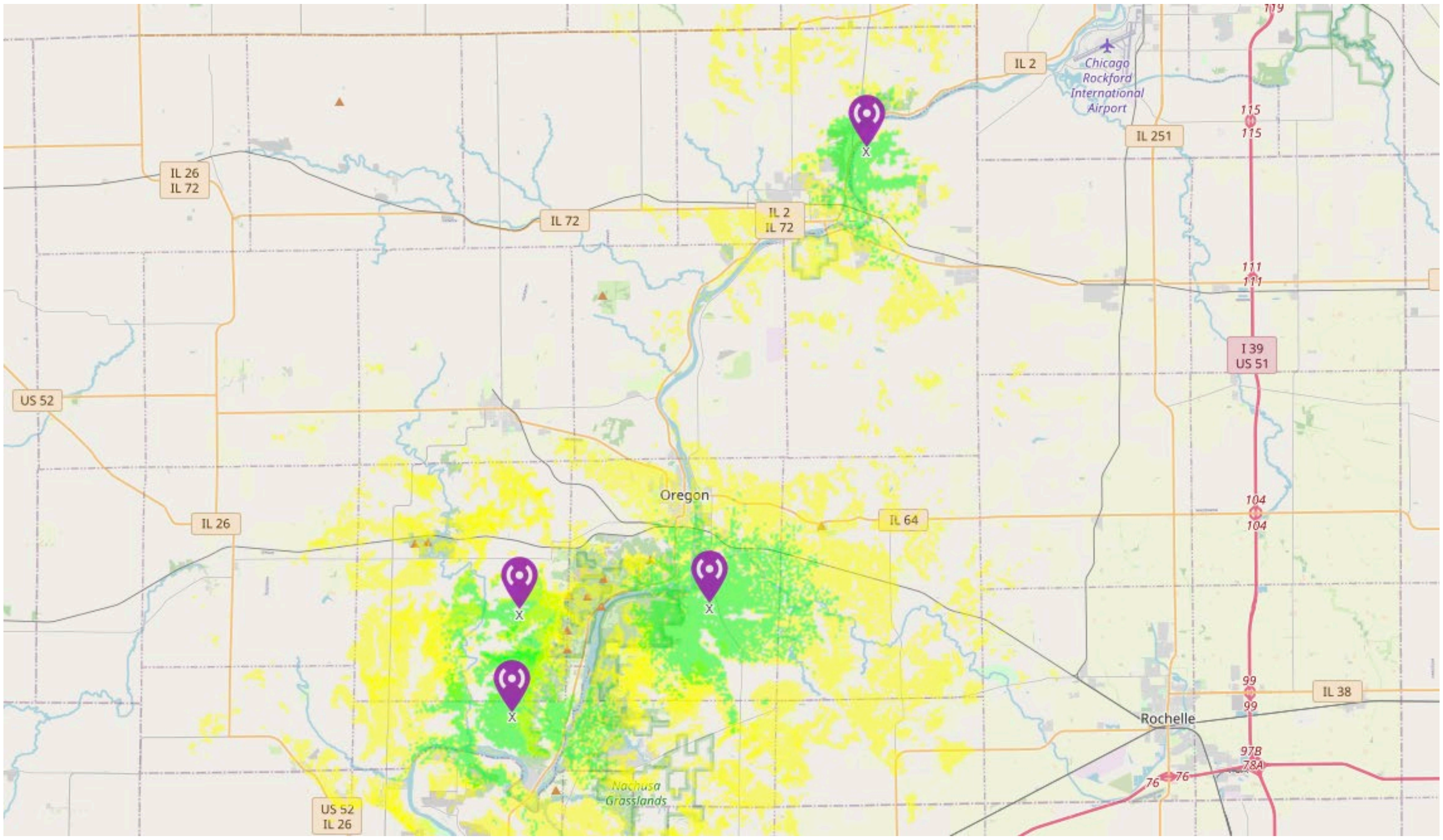

Figure 31: WRC simulation of coverage in Ogle County with 4 CBRS towers

SCHUYLER COUNTY

TABLE 9: WIRELESS PROVIDERS in SCHUYLER COUNTY

CELLULAR PROVIDER	FIXED WIRELESS PROVIDER
T-Mobile	Cass Communications
AT&T	S&B Technology Consultants
Verizon	

Some wireless providers may only serve portions of the county.

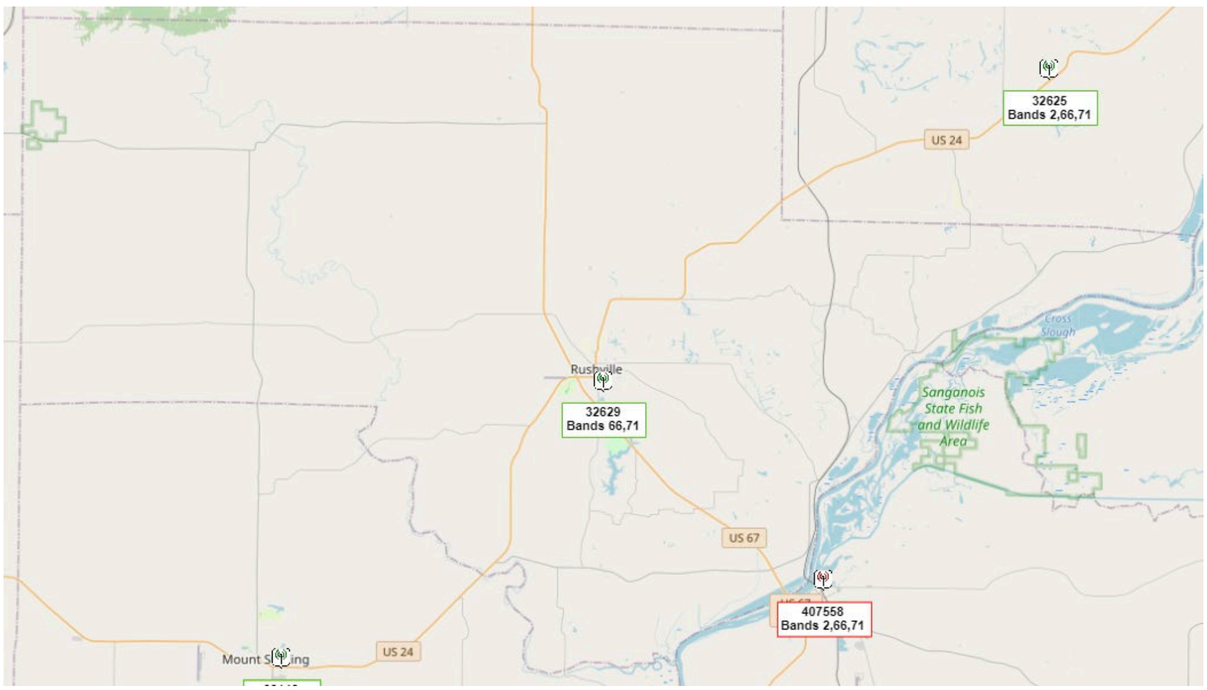

Figure 32: T-Mobile LTE cell sites in Schuyler County, 1 cell site

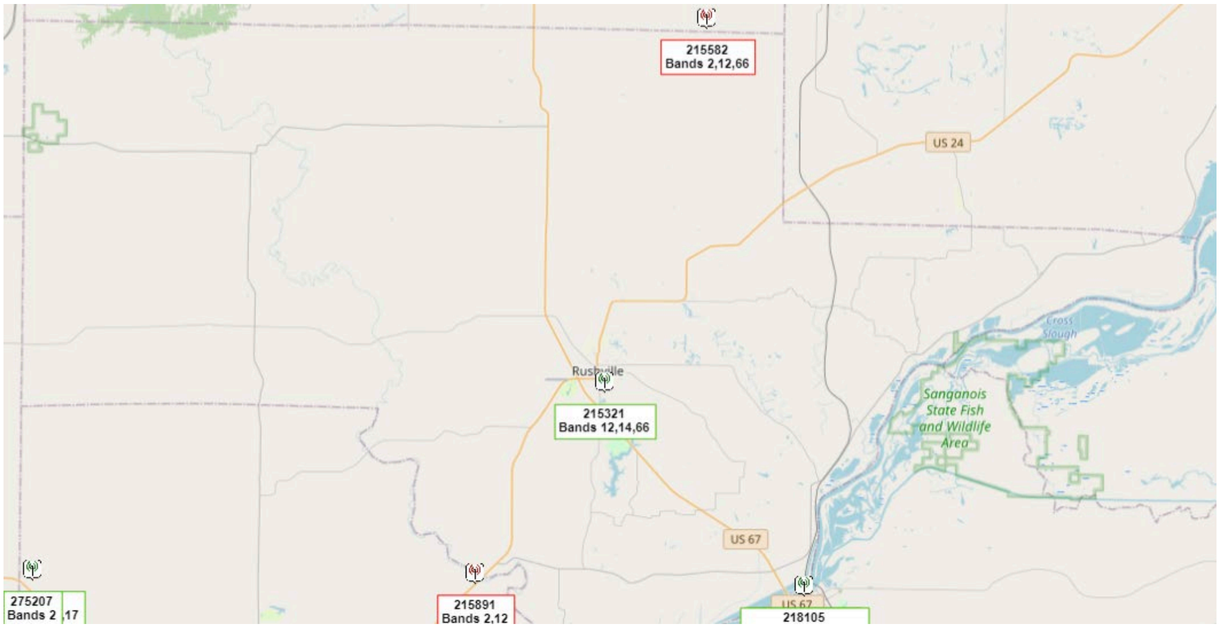

Figure 33: AT&T Mobility LTE cell sites in Schuyler County, 1 cell site

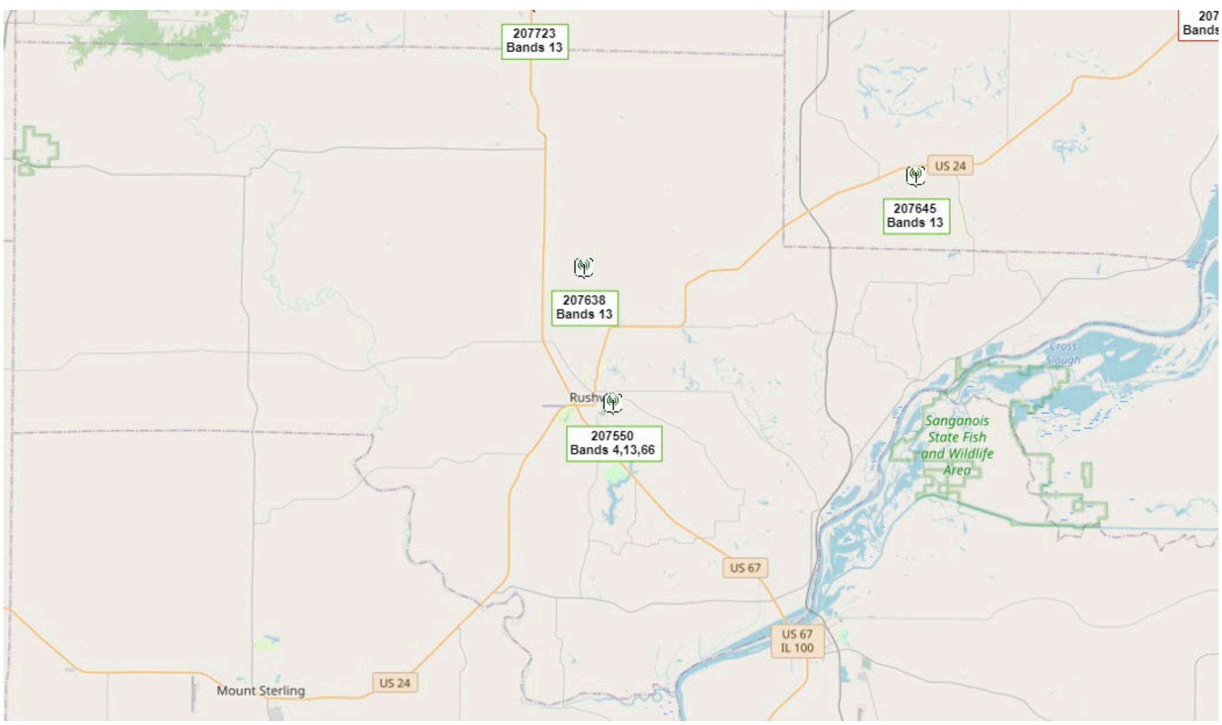

Figure 34: Verizon LTE cell sites in Schuyler County, 2 cell sites

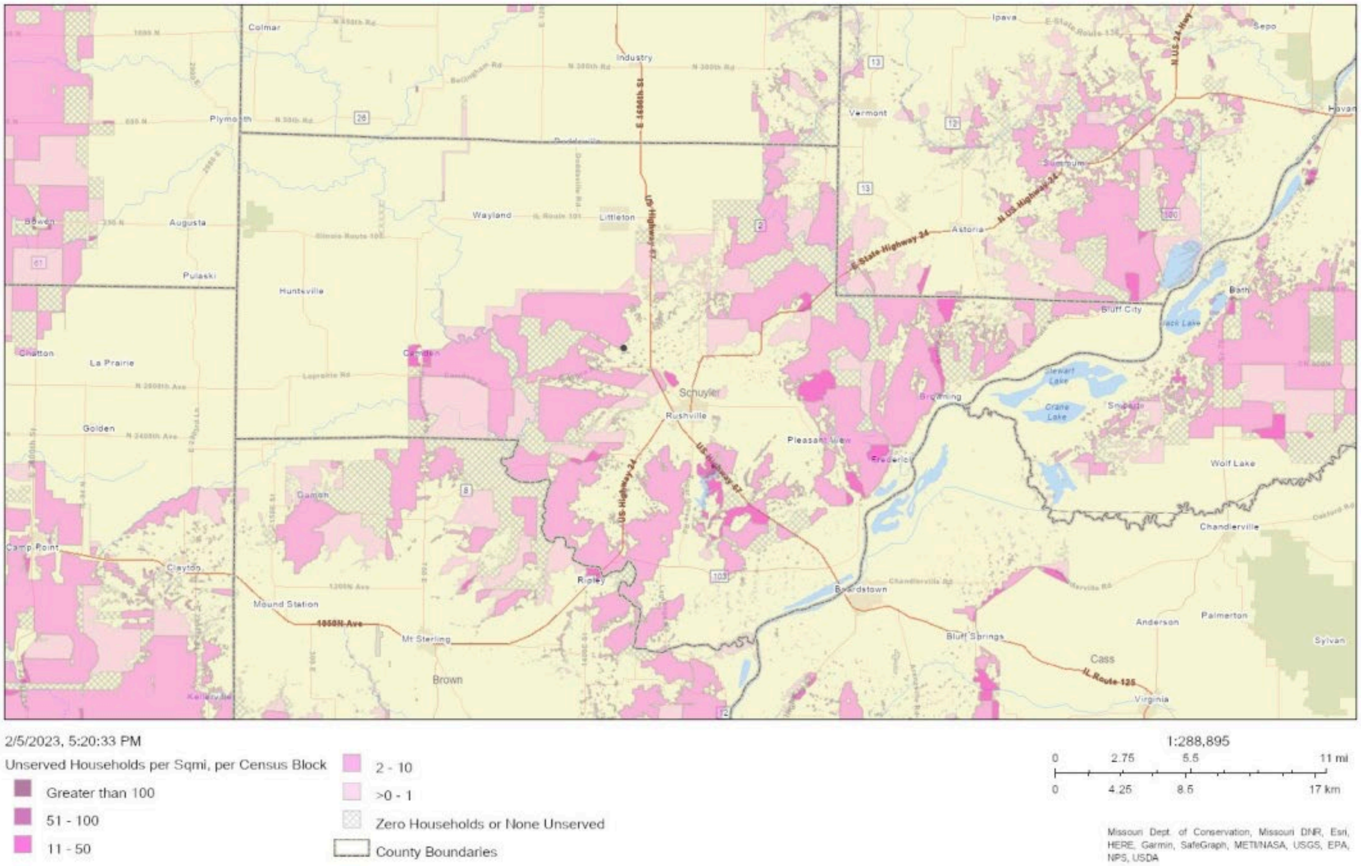

Figure 35: Unserved areas (All Fixed) in Schuyler County showing density of households (courtesy of State of Illinois)

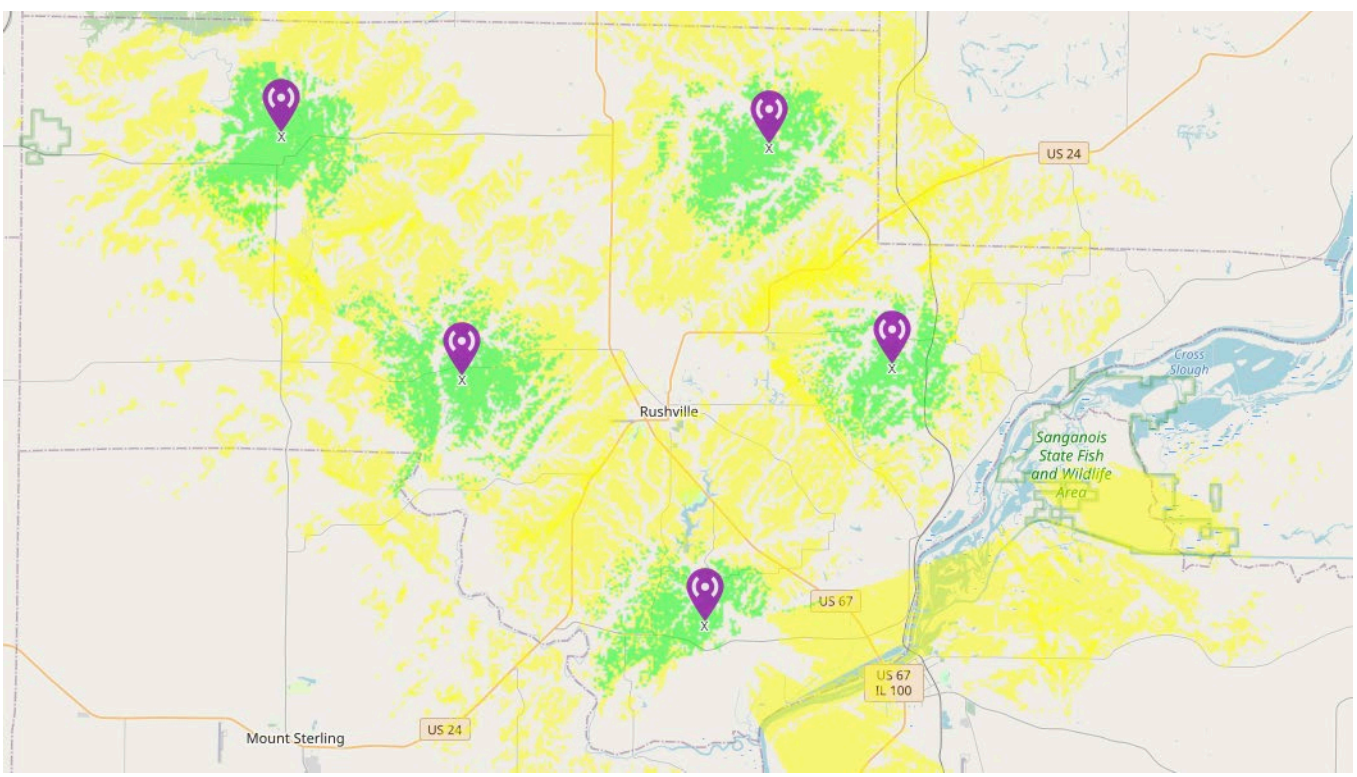

Figure 36: WRC simulation of coverage in Schuyler County with 5 CBRS towers

ORGANIZATIONAL BIOGRAPHY

Wireless Research Center of North Carolina

Over the past decade, **Wireless Research Center of North Carolina** has built a state-of-the-art organization to take antenna and wireless requirements and create deployable solutions. WRC Technologies specializes in the design, simulation, and testing of RF devices, wireless networks, and system architectures. Our clients include small and large companies, startups, academic institutions, and the U.S. government; we support industries including telecom, aerospace/avionics, energy, IoT/wearables, transportation, public safety, medical/healthcare, and government/defense.

WRC is a nonprofit and is IP neutral. As a result, we are able to bring innovative ideas for our clients to market faster and more cost effectively.

WRC is a leading provider of strategic engineering services for wireless technology, with demonstrated ability to deliver innovative wireless solutions from initial concept to prototypes and high-volume production. The WRC staff has over 350 years of combined experience in advanced antenna and RF electronics research, development, design, and testing. Collectively, the WRC staff has received more than 80 patents in antennas, sensors, RF, and communications systems.

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Dr. Barts received his bachelor's, master's, and Ph.D. degrees from Virginia Tech in electrical engineering, focusing on RF systems and antennas. He has more than 30 years of engineering experience as research faculty and in industry positions working on RF and communications systems for government programs as well as commercial applications. He has conducted RF propagation modeling for NASA on mobile satellite propagation as well as near-earth propagation measurements and characterization for DoD programs. He has designed and overseen engineering of VSAT terminal antennas for commercial systems as well as designed antennas for consumer over-the-air (OTA) television reception. He has also worked on industrial microwave heating systems producing multi-kilowatt microwave systems for heating, drying, and sterilization of food and other products. He holds two patents, one of which was the product of his Ph.D. dissertation on reduced-size helical antennas. He has been at WRC for five years and currently leads the deployment and operations for AERPAW, an NSF-funded 5G wireless test bed focusing on UAV applications, which is being built at and in conjunction with North Carolina State University.

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Dr. Takamizawa received his Ph.D. from Virginia Tech. He has more than two decades of experience in the design and manufacturing of antennas and RF systems development for broad spectrum of industries including consumer electronics, aerospace, medical, and industrial instrumentation. At Wireless Research Center of North Carolina, where he is currently employed, Dr. Takamizawa leads the engineering team to provide research, development, and consulting services for RF systems and antennas. He has specifically worked on the antenna designs and testing, propagation measurements and modeling, verification test methods and test fixture development, FCC and FAA certification test oversights, RF system design, testing, and debugging for various customers. He is also in charge of the technical oversight for the CTIA Over-the-Air (OTA), Verizon OTA, and Antenna performance certification testing services that Wireless Center provides. He has worked with antenna systems design and development for mobile handsets and machine-to-machine applications at Sony Ericsson and HTC, and geostationary communication satellite antennas and NASA deep-space spacecraft communication antennas design and development. He was also involved in developing advanced test measurement system design and development for the verification of new technologies at these companies. He was also involved in technology development and scouting for the near-future and long-term product development at those companies.

Dr. Gerard Hayes

President & Founder, Wireless Research Center of North Carolina

Dr. Hayes has nearly three decades of experience in government and commercial electromagnetic research and design. Prior to working with the Town of Wake Forest to establish the WRCNC in 2010, Dr. Hayes was the director of engineering at GreenWave Scientific, where he led the development of antenna and RF circuit designs for a diverse range of DoD applications. At Sony Ericsson Mobile Communications (USA) Inc., Dr. Hayes provided global technical leadership in the Technology and Research organization with contributions to handset antenna design, technology, and radiated performance optimization. At Lockheed Martin (formerly Lockheed Missiles and Space Co.), Dr. Hayes supported research and development efforts for space-based, phased array applications. The scope of his experience encompasses electromagnetic theory, bioelectromagnetics, antenna design, RF circuit analysis, and material engineering. He has participated in the development of international standards for OTA, HAC, and SAR evaluation (including IEEE, IEC, CTIA, and C63 standards). With more than 70 U.S. patents, Dr. Hayes has maintained a prominent technical role in the wireless industry.

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