FIXED WIRELESS TECHNOLOGIES and THEIR SUITABILITY for BROADBAND DELIVERY

Andrew Afflerbach, Ph.D., P.E.
CTC Technology & Energy

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Andrew Afflerbach, Ph.D., P.E., is CEO and CTO of CTC Technology & Energy. Andrew specializes in planning, designing, and overseeing the implementation of broadband communications networks. Over the course of more than 25 years in the field, Andrew has developed broadband engineering strategy and specifications for dozens of fiber and wireless networks in both rural and urban areas, ranging in size from small towns to large states to nation-wide efforts like the New Zealand fiber-to-the-premises initiative.

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benton.org

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1 Executive summary

This report offers an engineering analysis of fixed wireless technologies and their suitability for delivering broadband service in various environments. The report addresses a range of critical technology and cost considerations related to fixed wireless networks—and, as a point of comparison, to fiber-to-the-premises networks. The report seeks to do the following:

- Provide an accessible guide to current and anticipated future fixed wireless technologies[1]
- Demonstrate whether fixed wireless can be a viable approach to delivering broadband to currently unserved residents in various deployment scenarios, such as in urban and rural communities
- Suggest how and in what circumstances states should consider using public funds on fixed wireless technologies as a long-term solution to address residential broadband needs

At a high level, the report concludes the following:

- Fixed wireless technologies will continue to improve but will not match the performance of fiber optic networks—primarily because the existing and potential bandwidth of fiber is thousands of times higher than wireless, but also because fixed wireless networks have inherent capacity limitations that sharply limit the number of users on a network using a given amount of spectrum.
- Fixed wireless network coverage is adversely affected by line-of-sight obstructions (including buildings and seasonal foliage) and weather. While a fiber network can physically connect every household in a service area (and deliver predictable performance), it is significantly more complex for a fixed wireless network to deliver a line of sight to every household in a service area.
- Scalability is a critical challenge to fixed wireless deployments, both technically and financially. A given amount of wireless spectrum is capable of supporting a given amount of network capacity. If the number of network users increases, or users need more bandwidth, the network operator must increase the spectrum (which is both scarce and extremely expensive—and may not be possible), upgrade the technology, or add antennas. Even with the addition of costly new antenna sites (known as “densification”), it is challenging to design a fixed wireless network that will provide sufficient, robust upstream and downstream capacity and reach all the addresses in unserved areas. Line-

[1] This report presents an analysis of a range of fixed wireless spectrum (e.g., unlicensed, CBRS, EBS and millimeter wave), mobile network generations (e.g., 4G and 5G), and emerging technologies (e.g., MIMO and beamforming).

of-sight connections between antennas—which are critical to network performance—cannot always be achieved in a cost-effective and customer-friendly way. And upgrading the technology requires replacing the base station antennas and customer premises antennas, which are most of the capital cost of a fixed wireless network.

- The fastest fixed wireless technologies (such as those that use millimeter-wave spectrum) are effective in delivering short-range service to closely grouped households in urban and suburban settings. These technologies are largely unsuitable for serving rural communities because of the typical geographic dispersion of addresses and the lack of mounting structures (such as towers or building rooftops).

- Fiber is sustainable, scalable, and renewable. It offers greater capacity, predictable performance, lower maintenance costs, and a longer technological lifetime than fixed wireless technologies. Fiber service is not degraded by line-of-sight issues and is not affected by the capacity issues that constrain fixed wireless networks.

To further illustrate the relative strengths and weaknesses of fixed wireless technologies, this report presents an analysis of capital and operating costs for a candidate fixed wireless network as compared to a candidate fiber optic network in the same real-world settings. The candidate networks were each designed to deliver complete coverage to unserved residential locations.

The analysis of fixed wireless and fiber-to-the-premises network designs across four types of rural deployment scenarios identified the following key cost factors:

- Initial capital costs are higher for fiber than for fixed wireless network deployments; most of the capital cost for fiber relates to construction.

- Capital costs for fixed wireless deployments are dominated by the cost of customer premises equipment. Another large cost is construction of tower sites (where towers and buildings are not already available for antenna siting).

- Ongoing operational costs for fixed wireless are higher than for fiber—due largely to the need to regularly replace fixed wireless equipment. For a fixed wireless network, 40 to 80 percent of the capital investment needs to be replaced every five years. Only 1 to 10 percent of the capital cost of a fiber network is replaced every 10 years.[2] Financial sustainability of a fiber network is thus driven mostly by the network's upfront capital costs; in contrast, financial sustainability of a fixed wireless network that keeps up with the broadband needs of the households depends on the operator's ability to re-invest every five years.

[2] Assuming a 50-year lifetime of fiber plant.

While the cost analysis illustrates that fiber's upfront capital costs are higher than those of fixed wireless in many circumstances, the total cost of ownership over 30 years is comparable for fiber and fixed wireless (see Table 1 and Table 2).[3]

Table 1: Estimated total cost of ownership – fixed wireless (30 years, per passing)

Cost Element	Small Town		Medium Density Rural		Low Density Rural		Very Low Density Rural	
	Low	High	Low	High	Low	High	Low	High
Staff	$880	$3,000	$3,700	$13,100	$3,500	$12,200	$3,600	$12,700
Replacement	$3,300	$3,300	$7,100	$7,100	$10,700	$10,700	$15,300	$15,300
Maintenance	$1,100	$1,100	$5,400	$5,400	$7,200	$7,200	$11,100	$11,100
Leases	$1,100	$1,100	$5,100	$5,100	$7,100	$7,100	$11,100	$11,100
Wholesale internet	$1,000	$13,200	$1,000	$13,200	$1,000	$13,200	$1,000	$13,200
Construction	$465	$500	$1,520	$1,740	$2,030	$2,490	$3,090	$3,950
Total	**$7,845**	**$22,200**	**$23,820**	**$45,640**	**$31,530**	**$52,890**	**$45,190**	**$67,350**

Table 2: Estimated total cost of ownership – fiber-to-the-premises (30 years, per passing)

Cost Element	Small Town		Medium Density Rural		Low Density Rural		Very Low Density Rural	
	Low	High	Low	High	Low	High	Low	High
Staff	$1,500	$1,800	$3,900	$4,200	$3,600	$4,200	$3,900	$4,800
Replacement	$1,500	$4,800	$2,700	$8,700	$3,600	$13,500	$6,300	$24,900
Maintenance	$3,300	$3,900	$5,700	$6,900	$6,900	$9,000	$10,200	$14,400
Leases	$300	$300	$300	$300	$300	$300	$300	$300
Wholesale internet	$600	$6,300	$600	$6,300	$600	$6,300	$600	$6,300
Construction	$2,620	$8,550	$4,340	$15,310	$6,240	$23,210	$10,620	$42,370
Total	**$9,820**	**$25,660**	**$17,550**	**$41,720**	**$21,240**	**$56,500**	**$31,920**	**$93,070**

Given the above analysis, fiber offers the greater long-term value as compared to fixed wireless technologies because of fiber's long life, capabilities, scalability, and flexibility.[4] In the event that a state funds technologies other than fiber, such as in circumstances where the capital cost to build fiber is cost-prohibitive or the need for service cannot wait for fiber construction, the state should take steps to protect its investment—such as by requiring grantees to guarantee the long-term maintenance and operations of the fixed wireless network. This could be accomplished by requiring a 20-year performance and budget roadmap, and a viable strategy for full service where line-of-sight is a challenge.

[3] As the BEAD investment is meant not only to bring broadband to the unserved but to keep them served, it is warranted to compare the cost of operating both technologies over at least a 30-year period in assessing the value of the two approaches.

[4] While fiber networks have not yet existed for 50 years, a lifespan of at least that long is conservative based on the lifetime of copper infrastructure (which is less survivable) and the performance of fiber in a range of rugged conditions.

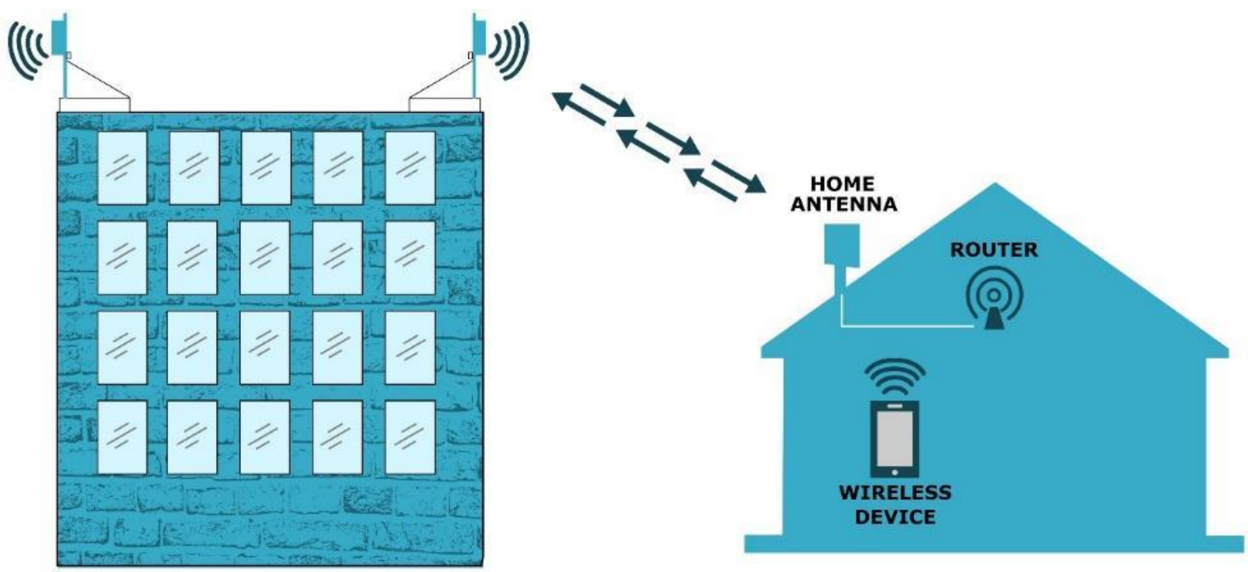
2 Introduction to fixed wireless technologies

Broadband service is delivered either through wireline technologies (such as fiber or coaxial cable) or wireless technologies—which can be grouped in three broad categories:

- Fixed wireless service delivered to homes, businesses, or institutions
- Mobile wireless service delivered to smartphones or other devices without a fixed location
- Satellite service delivered to homes, businesses, institutions, or mobile devices

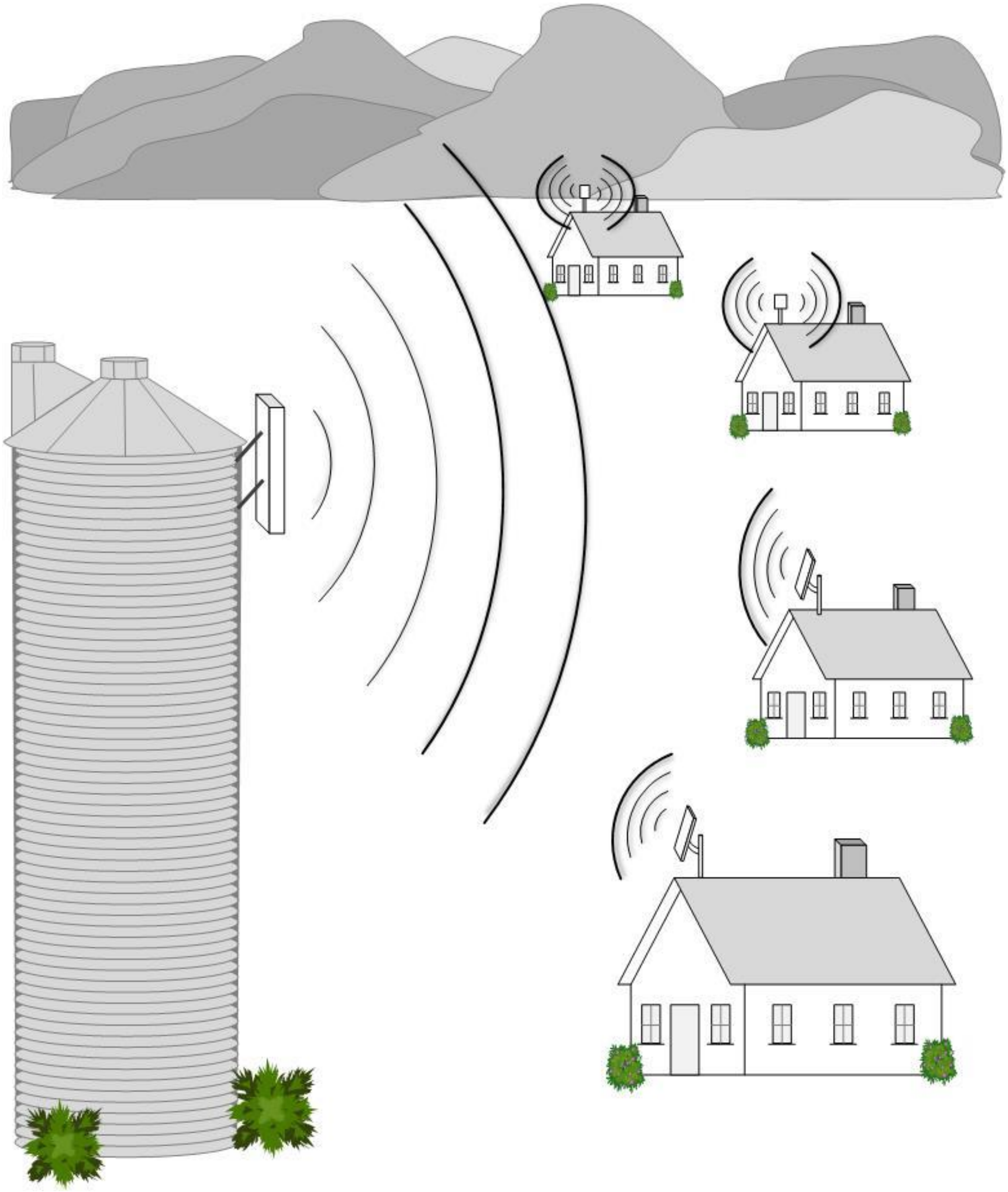
This report focuses on fixed wireless technologies, which deliver service via access point antennas at a base station (typically mounted on towers, masts, monopoles, or rooftops) to subscribers' antennas. Subscriber antennas (at a home or other building) can be located indoors or outdoors depending on the architecture of the network. Figure 1 shows a scenario where the base station antenna is on a rooftop and a subscriber's antenna is also placed on the roof.

Figure 1: Sample outdoor subscriber antenna configuration



A typical wireless internet service provider (WISP) network consists of a base station antenna site and dozens, sometimes hundreds, of users. A base station antenna site has three or four sectors, each covering a slice of the surrounding area and enabling the same wireless spectrum (see Section 2.2) to be re-used in each sector. The base station site is typically connected to the internet backbone via a combination of fiber and high-speed point-to-point wireless connections; it apportions capacity among the different users through various techniques (e.g., allocating different channels or portions of the spectrum, or allocating separate time slots for each user to transmit and receive). This topology—called point-to-multipoint—is illustrated in Figure 2.

Figure 2: Point-to-multipoint fixed wireless network



2.1 Network coverage and capacity

The concepts of coverage and capacity are critical to understanding fixed wireless network performance.

Coverage refers to the geographic area in which network users receive a signal that is strong enough to enable them to use their connected devices and applications. Anyone who has tried to join a Wi-Fi network at a coffee shop or another public location has likely seen a list of "available networks" pop up on their device; those are the networks that are providing coverage to that location—presented in rank order of the strength of the available signal. (A network may appear to be available to an end user, but the signal may not actually be strong enough to deliver high-quality, reliable service.)

Furthermore, it is not sufficient for the signal from the base station antenna to be merely receivable by the user's equipment. For two-way communications, the signal from the user's equipment (known as the uplink signal) must also be receivable at the base station.

At a high level, network coverage typically is determined by the network's technology and wireless spectrum (including the type and amount available, and the power allowed for that spectrum by the Federal Communications Commission). Network coverage is also affected by choices made by the network's designer, including the type of electronic equipment running the network and the number and configuration of access point antennas.

Within a network's coverage area, the quality of the fixed wireless signal, and therefore the service, depends on factors such as the distance between the access point antenna and the subscriber's antenna—as well as the amount of "clutter" between those two antennas. Clutter includes obstructions such as buildings, trees, and foliage. Weather events such as rain and fog can also impact the performance of a fixed wireless network. Due to these line-of-sight limitations, subscriber antennas mounted outdoors generally have better reception and transmission capabilities than antennas located indoors because the signal from the base station does not have to penetrate an outer wall or window.[5]

The **capacity** of a network is a measure of how much data can flow between the access point antenna and subscribers' antennas. A fixed wireless network's capacity is determined by the network's technology (i.e., a given technology is only capable of delivering a certain amount of capacity—like a pipe is capable of delivering a certain amount of water based on its diameter)

[5] Fixed wireless services delivered by cellular carriers (also known as mobile network operators, or MNOs) typically use hotspot-type indoor antennas that also function as routers to distribute the signal to nearby user devices; services provided by wireless internet service providers (WISP) may use either outdoor antennas attached to a router inside the house (as in Figure 1) or indoor hotspot-type devices.

and the network architecture (e.g., how many base station antennas have been installed—or, extending that analogy, how many pipes are available).

Because capacity is shared among all the users of a fixed wireless network, the speed of service available to an individual user also depends on the loading of the network—that is, how many other users are on the network at the same time. Thus, a fixed wireless network will only be capable of delivering a certain speed to a defined number of users; delivering that speed to more users would require expanding the network, such as by adding more access point antennas. Alternatively, adding more users would mean lower performance for all users.

2.2 Wireless spectrum

Broadband fixed wireless technologies are broadly organized by spectrum—each with its own coverage and capacity capabilities:

- Low-band and Mid-band licensed mobile cellular bands (600 MHz, 700 MHz, 850 MHz, 1900 MHz, 2100 MHz, 2300 MHz, 2500 MHz, 3700 MHz)
- Unlicensed fixed wireless bands (primarily 2.4 GHz and 5.8 GHz, including the recent extension up to 7.1 GHz)
- Educational Broadband Service (EBS) (2.5 GHz)
- Citizens Broadband Radio Service (CBRS) (3.5 GHz), licensed and unlicensed bands
- Millimeter wave (mmWave) (20 to 100 GHz), licensed and unlicensed bands

Mobile network operators (MNO) like AT&T, Dish, T-Mobile, and Verizon Wireless use licensed spectrum they have obtained through Federal Communications Commission (FCC) auctions, as well as EBS spectrum they lease from the license holders, and CBRS and unlicensed spectrum.

Wireless internet service providers (WISP)—which range in size from national and regional operators, such as Wisper, to localized, smaller providers—tend not to have licensed spectrum and therefore use the unlicensed bands and CBRS (as well as some EBS spectrum leased from the license holders) to deliver fixed wireless services.

The emerging mmWave networking technology is being used by WISPs and MNOs, primarily in urban and suburban areas where users are close together. WISPs using mmWave include Starry Internet and WeLink, which provide service in major cities and suburban areas. The City of San José is using mmWave to interconnect public Wi-Fi access points.[6] Increasingly, mmWave is also

[6] https://www.telecompetitor.com/city-of-san-jose-launches-downtown-public-wi-fi-network-with-gigabit-fixed-wireless-mesh/.

used as a backhaul wireless technology to connect antenna sites, and to serve multi-dwelling buildings (with service to the individual unit via Wi-Fi or in-building wiring).

Depending on the loading of the network and the technology type, as well as the age of the network, fixed wireless providers often can deliver a baseline performance of 25 Mbps downstream, 3 Mbps upstream (25/3—the FCC's current benchmark for broadband speeds) using LTE[7] technologies and 100/20 with 5G technologies that incorporate multiple-input multiple-output (MIMO) and higher order modulation (see Section 2.3 for more details). Gigabit speeds are possible with mmWave networks in urban and dense suburban areas but are not feasible over rural fixed wireless networks under typical conditions. (See Section 3 for details on fixed wireless network performance.)

2.2.1 Licensed mobile cellular bands

MNOs offer fixed wireless services in many areas—using the same spectrum and physical and electronic network as the carriers' mobile services. Rather than delivering cellular service to a user's smartphone, however, the carriers deliver a wireless signal to a hotspot-type device in the user's home (which perform the same role as a cable modem or router does for subscribers to wireline services). MNOs tend to limit the number of individuals who receive the fixed service in a given area to avoid reducing capacity for the mobile users that share the spectrum.

2.2.2 Unlicensed fixed wireless bands

Unlicensed communications bands have become central to broadband networking—most notably for Wi-Fi services. Unlicensed communications can be used by anyone with a device that complies with the FCC Part 15 power and spectrum rules. These rules enable anyone with a type-certified device (such as a Wi-Fi device) to use the spectrum, but they have to accept the interference and use of other users. The specific technologies using the band include Wi-Fi and Bluetooth, which are international standards.

The two most frequently used unlicensed bands are in the 2.4 GHz and 5 GHz range. As the 2.4 GHz band (the first band used in Wi-Fi) has become increasingly congested due to the proliferation of wireless home electronics devices, there is a great deal of interest in the 5 GHz bands, which are used in the second and later generations of Wi-Fi and other new wireless applications and services. There are multiple 5 GHz bands that together provide much more spectrum than the original 2.4 GHz band.

In early 2013, the FCC proposed rules governing the operation of Unlicensed National Information Infrastructure (U-NII) devices in the 5 GHz band. These U-NII devices include a wide

[7] Long-term evolution (LTE) is the 4G mobile technology standard. See: "LTE," 3GPP, https://www.3gpp.org/technologies/keywords-acronyms/98-lte.

array of high-data-rate mobile and fixed communications for institutions, businesses, and individuals.

In early 2014, the FCC made available an additional 100 MHz of unlicensed spectrum for high-speed, high-capacity Wi-Fi and other uses. The 2014 rules lifted the indoor use-only restriction and increased the permissible power output, which expanded the capabilities of 5 GHz equipment used for fixed wireless service, such as equipment used by WISPs and institutions such as governments or school districts providing broadband service within a few miles of a rooftop- or tower-mounted antenna.

As discussed in Section 2.3, range improvements are achieved with the use of beamforming enabled by multiple-input multiple-output (MIMO) technologies and the optional use of directional antennas, which focus the radiated energy more efficiently on the receiver devices.

In April 2020 the FCC allotted 1.2 GHz of spectrum from 5.925 – 7.125 GHz (i.e., 6 GHz spectrum) for unlicensed use. The new spectrum opened the door for improved fixed wireless technology that uses the new spectrum and incorporates other improvements, including a higher order of modulation (i.e., more bits per signal symbol), the use of up to 8x8 MIMO for upstream and downstream, which together translate to 7 Gbps capacity per sector, with peak subscriber speeds up to 1.7 Gbps (under ideal loading conditions), and the bonding of channels into a larger band.

Because of the higher frequency, the coverage area at 6 GHz is reduced in comparison with 5 GHz—and requires a more optimal line-of-sight between antennas.

2.2.3 Educational Broadband Service

Educational Broadband Service (EBS) is part of the 2.5 GHz band (which ranges from 2496 MHz to 2690 MHz). It was formerly licensed for educational-only purposes but is now available for commercial use. EBS was originally established as Instructional Television Fixed Service (ITFS). ITFS spectrum licenses were granted to educational institutions[8] to provide educational television over microwave. ITFS did not see large-scale adoption, however, and the FCC eventually relaxed the rules and allowed the educational entities to sublease the spectrum licenses to commercial entities with some provisions that required a minimum amount of educational content.

To spur the growth of 5G and broadband in rural areas, the FCC has relaxed the rules even further. In October 2019 the FCC eliminated the educational requirement and authorized EBS licenses to be opened for commercial use.[9]

[8] Originally only educational institutions, government, or nonprofit organizations could acquire licenses for educational purposes.

[9] https://www.federalregister.gov/documents/2019/10/25/2019-22511/transforming-the-25-ghz-band

The new band plan was developed with the intent of providing access to more entities to spur the growth of broadband and 5G initiatives. The plan, which incorporates existing EBS licensees, recognizes that the technology (including private 4G and 5G networks) is now more affordable, and the equipment more readily available.

Rural Tribal Nations were provided a priority window in 2020 to directly access unassigned EBS spectrum with a service area comprised of Tribal Land (as defined in Section 27.1204(b)(3) of the FCC Order). Because the FCC opted not to grant a priority window for organizations seeking spectrum for educational use, any eligible entity (including educational entities and commercial companies) will bid together in an upcoming FCC auction for the remaining EBS channel groups. This remaining spectrum will be sold in the FCC's auction 108, starting on July 29, 2022.[10]

Under the previous band plan, channel group licenses were issued for a 35-mile radius around a fixed point, called a Geographic Service Area (GSA).[11] Under the new band plan, the FCC will auction spectrum rights for an entire county (i.e., the new GSA), as opposed to a 35-mile range. This will be an overlay license: Although the winning bidder will obtain a license to spectrum for an entire county, there will effectively be a spatial and spectrum cut-out for incumbent license holders who will retain their license for existing GSAs and spectrum channel groups under the current assignments.

Historically, most existing EBS license holders leased their spectrum to private wireless carriers for use in cellular network deployment. As of 2019, there were 2,193 EBS licenses—2,046 of which were subject to long-term leases.[12] Sprint held most of these leases, but ownership transferred to T-Mobile as part of the 2018 acquisition. A recent analysis estimated that T-Mobile currently owns or controls about 85 percent of the 2.5 GHz band, of which about 45 percent is leased.[13]

In addition to establishing the new band plan, the FCC's 2019 rule change allowed incumbent EBS license holders to sell their licenses to commercial entities. Purchasers will enjoy the same incumbent protections as original license holders after the overlay auction takes place. T-Mobile has begun purchasing some of these leases, as have other commercial entities like the private investment firm WCO Spectrum, as well as smaller WISPs like SoniqWave, Mark Twain Communications, and AeroNet Wireless.[14]

[10] https://www.fcc.gov/auction/108
[11] https://www.nebsa.org/index.cfm/regulatory/ebs-spectrum-and-band-plan/
[12] Report and Order, Transforming the 2.5 GHz Band, 34 FCC Rcd 5446, ¶79 (2019).
[13] https://www.fiercewireless.com/5g/t-mobile-fights-hard-keep-its-25-ghz-leases-secret
[14] https://www.lightreading.com/5g/t-mobile-buys-some---but-not-all---of-its-25ghz-spectrum-licenses/d/d-id/776087

2.2.4 Citizens Broadband Radio Service (CBRS)

CBRS is a band of spectrum in the 3.5 GHz range that was authorized for both licensed and unlicensed use by the FCC in 2015. Ranging from 3550 MHz to 3700 MHz, CBRS provides spectrum to a broad audience of potential users. The diverse range of operators includes MNOs that augment their traditionally licensed spectrum; independent providers of fixed and mobile wireless service; and government and nonprofit entities and businesses and private individuals operating "private cellular service."

Access to the CBRS band is managed by a cloud-based dynamic frequency coordination system called a Spectrum Access System (SAS). Each channel spans 10 MHz. The FCC has divided access to the CBRS band into three tiers with different levels of interference protection: Incumbent Access, Priority Access Licenses (PAL), and General Authorized Access (GAA).

Point-to-multipoint 5G technology using CBRS spectrum provides an aggregate end-user throughput of about 800 Mbps downstream and 200 Mbps upstream using the full allotment of CBRS GAA spectrum (see Section 3.1), or the ability to provide dozens of users with 25/3 Mbps connectivity (i.e., the FCC's current benchmark standard for broadband service).[15]

2.2.4.1 Tier 1 – Incumbent Access

Tier 1 – Incumbent Access to the full CBRS band is granted to existing license holders, primarily U.S. Navy radar systems, and commercial fixed satellite stations.[16] Users in Tier 1 have the highest priority for their licensed frequencies. In practice, this means that the incumbent users, primarily in areas of naval operations, sometimes preempt use of channels by PAL and GAA users.

The SAS continuously monitors the channels and will prioritize a Tier 1 transmission over a Tier 2 or Tier 3 transmission on the Tier 1 incumbent's frequency.[17] For some military incumbent operations areas, exclusion zones are defined in which no CBRS operations over a specified frequency range are allowed at any time. The U.S. military operates radars that require protection from in-band interference that include the following:

1. Shipborne radars that operate both off the coast and within certain harbor areas that are protected from co-channel CBRS emissions in the 3550 – 3650 MHz band.

2. Land-based radars at specific locations that are protected from co-channel CBRS emissions in some or all of the 3550 – 3700 MHz band.

[15] Current broadband funding programs created by Congress in legislation such as the Infrastructure Investment and Jobs Act (IIJA) have effectively set 100/20 Mbps as the new standard for broadband speeds.

[16] Linda Hardesty, "What is CBRS?" *Fierce Wireless*, June 23, 2020, https://www.fiercewireless.com/private-wireless/what-cbrs (accessed May 11, 2022).

[17] Users who had been using this band before CBRS was created were supposed to have migrated to GAA in 2020.

These military operations are protected by the concept of Dynamic Protection Areas (DPA) and associated neighborhoods, or by exclusion zones. DPAs are defined areas, by the Department of Defense, in which these radar systems may operate and must be protected. In addition to its geographic area, each DPA includes a frequency range in which radar operation may occur. All points within the DPA must be protected from interference in the defined operation range, either by co-channel or out-of-bound (OOB) emissions. A grid of protection points within the DPA is defined, and in most cases, only a subset of the points is sufficient for the interference calculation depending on the geometry and nature of its location, such as open water.

In summary, these DPAs are always protected from any possible interference from the lower Tier 2 (PAL) and Tier 3 (GAA) users. If such interference is encountered, the SAS may initiate a temporary reduction in effective isotropic radiated power (EIRP) and/or channel re-allocation (bandwidth reduction) within the band for the applicable PAL or GAA users. Both the EIRP and channel re-allocation may result in a temporary link performance degradation affecting both downlink and uplink throughput.

2.2.4.2 Tier 2 – Priority Access channels

Tier 2 – Priority Access channels were auctioned in 2020 through competitive bidding.[18] PALs were granted for 10 MHz channels in the 3550 to 3650 MHz band in individual counties (as opposed to the 35-mile GSA that incumbents have) and must be renewed every 10 years. A total of 70 MHz, and thus seven PALs, are available in each county; however, no single licensee may operate more than 40 MHz (four PALs) in a single county. The SAS will prioritize a Tier 2 transmission over a Tier 3 transmission on the Tier 2 frequency licensed to that provider.

In metropolitan areas, the CBRS licensees are mostly the cable operator or mobile operators, or in some cases, the power company. Outside of metropolitan areas, they often include small ISPs, governments, or utilities. Operators with PAL licenses can expect priority access to spectrum over users of GAA spectrum.[19]

2.2.4.3 Tier 3 – General Authorized Access (GAA)

Tier 3 – General Authorized Access (GAA) allows open, unlicensed access to the full CBRS band. This spectrum is available for use by anyone using certified equipment and who has registered with the SAS. However, Tier 3 users have the lowest priority of the three Tiers and are granted access on a first-come, first-served basis.

As noted, the SAS coordinates use of the band, ensuring Tier 2 and Tier 3 users do not interfere with incumbents. The SAS is responsible for databasing spectrum users and prioritizing and granting access requests based on users' access Tiers and the spectrum load of a given area. The

[18] "Auction 105 – 3.5 GHz," FCC, https://auctiondata.fcc.gov/public/projects/auction105.
[19] A database of PAL auction award winners is available at https://www.ctcnet.us/analytics/us-cbrs/.

SAS is responsible for efficiently managing the user load to ensure access rules are enforced and interference is minimized.

In late January 2020, the FCC authorized full commercial deployment of OnGo[20] service in the 3.5 GHz CBRS band. This allows OnGo-certified antennas and devices to use the band as General Authorized Access (GAA) by unlicensed users. As PAL holders build out their networks, the SAS will give PAL licensees priority on the spectrum they have been allocated. In areas where all the PAL holders make use of their channels, GAA users will only be able to share 80 MHz of the band.

The SAS monitors the spectrum through the internet and provides a temporary license to that spectrum in its area to a user. This temporary license must be renewed at regular intervals. The SAS checks its national database and verifies the user's access priority (Tier). In an extremely congested situation where spectrum channels may not be available, the SAS will reduce or revoke access to existing users to accommodate a new request from a higher Tier user, with the Tier 1 users having the highest priority. Because the CBRS band is in the early days of use, there is no public record of congestion or spectrum availability—but anecdotal reports in both urban and rural areas indicate users have experienced limited access to GAA spectrum.

CBRS equipment is manufactured by a wide range of companies, including Airspan, Cambium, and Nokia. Most currently available CBRS equipment has a capacity of up to approximately 1 Gbps per sector using the full 80 MHz in the GAA band and is available in both fixed and mobile configurations. This total capacity does not reflect the data rate achieved at customer sites because the capacity is shared among concurrently active users.

5G CBRS equipment is becoming available, both in standards-based and proprietary form, improving on the 4G equipment with more spectrum efficiency (potentially a 1.5- to five-times improvement over 4G[21]). The use of multiple signal paths on MIMO technology and beamforming result in a substantial increase in available capacity relative to 4G. Equipment is manufactured by several companies including Nokia and Tarana. Improvements in CBRS technology are discussed in more detail in Section 2.3.

CBRS GAA spectrum currently is available in most of rural America according to Google Network Planner, which reads the CBRS Spectrum Access Service (SAS) (Figure 3). The spectrum is available in Taos County, N.M., which is the community selected as the basis for a candidate network design in Section 5 (see Figure 4). However, the availability of spectrum may change over a network's lifetime because of increased usage by fixed and mobile wireless providers, businesses, and nonprofit organizations.

[20] OnGo is a brand name that represents the networks and devices in the CBRS band.
[21] https://www.waveform.com/a/b/guides/5g-and-shannons-law

Figure 3: CBRS spectrum availability (continental U.S.)[22]

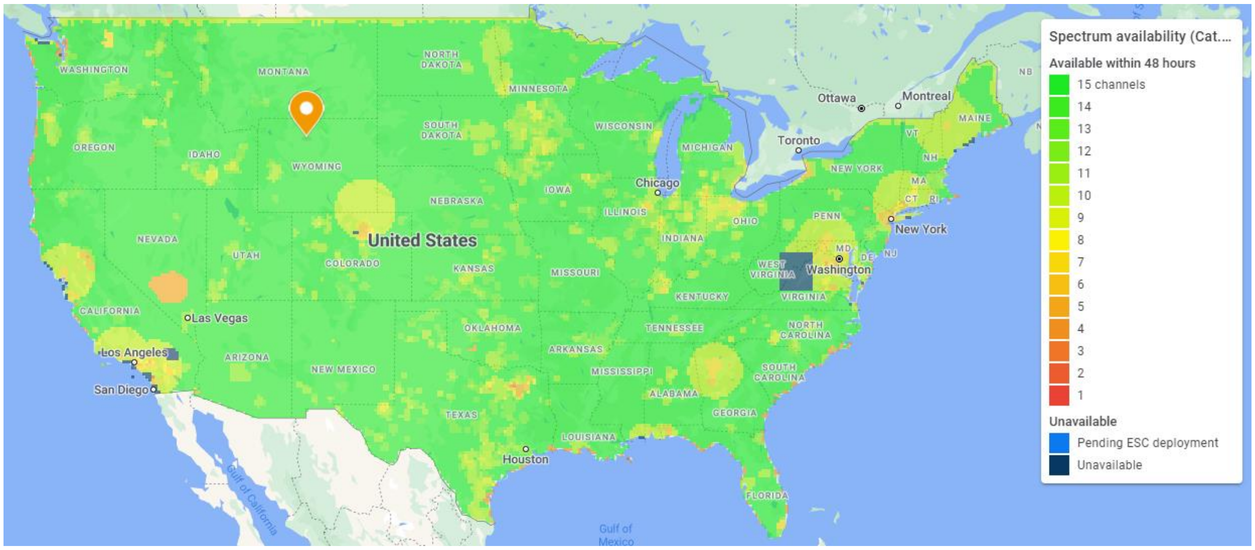
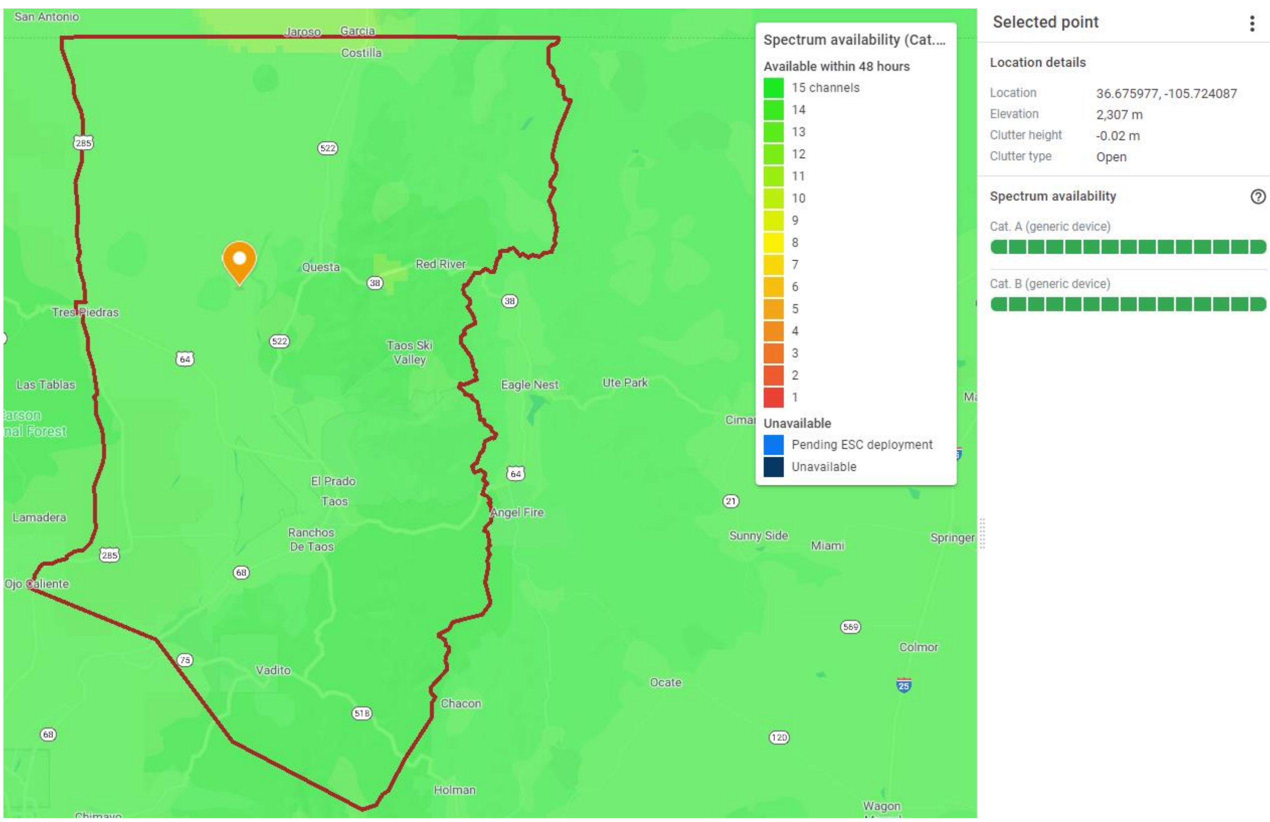


Figure 4: CBRS spectrum availability (Taos County, N.M.)[23]



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[22] Google Network Planner, https://wirelessconnectivity.google.com/networkplanner/welcome (accessed May 16, 2022).

[23] Google Network Planner.

2.2.5 Millimeter wave (mmWave)

Looking beyond the sub-6 GHz spectrum low-band and mid-band spectrum, high-frequency mmWave technologies expand the usable spectrum out to 100 GHz, multiplying the capacity for wireless signals by more than a factor of 10. mmWave spectrum is a mixture of licensed, unlicensed, and lightly licensed spectrum. Companies such as BridgeWave, Cambium, Ericsson, Nokia, Samsung, and Siklu are producing mmWave technology, including for the 28 GHz licensed band and the unlicensed/lightly licensed 60, 70, and 80 GHz bands.

Higher frequencies behave more like light beams than radio waves—meaning that higher-frequency transmissions travel in a narrow, straight line and require a direct line-of-sight, with few or no physical obstructions. Despite challenges in delivering a mobile service (when users are moving in and out of line-of-sight), higher-frequency spectrum offers certain benefits as compared to lower-frequency signals for delivering broadband. For example, many devices can use high-frequency spectrum in close proximity without interfering with each other. High-frequency signals have smaller wavelengths and therefore can be used with smaller radios. And, as is discussed below, technology advances using high-frequency signals offer new capacity and capabilities in wireless network design, as long as a line-of-sight can be obtained between the user and the network.

Millimeter wave technology can deliver high-speed service because of the large amount of spectrum available and the fact that the signal tends to be transmitted in a small beam instead of a large sector (which allows the spectrum to be reused many times in a physical area).

The 60 GHz band is an unlicensed mmWave band with a width of 14 GHz, several times the bandwidth of all cellular spectrum bands combined. There are proprietary versions of the technology and standards-based versions using 802.11 WiGig.

The technology is used in a point-to-multipoint mode, as well as in a mesh (for example, the Terragraph technology initiated by Facebook). The point-to-multipoint and mesh versions of mmWave deliver service in the hundreds of Mbps, with some networks able to reach a few Gbps in asymmetrical or symmetrical networking. There are also point-to-point versions, mostly using the 70 or 80 GHz bands, that can provide 10 Gbps links; these are used for backhaul and for service to multi-dwelling buildings or institutions.

Because mmWave does not have a long range (the 60 GHz band is limited to a few hundred feet in most cases), and does not penetrate walls or windows, the point-to-multipoint and mesh architectures used by mobile and fixed providers to deliver broadband internet service in urban and suburban areas are not viable options for serving rural areas—and will not be for the foreseeable future. Distance and line-of-sight requirements will remain obstacles to rural deployment.

2.3 New fixed wireless developments leading to higher performance

Ongoing hardware and software improvements continue to lead to faster fixed wireless network speeds and better performance. These include technologies such as MIMO and beamforming. Massive MIMO, for example, can increase sector-level capacity by up 10 times depending on the environment. Using a combination of massive MIMO, beamforming, and high-order modulation can increase the end user throughput of 5G technology in a lightly loaded network up to 1 Gbps—though performance in most environments is more likely in the few hundred Mbps range. These are significant improvements, but they still lag the speeds of 10 Gbps and beyond available with fiber-to-the-premises, and typically do not deliver the symmetrical performance that fiber-to-the-premises can provide.

2.3.1 Multiple-input multiple-output (MIMO)

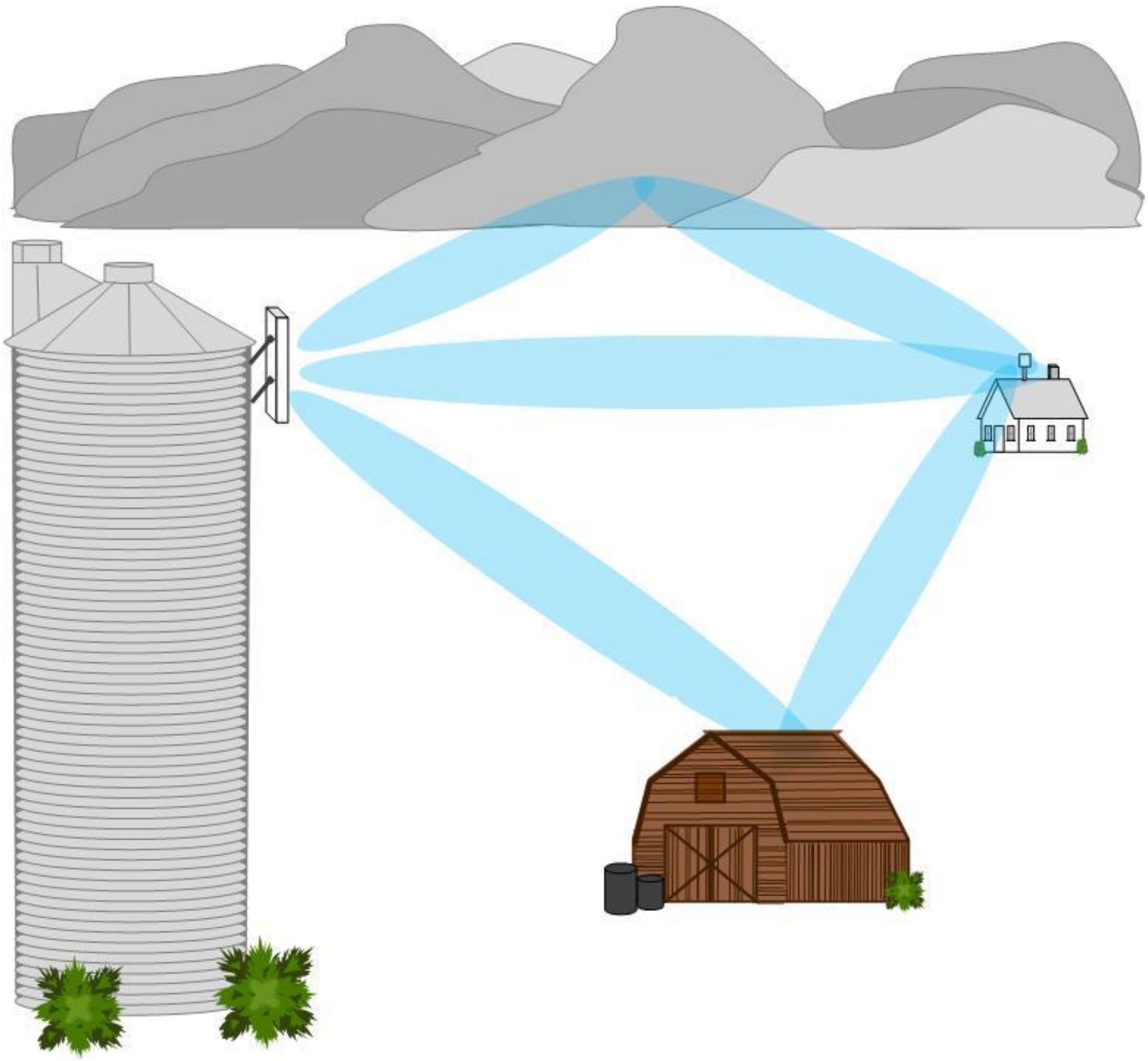
As more users are added to a fixed wireless network, each user has less available capacity and their connection speed decreases. MIMO offers an approach to increasing the capacity and overall performance of the network.

On a MIMO network, both the sector antenna in the base station and the user device have multiple internal antennas that allow for more robust reception and faster end user throughput. Multiple antennas enable communications over multiple signal paths at the same time, as each combination of antennas can have a separate signal over a separate path. These antennas can be described by the number of transmit and receiver ports. For example, a typical CBRS private LTE base station antenna with 4 transmit ports and 4 receive ports is described as a 4T4R antenna. So, a 64T64R[24] MIMO base station and a 4T4R UE configuration allows up to four separate paths to individual devices specially separated from each other, increasing capacity by up to a factor of four relative to traditional point-to-multipoint technology.

Single User (SU) MIMO (a sub-category of MIMO) greatly improves the quality of the signal connection in areas with challenging line-of-sight because signal paths can reflect off buildings or terrain. In this way, Single User MIMO can make it possible for a user to connect in situations where a traditional fixed wireless network could not work because of lack of line-of-sight. Figure 5 illustrates a Single User MIMO network with signals reflecting off a building and terrain.

[24] Antennas can be described by their number of transmit and receiver ports. For example, a typical CBRS private LTE base station antenna with four transmit ports and four receive ports is described as a 4T4R antenna. First-generation LTE UEs are 1T2R devices. The nomenclature "n" x "m" MIMO is a way to describe a single transmission path for a system based on the number of streams. N is the number of transmit streams. M is the number of receivers in the receiver chain. For example, from above, an LTE 4T4R base station transmitting to a 1T2R device would be described as 4x2 MIMO on the downlink and 1x4 MIMO on the uplink.

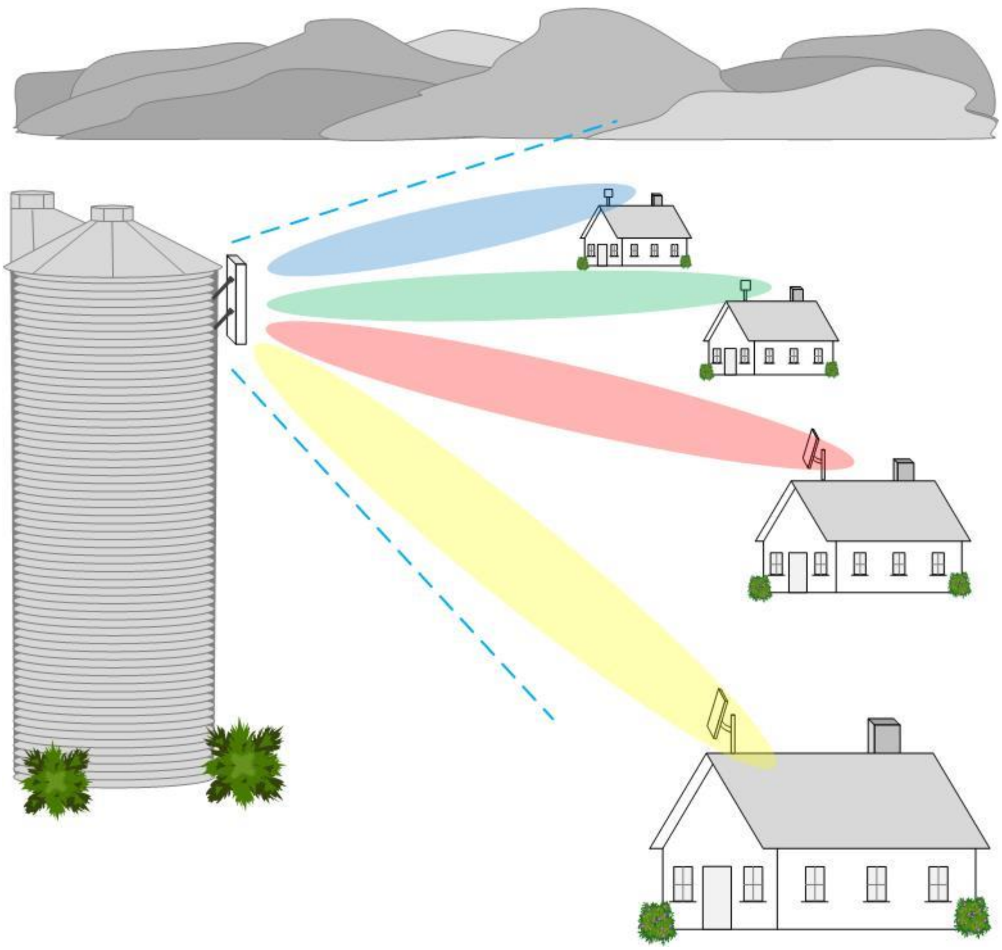
Figure 5: Point-to-multipoint fixed wireless network using SU-MIMO



2.3.2 Beamforming and multiuser MIMO

Another innovation is the use of beamforming and multiuser MIMO. Beamforming allows a beam to be narrowed by electronics in the base station antenna to focus on an individual user and minimize interference. Multiuser (MU) MIMO allows for multiple users to reuse the same system resources in different areas of the sector. With MU-MIMO and beamforming the network allocates separate beams from each sector, focused on individual users or small subsections of the service area (Figure 6). If a network uses beamforming, the spectrum at a site can be reallocated many times within a sector. Currently available 5G electronics operate with three or four separate beams per sector in rural environments, which effectively triple the capacity available to each user. As technology improves, there may be more beams per sector, and therefore more capacity per user.

Figure 6: Point-to-multipoint fixed wireless network using beamforming



2.3.3 Other innovations

Fixed wireless networking can continue to improve in performance by leveraging improvements in radio technology. For example, innovations in processing speed and the sensitivity of radios make it possible to use higher modulation schemes. These innovations increase the spectral efficiency of a network, allowing more capacity within a given amount of spectrum.

Similarly, adding processing and storage within the network electronics can allow devices to buffer streamed data or frequently accessed information and, in many cases, reduce the latency of communications—thus making the network less sensitive to congestion or interruption of data transmission.

From a network architecture standpoint, mesh capabilities can enable a network to connect users over multiple routes, making a network less dependent on individual lines of sight and individual antenna sites.

3 Current and potential future performance of fixed wireless and wireline technologies

This section establishes a baseline understanding of how much bandwidth typical users might need for reliable broadband service—then discusses the current and potential future capabilities of fixed wireless technologies to deliver those services. In the foreseeable future, many households may require more than 1 Gbps peak speed and require a greater degree of symmetrical service. They will also require latency less than 20 milliseconds to accommodate emerging interactive technologies such as Web 3.0 augmented and virtual reality applications.

The performance of wireline technologies, including fiber and cable, are presented for the sake of comparison. While wireless technologies continue to improve, fiber technologies provide greater capacity overall.

3.1 Current state of fixed wireless and wireline technologies

Table 3 summarizes the typical speeds available from fixed wireless technologies and, for the sake of comparison, cable, fiber-to-the-premises, and satellite. Figure 7 and Figure 8 (below) illustrate the comparisons. Because the maximum available speed depends on factors beyond just the technology, such as available spectrum, splitting and combining of the wireline network, loading of the network, and line-of-sight, the speeds are presented as ranges for each technology.

These factors also point to a larger consideration: While many fixed wireless technologies are technically capable of delivering high speeds to end users, the actual quality of an end user's service (e.g., speed, reliability) will depend on the network's architecture and external factors.

To be clear, the speeds in Table 3 reflect coverage and capacity needs similar to the coverage and capacity models in Section 5 in which the provider is bringing broadband to an unserved area and is required to serve any person in the area that wants to be connected. Therefore, service delivery is a challenging scenario that includes addressing line-of-sight and loading. The anticipated speeds per user are therefore different from an idealized scenario or a lab.

Most critically, Table 3 indicates that fiber-to-the-premises technologies consistently provide high speeds relative to the other options. (Section 4 discusses in more detail how fiber has the advantage through physics of being more scalable than other wireline technologies and wireless technologies—and does not have the disadvantage of requiring line-of-sight.)

Table 3: Typical speeds and applications for fixed wireless and fiber-to-the-premises technologies

Technology	Typical Speed Ranges per User		Round-trip Latency (ms)	Topology	Example Manufacturers
	Download (Mbps)	Upload (Mbps)			
Unlicensed fixed wireless	5 – 700	1 – 200	<100	Point-to-multipoint	Airspan, Cambium, Ubiquiti, Tarana
CBRS 4G	1 – 100	256 Kbps – 20 Mbps	<100	Point-to-multipoint	Airspan, Ericsson, Nokia
CBRS 5G	1 – 800	256 Kbps – 200 Mbps	<100	Point-to-multipoint	Nokia, Sierra Wireless
mmWave mesh	10 – 1,000	2 – 1,000	< 10	Mesh	ADTRAN, Cambium, Siklu
Cable	50 – 1,200	1 – 50	20	Tree with ring backbone	Commscope, Vecima, Cisco, ATX, Teleste
Fiber-to-the-premises	300 – 9,000*	50 – 9,000*	10	Tree with ring backbone	Calix, Adtran, Nokia, Commscope, Sumitomo
Low-Earth orbit (LEO) satellite	100	20	40	Point-to-multipoint	Starlink

*For PON using XGS-PON technology. 100 Gbps symmetrical speed is available in point-to-point Ethernet technology.

Wireless networks in general do not provide the speeds of fiber-to-the-premises or of cable. Wireless networks can in some instances support 1,000 Mbps service (i.e., mmWave), but the high end of the range would require good line-of-sight and low interference, which in general means short distances and light loading. Generally, the speeds will be lower in a scenario resembling those in the network described in Section 5.

The 4G or equivalent fixed wireless networks of the past few years can provide up to about 100 Mbps (download) if lightly loaded, but substantially less if loaded or with suboptimal line-of-sight.

Emerging 5G fixed wireless (in the 6 GHz or spectrum or lower) uses improved electronics, MIMO, and beamforming (as described in more detail in Section 2.3.2) to push maximum speeds toward 1 Gbps downstream, with loading and line-of-sight reducing the maximum more toward 100 Mbps in most situations. Upstream speeds for both 4G and 5G depend on how the operator assigns spectrum in the network, but usually they are about one-fourth the downstream speeds.

Millimeter wave technologies can exceed 1 Gbps and even reach 10 Gbps but, as discussed in Section 2.2.5, are limited in range to hundreds of feet and thus suited to an urban or suburban environment. Also, the speed is further reduced if the network is in a mesh configuration, where the bandwidth and antennas are shared between the backbone mesh and the communications with the users.

Cable broadband technologies can also provide gigabit speeds, as long as the cable plant is designed with fiber deep into the network and the coaxial segment of the network is not heavily loaded. If the fiber deployment is less deep, cable technology requires more signal amplifiers, which in turn reduces both the signal-to-noise ratio and the maximum available speed. Unlike fiber-to-the-premises, the standard DOCSIS 3.1 technology used by cable operators has substantially lower upstream speeds because of the conventional spectrum assignment within the coaxial portion of the network. Furthermore, in classic hybrid fiber-coaxial cable network designs, the number of customers that share the available bandwidth ranges between 125 to 500 or more users, whereas in PON architectures a maximum of 128 users share the full access network capacity. Future cable networks may address this limitation with upgrades of the cable plant and the electronics.

Fiber-to-the-premises technology provides the highest speeds, with the gigabit passive optical networks (GPON) of the previous decade able to provide symmetrical gigabit service (i.e., 1,000 Mbps download and upload) under typical loading conditions. PON technology relies on splitters in cabinets in the system to aggregate connections from multiple premises (usually 32 or 64) to a single fiber. Next-generation PON technologies can deliver symmetrical 10 Gbps service. Fiber-to-the-premises configured using direct Ethernet technology can provide 40 Gbps and 100 Gbps connections with off-the-shelf equipment. More costly off-the-shelf enterprise-grade equipment can provide thousands of Gbps (Tbps) speeds.

Geostationary satellites, which share capacity among users in a large area, have download speeds less than 20 Mbps and upload speeds of a few Mbps. GEO satellites provide a latency of 250 to 400 milliseconds.[25]

Low earth orbit (LEO) satellites share capacity among users in a smaller area and can provide faster service, up to about 100 Mbps downstream and about 20 Mbps upstream.[26] LEO satellites provide a latency of approximately 40 milliseconds.[27]

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[25] Y. Zhang, D. DeLucia, B. Ryu, S.K. Dao, "Satellite Communications in the Global Internet: Issues, Pitfalls, and Potential," Internet Society, https://web.archive.org/web/20160103125227/https://www.isoc.org/inet97/proceedings/F5/F5_1.HTM#:~:text=For%20GEO%20satellite%20communications%20systems,as%20high%20as%20400%20milliseconds (accessed May 19, 2022).

[26] "Elon Musk's Starlink Is Quietly Expanding, But Speeds Are Getting Worse," *Forbes*, Dec. 23, 2021, https://www.forbes.com/sites/ajdellinger/2021/12/23/elon-musks-starlink-is-quietly-expanding-but-speeds-are-getting-worse/?sh=5a18cc512419 (accessed May 19, 2022).

[27] J. Fomon, "Starlink Hits 100+ Mbps Download Speed in 15 Countries During Q4 2021," Ookla, March 16, 2022, https://www.ookla.com/articles/starlink-hughesnet-viasat-performance-q4-2021#:~:text=Starlink's%2014.84%20Mbps%20median%20upload,for%20all%20fixed%20broadband%20combined (accessed May 19, 2022).

Latency is typically longer on fixed wireless networks than on wireline networks, for reasons including the protocols used to share bandwidth among multiple users over the air. Latency numbers vary also by provider and technology. T-Mobile expects latencies between 30 milliseconds and 40 milliseconds on its mobile network and the fixed wireless service it delivers on that network, while Verizon claims sub-30-millisecond latency on its 28 GHz fixed wireless service architecture.

For cable broadband networks, a typical residential service has latency in the 20-millisecond range. On fiber-to-the-premises networks, a typical residential service provides roundtrip latency in the 10-millisecond range.

Figure 7: Typical download speeds of fixed wireless and wireline technologies

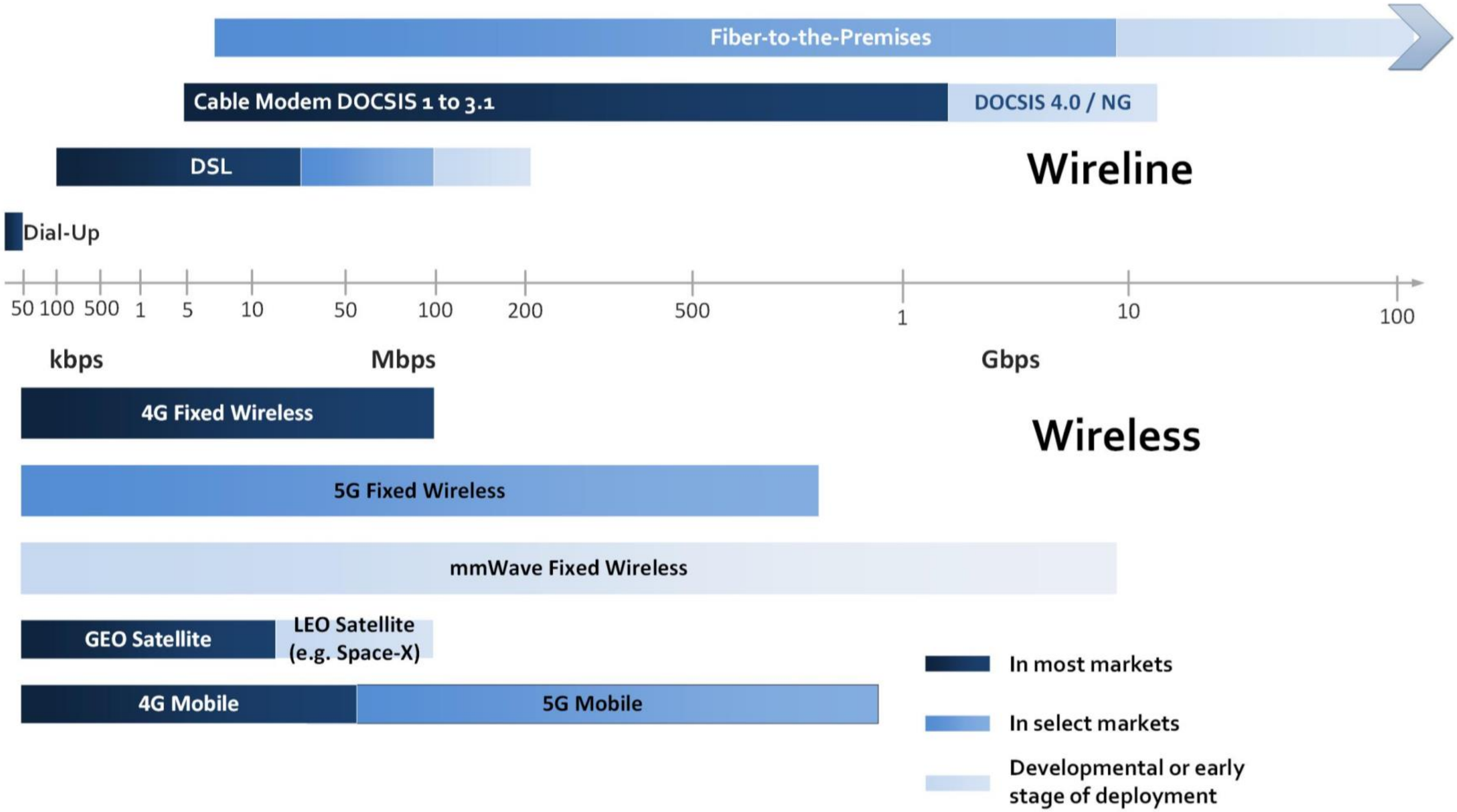
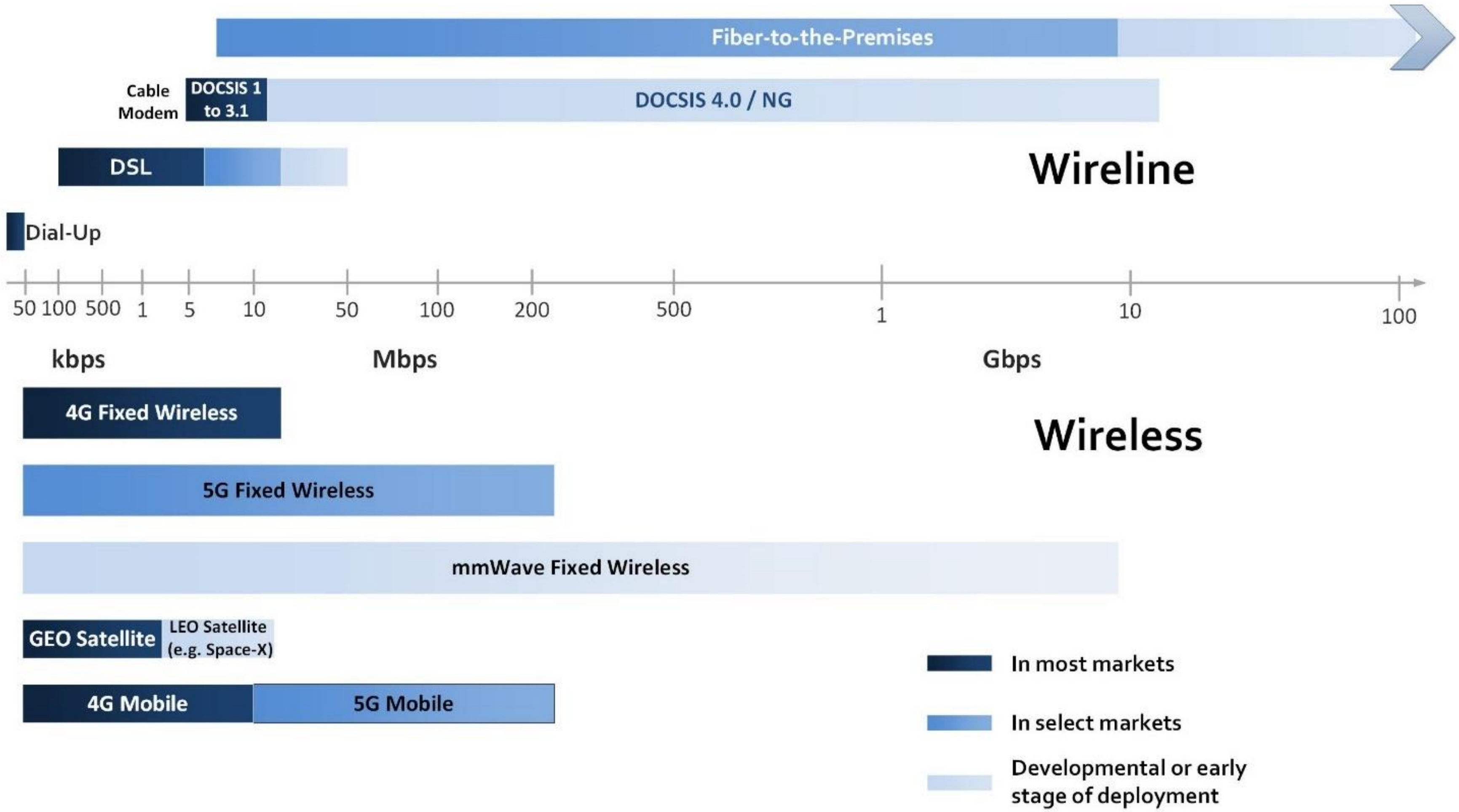


Figure 8: Typical upload speeds of fixed wireless and wireline technologies



3.2 How much bandwidth do subscribers really need?

To frame the analysis of the performance of fixed wireless technologies, it is important to understand potential use cases—specifically, how much bandwidth each subscriber might need. While the FCC's standard is 25/3, new federal broadband funding programs have essentially increased that benchmark to 100/20[28]—and even that level may be insufficient for many users. For example, capacity needs will increase sharply as Web 3.0 applications such as virtual reality enter common use.[29]

To set a baseline for this analysis, consider a hypothetical family of four. If two children are attending school classes using Zoom and two adults are using their broadband connections to attend occasional meetings, send e-mail, and do research, the combined required bandwidth could easily exceed the FCC's minimums (see Figure 9).[30] Those minimum speeds might be workable if internet usage were mainly in the form of internet browsing, email, and even streaming movies (i.e., primarily downloads). But video conferencing, telemedicine, and other essential applications demand high bandwidth in the upload direction as well. Even the FCC's next tier of service—50/5, which the FCC calls "baseline"—would be straining to supply the needed bandwidth.[31] And bandwidth needs are constantly increasing, so the baseline today will be inadequate tomorrow.

[28] See, for example: "Notice of Funding Opportunity: Broadband Equity, Access, and Deployment Program," National Telecommunications and Information Administration (NTIA), U.S. Department of Commerce, May 2022, https://broadbandusa.ntia.doc.gov/sites/default/files/2022-05/BEAD%20NOFO.pdf.

[29] S. Mangiante, G. Klas, A. Navon, G. Zhuang, J. Ran, M. Silva, "VR is on the Edge: How to Deliver 360° Videos in Mobile Network," Proceedings of VR/AR Network, August 2017, https://www.researchgate.net/publication/319049968_VR_is_on_the_Edge_How_to_Deliver_360_Videos_in_Mobile_Networks (accessed May 12, 2022).

[30] https://www.fcc.gov/consumers/guides/broadband-speed-guide?contrast=

[31] https://www.federalregister.gov/documents/2020/03/10/2020-03135/rural-digital-opportunity-fund-connect-america-fund

Figure 9: Peak bandwidth utilization for a family of four

	PEAK BANDWIDTH UTILIZATION TYPICAL FAMILY OF FOUR (DAYTIME)	TOTAL DOWNLOAD / UPLOAD
x2	Telework / telehealth video conferencing (4 Mbps / 4 Mbps per user)	8 Mbps / 8 Mbps
x2	Distance learning remote classroom (4 Mbps / 4 Mbps per user)	8 Mbps / 8 Mbps
x1	HD streaming video applications (Netflix, Disney+, etc.) (5 Mbps / 0.2 Mbps per stream)	5 Mbps / 0.2 Mbps
x1	Home security (Ring, etc.) and other household smart devices (Alexa, Google Nest, etc.) (2 Mbps / 2 Mbps per home)	2 Mbps / 2 Mbps
	TOTAL BANDWIDTH USE (rounded)	**23 Mbps / 18 Mbps**

	PEAK BANDWIDTH UTILIZATION TYPICAL FAMILY OF FOUR (EVENING)	TOTAL DOWNLOAD / UPLOAD
x1	Online video gaming (3 Mbps / 0.5 Mbps per user)	3 Mbps / 0.5 Mbps
x2	Streaming video applications (1 UHD at 25 Mbps / 0.2 Mbps, 1 HD at 5 Mbps / 0.2 Mbps per stream)	30 Mbps / 0.4 Mbps
x3	Surfing internet (1.3 Mbps / 0.3 Mbps per user)	4 Mbps / 1.0 Mbps
x1	Home security (Ring, etc.) and other household smart devices (Alexa, Google Nest, etc.) (2 Mbps / 2 Mbps per home)	2 Mbps / 2 Mbps
	TOTAL BANDWIDTH USE (rounded)	**39 Mbps / 4 Mbps**

And while a family of four in this example might require 39 Mbps downstream and 3.9 Mbps upstream during peak evening usage, this represents a modest set of assumptions that likely underestimate real-world bandwidth needs. Bandwidth demands are much more symmetrical in the upstream and downstream directions than many broadband technologies deployed today assume, with interactive video, uploading of security camera video, and cloud-based file sharing driving upstream bandwidth demands.

As an example of higher peak bandwidth needs that exist today, consider a multi-generational family with 11 people living in the same house. While not everyone in this household is a frequent user of broadband devices, it is not uncommon for as many as seven members of the family to be using bandwidth simultaneously for activities such as schoolwork, online gaming, streaming video applications, or browsing the internet. This family would require at least 51 Mbps downstream and 8.6 Mbps upstream during peak evening usage (Figure 10).

In another example, a resident who runs a business from their home needs to use their broadband connection to process financial transactions through e-commerce applications (Square, etc.), conduct occasional video meetings with customers, transfer files to online cloud storage providers, and send e-mail. This subscriber's spouse is working from home and at least two children are also at home (and require additional bandwidth for homework and entertainment needs). During peak times the family would need at least 29 Mbps downstream and 24.2 Mbps upstream (Figure 10).

Figure 10: Peak bandwidth utilization for a home business and large family

	PEAK BANDWIDTH UTILIZATION HOME BUISNESS (DAYTIME)	TOTAL DOWNLOAD / UPLOAD
x1	Home business operations (10 Mbps / 10 Mbps per user)	10 Mbps / 10 Mbps
x1	Telework / telehealth video conferencing (4 Mbps / 4 Mbps per user)	4 Mbps / 4 Mbps
x1	HD streaming video applications (Netflix, Disney+, etc.) (5 Mbps / 0.2 Mbps per stream)	5 Mbps / 0.2 Mbps
x2	Distance learning remote classroom (4 Mbps / 4 Mbps per user)	8 Mbps / 8 Mbps
x1	Home security (Ring, etc.) and other household smart devices (Alexa, Google Nest, etc.) (2 Mbps / 2 Mbps per home)	2 Mbps / 2 Mbps
	TOTAL BANDWIDTH USE (rounded)	**29 Mbps / 24 Mbps**

	PEAK BANDWIDTH UTILIZATION MULTI-GENERATIONAL FAMILY OF ELEVEN (EVENING)	TOTAL DOWNLOAD / UPLOAD
x2	Online video gaming (3 Mbps / 0.5 Mbps per user)	6 Mbps / 1 Mbps
x3	Streaming video applications (1 UHD at 25 Mbps / 0.2 Mbps, 2 HD at 5 Mbps / 0.2 Mbps per stream)	35 Mbps / 0.6 Mbps
x3	Surfing internet (1.3 Mbps / 0.3 Mbps per user)	4 Mbps / 1 Mbps
x1	Video chat (Zoom, etc.) (4 Mbps / 4 Mbps per user)	4 Mbps / 4 Mbps
x1	Home security (Ring, etc.) and other household smart devices (Alexa, Google Nest, etc.) (2 Mbps / 2 Mbps per home)	2 Mbps / 2 Mbps
	TOTAL BANDWIDTH USE (rounded)	**51 Mbps / 9 Mbps**

Networks should not be designed for today's needs but rather to anticipate future needs. If a network has barely enough capacity for current use, it will fall far behind in five or 10 years as applications and services become more data intensive. As an indicator of the upward trendline in bandwidth needs, consider the FCC's shifting definition of broadband—from 0.2 Mbps in 1996 to 4/1 Mbps in 2010 to 25/3 Mbps in 2015[32]—and the 100/20 Mbps minimum for infrastructure funded by new federal broadband programs.

The capacity of earlier networks appeared to many to be sufficient in their early years, and it was difficult to envision why the average household would need more. Users of those earlier networks viewed static websites with words and some pictures on a single computer—but internet applications evolved to include voice and graphics and games, then multiple connected laptops and smartphones, audio streaming, video streaming, two-way video, interactive gaming, and home automation. Furthermore, these technologies are no longer optional, but rather are necessary to work, learn, vote, and obtain care.

[32] "2015 Broadband Progress Report," FCC, Feb. 4, 2015, https://www.fcc.gov/reports-research/reports/broadband-progress-reports/2015-broadband-progress-report.

3.3 How do future needs drive the requirement for capacity and latency?

It is difficult to predict how data needs will change. One approach is to consider Web 3.0 technologies, such as augmented reality (AR) and virtual reality (VR). Early versions of these applications are the Oculus headsets and software, which provide 360-degree video and audio and haptic signals. Augmented reality is used for training and therapy as well as games.

As with video, the requirements of a given network depend on the quality and resolution needed. (Indeed, hardware and software developers design their systems to reduce the dependence on users' networks.) One analysis that considered the capacity and latency requirements of AR/VR estimated a range from 25 Mbps (for low-resolution video) to 2.5 Gbps (for interactive 4K).[33] Considering the use of mid-range HD video, the requirement is 400 Mbps symmetrical capacity for a single session, and 20-millisecond roundtrip latency.

The latency requirement for that application is strikingly lower than that put forward by the fixed wireless industry, which claims that 100-millisecond latency is sufficient (and cites to the ConnectAmerica standards from 2013 as justification).[34] While this level of capacity in theory will "work" for Zoom and streaming video and less intensive interactive gaming, it is important to note that higher latency has other impacts beyond just the delays in the applications—and as a result, 100 milliseconds may lead to sharply reduced bandwidth relative to latency of 10 milliseconds. Therefore the 20-millisecond latency target is crucial, both for future applications and for the health of the network.[35]

Revisiting the above analysis in light of this application, it is logical that a home or home business five to 10 years in the future will include many additional enhancements, such as more intensive telework and learning applications and standard use of 4K television (Figure 9). It would also include AR/VR, with one session in smaller households and perhaps three in a large one. *Taken*

[33] S. Mangiante, G. Klas, A. Navon, G. Zhuang, J. Ran, M. Silva, "VR is on the Edge: How to Deliver 360° Videos in Mobile Network," Proceedings of VR/AR Network, August 2017, https://www.researchgate.net/publication/319049968_VR_is_on_the_Edge_How_to_Deliver_360_Videos_in_Mobile_Networks (accessed May 12, 2022).

[34] "Comments of the Wireless Internet Service Providers Association Before the Department of Commerce, National Telecommunications and Information Administration Infrastructure Investment and Jobs Act Implementation Docket No. 220105-0002 RIN 0660-ZA33, p. 21, citing to Connect America Fund, WC Docket No. 10-90, Report and Order, 28 FCC Rcd 15060, 15071-72 (WCB 2013).

[35] Consider that on the internet, most applications rely on the network retransmitting any errors in transmission, using the transmission control protocol (TCP). Under normal circumstances, retransmission is infrequent, but it becomes more frequent in high noise and high interference conditions that exist with a challenging line-of-sight. If a link has both high retransmission and high latency, the two effects combine to sharply reduce the network speed. Slides 5 and 6 of this presentation (https://netcraftsmen.com/wp-content/uploads/2014/12/20120410_Impact-of-packet-loss.pdf) illustrate the impact of the Mathis Equation, in this case, on a 1 Gbps fiber link with different latency (Round Trip Time RTT). While the problem can be addressed with increased buffering in the network and on the devices, the network of the future will be far more demanding than this simulation, and low latency will be key to transporting any network traffic.

together, these more intensive applications would increase the typical peak capacity use range in a small household from the current 20 to 30 Mbps up to 500 Mbps—and up to 1.3 Gbps in a large household—with latency of 20 milliseconds or less. Furthermore, the capacity use would be almost symmetrical.

Figure 11: Future estimated peak bandwidth utilization for a family of four and a large family

	FUTURE PEAK BANDWIDTH UTILIZATION TELEWORK/TELELEARNING (DAYTIME)	TOTAL DOWNLOAD / UPLOAD
x1	Home business operations (20 Mbps / 20 Mbps per user)	20 Mbps / 20 Mbps
x1	Telework / telehealth video conferencing (6 Mbps / 6 Mbps per user)	6 Mbps / 6 Mbps
x1	UHD streaming video applications (25 Mbps / 0.2 Mbps per stream)	25 Mbps / 0.2 Mbps
x2	Distance learning remote classroom (6 Mbps / 6 Mbps per user)	12 Mbps / 12 Mbps
x1	Home security (Ring, etc.) and other household smart devices (Alexa, Google Nest, etc.) (4 Mbps / 4 Mbps per home)	4 Mbps / 4 Mbps
X 1	Augmented/virtual reality HD advanced level (400 Mbps / 400 Mbps per user)	400 Mbps / 400 Mbps
	TOTAL BANDWIDTH USE (rounded)	**467 Mbps / 442 Mbps**

	FUTURE PEAK BANDWIDTH UTILIZATION MULTI-GENERATIONAL FAMILY OF ELEVEN (EVENING)	TOTAL DOWNLOAD / UPLOAD
x2	Online video gaming (4 Mbps / 2 Mbps per user)	8 Mbps / 4 Mbps
x3	UHD streaming video applications (25 Mbps / 0.2 Mbps per user)	75 Mbps / 0.6 Mbps
x3	Surfing internet (2 Mbps / 0.7 Mbps per user)	6 Mbps / 2 Mbps
x1	Video chat (Zoom, etc.) (6 Mbps / 6 Mbps per user)	6 Mbps / 6 Mbps
x1	Home security (Ring, etc.) and other household smart devices (Alexa, Google Nest, etc.) (4 Mbps / 4 Mbps per home)	4 Mbps / 4 Mbps
X 3	Augmented/virtual reality HD advanced level (1200 Mbps / 1200 Mbps per user)	1,200 Mbps / 1,200 Mbps
	TOTAL BANDWIDTH USE (rounded)	**1,299 Mbps / 1,217 Mbps**

If the network is a fiber network, there are many ways to upgrade speed without uprooting the fundamental infrastructure, including upgrading the electronics at the home and the central office, and modifying the configuration of fiber in the cabinets. However, in a rural wireless network, the upgrade is more challenging, requiring replacement of the site and home antennas that make up most of the cost of the network, plus adding antenna sites to "densify" the network—usually at locations requiring new siting.

4 Challenges in deploying fixed wireless to deliver broadband service in rural areas

In order to maintain and operate a network and to keep up with the demands of users, network operators need to have a toolkit of engineering and deployment techniques as well as a roadmap of the future. Designers and operators of wireless networks often face a higher level of complexity than designers of wireline networks. While wireline networks, once built, have a predictable physical connection, designing a fixed wireless network—particularly one intended to serve a large area—requires making assumptions and allowances for many unknown and uncontrollable parameters such as line-of-sight requirements between antennas, spectrum availability, and weather (i.e., reducing signal quality and alignment of antennas). Some of these challenges, such as the need to "densify" antenna deployments to achieve capacity or line-of-sight requirements, have significant cost implications. So, too, does the need to regularly upgrade antennas and electronics.

In general, fixed wireless networks in rural areas need mid-band and low-band spectrum (i.e., 6 GHz and less). Also, many networks will be built by providers that have not obtained licensed spectrum. Those providers will be using the unlicensed and CBRS GAA bands, which can provide acceptable service but must be shared with any other provider or user and may vary in their availability.

The sections below identify and discuss some of the technical challenges of deploying fixed wireless technologies to deliver broadband services to unserved areas:

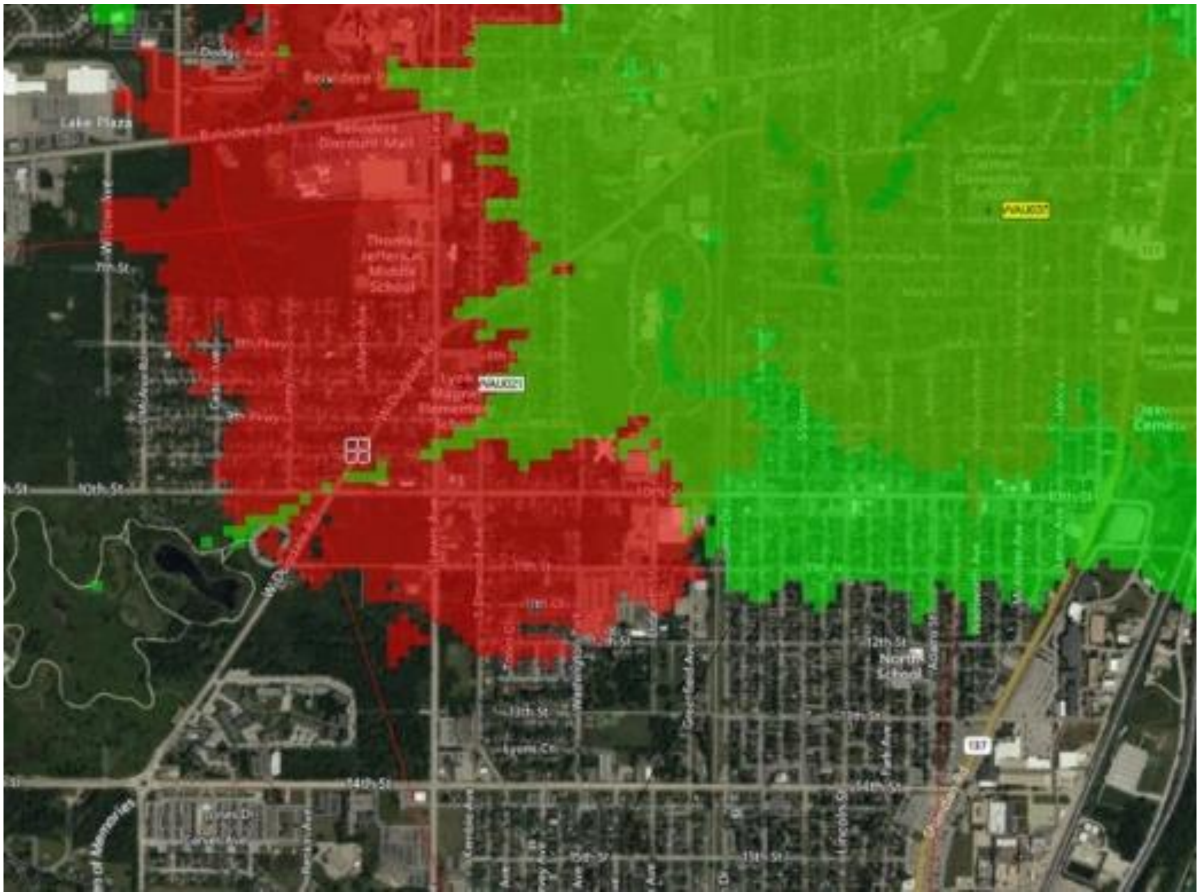
- Addressing line-of-sight to all unserved addresses, taking into account terrain and foliage
- Replacing base station and customer equipment as equipment breaks or becomes obsolete
- Adding sites to increase capacity to addresses

4.1 Line-of-sight

While most fixed wireless technologies using spectrum below 6 GHz technologies do not require perfect line-of-sight, they are significantly affected by terrain and obstructions and often will not work when terrain or significant foliage are in the way. Figure 12 illustrates how wireless signals are affected by obstructions and terrain, and how some addresses will be in "shadow" in almost any type of antenna siting.

Locations in the green area receive acceptable performance. The addresses in the red areas receive deteriorated performance because trees block the signals. Further, the green areas do not end smoothly; they have rough fingers delineating what the wireless industry refers to as the "cell edge." The fingers receive service because of favorable terrain. Sometimes the service area will have green "islands" where the addresses have a clear view of the base station, perhaps because they sit on a hilltop, while the surrounding areas cannot be served from the same base station.

Figure 12: Illustration of obstructed fixed wireless signal propagation



A wireless provider that is required to serve all residents in a given area because of the terms of a broadband grant will need to take seriously the effect of line-of-sight and have strategies to get service to everyone. There are many approaches that can help fill gaps, some of which are more systematic and resilient than others, though there is often a tradeoff between the robustness of an approach and its cost. For example, one rural provider in the mid-Atlantic region asserted that anyone could receive service, as long as the provider could install a 60-foot wooden pole on their property.

A more customer-friendly strategy may be to set up base stations or intermediate relay points on the property of other customers. In this case, a provider may contract with a customer, perhaps by providing discounted or free service, for placement of an access point on their property to reach other customers, in a long-term arrangement including access and power. It is important, however, that the installation be sufficiently robust to provide the needed quality of service.

If relay points are designed in an ad-hoc way, they can create unreliable connections. Figure 13 illustrates an antenna a WISP installed on a customer's lawn as a relay point; the antenna is vulnerable to impact from a lawn mower. Figure 14 illustrates signal reflectors on trees. Better approaches would be to place the infrastructure on a secure part of a building, with wiring and power done according to code.

Figure 13: Ad-hoc antenna installed by a WISP

Figure 14: Reflectors installed on trees

4.2 Replacing base station and customer equipment

The evolution of fixed wireless technologies implies that the performance of wireless networks likely will continue to improve over time. However, it is important to note that each significant improvement requires a replacement of the site antennas and the devices at the home or business. Moreover, this replacement is on average every five years—when the equipment wears out, when the manufacturer declares the model is "end-of-life" and hence not eligible for warranty repairs and software upgrades, and when the customers require more speed.

This spending cycle is in contrast to a fiber network. A similarity with the fiber network is that the fixed infrastructure—for wireless, the towers and mounts, and for fiber, the conduit, cables, and pole attachments, have a long life. And both the wireless and fiber networks have electronics with a relatively short life—usually a little longer than that of a laptop. The difference is that, in a wireless network, the electronics cost is both significantly higher than in a fiber network and also a much higher proportion of the capital cost. As described in Section 5.2, a significant portion of the capital cost of the wireless network (40 to 85 percent) needs to be spent, again, with each major upgrade. This is in contrast to the electronics making up 1 to 10 percent of the capital cost of the fiber network.

Another factor is that the improved wireless technology may require more antennas in the network. This is the case, for example, if the new technology uses a higher-frequency spectrum than the previous technology and hence needs to be closer to the user or at a better line-of-sight. It is also the case that the technology requires a denser deployment of antennas to handle capacity (as described in Section 4.3).

As discussed in Section 5.2, the cost of new sites is one of the largest components of the capital costs (between 15 and 50 percent).

4.3 Network scalability through densification of antenna sites

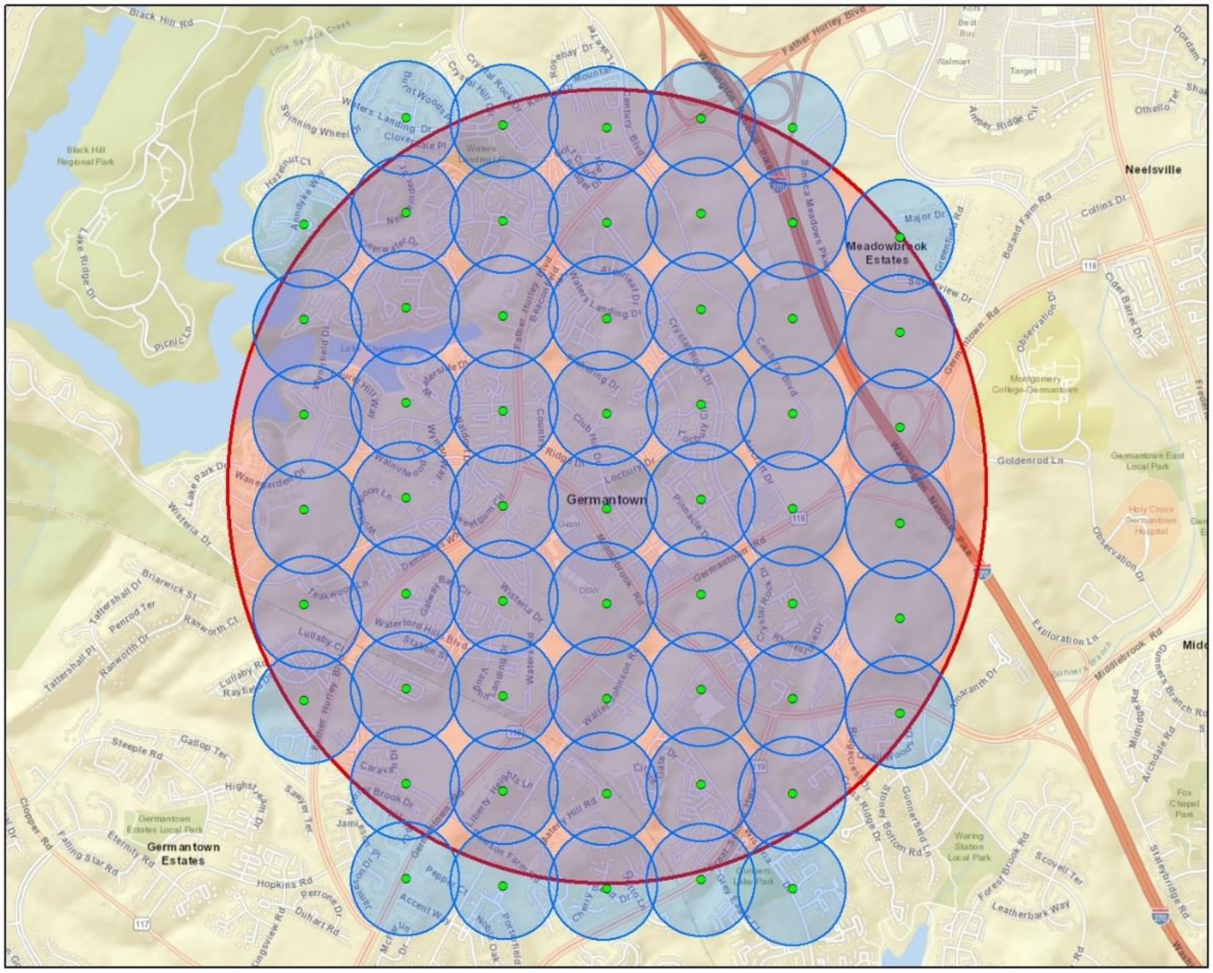
Along with adding spectrum or upgrading antennas and electronics, fixed wireless providers can increase the performance of their networks—to increase the speeds delivered to an existing set of users, or to serve more users at a baseline speed—by adding antenna sites.

While mobile providers have their allotments of licensed spectrum, fixed wireless service providers may have availability of 80 MHz in CBRS and approximately 200 MHz in unlicensed bands. In isolated rural areas, there is less demand for spectrum by the mobile providers, so additional spectrum, such as up to 70 MHz of additional CBRS PAL and 112.5 MHz of the 2.5 GHz EBS spectrum, may be available.

The aggregate capacity of an antenna site corresponds roughly to the amount of spectrum available. For example, 80 MHz of spectrum corresponds to about 1.5 Gbps of network capacity using typical 4G technology, and may reach 6 Gbps using 5G technology, including beamforming and MIMO. In other words, about 1,200 users can get 100 Mbps service using 5G technology.[36]

[36] Oversubscription assumed is 20:1 so a 100 Mbps burst would average a 5 Mbps load. SU-MIMO gains can vary up to four times that of a single stream—increasing end user throughput. Each site is assumed to have three sectors. Beamform in conjunction with MU-MIMO enables massive MIMO giving a sector an average of four times the throughput gains of a conventional sector antenna.

Figure 15: Densification of fixed wireless antennas



Wireless network engineers consider the amount of capacity at their disposal and the distribution of potential users when they design a network. They design the spacing between antenna sites to cover an expected number of users in an area using a particular level of capacity.

In order to increase the number of users or the level of capacity using a given technology or amount of spectrum,[37] the provider must add another site in a process known as "densification." Because sites are costly, sometimes up to $200,000 if no tower or usable high rooftop exists, it can be costly to build and operate a network with growing capacity needs, particularly in an unserved area that may have few or no structures or high towers. If a tower or rooftop does exist, the operator must cover lease costs in its operating budget. Figure 15 illustrates how a provider can increase its average capacity fifty-fold by using many antennas at lower power to replace a

[37] Adding more spectrum would be another approach to scaling the fixed wireless network's capacity, but that is more costly than adding antennas.

single antenna site and reusing spectrum in each small area. The red circle illustrates the service area of the original antenna, and the blue circles illustrate each new small area.

One illustration of the need for dense placement of antennas is in the model for the Town of Deming, N.M. Only one site would be needed to get a signal to all of the town's homes and businesses. However, 10 towers would be needed to deliver broadband capacity of 100 Mbps to those locations, even using 5G fixed wireless technology with beamforming and MIMO.

By comparison, the capacity of a fiber optic strand is very high—so high that even a 100 Gbps service is only using a small portion of what is available. Physics imposes the bandwidth limit and maximum range of a medium. Whether a signal goes over the air or through the glass in an optical fiber network, the physical medium propagates some signals and not others. The electronics on a fiber network impose additional limitations in physical medium, in that cost-effective, off-the-shelf fiber electronics use only certain frequencies or "colors" over the fiber.

Given the above, the theoretical limit of fiber capacity relates to fiber electronics and fiber manufacturing as they exist now. Off-the-shelf fiber optic technology makes use of "channels" on wavelengths between 1285 nm to 1330 nm and 1525 to 1575 nm. Using a unit conversion, the width of the channels is 14,000 GHz. Furthermore, the transmission range on a single path without amplification is over hundreds of miles.

The physical limit of 14,000 GHz in fiber far exceeds the physical limit of the entire broadband-usable wireless spectrum, which is about 100 GHz. And with wireless, the range is limited—from about 40 miles in very low frequency bands to only a few hundred feet in some of the high-frequency mmWave bands.

The available capacity of fiber starts at 1 Gbps for low-cost equipment and ranges to 100 Gbps for moderately priced equipment; because fiber does not depend on the line-of-sight, it will operate predictably according to the network's design and will not change with the seasons.

Fiber upgrades are accomplished by replacing the electronics at the cabinet or hub facility, and at the home or business address. These upgrades do not require construction or replacement of fiber cables or strands and involve only minimal adjustments in intermediate cabinets. In many cases, they do not require a truck roll by the network operator and can be done by the customer. An example would be an upgrade from the GPON equipment of the previous decade—which provides approximately 1 Gbps per customer (depending on configuration of the network)—to the emerging XGS-PON standard that can provide 10 Gbps symmetrical service. The equipment at the cabinet or hub facility costs approximately $200 per premises passed and the equipment at the premises costs approximately $70. Together these upgrades comprise only 1 to 10 percent of the capital cost of the network, in comparison to the 40 to 80 percent of the capital cost of a fixed wireless network that needs to be replaced every upgrade cycle.

5 A cost comparison of candidate fixed wireless and fiber networks in rural areas illustrates the shortcomings of fixed wireless as a long-term solution

Experience with fixed wireless network deployments in a wide range of environments—including urban settings (with congestion and old infrastructure), suburbs, greenfield areas, and rural communities—demonstrates that each scenario has its own advantages and disadvantages from an engineering and construction perspective.

Setting aside the issues related to technical capacities and coverage challenges, the costs to deploy a fixed wireless network—both in terms of the initial capital investment (capex) and the long-term operating expenses (opex)—are key factors in determining whether that approach is a suitable solution in a given environment. The analysis is strengthened by comparing those costs to the cost of implementing an alternative technology.

Accordingly, this section presents an apples-to-apples comparison of candidate fixed wireless and fiber-to-the-premises network deployments in four unserved rural settings:

1. Small town
2. Medium density rural
3. Low density rural
4. Very low density rural

The analysis addresses capital costs, operating costs, and total cost of ownership over 30 years. The models were built using a range of real-world inputs[38] that included GIS maps, current labor and materials unit costs, advanced fiber design tools, and RF models (including different spectrum, modulation schemes, MIMO levels, and beamforming).

The goal for each scenario was 100 percent coverage. Details on the fixed wireless and fiber-to-the-premises network design methodologies are in the appendices to this report; because each network deployment environment is unique and local, the costs are presented as ranges that consider variations relevant to the network technology, as well as potential variations in construction approaches. The following maps illustrate the coverage of the candidate fixed wireless and fiber-to-the-premises networks in each of the four environments.

[38] The models developed for this analysis use real-world data from two sample communities in New Mexico: The Town of Deming and Taos County.

Figure 16: Small town network coverage (fixed wireless and fiber-to-the-premises)

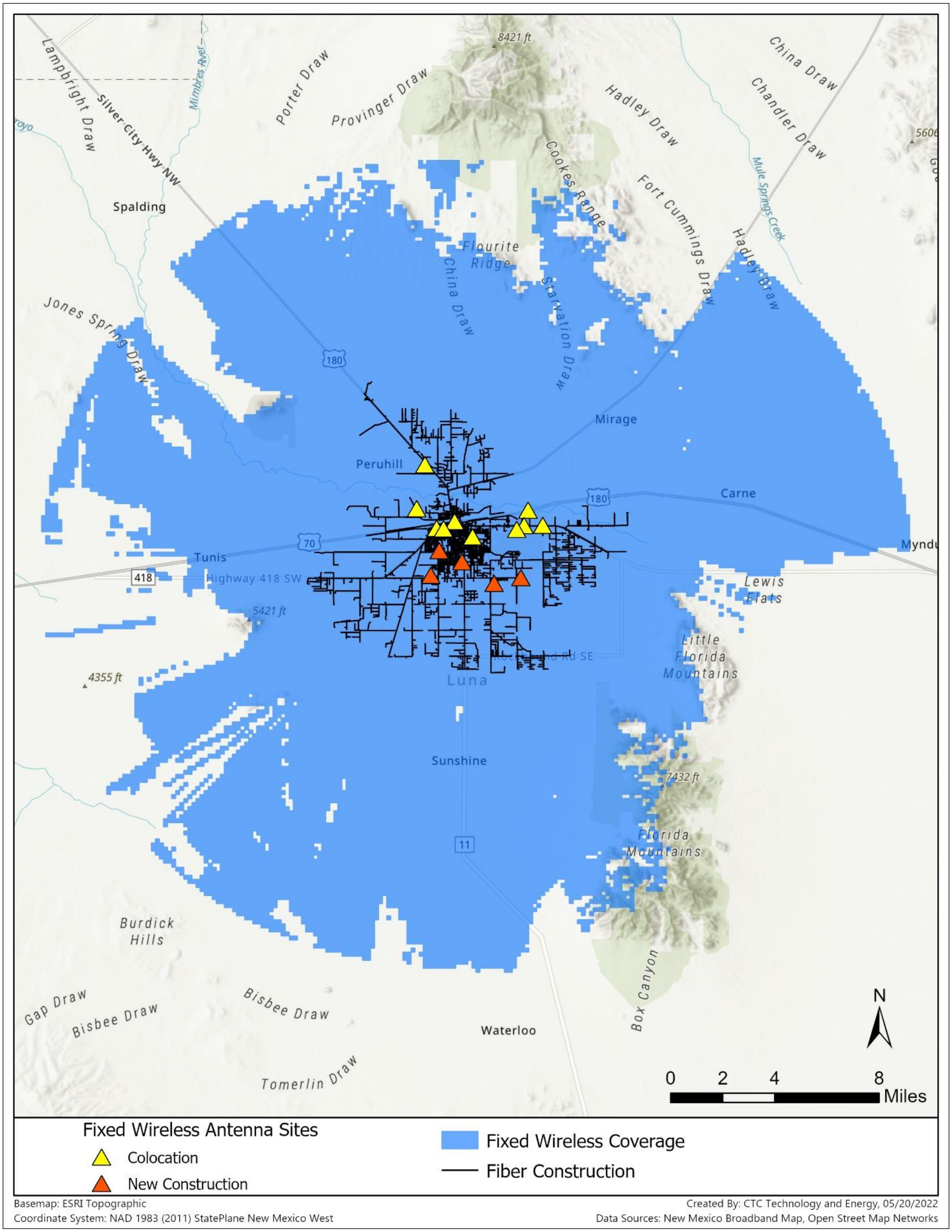


Figure 17: Medium density rural network coverage (fixed wireless and fiber-to-the-premises)

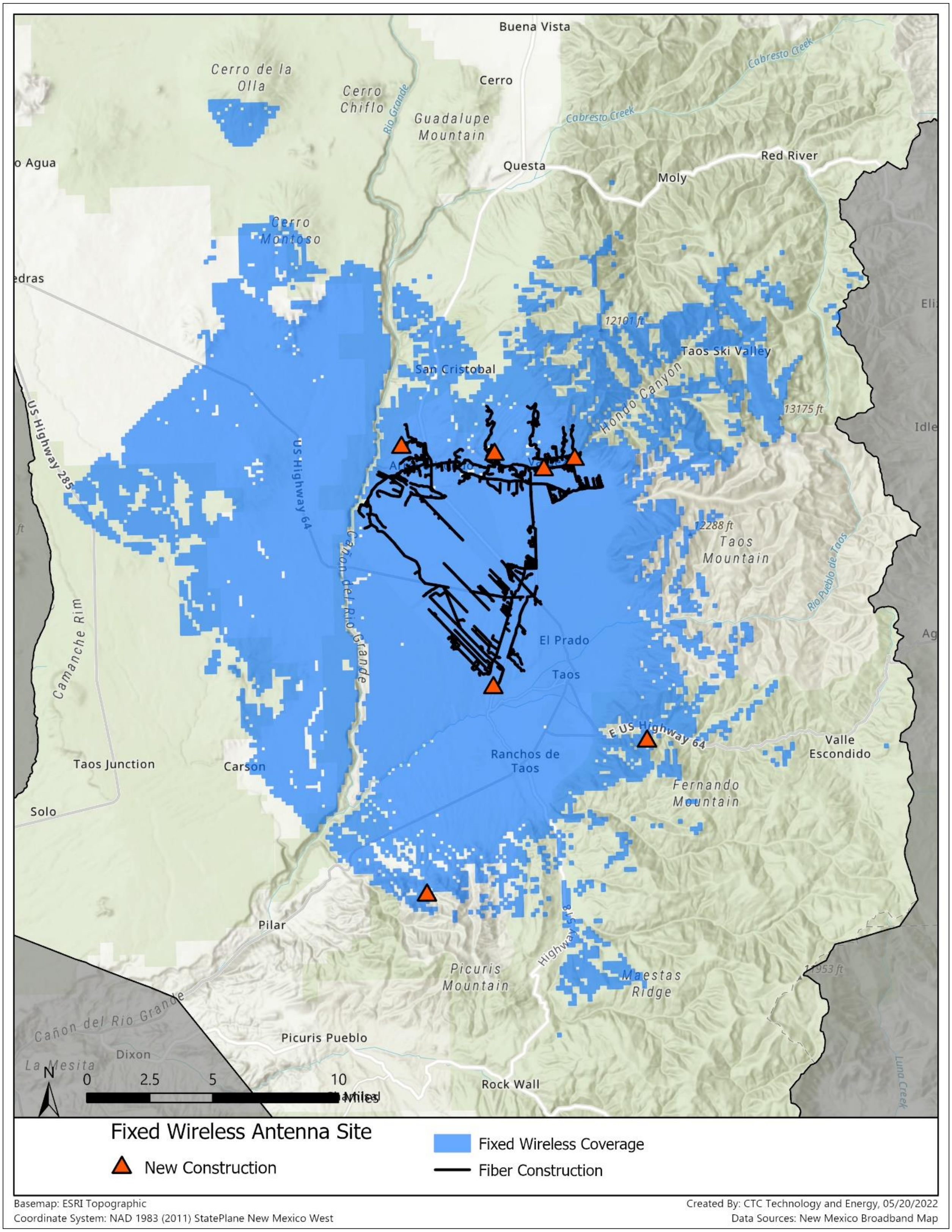


Figure 18: Low density rural network coverage (fixed wireless and fiber-to-the-premises)

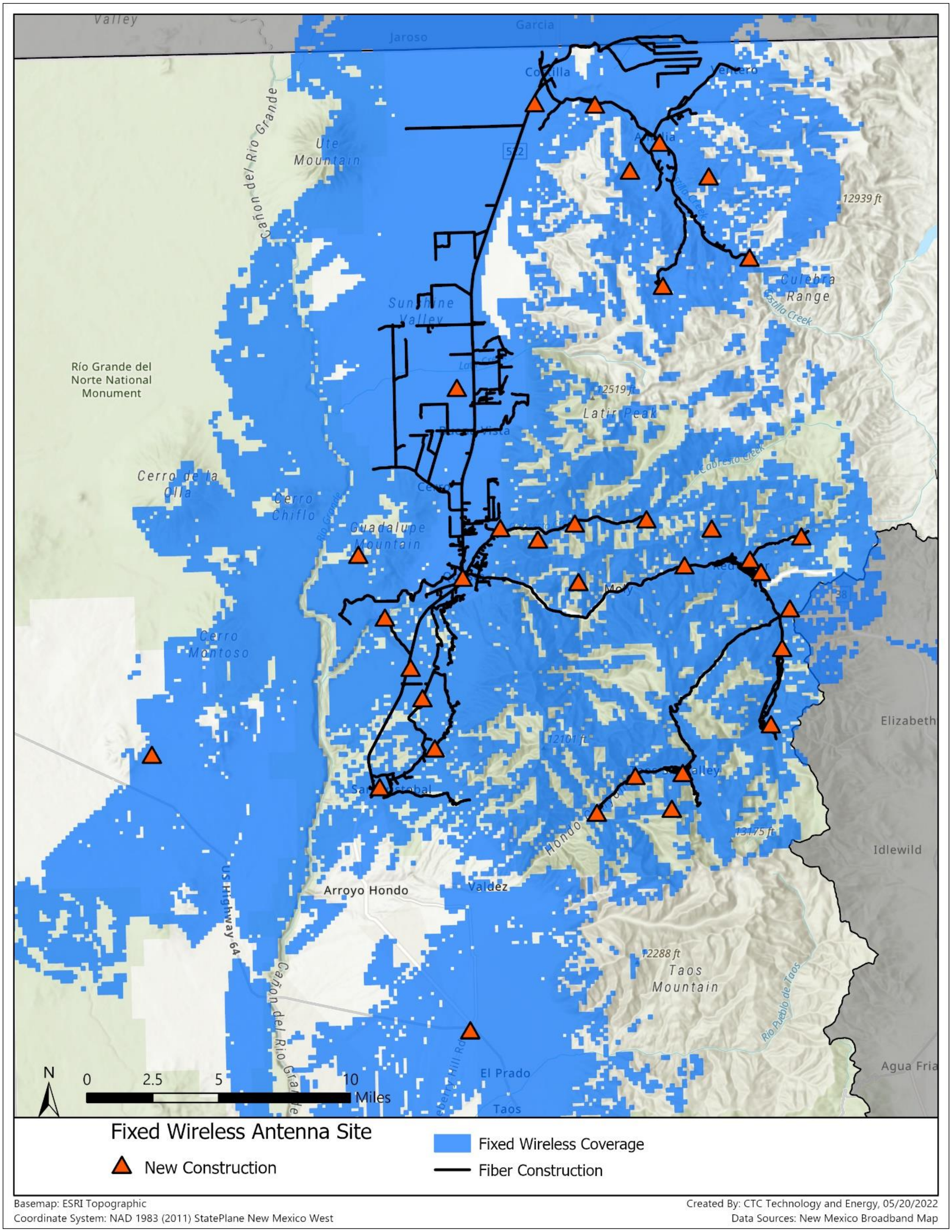
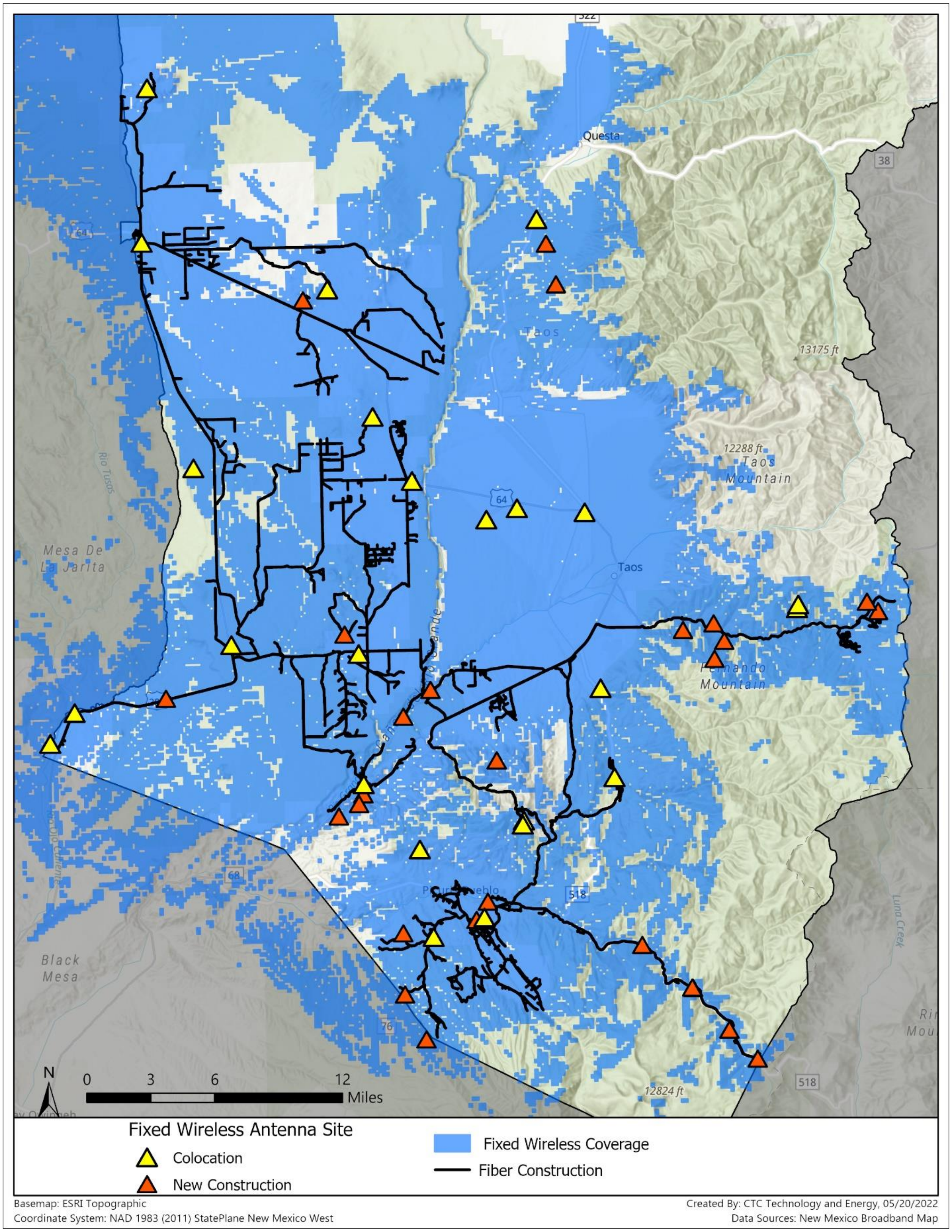


Figure 19: Very low density rural network coverage (fixed wireless and fiber-to-the-premises)



5.1 Key factors identified in cost analysis

The analysis of fixed wireless and fiber-to-the-premises network designs across four types of rural deployment scenarios identified the following key cost factors:

- Initial capital costs are higher for fiber than for fixed wireless network deployments; most of the capital cost for fiber relates to construction.
- Ongoing operational costs for fixed wireless are higher than for fiber. A major operational cost for fixed wireless is equipment replacement: For a fixed wireless network, 40 to 80 percent of the capital investment needs to be replaced every five years.[39] This is compared to 1 to 8 percent of the capital cost of a fiber network, with replacement every 10 years.
- Capital costs for fixed wireless deployments are dominated by the cost of customer premises equipment. Another large cost is construction of tower sites (where towers and buildings are not available for antenna siting).
- A major operational cost in any model, whether fixed wireless or fiber, is wholesale internet. This cost can be reduced by the availability of cost-effective middle-mile fiber, which lessens the construction costs necessary for providers to reach service locations.

Looking at both the fixed wireless and fiber-to-the-premises models, the main elements of capital cost are construction (fiber, towers), network core equipment, antennas, customer premises equipment, and project management. Key elements of operations include equipment replacement,[40] staffing, wholesale internet, maintenance, and site leases.

5.2 Capital cost analysis

The charts below illustrate the ranges of estimated capital costs for fixed wireless and fiber-to-the-premises networks in four rural deployment scenarios. The models comprise four cost categories:

- *Construction*—for fixed wireless, the construction and preparation of tower and rooftop sites and the associated equipment; for fiber-to-the-premises, the construction of conduit and fiber in the right-of-way and the construction and preparation of hub facilities
- *Customer installation*—for fixed wireless, the installation of outdoor customer premises equipment (if applicable) and provisioning of services; for fiber-to-the-premises, the installation of a drop cable from the street to the address and the installation of the customer premises equipment and provisioning of services

[39] Assuming a 50-year lifetime of fiber plant.
[40] Budgeted as an average yearly amount.

- *Design*—for fixed wireless, the radio frequency design and planning; for fiber-to-the-premises, the system-level design and detailed digital design of the fiber, hub facilities, and electronics
- *Electronics*—for fixed wireless, the network core electronics, radios, antennas, and customer premises equipment; for fiber-to-the-premises, the core electronics, hub and cabinet electronics, and customer premises equipment

These cost categories are described in more detail in Appendices A and B. The following tables present the ranges of costs for the four rural settings.

Table 4: Fixed wireless capital cost summary (estimated, per passing)

Cost Element	Small Town		Medium Density Rural		Low Density Rural		Very Low Density Rural	
	Low	High	Low	High	Low	High	Low	High
Construction	$60	$90	$310	$510	$600	$1,000	$940	$1,700
Customer installation	$5	$5	$330	$330	$110	$110	$210	$210
Design	$10	$15	$50	$70	$90	$150	$140	$240
Electronics	$390	$390	$830	$830	$1,230	$1,230	$1,800	$1,800
Total	**$465**	**$500**	**$1,520**	**$1,740**	**$2,030**	**$2,490**	**$3,090**	**$3,950**

Table 5: Fiber-to-the-premises capital cost summary (estimated, per passing)

Cost Element	Small Town		Medium Density Rural		Low Density Rural		Very Low Density Rural	
	Low	High	Low	High	Low	High	Low	High
Construction	$1,380	$6,740	$2,700	$12,620	$4,050	$20,160	$7,310	$37,370
Customer installation	$650	$1,030	$750	$1,450	$820	$1,120	$940	$1,600
Design	$390	$590	$700	$1,050	$1,170	$1,720	$2,180	$3,210
Electronics	$200	$200	$200	$200	$200	$200	$190	$190
Total	**$2,620**	**$8,550**	**$4,340**	**$15,310**	**$6,240**	**$23,210**	**$10,620**	**$42,370**

The cost of fixed wireless construction varies by location; it is lowest in the small town, where there are towers and buildings for most antennas and fewer sites are needed per customer. In less dense rural areas, there are fewer potential mounting structures and it is necessary to build new ones. Furthermore, because the addresses are spread out, some antenna sites serve fewer addresses (as described in more detail in Appendix B).

The cost of fiber construction can vary significantly by construction type. Aerial construction is typically less expensive than underground fiber placement. Costs further depend on local circumstances, such as utility pole conditions and soil composition. Utility poles quite often require make-ready work, which may entail restructuring existing pole attachments or replacing poles. The cost of underground construction, on the other hand, is dependent on the suitable trenching options. For instance, soft soil is conducive to a much preferred and more cost-efficient plowing technique, whereas rock ground requires expensive rock cutting and drilling.

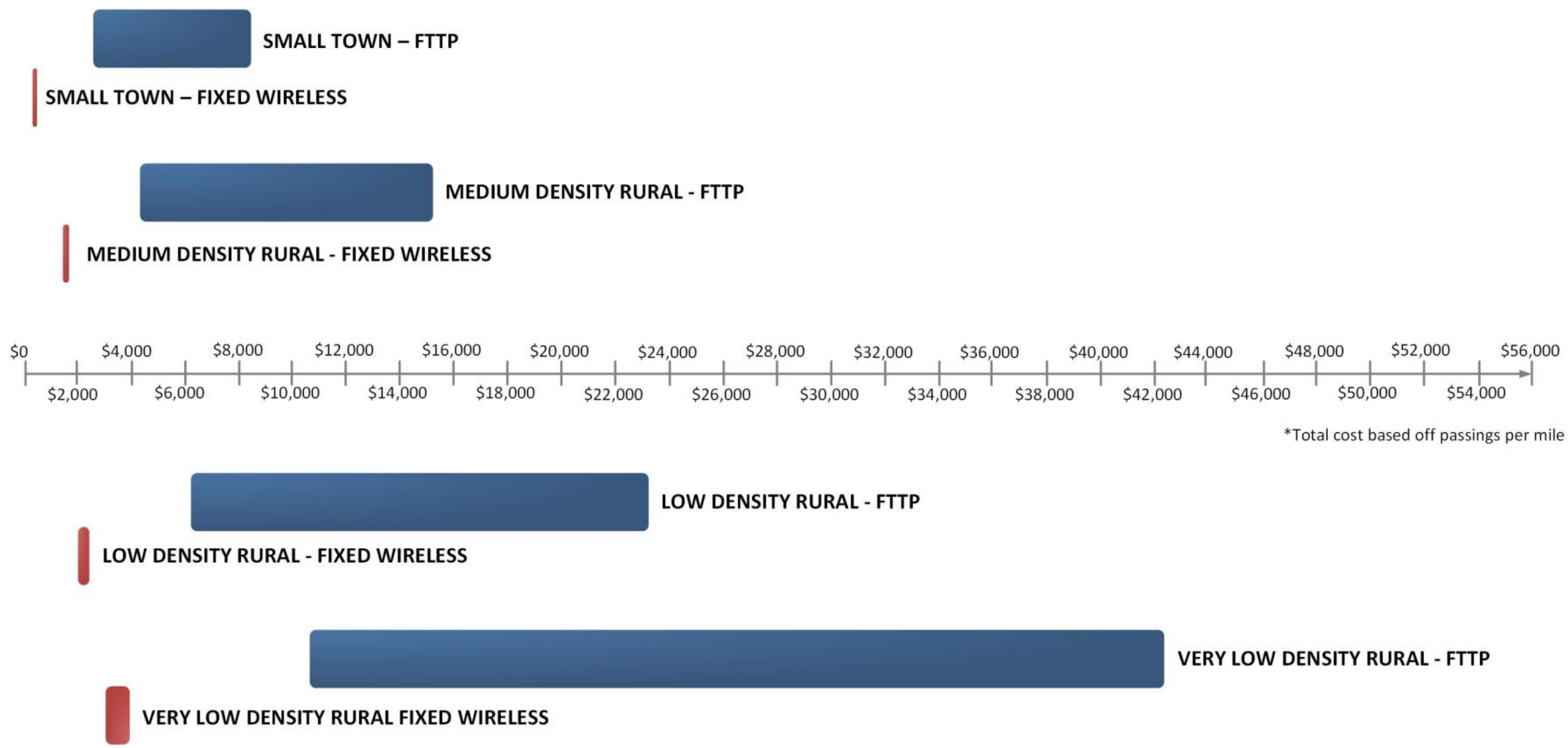
The capex range for the fiber-to-the-premises implementation in Figure 20 illustrates the impact of two construction methods on the overall implementation cost. For the upper limit, 100 percent underground is assumed with the fiber cables placed in 1- and 2-inch conduits. The cost model assumes directional drilling, which is a suitable construction method for medium soil hardness. For the least costly scenario, an aerial cable infrastructure build model is applied that assumes that no poles would require make-ready.

The cost of customer installation is lower for fixed wireless in the small town, because many of the addresses can be served using indoor devices resembling Wi-Fi hotspots. The provider can mail these to the customer with self-installation instructions. The use of outdoor customer premises equipment is also why the cost for electronics is higher for the less dense areas.

The cost of customer installation for fiber-to-the-premises increases in lower density areas because houses are further from the road, on average, in those areas.

Appendix C includes detailed capital cost analyses by technology type and density.

Figure 20: Capital cost comparison



5.3 Operating cost analysis

The charts below illustrate the ranges of estimated operating costs for fixed wireless and fiber-to-the-premises networks in four rural deployment scenarios.

The models comprise four cost categories:

- *Staff*—including managers, engineers, technicians, and customer service. The low-end estimate assumes the network is being built by a larger operator that leverages staff from a larger organization; the high-end estimate assumes a standalone operation.
- *Replacement*—the cost of new core, hub, antenna site, and customer premises electronics to replace equipment that becomes technically obsolete or is damaged or worn out. For fiber-to-the-premises it also includes 50-year depreciation of the physical fiber network.
- *Maintenance*—including maintenance of physical infrastructure, location of underground utilities, software licenses, service contracts, and utility pole space rental.
- *Leases*—including antenna sites and hub sites.
- *Wholesale internet*—bandwidth and transport of internet capacity from the internet backbone to the local network. The low-end estimate assumes low-end cost for internet bandwidth and favorable terms on a middle mile network; the high-end estimate assumes high cost for bandwidth and transport in many rural areas.

These categories are described in more detail in Appendices A and B. The following tables and Figure 21 (below) present the ranges of operating costs for the four rural settings.

Table 6: Fixed wireless annual operating cost summary (estimated, per passing)

Cost Element	Small Town		Medium Density Rural		Low Density Rural		Very Low Density Rural	
	Low	High	Low	High	Low	High	Low	High
Staff	$20	$70	$85	$300	$80	$280	$80	$290
Replacement	$75	$75	$160	$160	$240	$240	$350	$350
Maintenance	$25	$25	$120	$120	$160	$160	$250	$250
Leases	$25	$25	$120	$120	$160	$160	$250	$250
Wholesale internet	$25	$300	$25	$300	$25	$300	$25	$300
Total	**$170**	**$495**	**$510**	**$1,000**	**$665**	**$1,140**	**$955**	**$1,440**

Table 7: Fiber-to-the-premises annual operating cost summary (estimated, per passing)

Cost Element	Small Town		Medium Density Rural		Low Density Rural		Very Low Density Rural	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Staff	$50	$60	$130	$140	$120	$140	$130	$160
Replacement	$50	$160	$90	$290	$120	$450	$210	$830
Maintenance	$110	$130	$190	$230	$230	$300	$340	$480
Leases	$10	$10	$10	$10	$10	$10	$10	$10
Wholesale internet	$20	$210	$20	$210	$20	$210	$20	$210
Total	**$240**	**$570**	**$440**	**$880**	**$500**	**$1,110**	**$710**	**$1,690**

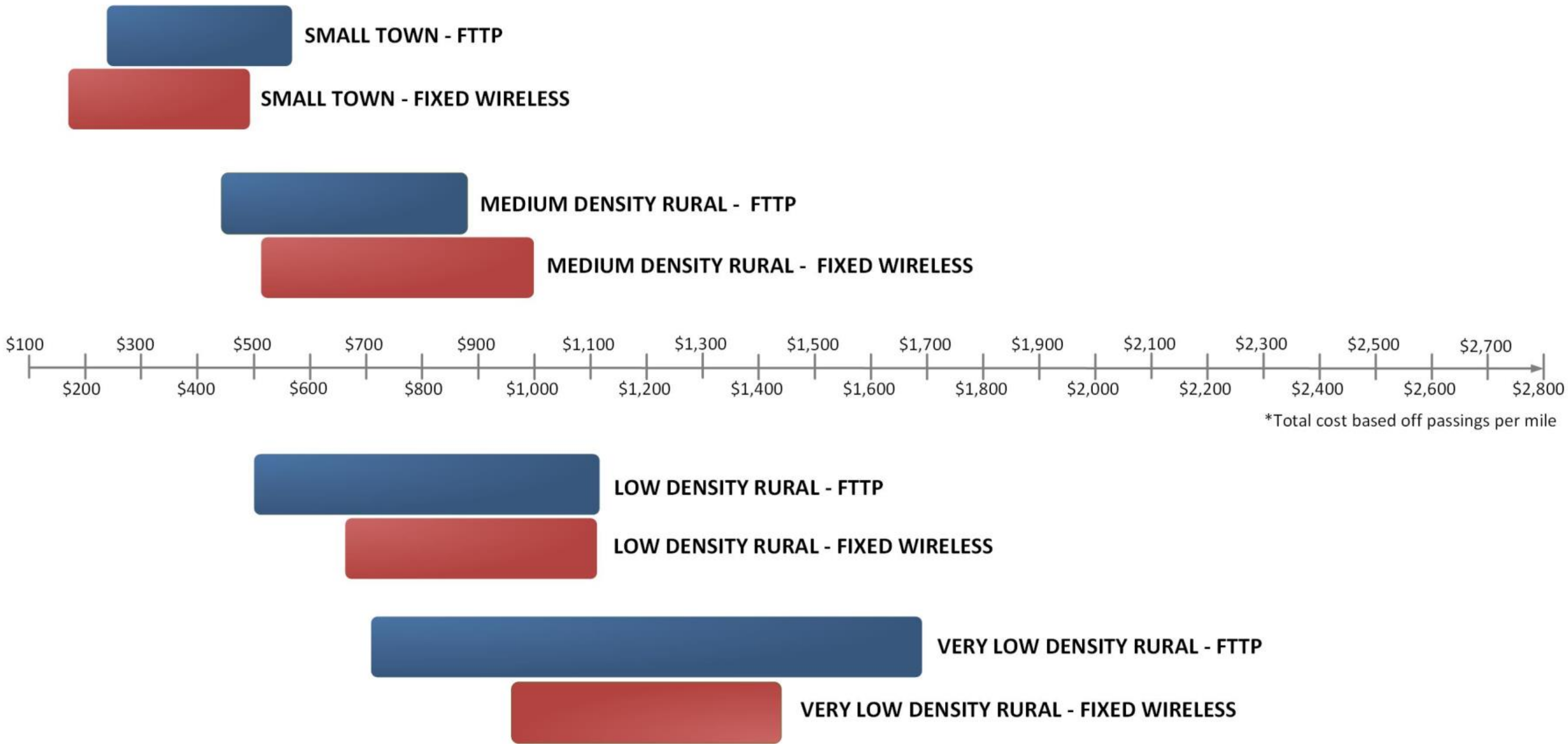
A primary cost for fixed wireless networks is equipment replacement due to obsolescence, with all of the equipment (i.e., most of the capital cost of the network) replaced in an average period of five years.

For fiber-to-the-premises, replacement cost is also high in the lowest-density areas owing to the relatively large mileage of fiber per premises and the cost of depreciation.

Wholesale internet can be a high cost in any network if the middle mile network options in an area are costly.

Appendix D includes detailed operating cost analyses by technology type and density.

Figure 21: Estimated operating cost comparison



5.4 Total cost of ownership analysis

The charts below illustrate the ranges of estimated 30-year total costs of ownership for fixed wireless and fiber-to-the-premises networks in four rural deployment scenarios. This is the capital cost plus 30 years of the operational cost.

The costs per premises increase with both technologies as density decreases. With any network technology, density tends to be a key cost factor, hence the lack of broadband in many rural areas.

In all scenarios, there is a wide range of costs because of the wide variation in local conditions, as well as the business model that will be used (for example, an incumbent provider with existing infrastructure will have different costs than a new entrant). Also, the ranges of total costs of ownership for fiber and fixed wireless tend to overlap (see Figure 22, below); thus, it is prudent to make a deployment determination based primarily on performance and quality.

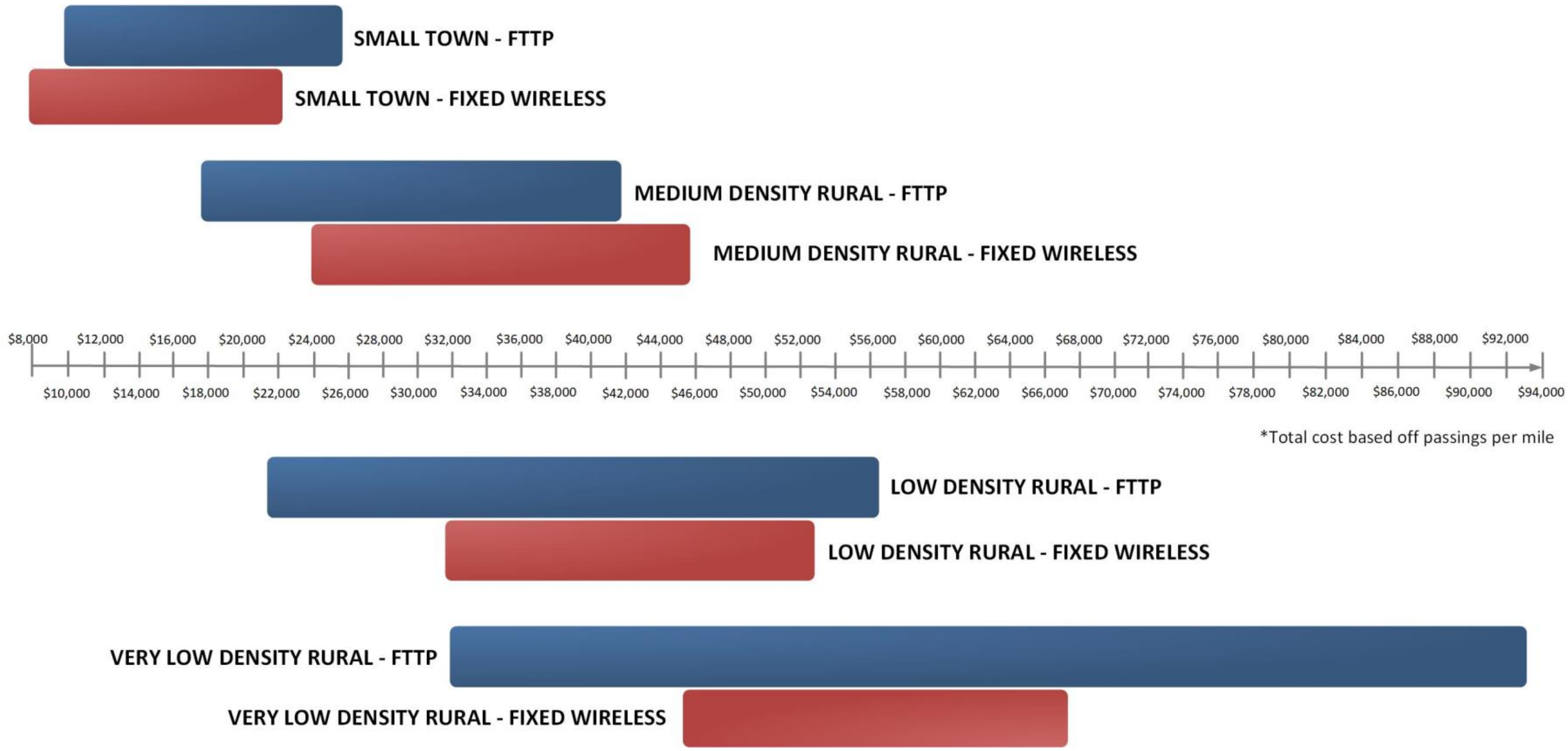
Table 8: Estimated total cost of ownership – fixed wireless (30 years, per passing)

Cost Element	Small Town		Medium Density Rural		Low Density Rural		Very Low Density Rural	
	Low	High	Low	High	Low	High	Low	High
Staff	$880	$3,000	$3,700	$13,100	$3,500	$12,200	$3,600	$12,700
Replacement	$3,300	$3,300	$7,100	$7,100	$10,700	$10,700	$15,300	$15,300
Maintenance	$1,100	$1,100	$5,400	$5,400	$7,200	$7,200	$11,100	$11,100
Leases	$1,100	$1,100	$5,100	$5,100	$7,100	$7,100	$11,100	$11,100
Wholesale internet	$1,000	$13,200	$1,000	$13,200	$1,000	$13,200	$1,000	$13,200
Construction	$465	$500	$1,520	$1,740	$2,030	$2,490	$3,090	$3,950
Total	**$7,845**	**$22,200**	**$23,820**	**$45,640**	**$31,530**	**$52,890**	**$45,190**	**$67,350**

Table 9: Estimated total cost of ownership – fiber-to-the-premises (30 years, per passing)

Cost Element	Small Town		Medium Density Rural		Low Density Rural		Very Low Density Rural	
	Low	High	Low	High	Low	High	Low	High
Staff	$1,500	$1,800	$3,900	$4,200	$3,600	$4,200	$3,900	$4,800
Replacement	$1,500	$4,800	$2,700	$8,700	$3,600	$13,500	$6,300	$24,900
Maintenance	$3,300	$3,900	$5,700	$6,900	$6,900	$9,000	$10,200	$14,400
Leases	$300	$300	$300	$300	$300	$300	$300	$300
Wholesale internet	$600	$6,300	$600	$6,300	$600	$6,300	$600	$6,300
Construction	$2,620	$8,550	$4,340	$15,310	$6,240	$23,210	$10,620	$42,370
Total	**$9,820**	**$25,660**	**$17,550**	**$41,720**	**$21,240**	**$56,500**	**$31,920**	**$93,070**

Figure 22: Estimated total cost of ownership (30 years) comparison



6 Fiber represents the most fiscally prudent expenditure of public funds in most circumstances because of its longevity and technical advantages

The technical analysis and cost comparisons in this report support the preference in the Broadband Equity, Access, and Deployment (BEAD) Program's notice of funding opportunity (NOFO) for fiber over fixed wireless.[41]

Fiber is sustainable, scalable, and renewable. It offers greater capacity, predictable performance, lower maintenance costs, and a longer technological lifetime than fixed wireless technologies. Fiber service is not degraded by line-of-sight issues and is not affected by the capacity issues that constrain fixed wireless networks. In that light, fiber's high construction costs represent a short-term impediment but a long-term value as compared to fixed wireless technologies.

Of course, broadband funding decisions are made on a custom basis depending on local conditions. The parameters state grant makers should investigate, in order to ensure a high-performance, scalable, financially sustainable, long-lasting solution, include:

- The proposed network's speed and latency that will be immediately available, starting with a requirement of 100/20 Mbps to the premises, with increased score for those who can provide 100/100 Mbps and 1,000/1,000 Mbps
- The network's speed and latency in five years, 10 years, 15 years, and 20 years
- The capital cost to construct the network and to deliver the level of service promised in five, 10, 15, and 20 years
- The cost to operate the network over five, 10, 15, and 20 years, including replacement of equipment that becomes technologically obsolete because it cannot provide the needed speed and latency
- The network's ability to cost-effectively provide service to all individuals in the service area, including the strategy for obtaining line-of-sight for fixed wireless deployments
- The network's resiliency, including the ability for key components to continue operating during a power failure or service cut and the ability to restore service quickly

[41] The BEAD program guidance refers to a project that would deploy an all-fiber network as a "priority broadband project" because "A project that will rely entirely on fiber-optic technology to each end-user premises will ensure that the network built by the project can easily scale speeds over time to meet the evolving connectivity needs of households and businesses and support the deployment of 5G, successor wireless technologies, and other advanced services" See: "Notice of Funding Opportunity: Broadband Equity, Access, and Deployment Program," National Telecommunications and Information Administration (NTIA), U.S. Department of Commerce, May 2022, https://broadbandusa.ntia.doc.gov/sites/default/files/2022-05/BEAD%20NOFO.pdf.

In the event that a state funds technologies other than fiber, such as in circumstances where the capital cost to build fiber is cost-prohibitive or the need for service cannot wait for fiber construction, the state should then take steps to protect its investment—such as by requiring grantees to guarantee the long-term maintenance and operations of the fixed wireless network. As described above, this could be accomplished by requiring a 20-year performance and budget roadmap, and a viable strategy for full service where line-of-sight is a challenge.

Appendix A: Rural fiber-to-the-premises designs and cost estimates

This report presents cost ranges for fiber-to-the-premises (FTTP) implementations, which comprise material and labor for outside plant, distribution, and CPE equipment, and required facilities. This appendix describes the network design and associated cost elements in detail.

General assumptions made for the design and operations parameters include:

- The network achieves a penetration of 100 percent of homes passed.
- The operation of the fiber network is understood to be part of a larger organization that is an established service provider in other markets. As such, economies of scale are achieved in terms of staffing, back-office support, and core network functions.

Conceptual, high-level FTTP network designs were developed for a small rural town (Deming, N.M.) and a rural county comprised of areas with varying population densities (Taos County, N.M.) as the basis for estimating the networks' capital and operating costs.

The small-town model assumes the network would comprise 364.6 route miles to target addresses within a 3-mile boundary of the town and would be capable of serving 9,872 passings within the service area, at 27 homes per mile.

The rural county models reflect three distinctly different population densities that can be characterized as medium density (2,279 passings, at 15 homes per mile), low density (2.445 passings, at nine homes per mile), and very low density (2,339 passings, at five homes per mile).[42] The candidate fiber network was designed to supplement existing broadband infrastructure in the county for the sole purpose of delivering service to identified unserved homes.

The estimated costs for each model are presented as a range (low-end and high-end). The low-end estimate is based on assumptions that would minimize deployment costs, while the high-end cost estimate assumes that construction variables would lead to increases deployment costs.

Objectives and key attributes

The models would deliver cost-effective and flexible infrastructure—optimized for long-term use.

The recommended architecture is a hierarchical data network that would provide scalability and flexibility, both in terms of initial network deployment and ability to accommodate the increased demands of future applications and technologies. The central characteristics of this hierarchical FTTP data network include:

[42] The unserved populations are 2,279 (medium density), 2,445 (low density), and 2,339 (very low density).

- **Capacity** – ability to consistently provide efficient transport for subscriber data at advertised speeds, even at peak times
- **Availability** – high levels of reliability and resiliency; the ability to quickly detect faults
- **Scalability** – ability to grow in terms of physical service area and increased data capacity, and to integrate newer technologies without new construction

This architecture offers scalability to meet long-term needs. It is consistent with best practices for either a standard or an open-access network model to provide customers with the option of multiple network service providers. This design would support the current industry standard Gigabit Passive Optical Network (GPON) technology, which enables aggregated download speeds of 2.4 Gbps and upload speeds of 1.2 Gbps per segment and effectively delivers symmetrical 1 Gbps with appropriate loading. It can be upgraded to the emerging symmetrical 10 Gbps XGS-PON and NG-PON2 standards without modification of the fiber plant. It could also provide the option of direct Active Ethernet (AE) services on a limited basis, such as for business customers, using spare fiber capacity built into the designs.

Conceptual network design

PON networks are characterized by tree-and-branch architectures that split the optical signals in the individual fibers typically 16 or 32 ways in rural deployments. Figure 23, below, shows the conceptual architecture for the physical plant in the FTTP network. A hub will feed primary distribution conduit through distribution vaults located throughout the County. The distribution hubs or fiber distribution cabinets (FDC) house splitters that feed secondary fibers for connectivity of groups of homes. Connectivity with individual households is accomplished by means of taps, which are spliced into secondary fibers at vaults and drop cables that plug into the taps. For aerial construction taps are placed with the splitters, which are placed in weather-tight enclosures mounted on utility poles. In underground construction, tap access is placed in handholes located at the edge of the homeowners' parcel but still within the right-of-way. By installing infrastructure all the way to the edge of each premises parcel, costs are reduced for future installation to a subscriber.

Subscribers more than about 12 miles away from the hub may exceed the distance and signal timing limits of the electronic distribution equipment located in the hub. In those situations, additional hub equipment or active fiber distribution equipment (active FDC) would be required that could be installed in field cabinets along the fiber route.

Figure 23: FTTP network conceptual design

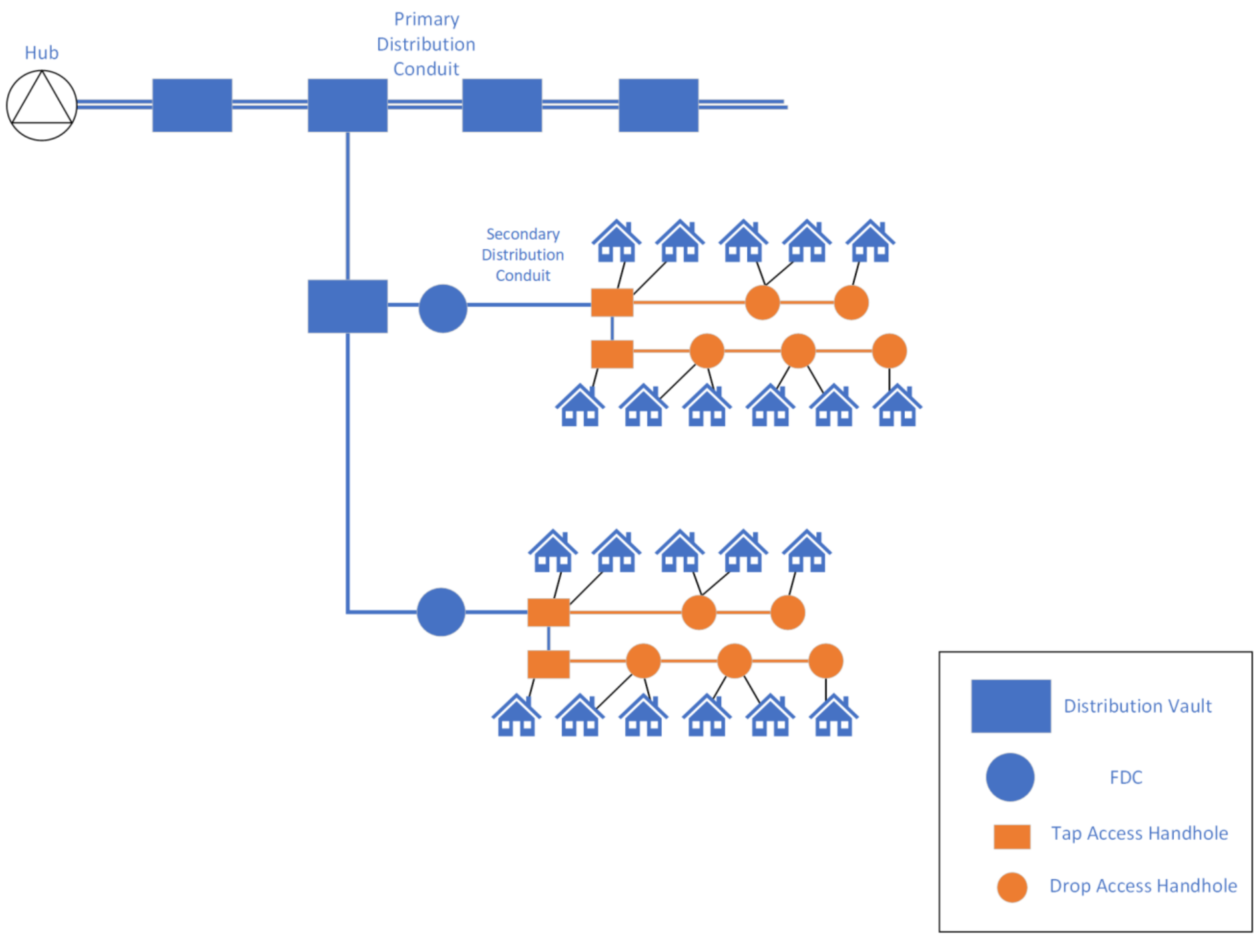
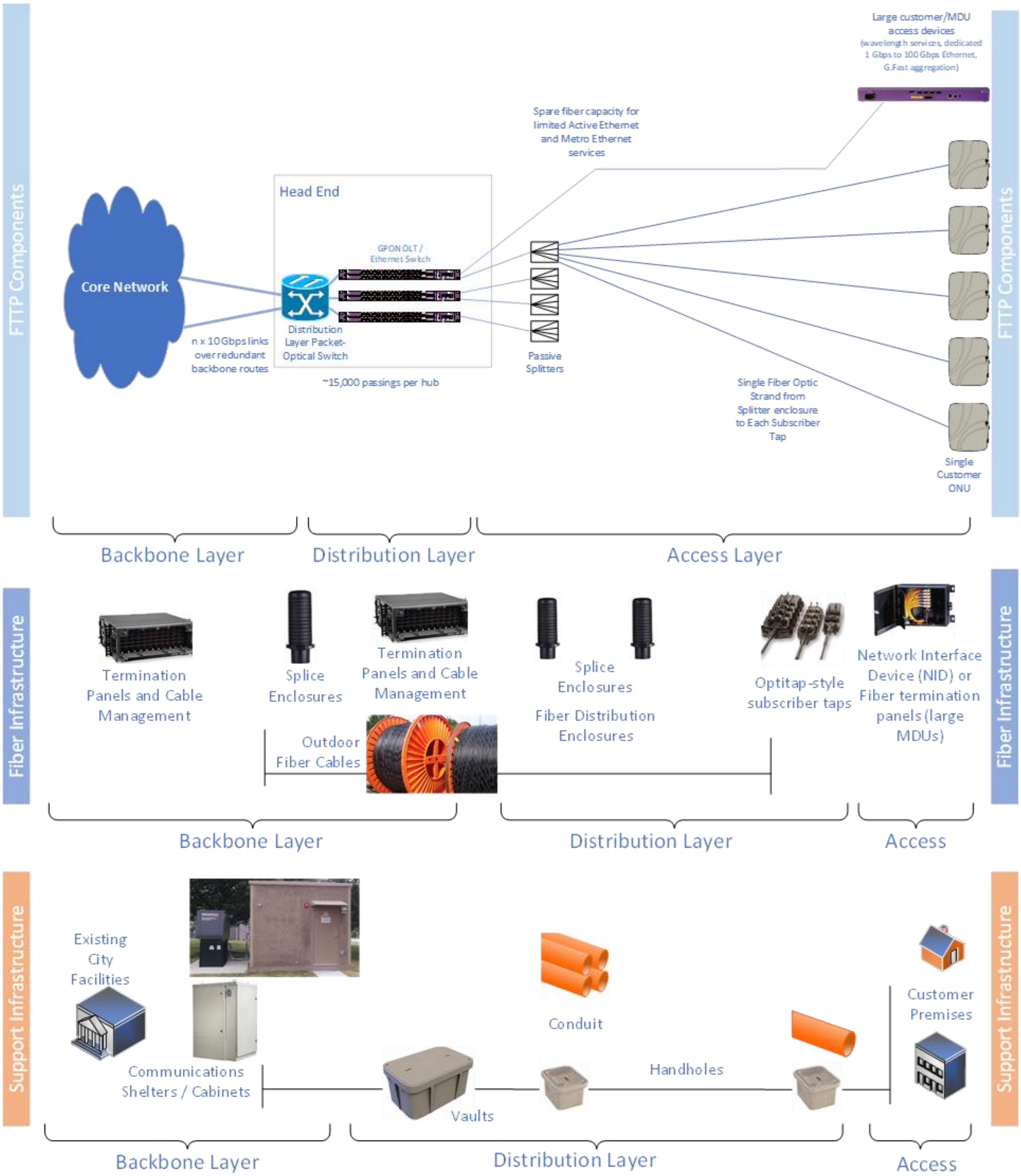


Figure 24 below, displays the FTTP network architecture based on the conceptual outside plant design above. It illustrates the primary functional components in the FTTP network, their relative positions, and the flexibility of the architecture to support multiple subscriber models and classes of service.

Figure 24: High-level FTTP architecture and components



Design parameters and model assumptions

The low-end and high-end cost estimates incorporate different assumptions on the amount of aerial and underground infrastructure. The low-end estimate assumes the entire network will be deployed aerially while the high-end estimate assumes the entire network will be deployed underground.

In addition, the network design and cost estimates assume the network will:

- Use manufacturer-terminated fiber tap enclosures within the public right-of-way or easements, providing watertight fiber connectors for customer service drop cables, which eliminate the need for service installers to perform splices in the field. This is an industry-standard approach to reducing both customer activation times and the potential for damage to distribution cables and splices.

The network design is guided by the following elements:

- Underground conduit and fiber will be installed in the public right-of-way or in an easement on the side of the road.
- Underground conduits are SDR-11 rated of 1- or 2-inch diameter. All underground conduits for customer access are 1-inch conduits.
- The aerial fiber design will make use of existing poles where possible.
- Extended lateral fiber sizes will range from 48-to 144-count cable; and short lateral and drop fiber will contain 12 strands.
- Fiber cables for backbone used for hub-to-hub connectivity and primary fiber routes hold 144 fibers; secondary fiber routes and drop cables have 12 fibers.
- The network will target up to 144 passings per secondary distribution point, each served from a fiber distribution cabinet (FDC) containing optical splitters.
- Distribution plant will terminate at multi-port subscriber tap terminals (i.e., “taps”) in underground handholes or mounted on poles for aerial residential drops.
- Access conduit where needed will be placed in drop access handholes placed at the edge of the parcel for each serviceable passing (one handhole per one or up to four passings).
- Underground vault spacing will be no more than 750 feet along distribution routes.
- The hub will be constructed to support network electronics with backup power generation, redundant cooling systems, robust physical security, and inert gas fire-

suppression systems. For the network design, existing locations owned by the small town, such as fire-stations, were considered for the hub.

- Each unit inside an MDU is treated as an individual address.
- A powered distribution cabinet (called an "active FDC") will be deployed in locations for residences with distances greater than 12 miles from the hub.
- The head end and active FDCs will be constructed to support network electronics with backup power generation, redundant cooling systems, robust physical security, and inert gas fire-suppression systems. The design uses one hub for the small town and the medium density rural case and two or more hubs to account for the large distances of the middle mile segments of the network for the low density and the very low-density rural case studies. For the network design, existing County-owned locations, such as City Hall or fire-stations, were considered as head ends and active hub sites.
- Where possible, the distribution plant network routes will avoid crossing major roadways, railways, and waterways.
- For aerial construction, the model assumes the builder can obtain attachment agreements from the pole owners.
- The model assumes up to 25 percent of poles would require minor make-ready work or pole replacement.

Network designs

Network design for small town

The maps below illustrate the candidate FTTP network design in the small town. The fiber construction is a town-wide infrastructure overbuild, irrespective of existing broadband infrastructure. Due to the home density, the town can be served with one hub location.

Figure 25: Small town FTTP network core components

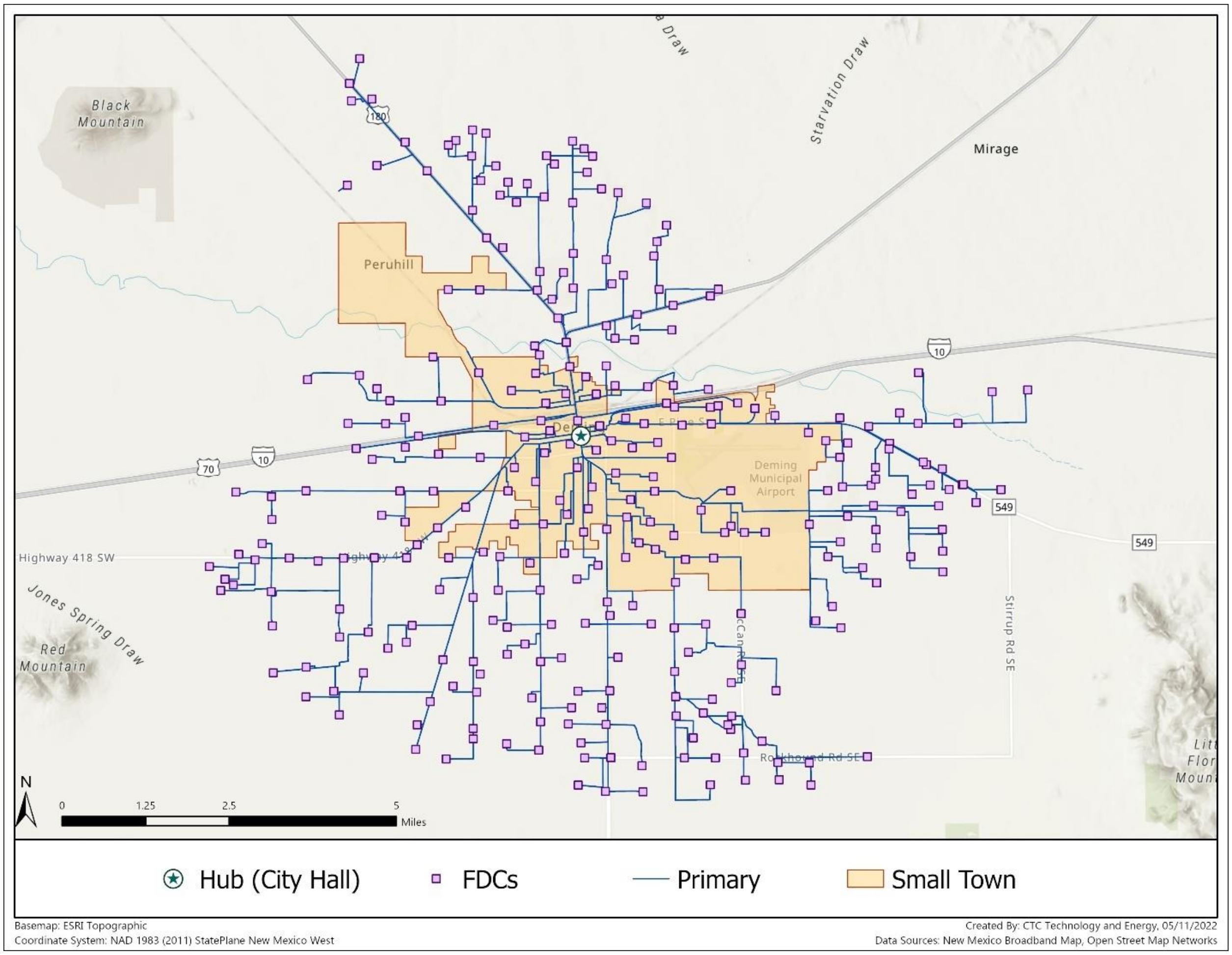
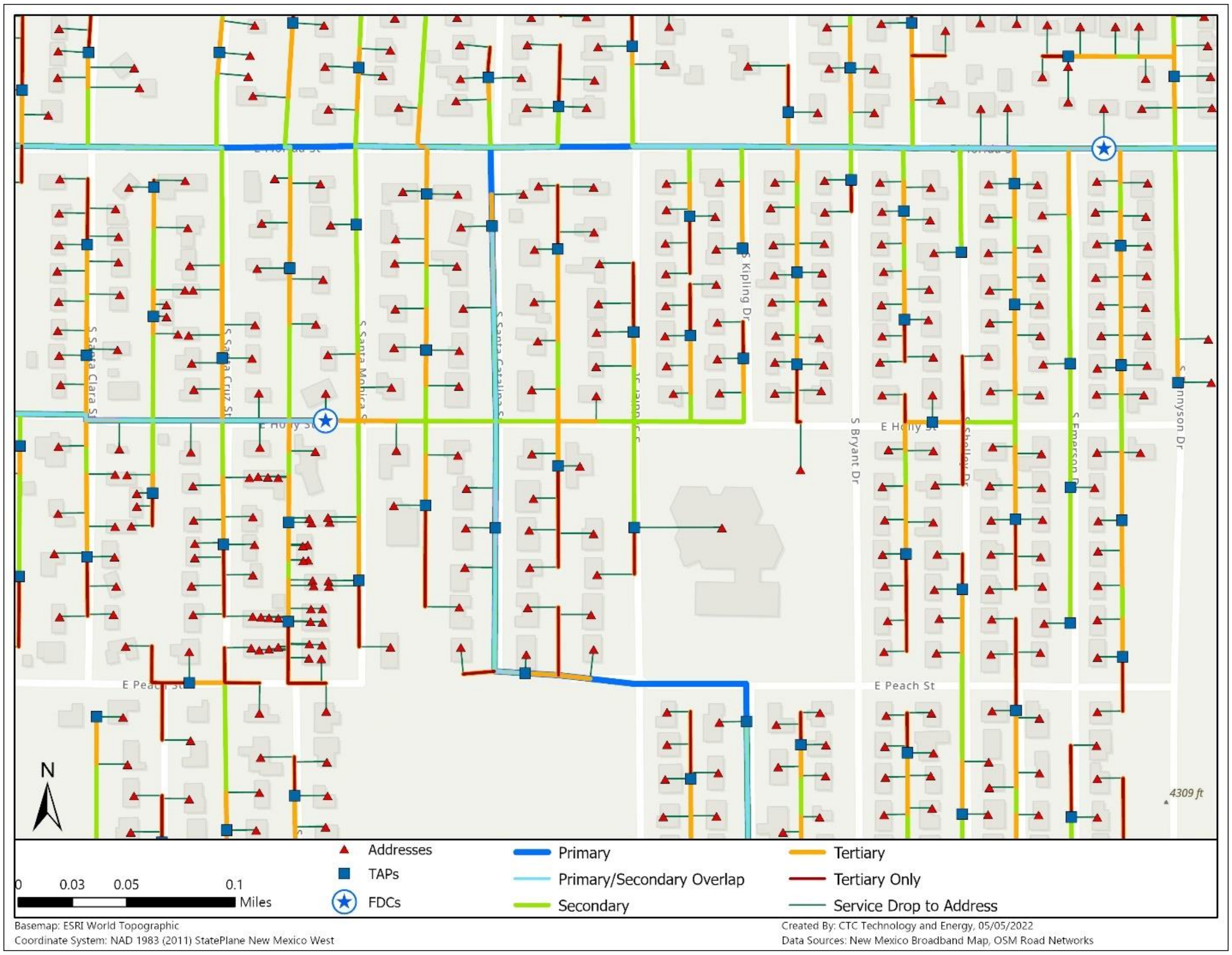


Figure 26: Small town FTTP network close-up



Network design for medium density, low density, and very low density rural region

The maps below illustrate the FTTP network topologies in the rural county. These designs close broadband service gap in the communities. (Figure 30 illustrates a fiber route that must travel through served areas to reach pockets of unserved addresses.) While the medium density area can be served out of one hub facility, the more sparsely populated regions require additional active hubs or active fiber distribution cabinets due to the distance and the power-loss budget limitations of the FTTP optical equipment.

Figure 27: Rural FTTP networks (all densities)

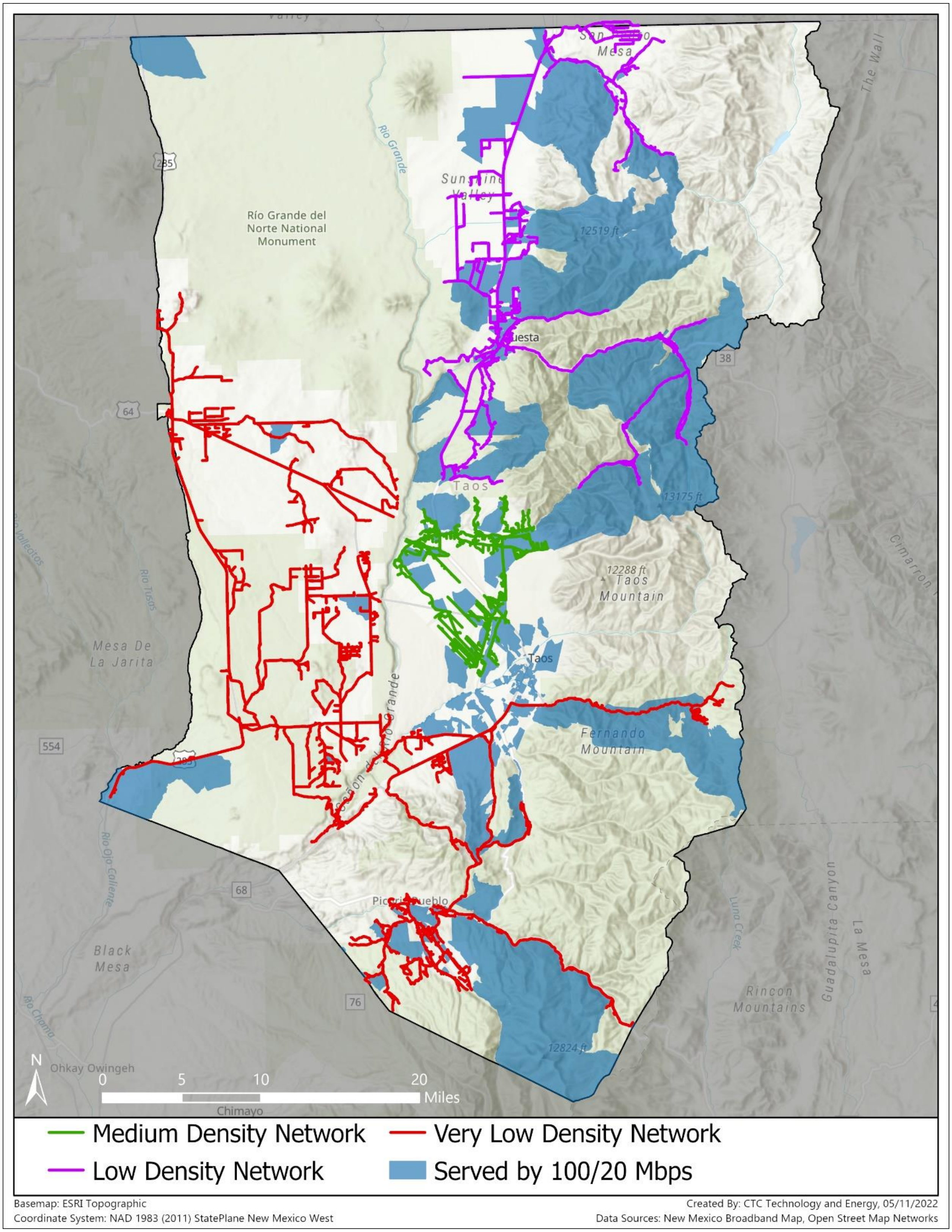


Figure 28: Very low density rural FTTP network

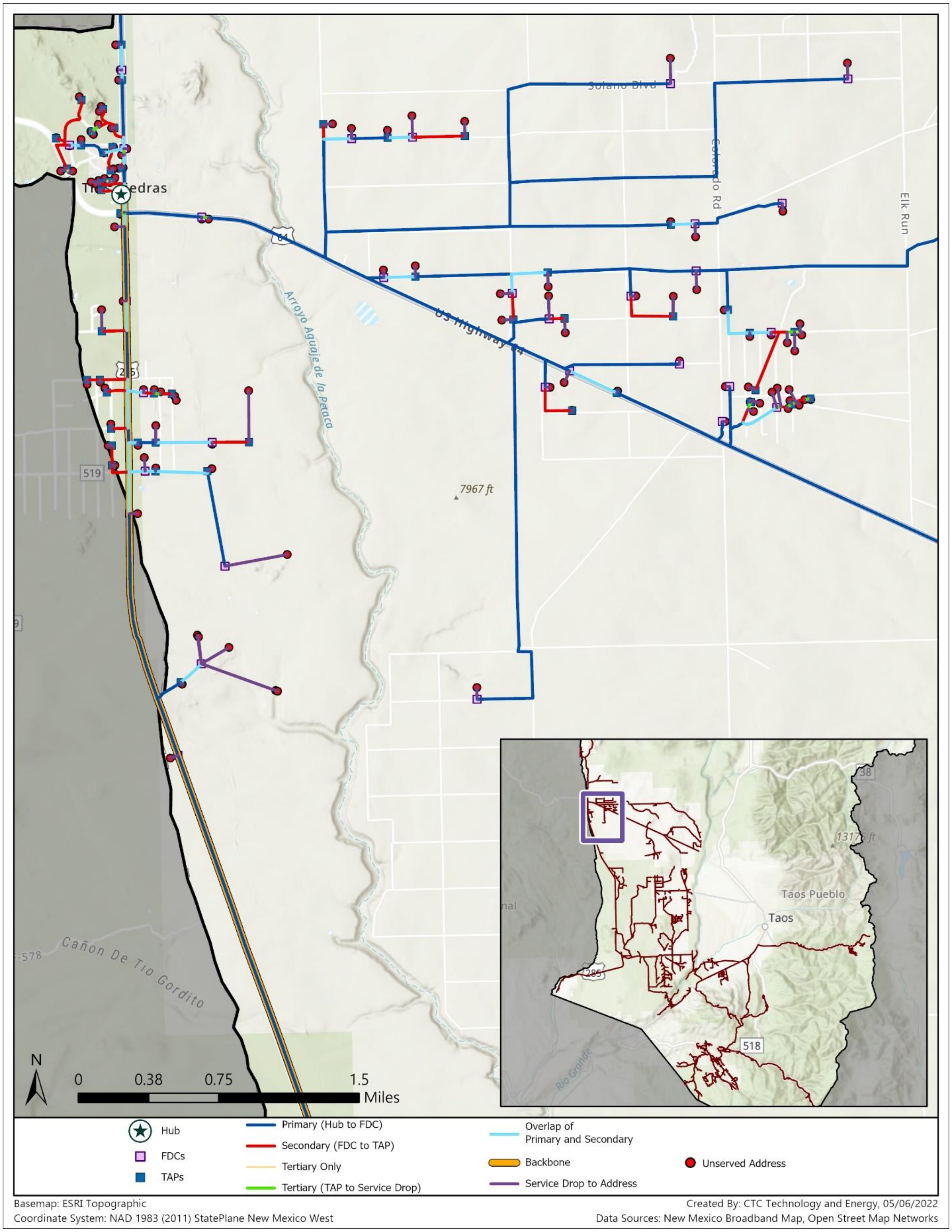


Figure 29: Very low density rural FTTP network close-up

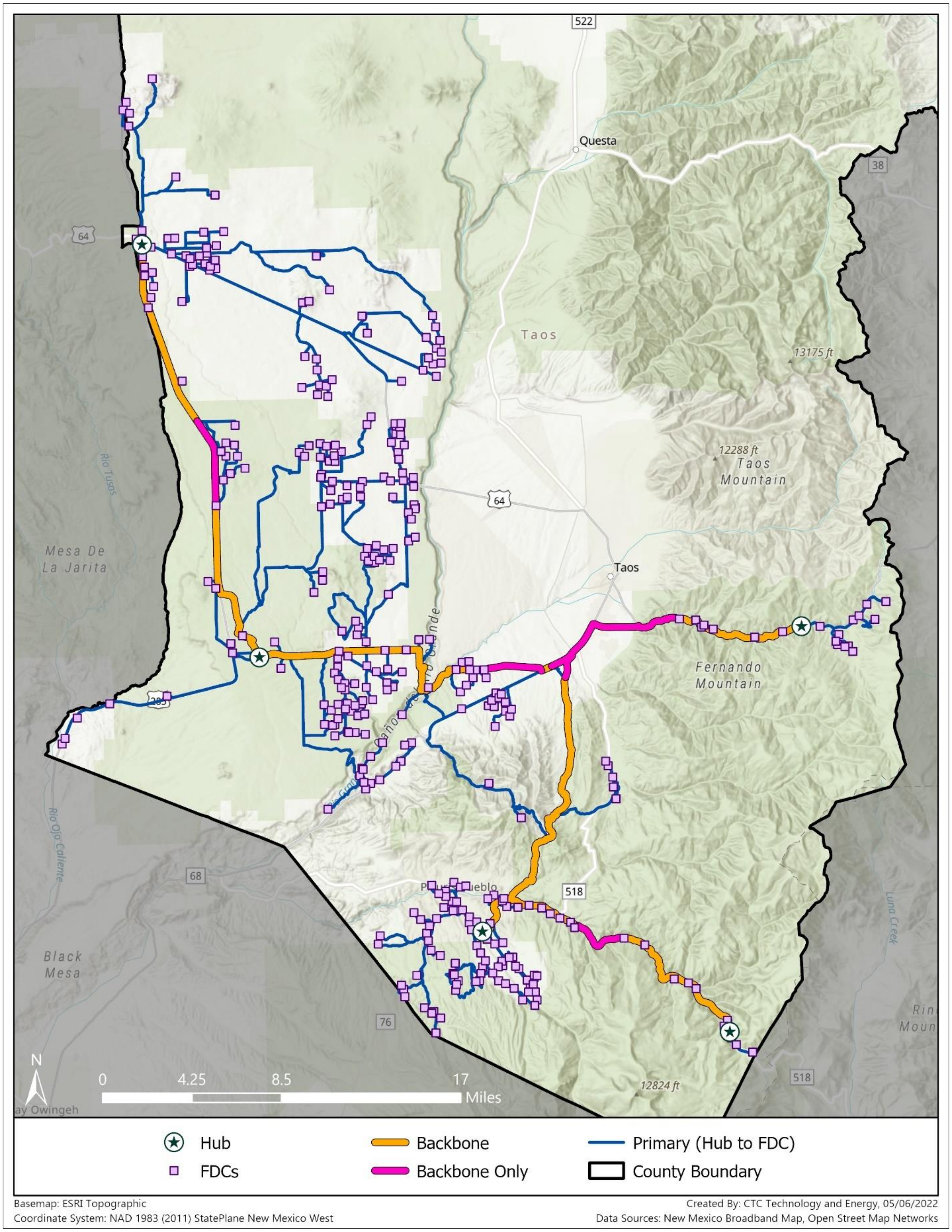
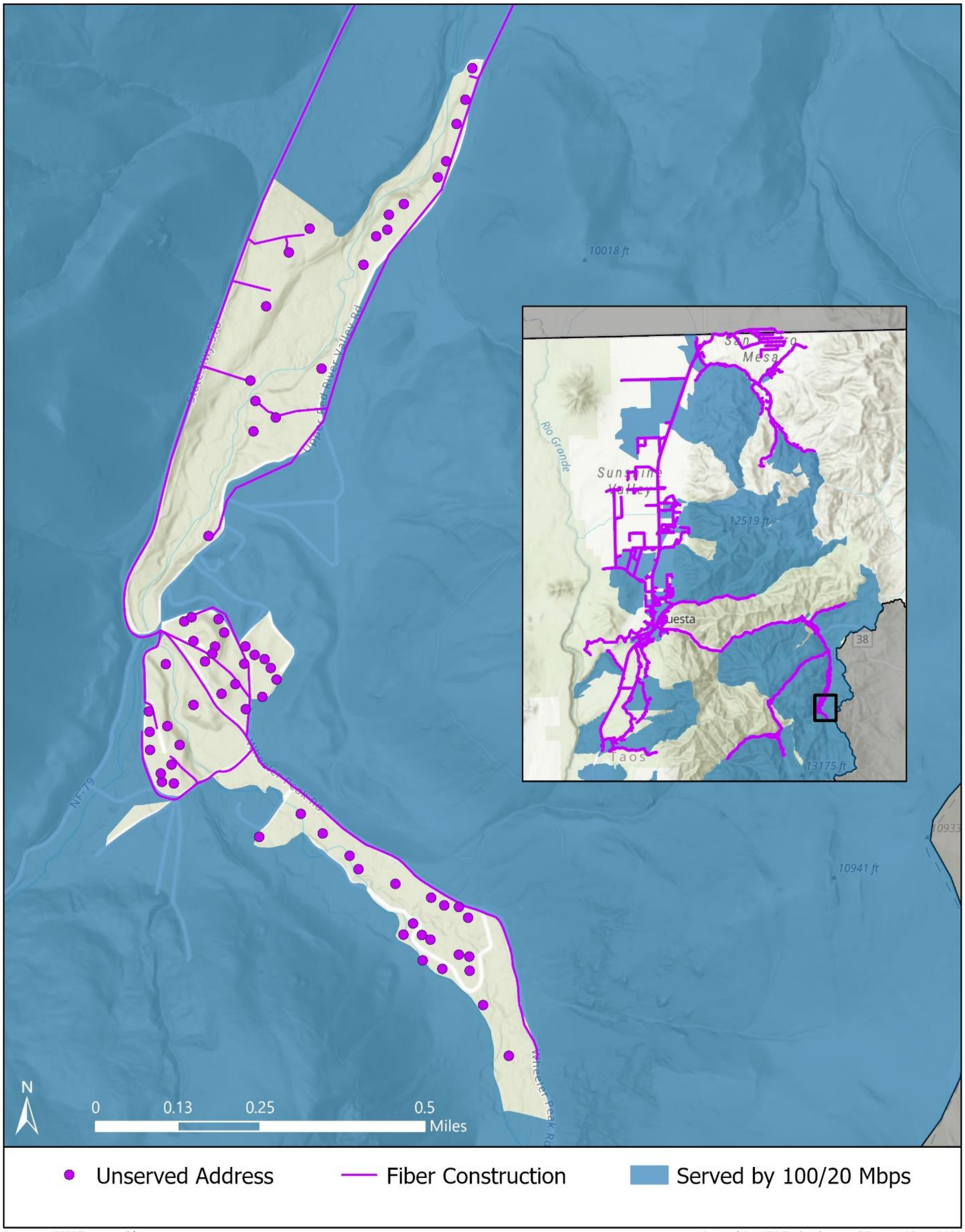


Figure 30: Low density rural FTTP network



Basemap: ESRI Topographic
Coordinate System: NAD 1983 (2011) StatePlane New Mexico West

Created By: CTC Technology and Energy, 05/11/2022
Data Sources: New Mexico Broadband Map, Open Street Map Networks

Figure 31: Low density rural FTTP network close-up

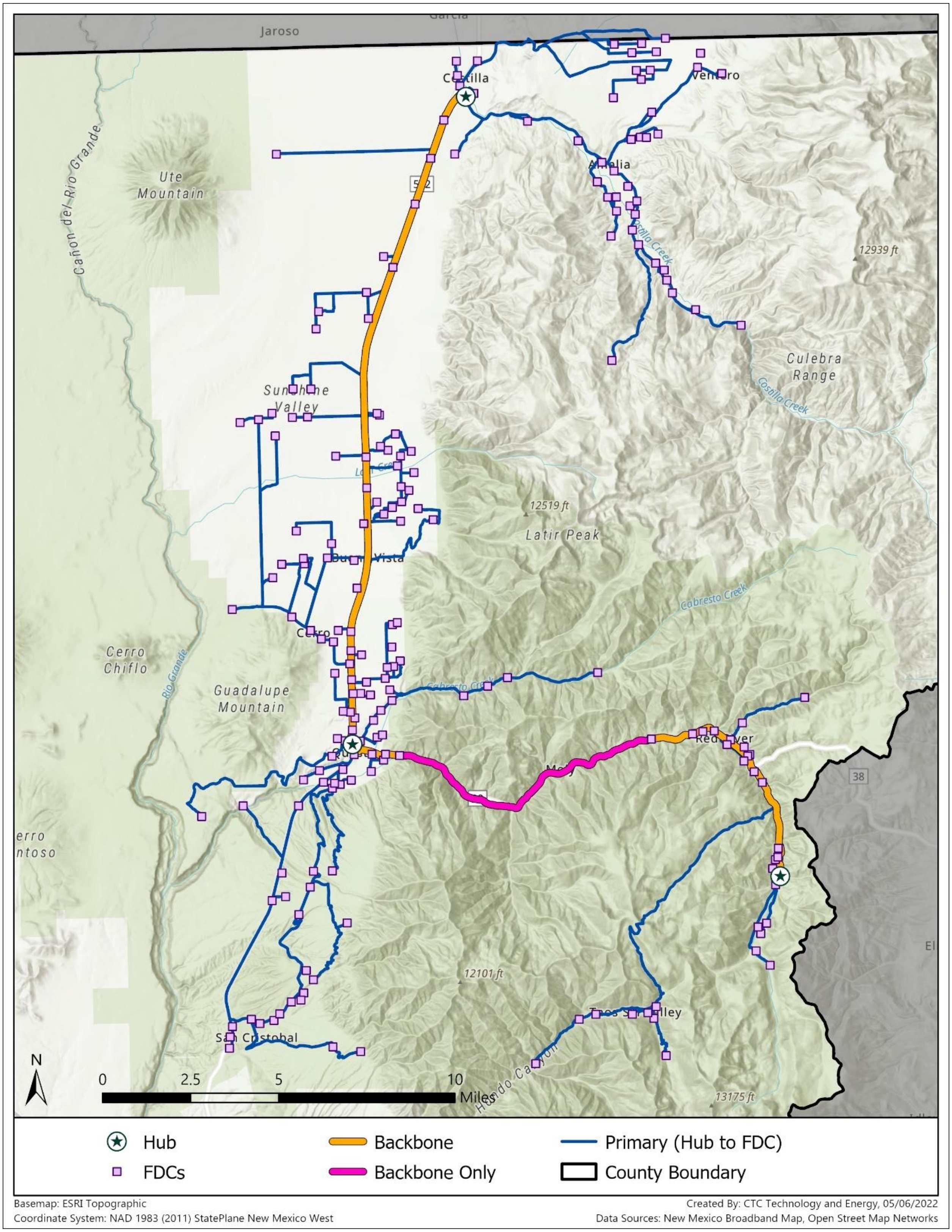


Figure 32: Low density rural FTTP network core components

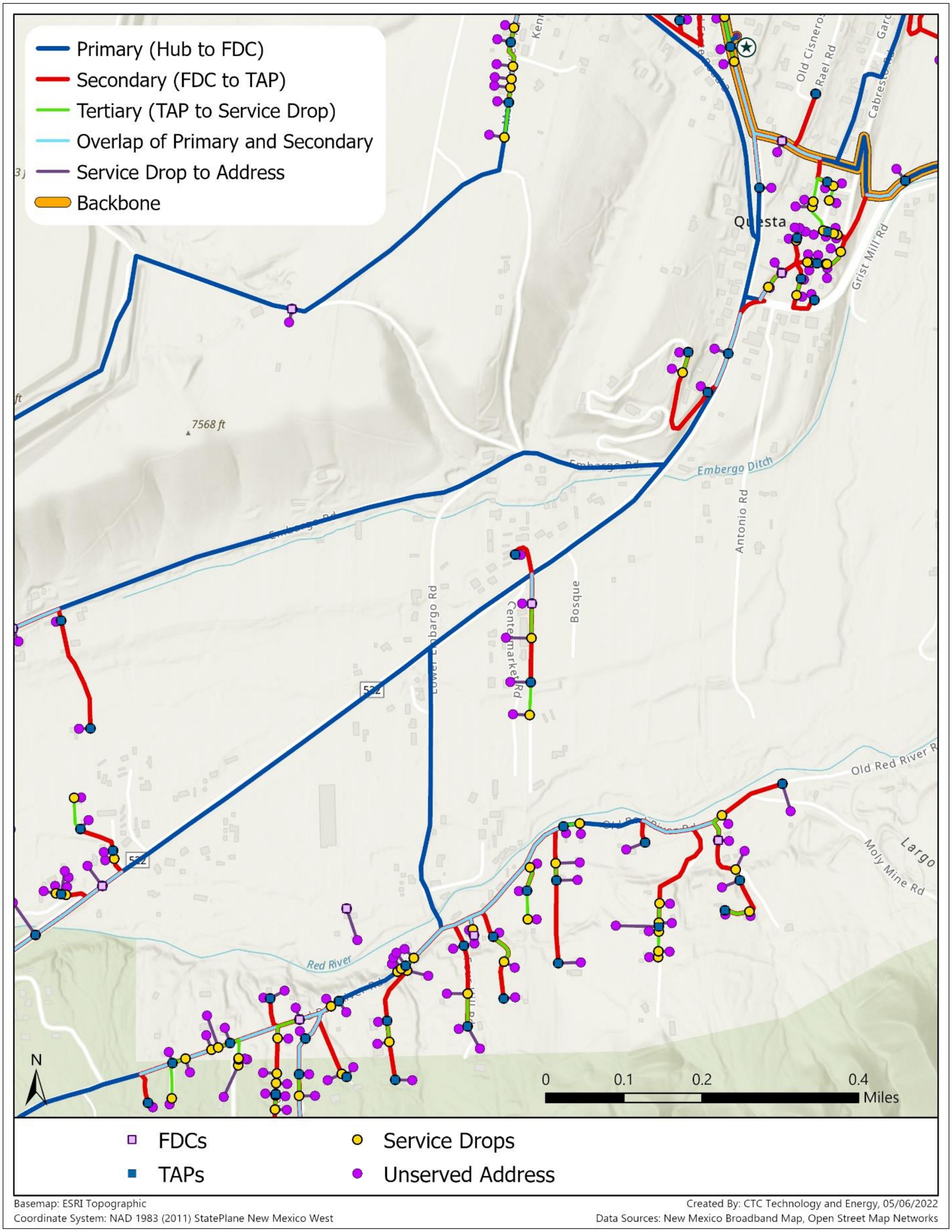


Figure 33: Medium density rural FTTP network core components

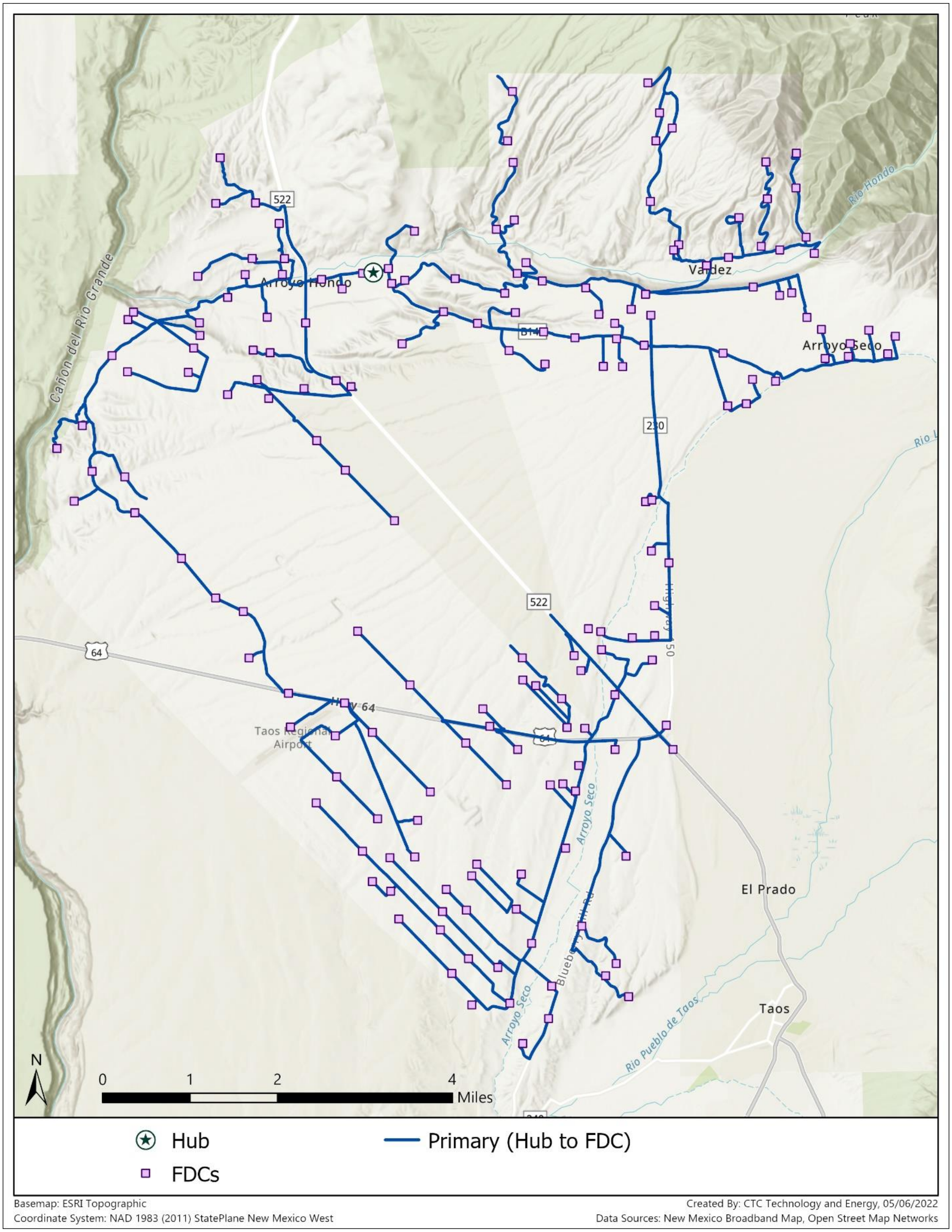
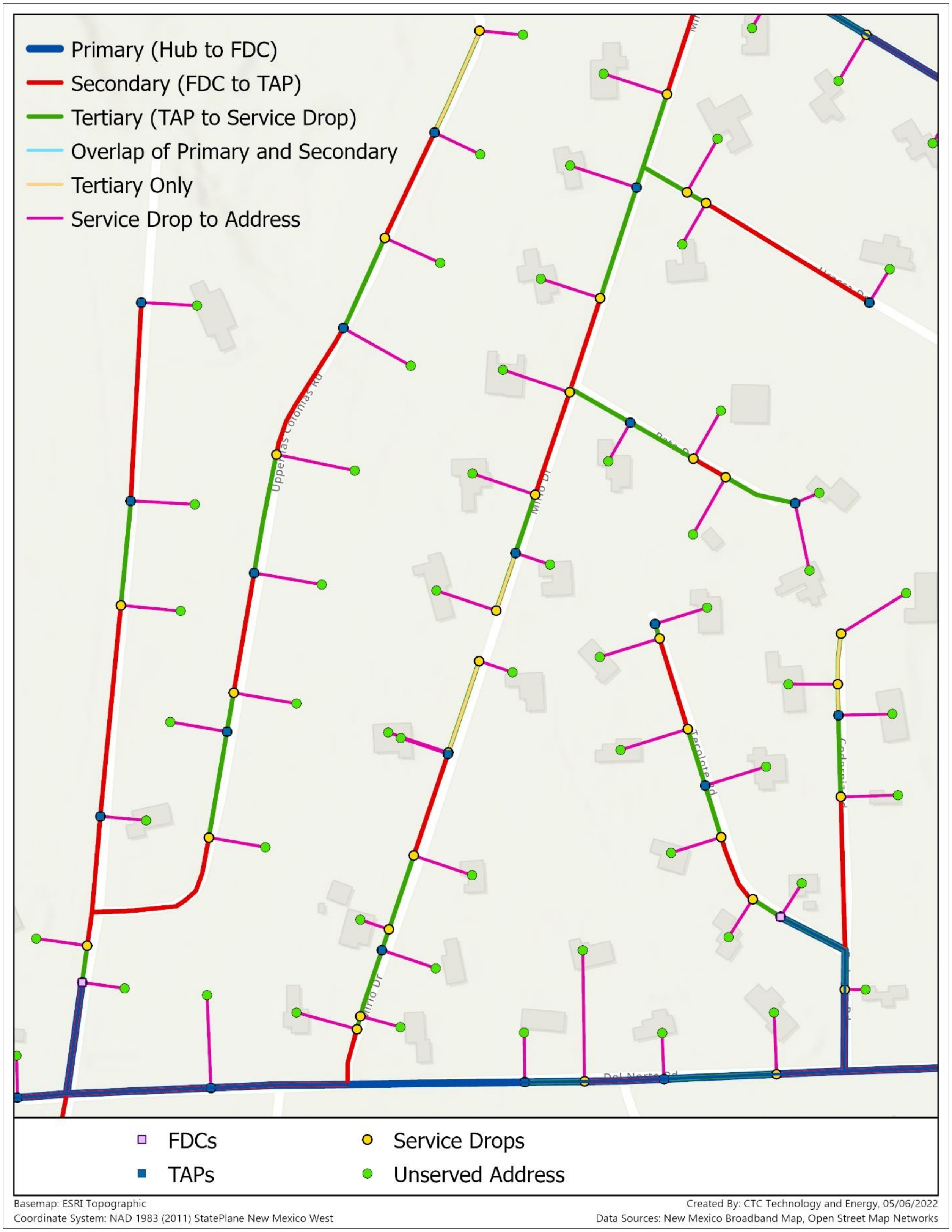


Figure 34: Medium density rural FTTP network close-up



Elements of capital costs

The construction cost of the fiber distribution plant includes the following elements:

Design

- **Engineering and as-builts** – includes system-level architecture planning, preliminary designs, and field walkouts to determine candidate fiber routing; development of detailed engineering prints and preparation of permit applications; and post-construction "as-built" revisions to engineering design materials.

Construction

- **Project management** – encompasses overall project and contract management, including oversight of the construction and engineering contractor(s), equipment suppliers, and right-of-way agreements; the model assumed a one-person project management team for three years to construct the entire county-wide network. This cost is only included on the countywide design and is excluded from the estimates for individual middle-mile segments and towns.

- **Conduit and vault infrastructure** – consists of all labor and materials related to underground communications conduit construction, including conduit placement, vault/handhole installation, and surface restoration; includes all work area protection and traffic control measures inherent to roadway construction activities.

- **Utility pole make-ready** – consists of the labor needed for preparing poles for the addition of new aerial cabling. This includes moving existing cables to make room for new cables or replacing poles if the existing pole is at maximum capacity.

- **Fiber optic cables and components** – consists of the material and labor costs specific to the installation of fiber optic cables, taps, splice enclosures, and other related components, irrespective of the cable pathway (underground conduit or aerial placement).

- **Fiber splicing, testing, and documentation** – includes all labor related to splicing of outdoor fiber optic cables.

- **Hub and active FDC facilities and systems** – consists of the material and labor costs of placing hub and active FDC shelters and enclosures; related hub systems (backup power generation, cooling systems, etc.); and terminating middle-mile fiber cables within the head end and active hub site.

Electronics

- **FTTP distribution network electronic**s – includes core network electronics such as switches, line cards, and splitters.

Customer installation

- **Subscriber drop costs** – consists of material for deploying on a subscriber's premises, such as aerial drop cables, underground conduit, and NIDs.
- **FTTP customer premises equipment** – includes the material and labor for installing customer premises equipment inside a subscriber's building.

Capital cost estimates

The pricing models summarized in the table below have been developed for the four regions individually and do not consider any potential economies of scale if they were implemented together. The cost elements reflect industry-typical values. Actual implementation costs could deviate from numbers used in the model based on local labor market situations and market-driven pricing exacerbated by supply-chain issues.

The cost model includes all electronic equipment required for customer service access but does not include core management systems, such as customer authentication or network management systems, which are functions typically hosted in cloud-based server farms.

The capital cost of the network is strongly dependent on the number of homes per fiber mile—and increases as population density decreases. In the small-town scenario with 28 homes per mile the implementation cost is approximately $2,620 (low-end) to $8,550 (high-end) per passing. Conversely, for the very low-density scenario with 4.8 homes per mile, the implementation cost is approximately $10,620 (low-end) to $42,370 (high-end).

Table 10: Estimated capital cost for candidate FTTP networks (low end)

Cost Element	Small Town	Medium Density	Low Density	Very Low Density
Design				
Engineering and As-builts	$3,850,000	$1,600,000	$2,850,000	$5,100,000
Construction				
Project Management	$600,000	$450,000	$450,000	$450,000
Conduit and Vault Infrastructure	$0	$0	$0	$0
Materials	*$0*	*$0*	*$0*	*$0*
Labor	*$0*	*$0*	*$0*	*$0*
Aerial Strand	$4,250,000	$1,750,000	$3,100,000	$5,600,000

Cost Element	Small Town	Medium Density	Low Density	Very Low Density
Materials	*$1,100,000*	*$450,000*	*$800,000*	*$1,450,000*
Labor	*$3,150,000*	*$1,300,000*	*$2,300,000*	*$4,150,000*
Utility Pole Make-ready	$1,800,000	$600,000	$1,050,000	$1,900,000
Fiber Optic Cables and Components	$6,000,000	$2,800,000	$4,650,000	$8,250,000
Materials	*$3,850,000*	*$1,900,000*	*$3,100,000*	*$5,500,000*
Labor	*$2,150,000*	*$900,000*	*$1,550,000*	*$2,750,000*
Fiber Splicing, Testing and Documentation	$750,000	$300,000	$350,000	$550,000
Hub and Active FDC Facilities and Systems	$250,000	$250,000	$300,000	$350,000
Electronics				
FTTP Distribution Network Electronics	$1,950,000	$450,000	$500,000	$450,000
Customer Installation				
Subscriber Drop Cost	$3,300,000	$950,000	$1,200,000	$1,450,000
FTTP Customer Premises Equipment	$3,150,000	$750,000	$800,000	$750,000
Total Capital Cost				
Total	$25,900,000	$9,900,000	$15,250,000	$24,850,000
Total per Passing	$2,620	$4,340	$6,240	$10,620

Table 11: Estimated capital cost for candidate FTTP networks (high end)

Cost Element	Small Town	Medium Density	Low Density	Very Low Density
Design				
Engineering and As-builts	$5,800,000	$2,400,000	$4,200,000	$7,500,000
Construction				
Project Management	$600,000	$450,000	$450,000	$450,000
Conduit and Vault Infrastructure	$58,600,000	$24,800,000	$43,000,000	$76,700,000
Materials	*$7,900,000*	*$3,400,000*	*$5,700,000*	*$10,000,000*
Labor	*$50,700,000*	*$21,400,000*	*$37,300,000*	*$66,700,000*
Aerial Strand	$0	$0	$0	$0
Materials	*$0*	*$0*	*$0*	*$0*
Labor	*$0*	*$0*	*$0*	*$0*
Utility Pole Make-ready	*$0*	*$0*	*$0*	*$0*
Fiber Optic Cables and Components	$6,600,000	$3,150,000	$5,400,000	$9,750,000

Cost Element	Small Town	Medium Density	Low Density	Very Low Density
Materials	*$3,050,000*	*$1,450,000*	*$2,550,000*	*$4,600,000*
Labor	*$3,550,000*	*$1,700,000*	*$2,850,000*	*$5,150,000*
Fiber Splicing, Testing and Documentation	$450,000	$100,000	$150,000	$150,000
Hub and Active FDC Facilities and Systems	$250,000	$250,000	$300,000	$350,000
Electronics				
FTTP Distribution Network Electronics	$1,950,000	$450,000	$500,000	$450,000
Customer installation				
Subscriber Drop Cost	$7,000,000	$2,550,000	$1,950,000	$3,000,000
FTTP Customer Premises Equipment	$3,150,000	$750,000	$800,000	$750,000
Total Capital Cost				
Total	$84,400,000	$34,900,000	$56,750,000	$99,100,000
Total per Passing	$8,550	$15,310	$23,210	$42,370

Operating cost estimates

Operating costs include the following elements:

Maintenance

- Pole attachment fees are $20 per utility pole per year.
- Underground locates are estimated to be $600 per fiber route mile per year based on industry samples for rural and suburban situations. The cost of locates is dependent on the rate of underground construction activity by building construction and utility companies. In rural environments, where underground construction is less frequent, locates can have a significantly lower cost per mile than in metropolitan areas.
- Fiber cable repairs are factored in at $600 per year per fiber route mile.
- Maintenance of distribution electronics is assumed to be 15 percent of the purchase price per year.
- Due to the small scale of each of the medium, low, and very low-density scenarios, one service technician for electronics is assumed in each region. The small-town scenario assumes four technicians due to the larger number of subscribers.
- One fiber and plant O&M technician per 200 miles of plant.

- One service technician per 2,500 customers.

Staff

- Staffing for business management. The model assumes the business management, fiber technicians, and network technicians to be able to fulfil more than one specific job responsibility, which is quite common in the industry.

- Billing and customer service is a function of subscriber count and estimated at $18 per subscriber per year.

- Power is $0.12 per kWh. Power consumption depends on the number of active plant elements. For the scenarios of medium, low density, and very low density, power requirements are estimated at 5 kW, 7 kW, and 10 kW, respectively.

Replacement

- A funded depreciation of the fiber infrastructure for complete replacement after 50 years of operation is on a linear schedule. Fiber infrastructure lifespan cannot be determined solely by statistics of empirical data, as the history of fiber optics is only 40 years old. Therefore, a lifespan of 50 years may be conservative.

- Funded depreciation for electronic equipment and replacement has a 10-year linear depreciation schedule.

Leases

- Hub space lease for distribution electronics is estimated at $500 per month.

Wholesale Internet

- Commodity internet service pricing and accompanying transport from data centers varies greatly and depends to a large extent on the volume commitment and the location of the last mile provider as well as particulars of the service level agreement between provider and customer. For the model, a high-end cost of $5 per Mbps per month and a low-end cost of $0.375 per Mbps per month are used. The average capacity per subscriber for a large sample of internet users ranges industry-wide between 2.5 Mbps and 4.5 Mbps during peak usage times.

Table 12: Estimated annual operating costs for candidate FTTP network (low end)

Cost Element	Small Town	Medium Density	Low Density	Very Low Density
Maintenance				
Underground Locates	$0	$0	$0	$0
Pole Attachment Fees	$180,000	$80,000	$130,000	$240,000
Repairs	$220,000	$90,000	$160,000	$290,000
Fiber and Plant O&M Technician	$120,000	$120,000	$120,000	$120,000
Distribution Network Maintenance	$160,000	$37,000	$41,000	$39,000
Service Technicians	$390,000	$100,000	$100,000	$100,000
Maintenance Total	***$1,070,000***	***$427,000***	***$551,000***	***$789,000***
Staff				
Operations Staff	$130,000	$130,000	$130,000	$130,000
Billing and CSR Services	$180,000	$41,000	$44,000	$42,000
Insurance	$20,000	$10,000	$15,000	$20,000
Utilities	$6,000	$5,000	$8,000	$11,000
Office Expenses	$15,000	$15,000	$15,000	$15,000
Billing Maintenance Contract	$10,000	$10,000	$10,000	$10,000
Legal Fees	$25,000	$10,000	$10,000	$10,000
Consulting	$25,000	$25,000	$25,000	$25,000
Marketing	$25,000	$25,000	$25,000	$25,000
Education and Training	$10,000	$10,000	$10,000	$10,000
Customer Billing	$35,000	$5,000	$5,000	$5,000
Customer Churn	$30,000	$8,000	$9,000	$8,000
Staff Total	***$511,000***	***$294,000***	***$306,000***	***$311,000***
Replacement				
Funded Depreciation of Electronics	$160,000	$40,000	$40,000	$40,000
Depreciation, Plant	$350,000	$155,000	$255,000	$444,000
Replacement Total	***$510,000***	***$195,000***	***$295,000***	***$484,000***
Leases				
Hub Space Lease	$6,000	$6,000	$6,000	$6,000
Wholesale Internet				
Commodity Internet Capacity	$155,000	$36,000	$39,000	$37,000
Total Annual Operating Costs				
Total	**$2,252,000**	**$958,000**	**$1,197,000**	**$1,627,000**
Total per Subscriber	**$230**	**$420**	**$490**	**$700**

Table 13: Estimated annual operating costs for candidate FTTP network (high end)

Cost Element	Small Town	Medium Density	Low Density	Very Low Density
Maintenance				
Underground Locates	$440,000	$180,000	$320,000	$570,000
Pole Attachment Fees	$0	$0	$0	$0
Repairs	$220,000	$90,000	$160,000	$290,000
Fiber and Plant O&M Technician	$120,000	$120,000	$120,000	$120,000
Distribution Network Maintenance	$160,000	$37,000	$41,000	$39,000
Service Technicians	$390,000	$100,000	$100,000	$100,000
Maintenance Total	***$1,330,000***	***$527,000***	***$741,000***	***$1,119,000***
Staff				
Operations Staff	$130,000	$130,000	$130,000	$130,000
Billing and CSR Services	$180,000	$41,000	$44,000	$42,000
Insurance	$70,000	$30,000	$55,000	$95,000
Utilities	$6,000	$5,000	$8,000	$11,000
Office Expenses	$15,000	$15,000	$15,000	$15,000
Billing Maintenance Contract	$10,000	$10,000	$10,000	$10,000
Legal Fees	$25,000	$10,000	$10,000	$10,000
Consulting	$25,000	$25,000	$25,000	$25,000
Marketing	$25,000	$25,000	$25,000	$25,000
Education and Training	$10,000	$10,000	$10,000	$10,000
Customer Billing	$35,000	$5,000	$5,000	$5,000
Customer Churn	$30,000	$8,000	$9,000	$8,000
Staff Total	***$561,000***	***$314,000***	***$346,000***	***$386,000***
Replacement				
Funded Depreciation of Electronics	$160,000	$40,000	$40,000	$40,000
Depreciation, Plant	$1,446,000	$623,000	$1,070,000	$1,898,000
Replacement Total	***$1,606,000***	***$663,000***	***$1,110,000***	***$1,938,000***
Leases				
Hub Space Lease	$6,000	$6,00	$6,000	$6,000
Wholesale Internet				
Commodity Internet Capacity	$2,073,000	$479,000	$513,000	$490,000
Total Annual Operating Costs				
Total	**$5,576,000**	**$1,989,000**	**$2,716,000**	**$3,939,000**
Total per Subscriber	**$570**	**$870**	**$1,110**	**$1,680**

Appendix B: Rural fixed wireless designs and cost estimates

Conceptual, high-level fixed wireless network designs were developed for a small town (Deming, N.M.) and a rural county comprised of areas with varying population densities (Taos County, N.M.) as the basis for estimating the networks' capital and operating costs.

Network objectives and design assumptions

Each of the two candidate designs had common key network objectives and design assumptions. The key objectives include:

- **Delivering at least 100 Mbps download and 20 Mbps upload (100/20 Mbps)** to align with what many federal and state agencies and departments define as the speed needed for adequate service
- **Achieving consistent capacity** – the network should deliver advertised speeds, even at peak times
- **Delivering a highly available service** – the network should have high levels of reliability and resiliency
- **Use a 5G Massive MIMO fixed wireless technology to support higher speeds and have wider coverage than LTE-based wireless systems**
- **Serving 100 percent of unserved locations** while providing broadband speeds at consistent capacity with highly available service.

Accordingly, the network design and cost estimates assume the network will:

- Provide consistent speeds of at least 100/20 Mbps
- Use 5 GHz unlicensed spectrum due to the lack of availability of licensed spectrum. The subsequent section goes into more detail about how spectrum used impacts a fixed wireless network.
- Use existing towers to expand coverage
- Use off-the-shelf fixed wireless network equipment
- Use a point-to-multipoint topology, suitable for a network providing services to a residential area
- Use wireless backhaul that provides adequate capacity and speeds
- Serve as many locations as possible

- An oversubscription factor of 20 is used thus resulting in an overall load of 5 Mbps per address for wholesale internet use

Beamforming and massive MIMO technology

To achieve the 100/20 Mbps requirements for fixed wireless to a large number of addresses, spectral efficiencies above what is available in conventional LTE technologies must be employed. The technology chosen for this analysis is a beamforming, high-bandwidth solution currently available on the market that uses beamforming and very large multiple-input and multiple output (MIMO) or massive MIMO.

Beamforming is a type of radio frequency management in which a wireless signal is directed toward a specific receiving device, instead of spreading out uniformly. Massive MIMO enables the delivery of multipath beams from a single antenna to create several simultaneous beams, thus increasing system capacity.

Beamforming and massive MIMO were incorporated by segmenting the sector area into four beam areas. Beamforming and massive MIMO can improve the throughput to the end user device as well as improve sector level capacity.

Base station locations

Fixed wireless broadband is delivered via access point antennas at a base station (typically mounted on towers, masts, monopoles, or rooftops) to a subscriber antenna. Subscriber antennas (at a home or other building) can be located indoors or outdoors depending on the distance to the access point antenna and the amount of "clutter" between the subscriber antenna and the access point antenna. Clutter includes obstructions such foliage, buildings and terrain. Weather events such as rain and fog can also impact the performance of a wireless transmission.

The network was designed using information from a publicly available database. Locations were selected to obtain the best physical distribution across the service area and to emphasize taller structures. Coverage was modeled for each location so that users within the coverage area would receive a sustained throughput of 100 Mbps download and 20 Mbps upload speeds.

As discussed in Section 3, a single site could cover most addresses in the small town, but this design would not provide sufficient capacity at the addresses. Therefore, additional sites were added to provide additional capacity. The design was optimized by removing sites to reduce overlap and interference and kept the sites that covered the most addresses. In the southern part of the town, the existing sites in the database do not provide sufficient capacity, so several new towers must be constructed.

In the medium, low, and very low-density rural areas, sites were systematically added one by one to the design to expand coverage. As sites are added the number of serviceable addresses increases—however, as the process is continued, the resulting number of additional households covered is diminished. To attain the coverage objective of 100 percent address coverage the model added new towers. It is significant the overwhelming majority of the tower construction cost serves 20 percent or fewer of the addresses in the area.

Coverage

The coverage area of an access point for any wireless network is typically determined by the spectrum, technology, (allowable) power, receiver gain, equipment, antenna pattern, antenna physical configuration, and clutter. Capacity, or number of users with suitable service, in a wireless network is primarily limited by the bandwidth of the spectrum in use, as well as these other characteristics.

The design was developed using the Longley-Rice type propagation model (typical for modeling coverage in irregular terrain) with 10-meter resolution and the following assumptions to simulate a "real world" scenario:[43]

- A single 80 MHz CBRS channels at 3.6 GHz
- Three-sector antenna at site (typical)
- Antenna tilted down
- Configuration parameters that represent the technology being modeled
- EIRP (signal level) that compensates for other users on the spectrum

Using the above parameters and our stated assumptions, the model led to an estimated number of addresses within the coverage range of the selected sites that could be served with broadband (100 Mbps download/20 Mbps upload by the FCC standard).

The maps below illustrate the fixed wireless network coverage for the town and the rural areas.

[43] Three-sector antenna at site with antenna tilted down; standard 5G configuration parameters; and EIRP (signal level) that compensates for other users on the spectrum.

Figure 35: Rural fixed wireless coverage (small town)

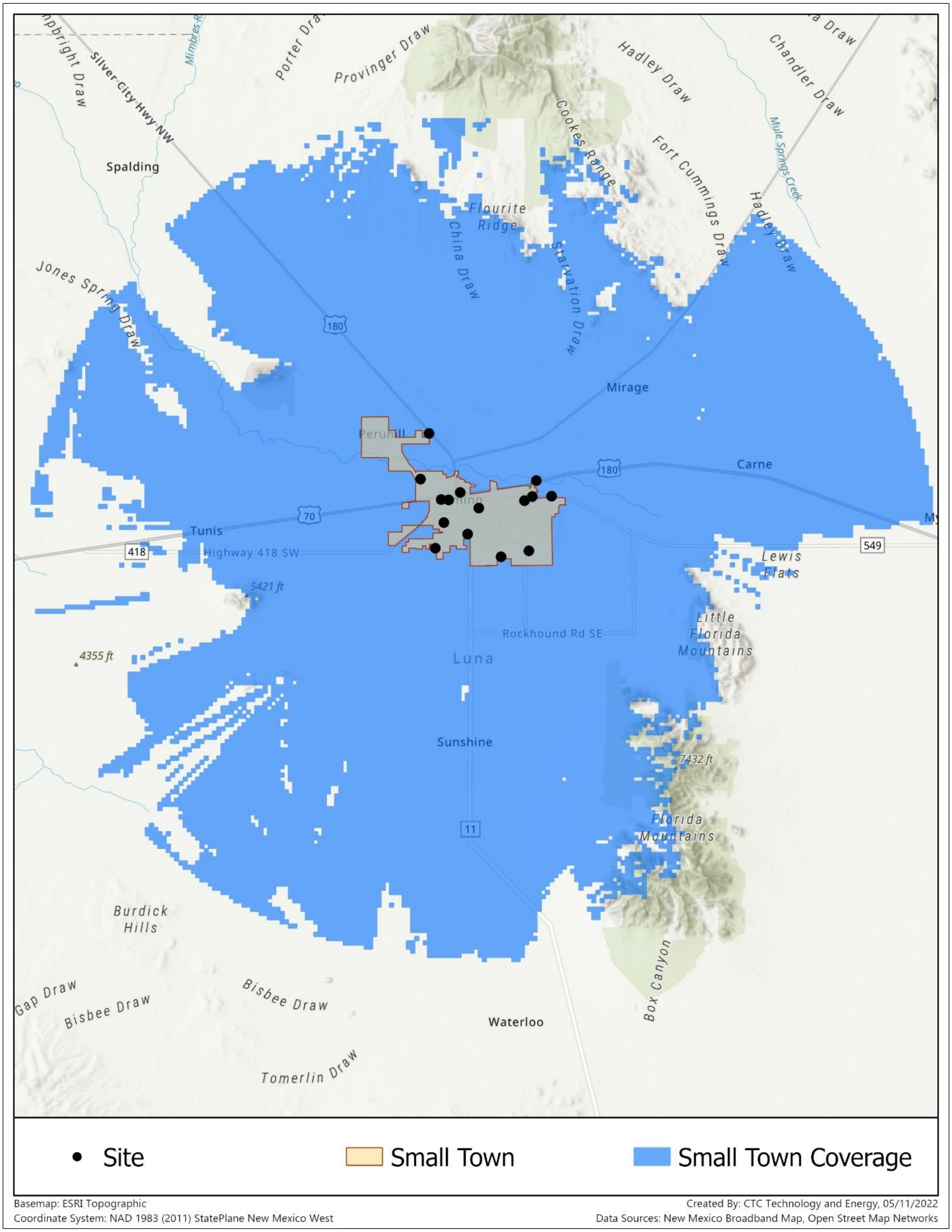
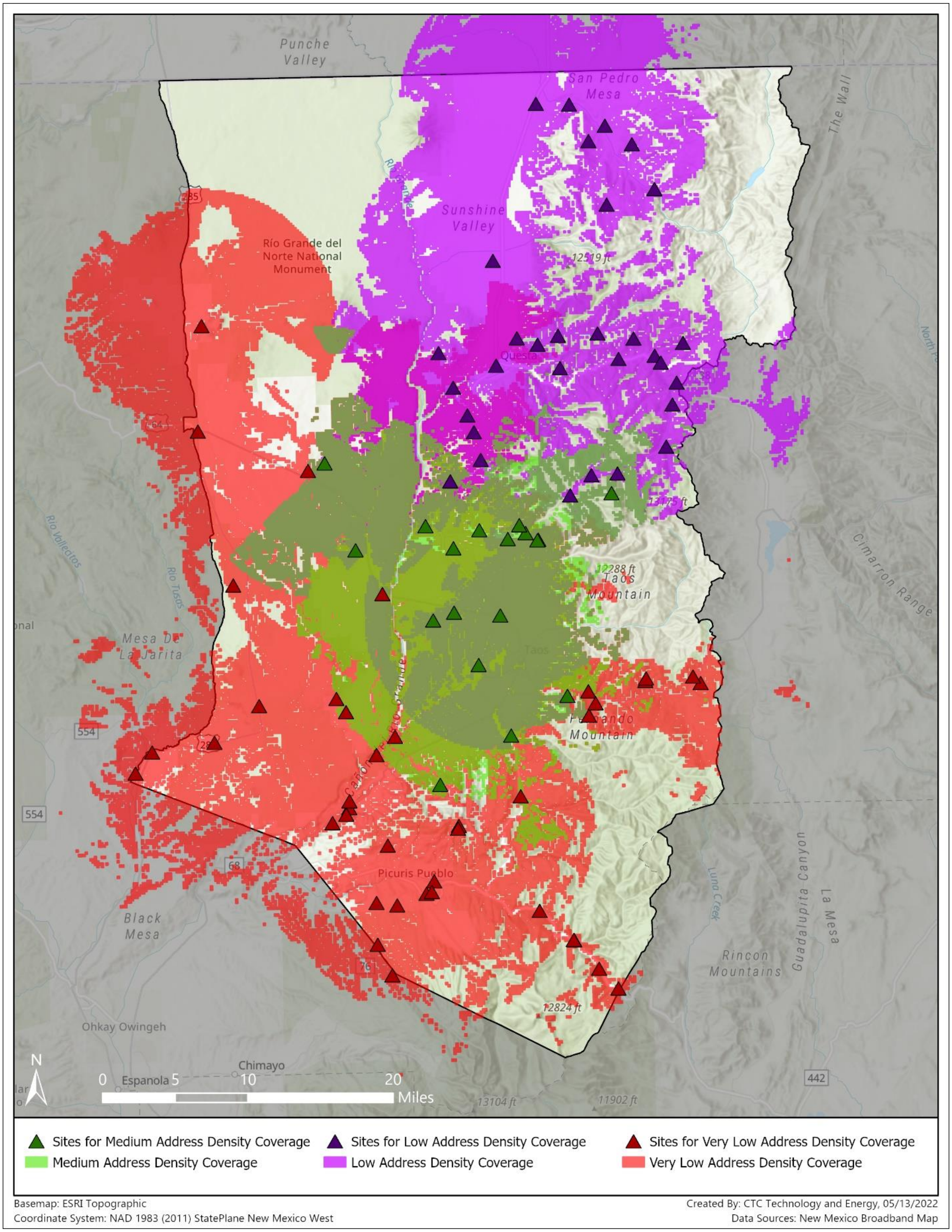


Figure 36: Rural fixed wireless coverage (medium, low, and very low density)



Access points and customer premises equipment (CPE)

Fixed wireless broadband is delivered via access point antennas (typically mounted on towers, masts, monopoles, or rooftops) to a subscriber antenna at the customer premises. Subscriber antennas (at a home or other building) can be located indoors or outdoors depending on the distance to the access point antenna and the amount of "clutter" between the subscriber antenna and the access point antenna. Clutter includes obstructions such as trees and their foliage and buildings. Weather events such as rain and fog can also impact the performance of a wireless transmission. Line-of-sight between the two antennas is ideal.

Outdoor subscriber antennas will have better reception and transmission capabilities than antennas located indoors because the signal does not have to penetrate the building's outer wall. Outdoor antennas may be attached to a building or a mast on the premises; Figure 2 shows a scenario where subscribers have placed the antennas on their roofs.

The technology used for our analysis uses a mixture of indoor and outdoor CPEs. For user locations with exceptional coverage, an indoor self-installed CPE is considered. The outdoor CPEs are often more expensive but, in addition to better connection to an access point, employ weatherproofing and ruggedized reinforcements to better withstand all four seasons. Each of the CPE's includes a Wi-Fi router, typically resembling a hotspot provided by a mobile provider, communicating with end user devices.

Wireless backhaul

The backhaul network is assumed to be a wireless network with a ring topology. A ring network is a network topology in which base stations are connected to only two other terminals at a time in a closed loop configuration.

The network assumes a mix of 18 GHz microwave and 80 GHz E-band point-to-point radios for backhaul. The backhaul ring can operate at speeds of approximately 1 Gbps to 10 Gbps. Detailed individual path analyses were not performed. This model was generated for cost estimation purposes. In a real-life deployment, there would be a mixture of technologies specific to the area.

Appendix C: Fixed wireless cost analyses by density (estimated)

Small town – low-end fixed wireless cost analysis

Figure 37: Small town – low-end fixed wireless capex (per passing)

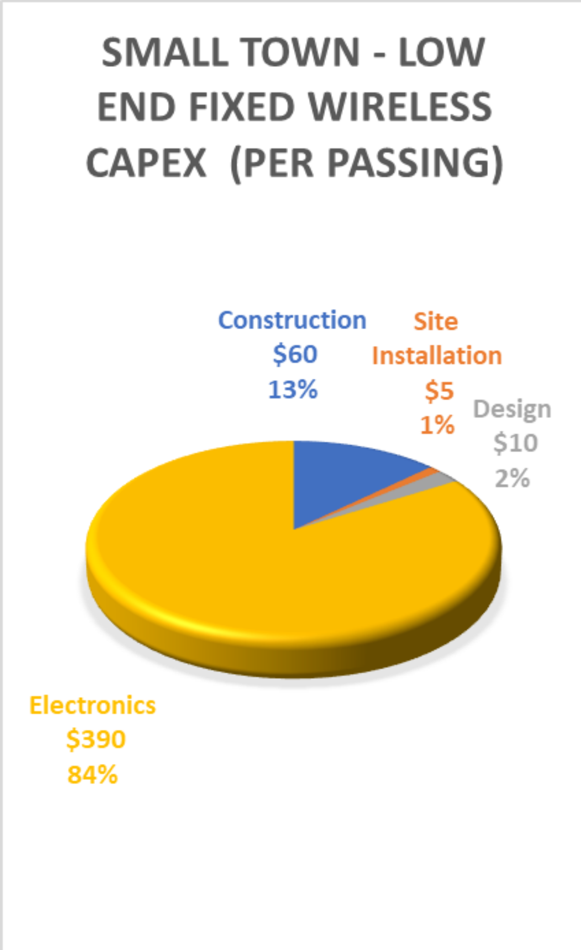


Figure 38: Small town – low-end fixed wireless annual opex (per passing)

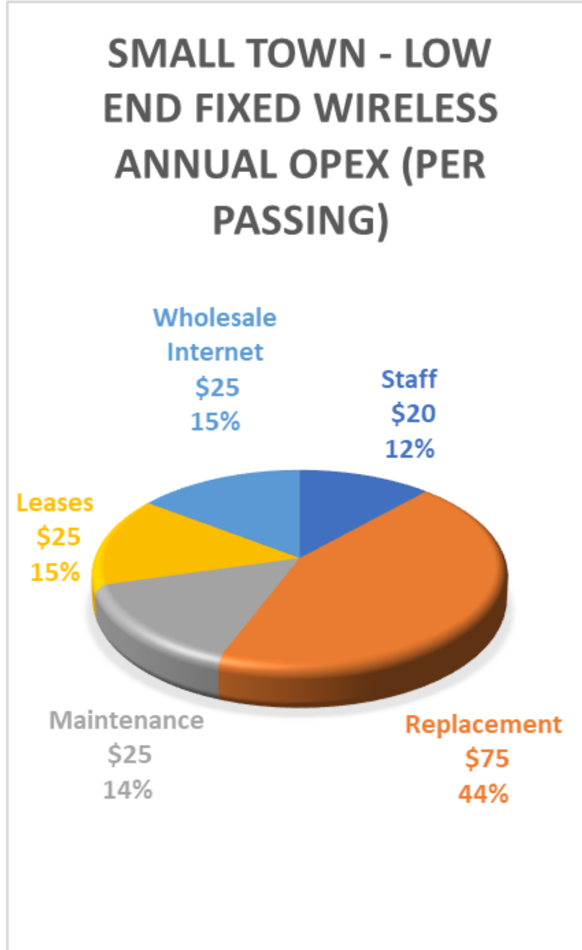
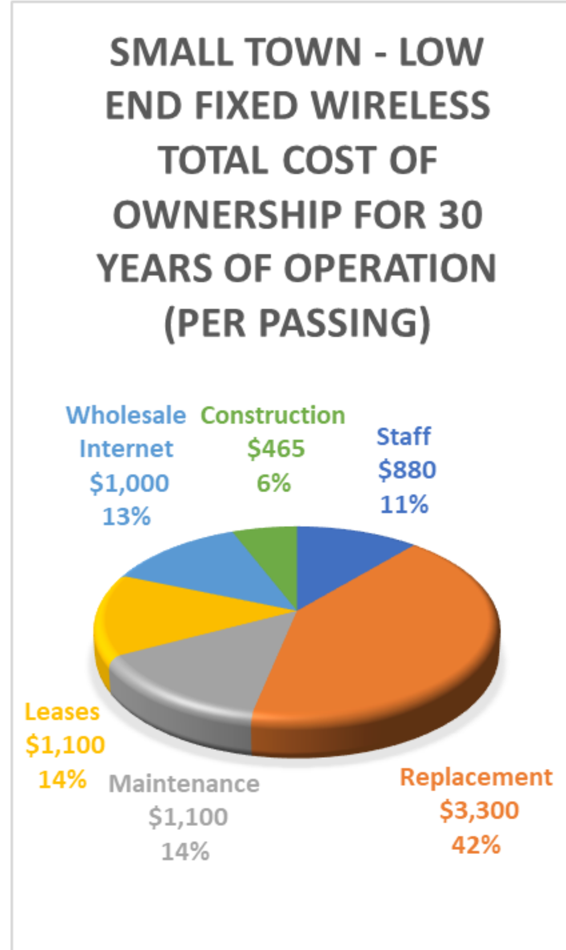


Figure 39: Small town – low-end fixed wireless total cost of ownership (30 years, per passing)



Small town – high-end fixed wireless cost analysis

Figure 40: Small town – high-end fixed wireless capex (per passing)

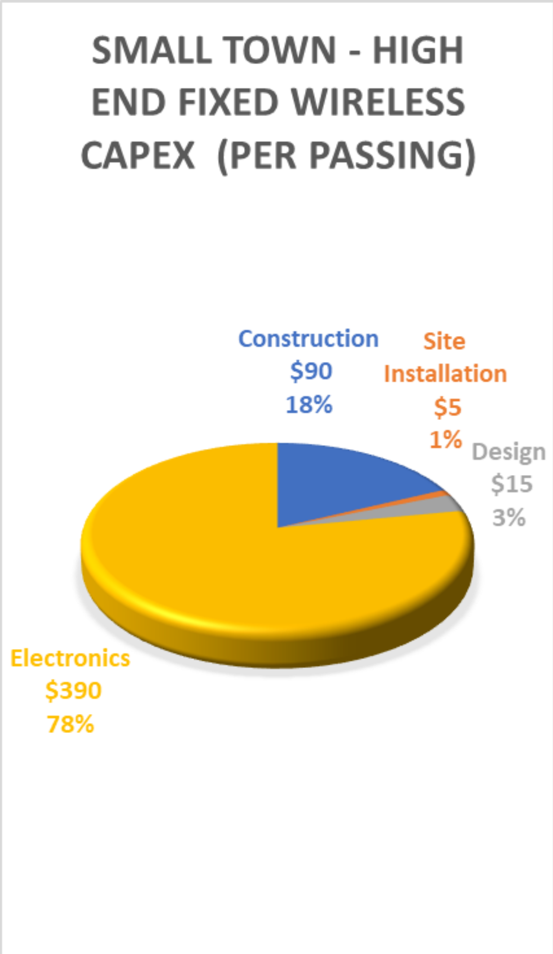


Figure 41: Small town – high-end fixed wireless annual opex (per passing)

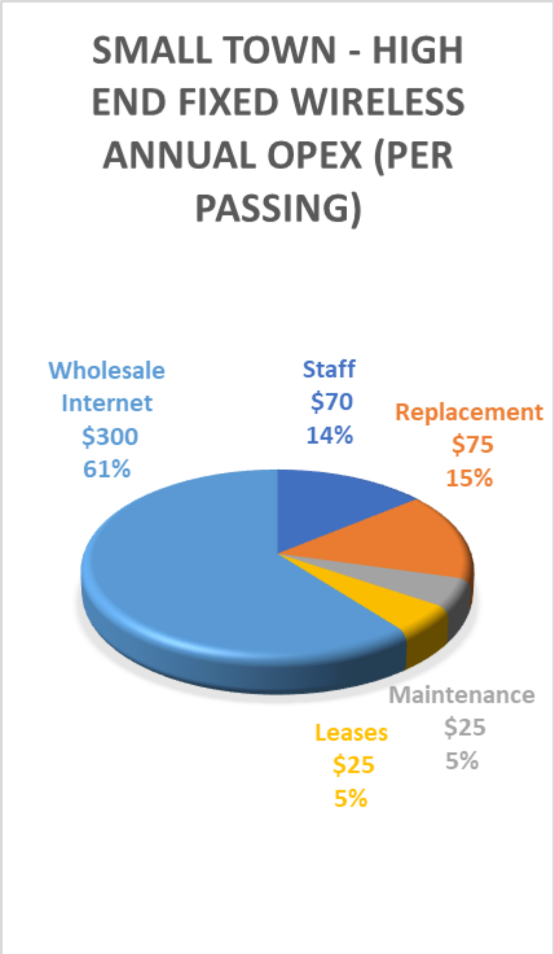
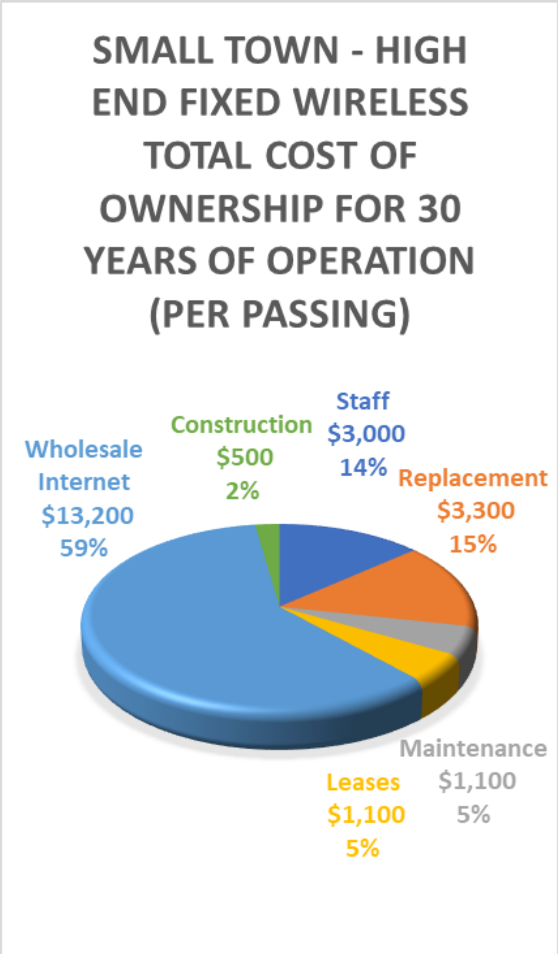


Figure 42: Small town – high-end fixed wireless total cost of ownership (30 years, per passing)



Medium density – low-end fixed wireless cost analysis

Figure 43: Medium density rural – low-end fixed wireless capex (per passing)

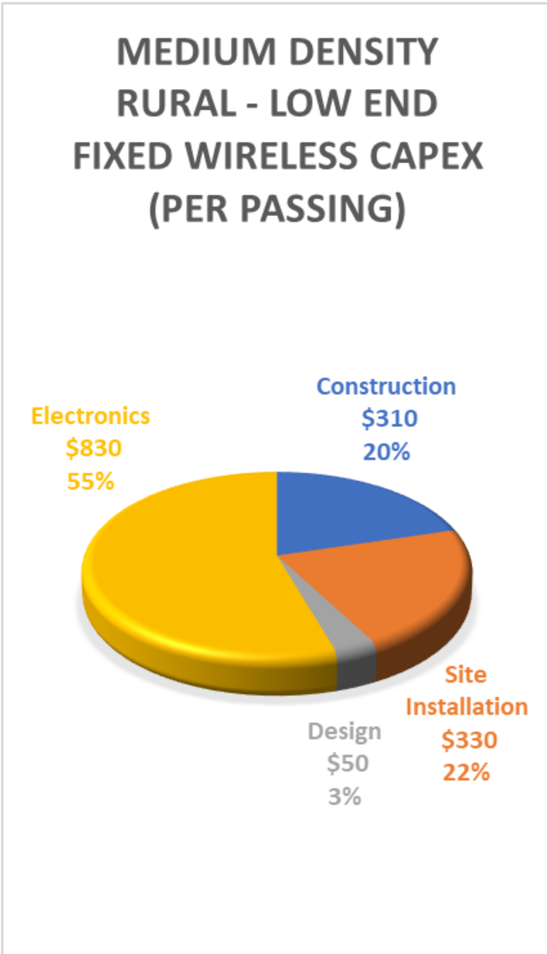


Figure 44: Medium density rural – low-end fixed wireless annual opex (per passing)

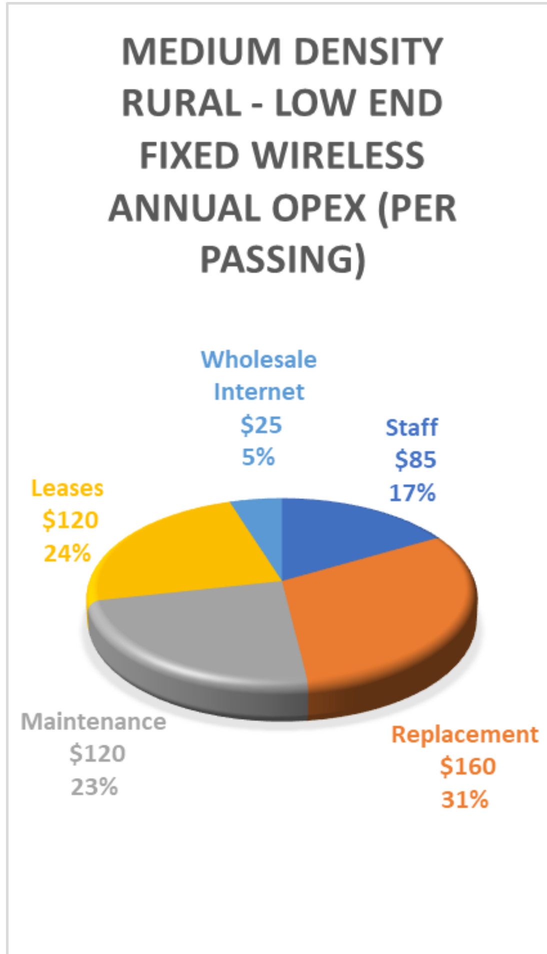
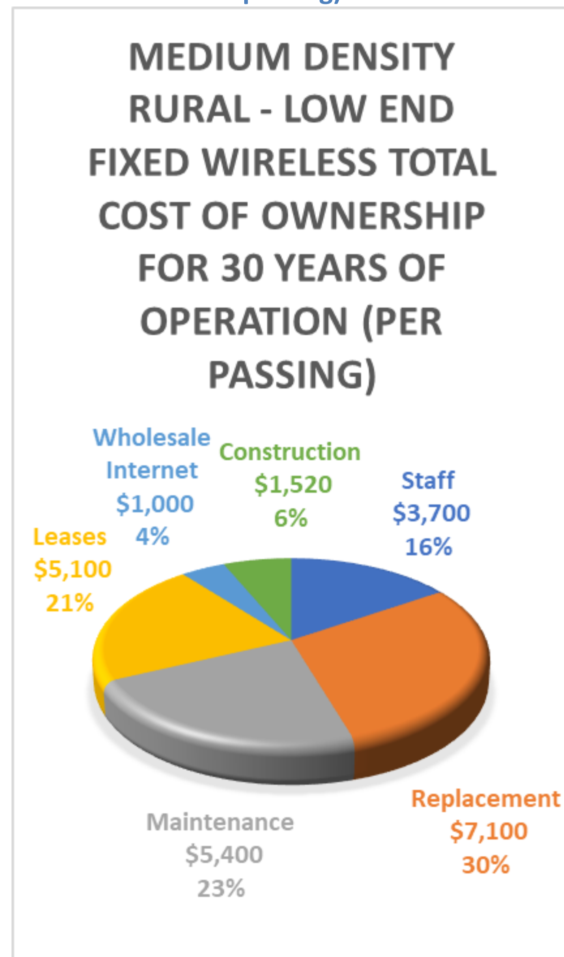


Figure 45: Medium density rural – low-end fixed wireless total cost of ownership (30 years, per passing)



Medium density – high-end fixed wireless cost analysis

Figure 46: Medium density rural – high-end fixed wireless capex (per passing)

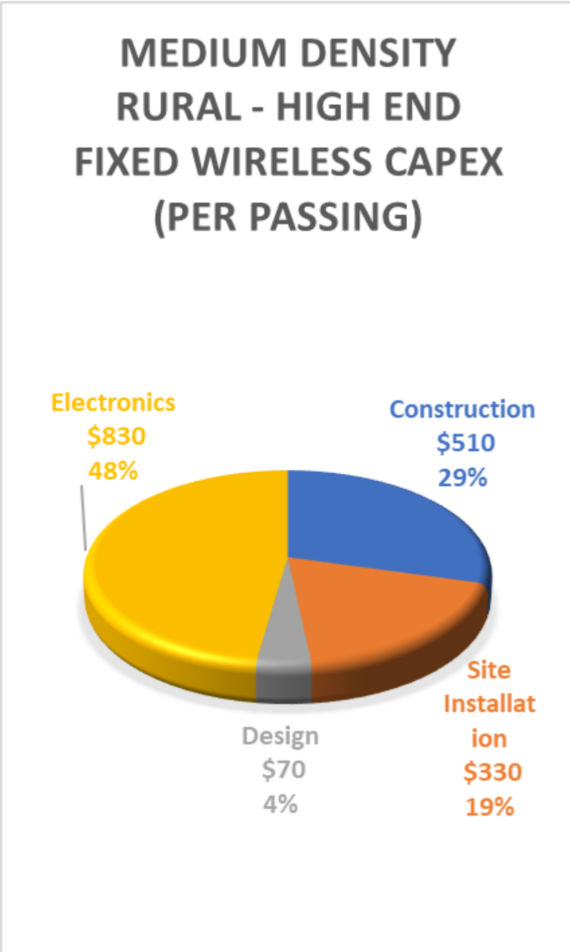


Figure 47: Medium density rural – high-end fixed wireless annual opex (per passing)

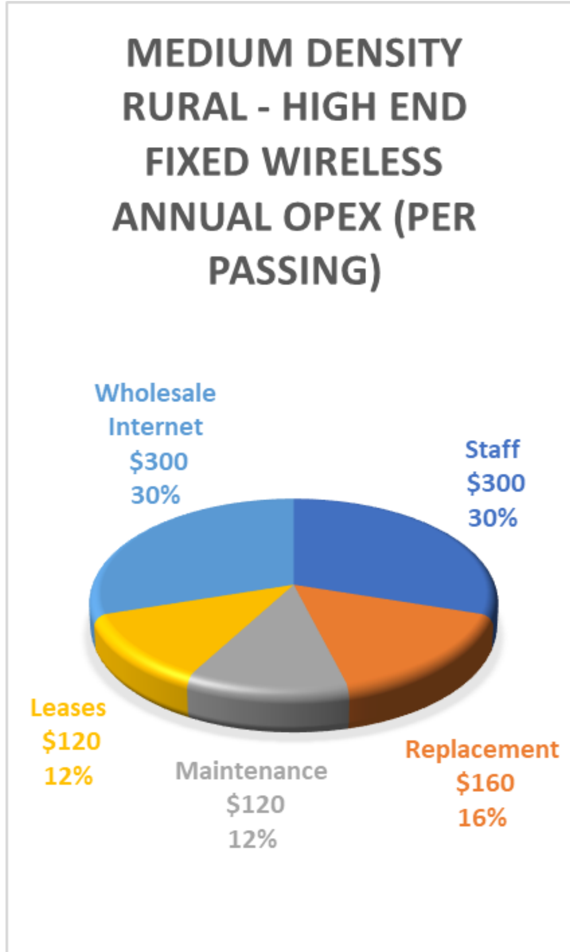
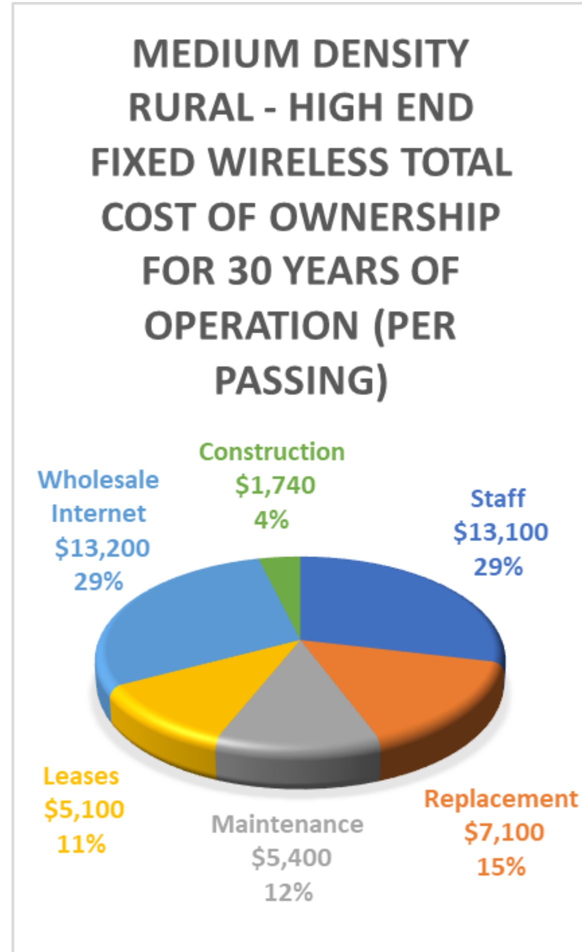


Figure 48: Medium density rural – high-end fixed wireless total cost of ownership (30 years, per passing)



Low density – low-end fixed wireless cost analysis

Figure 49: Low Density rural – low-end fixed wireless capex (per passing)

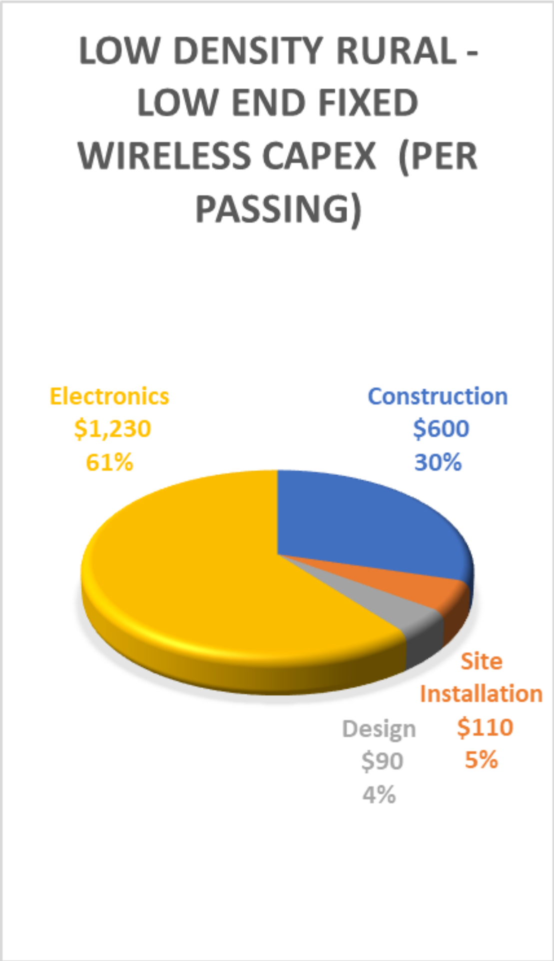


Figure 50: Low density rural – low-end fixed wireless annual opex (per passing)

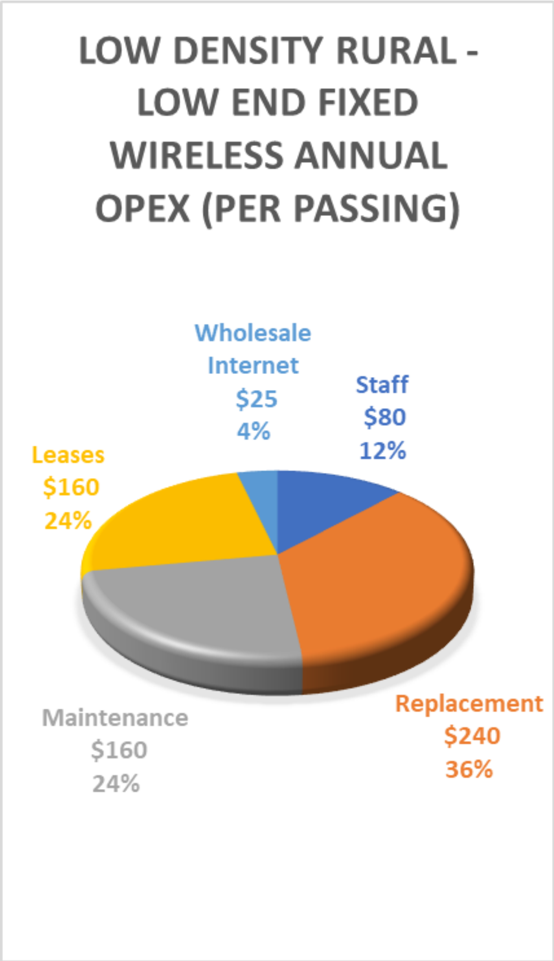
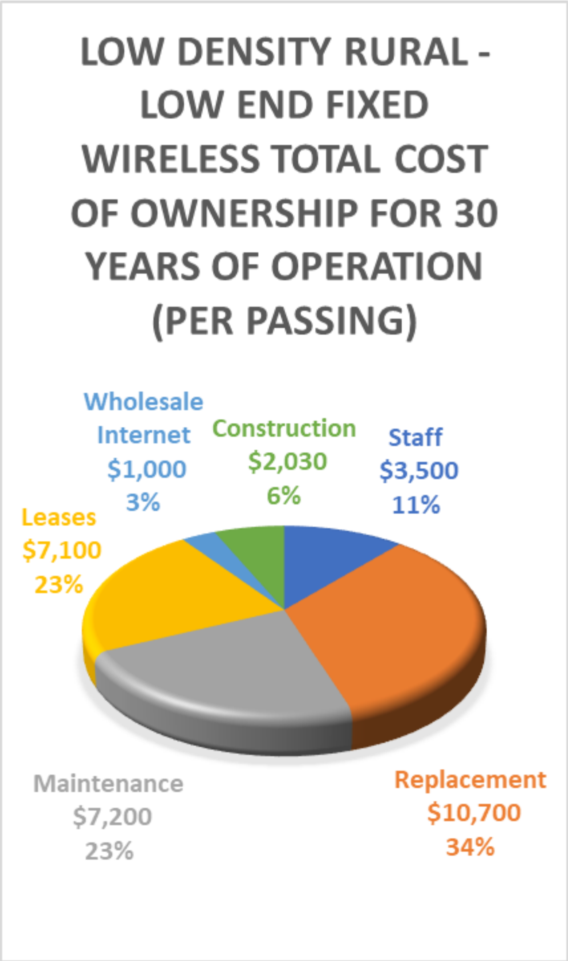


Figure 51: Low density rural – low-end fixed wireless total cost of ownership (30 years, per passing)



Low density – high-end fixed wireless cost analysis

Figure 52: Low density rural – high-end fixed wireless capex (per passing)

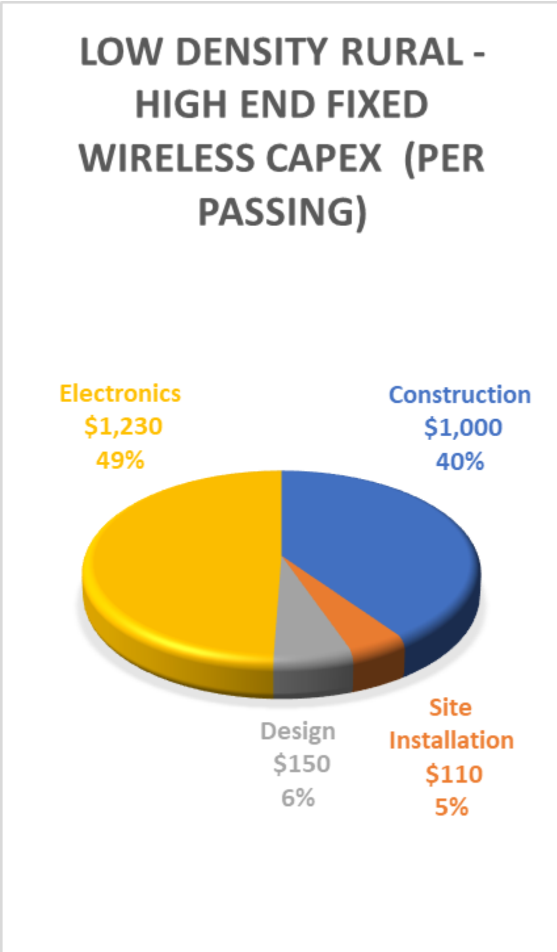


Figure 53: Low density rural – high-end fixed wireless annual opex (per passing)

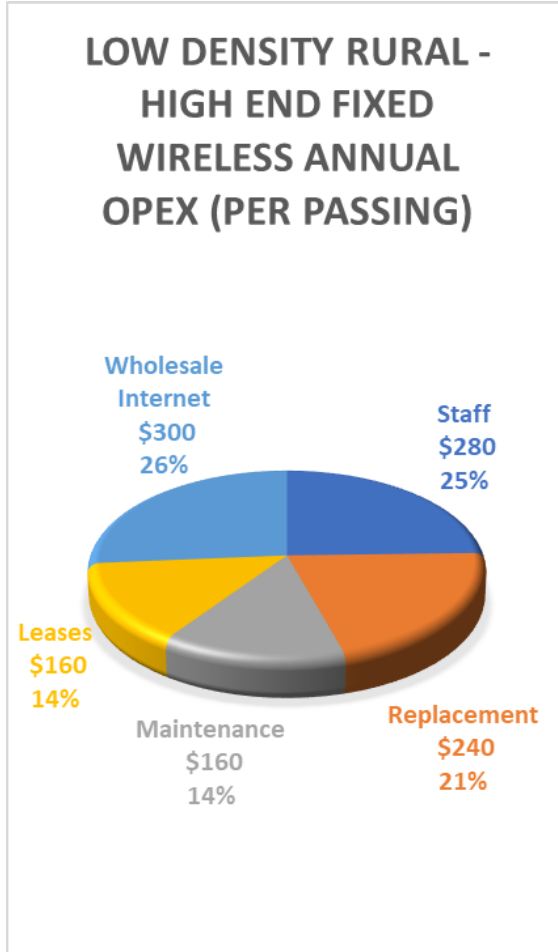
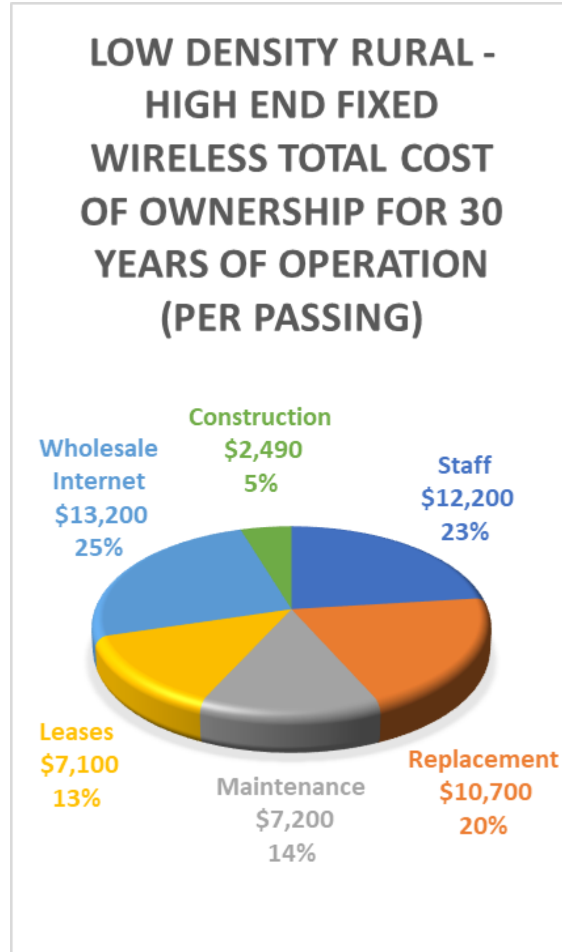


Figure 54: Low density rural – high-end fixed wireless total cost of ownership (30 years, per passing)



Very low density – low-end fixed wireless cost analysis

Figure 55: Very low density rural – low-end fixed wireless capex (per passing)

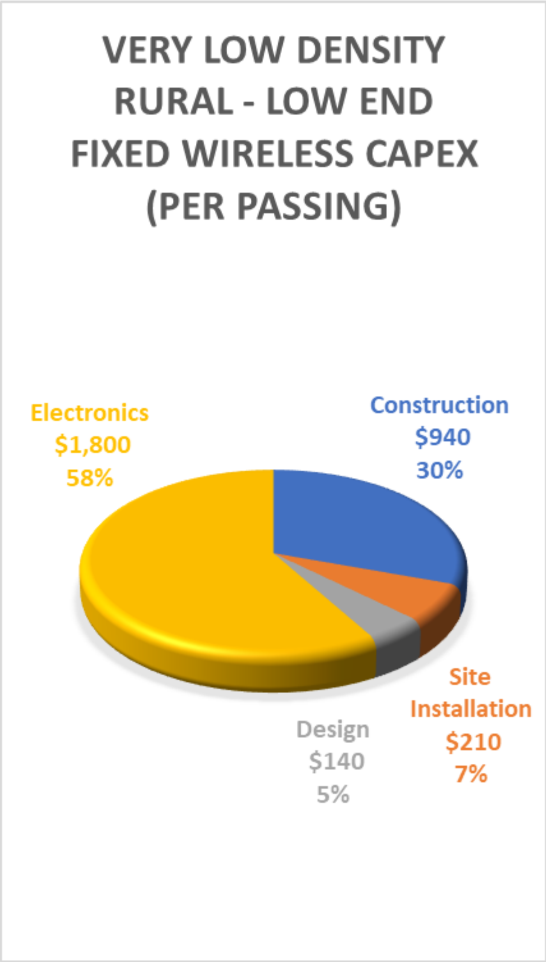


Figure 56: Very low density rural – low-end fixed wireless annual opex (per passing)

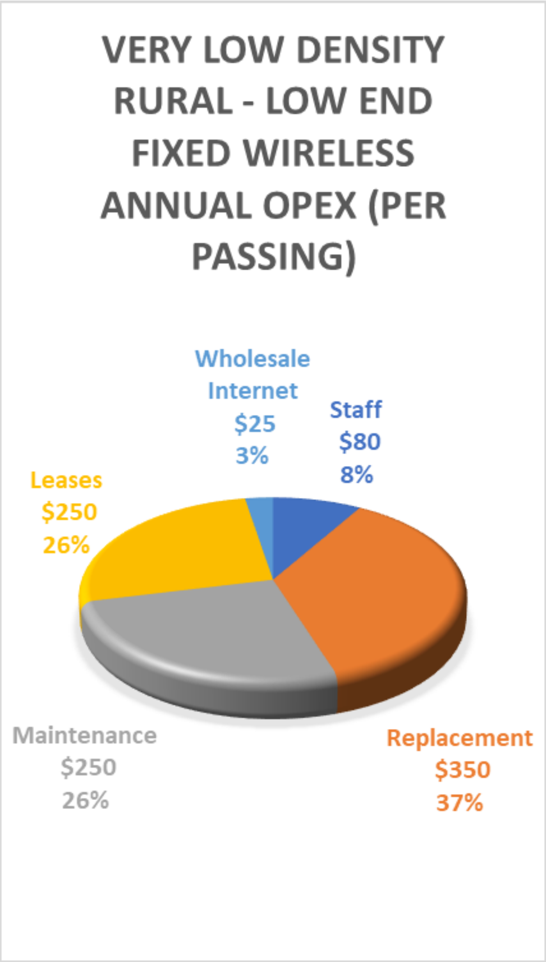
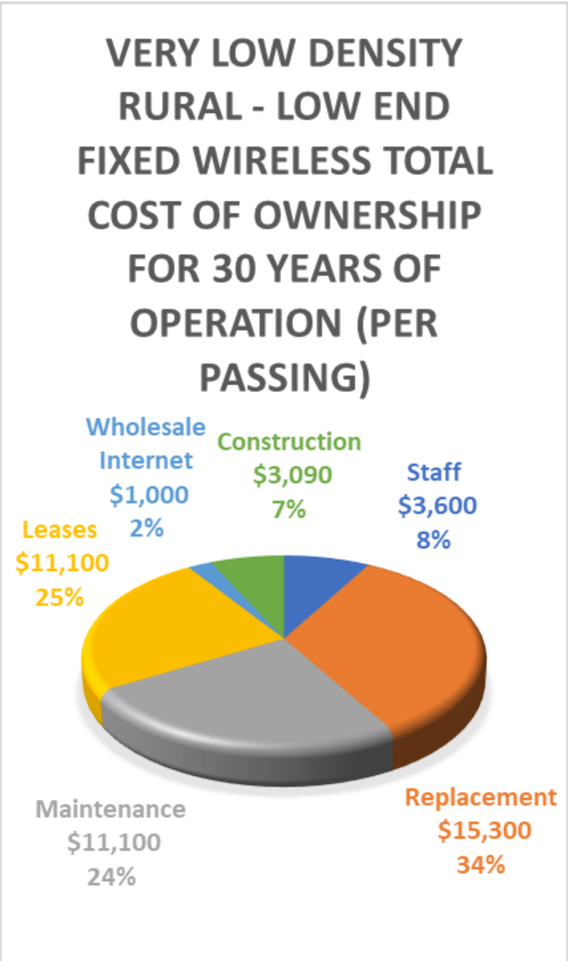


Figure 57: Very low density rural – low-end fixed wireless total cost of ownership (30 years, per passing)



Very low density – high-end fixed wireless cost analysis

Figure 58: Very low density rural – high-end fixed wireless capex (per passing)

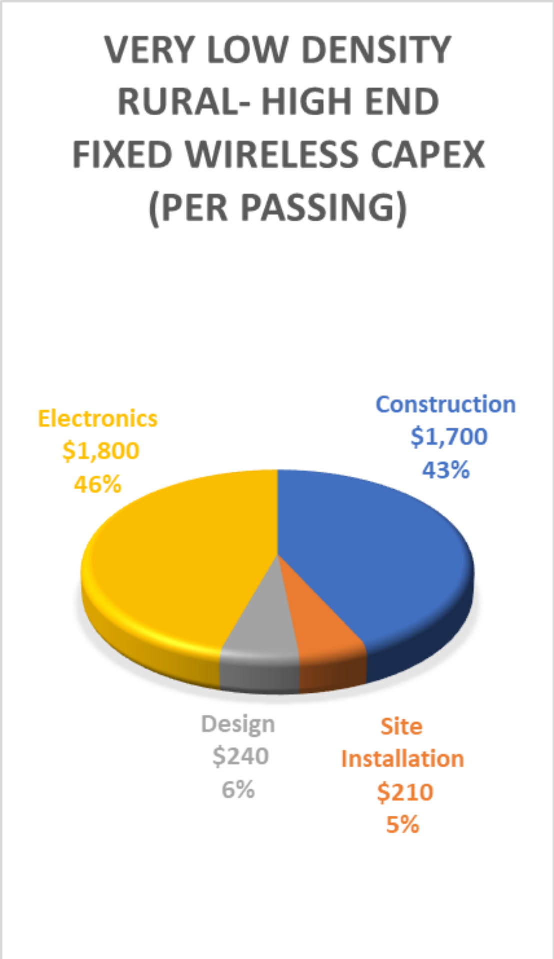


Figure 59: Very low density rural – high-end fixed wireless annual opex (per passing)

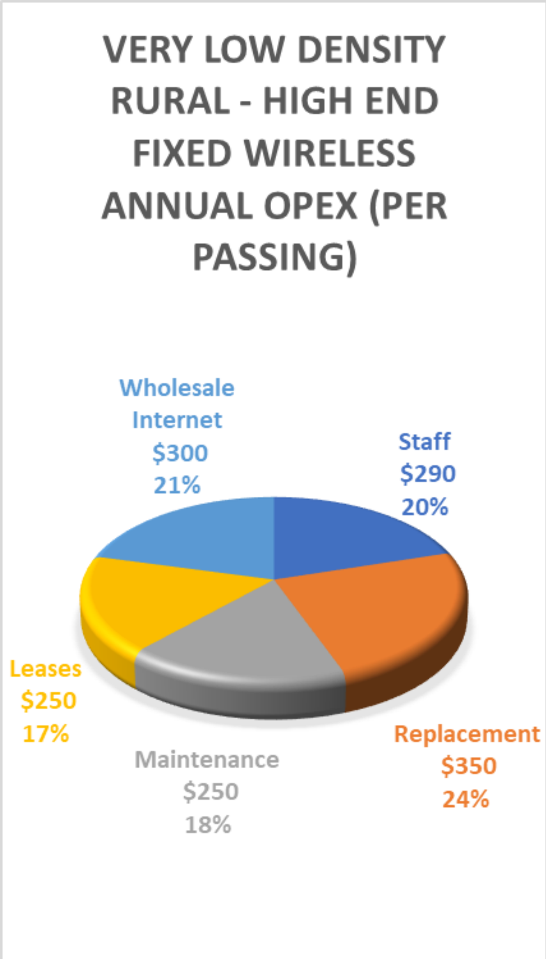
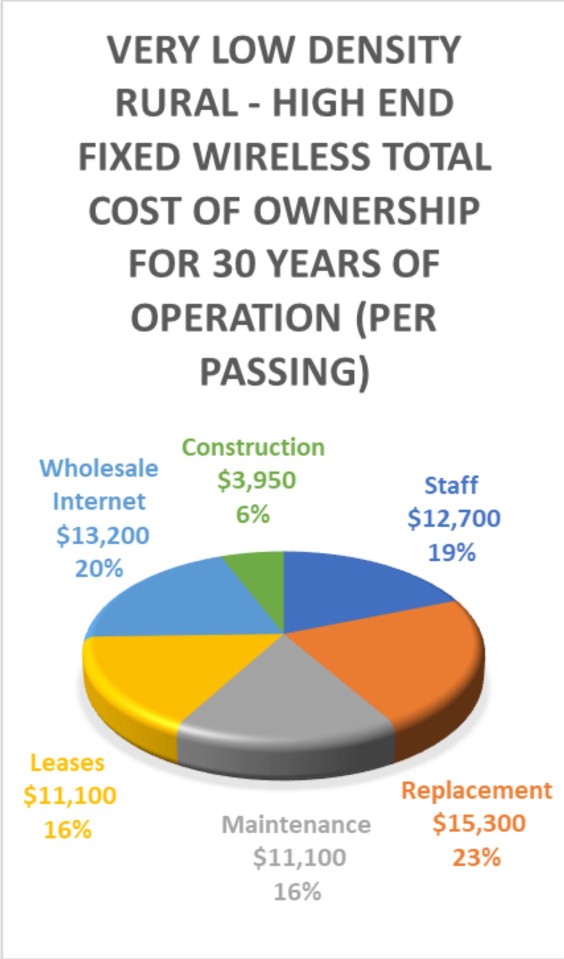


Figure 60: Very low density rural – high-end fixed wireless total cost of ownership (30 years, per passing)



Appendix D: Fiber cost analyses by density (estimated)

Small town – low-end FTTP cost analysis

Figure 61: Small town – low-end FTTP capex (per passing)

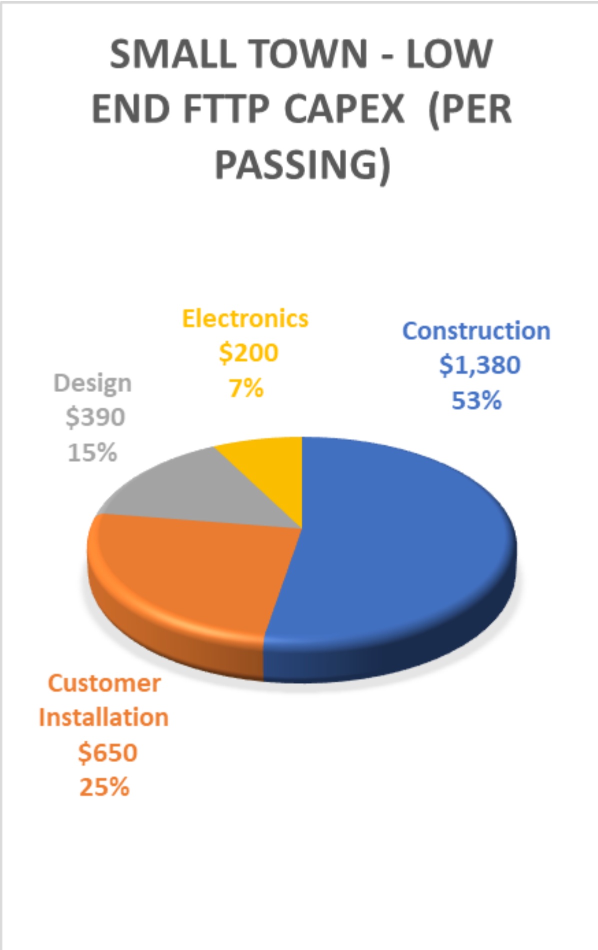


Figure 62: Small town – low-end FTTP annual opex (per passing)

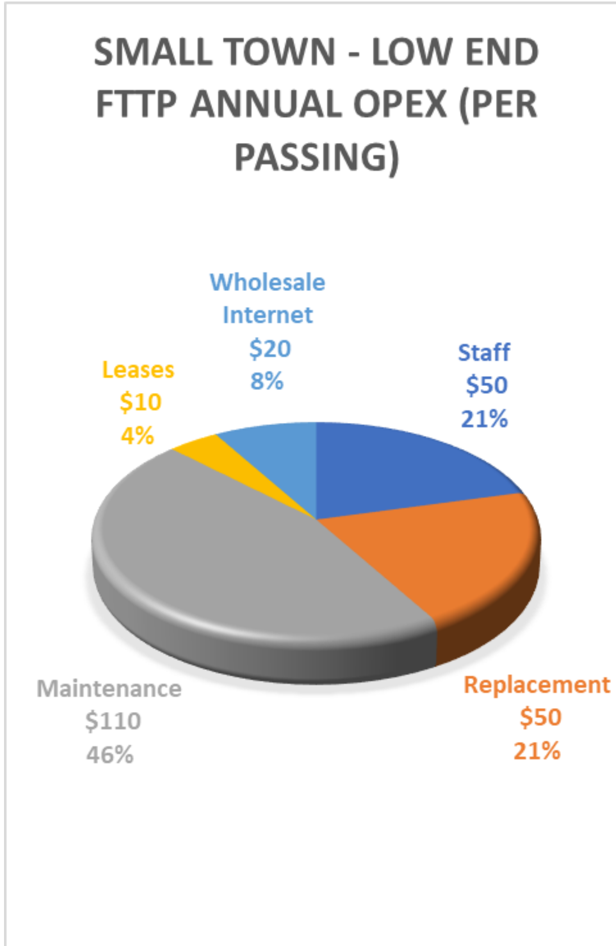
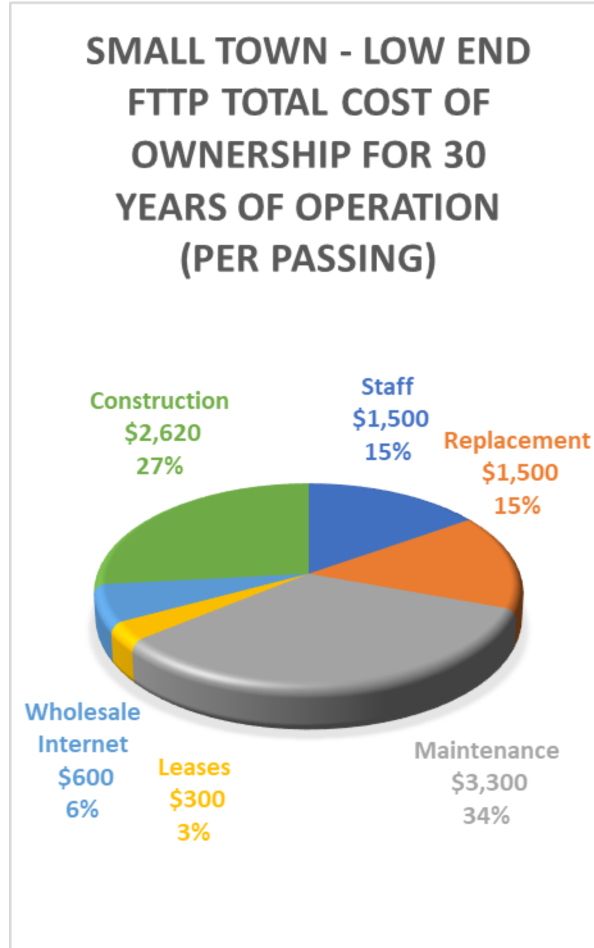


Figure 63: Small town – low-end FTTP total cost of ownership (30 years, per passing)



Small town – high-end FTTP cost analysis

Figure 64: Small town – high-end FTTP capex (per passing)

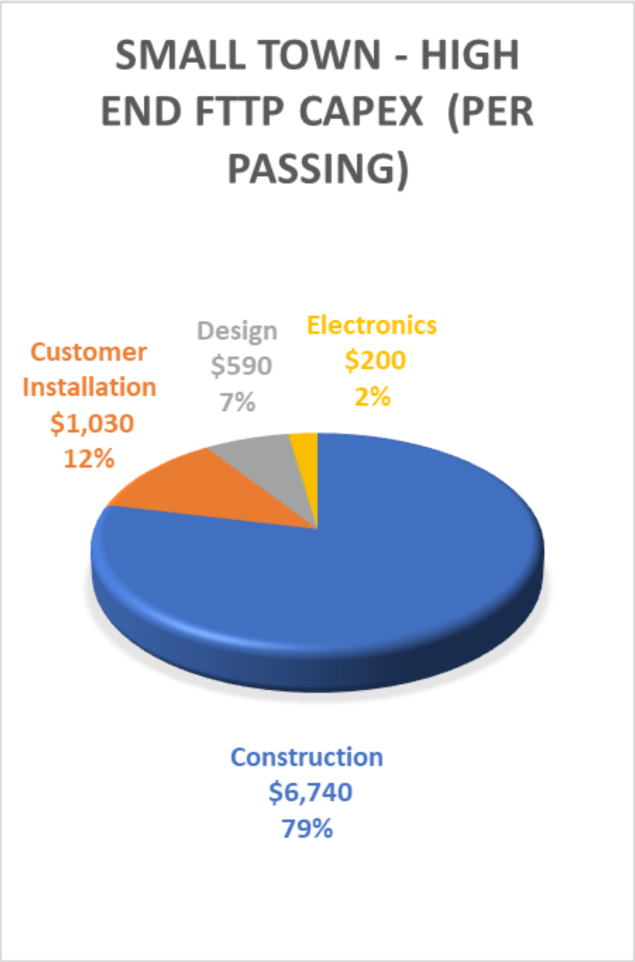


Figure 65: Small town – high-end FTTP annual opex (per passing)

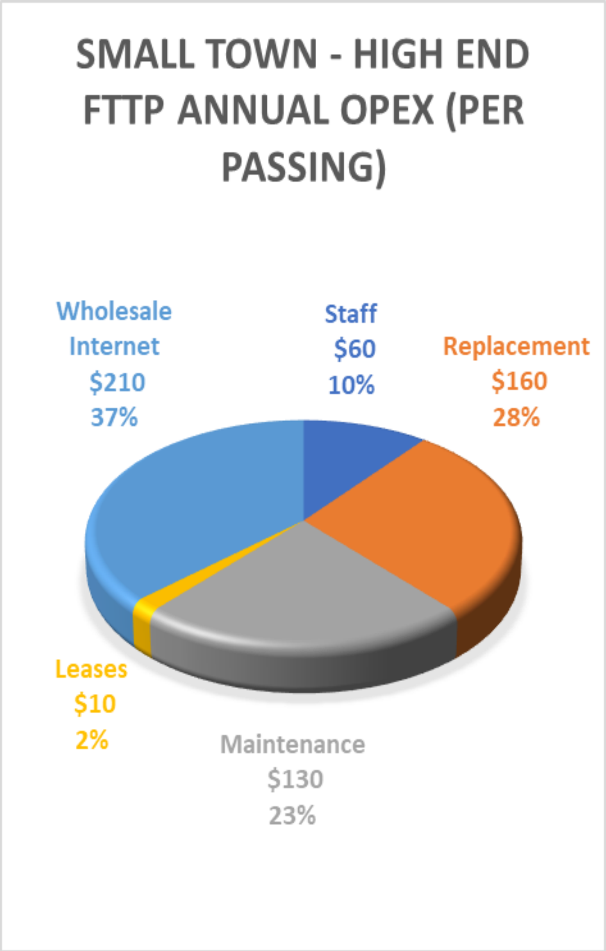
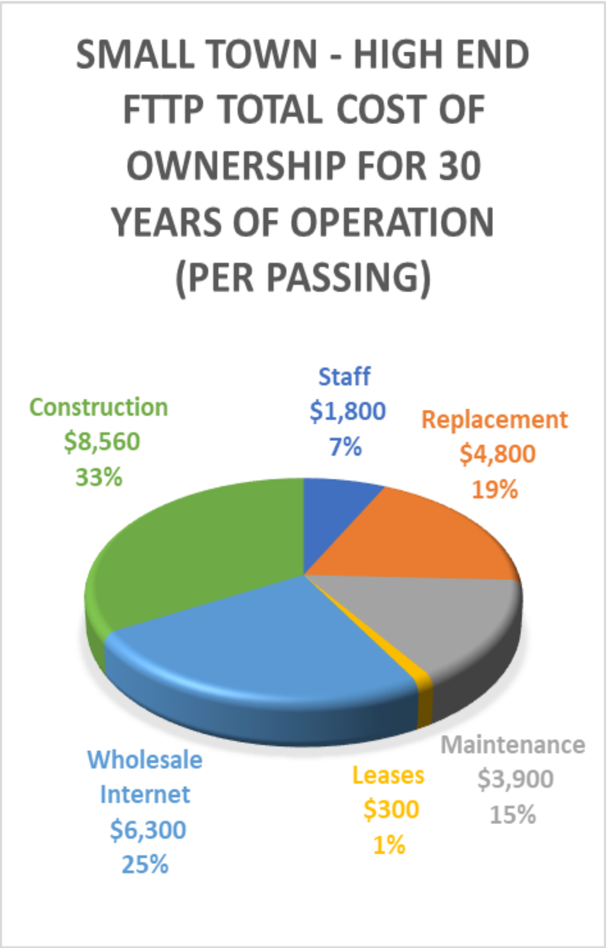


Figure 66: Small town – high-end FTTP total cost of ownership (30 years, per passing)



Medium density – low-end FTTP cost analysis

Figure 67: Medium density rural – low-end FTTP capex (per passing)

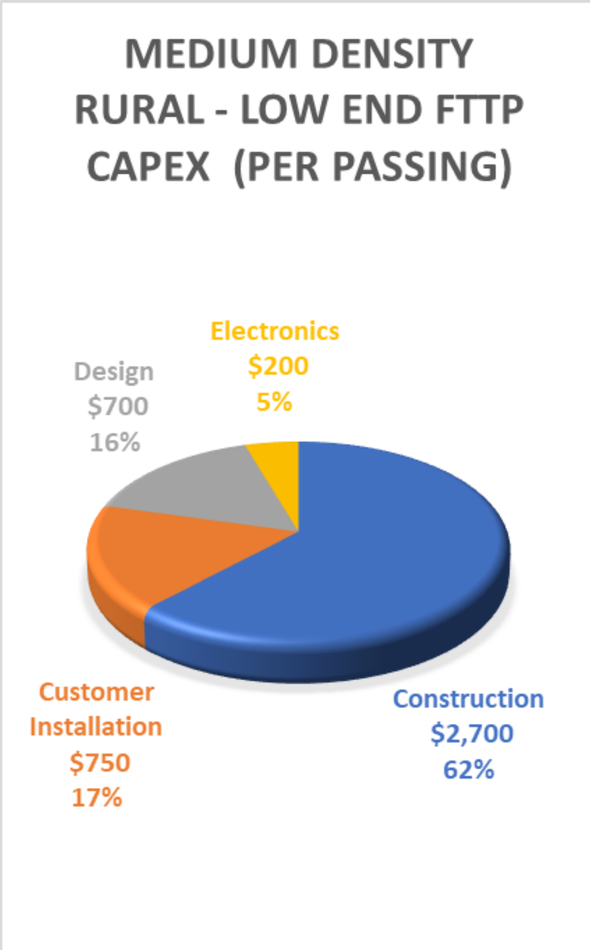


Figure 68: Medium density rural – low-end FTTP annual opex (per passing)

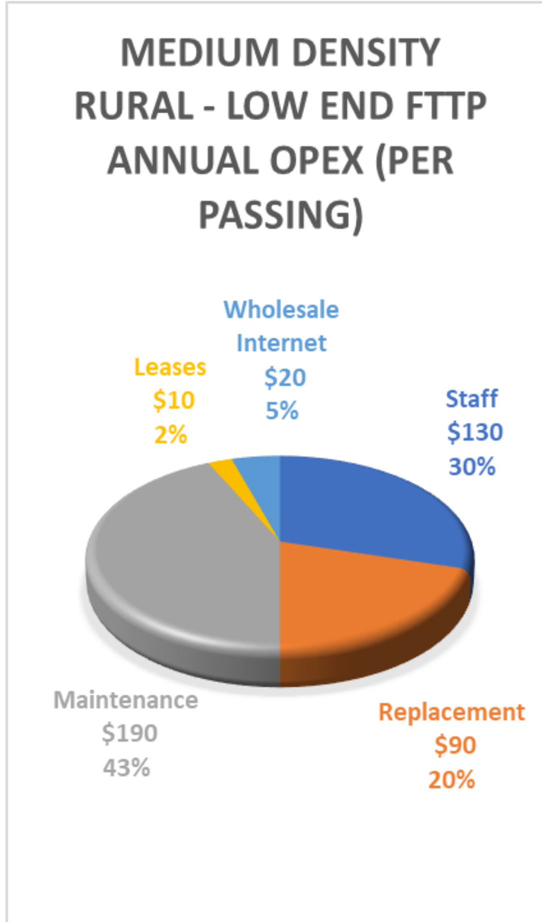
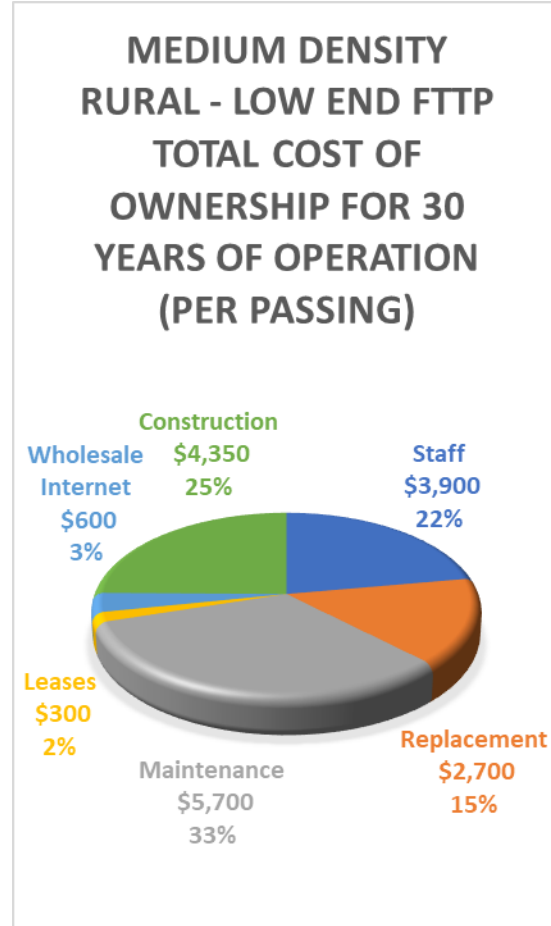


Figure 69: Medium density rural – low-end FTTP total cost of ownership (30 years, per passing)



Medium density – high-end FTTP cost analysis

Figure 70: Medium density rural – high-end FTTP capex (per passing)

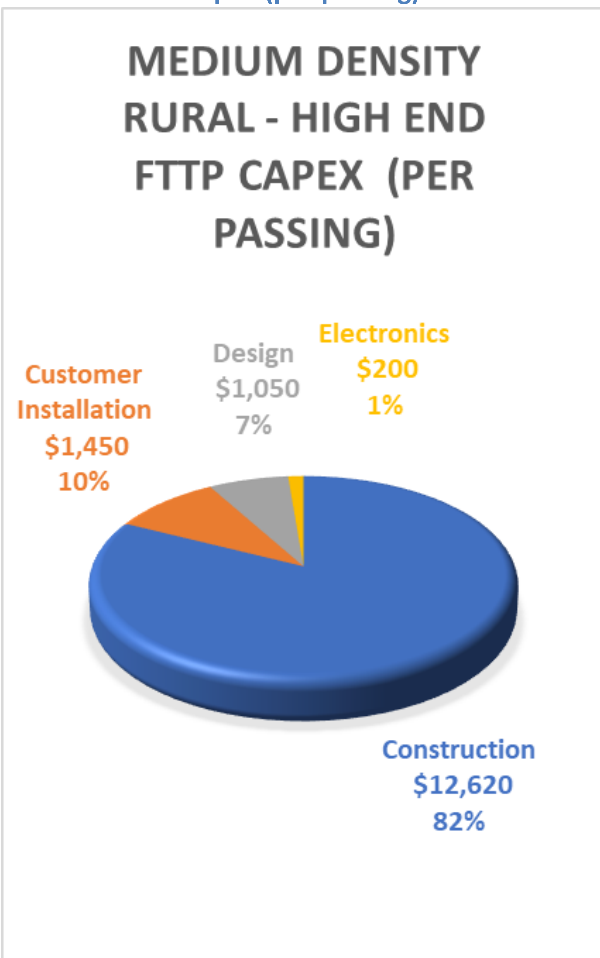


Figure 71: Medium density rural – high-end FTTP annual opex (per passing)

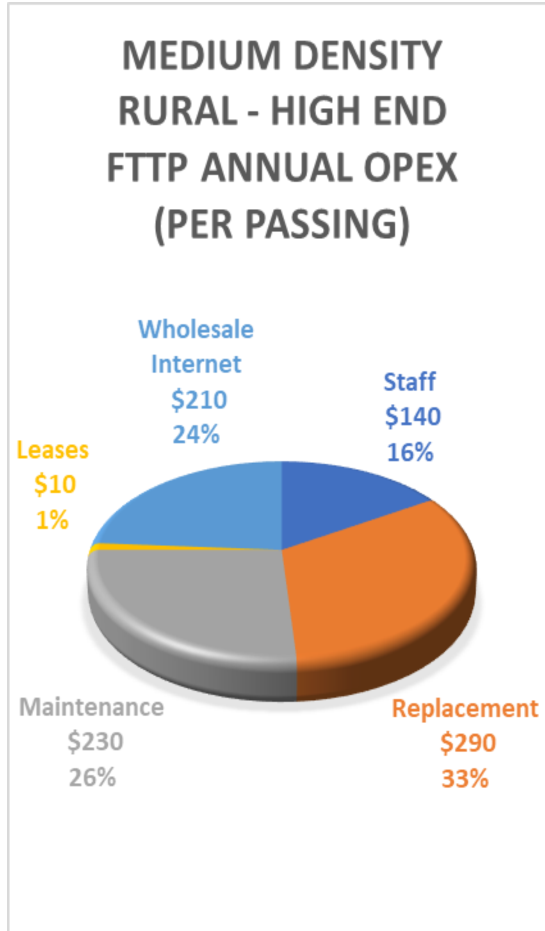
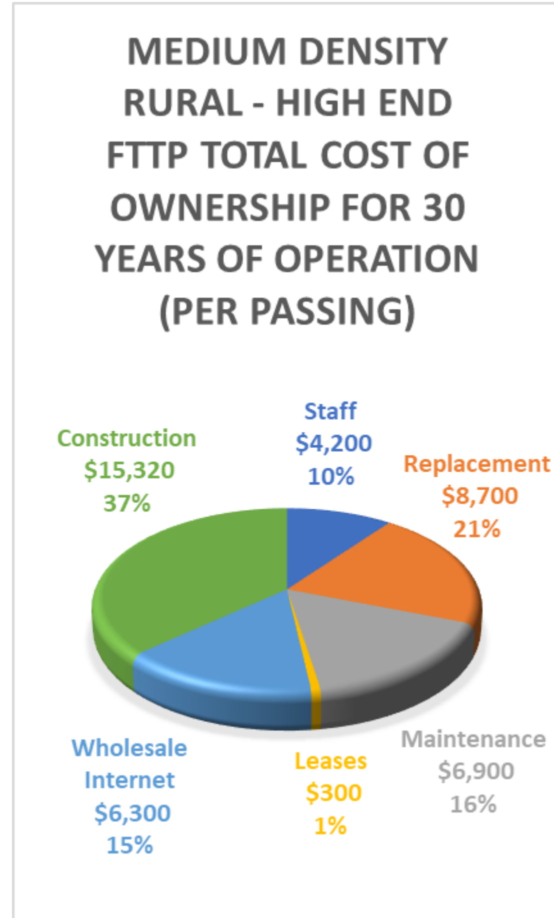


Figure 72: Medium density rural – high-end FTTP total cost of ownership (30 years, per passing)



Low density – low-end FTTP analysis

Figure 73: Low density rural – low-end FTTP capex (per passing)

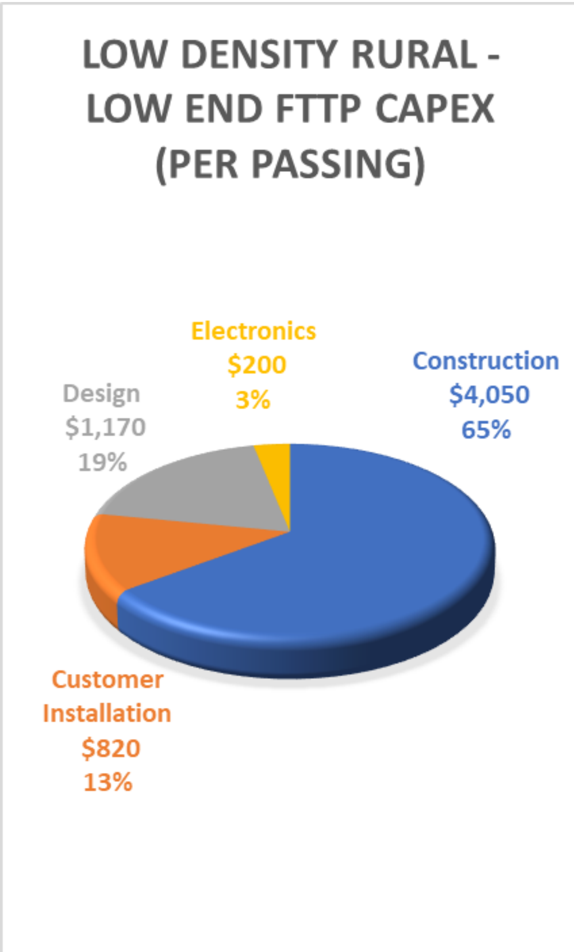


Figure 74: Low density rural – low-end FTTP annual opex (per passing)

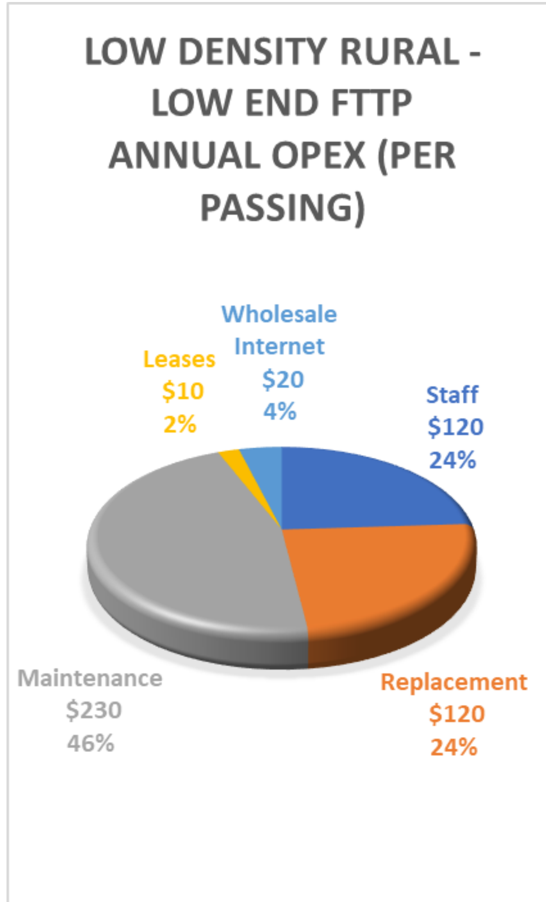
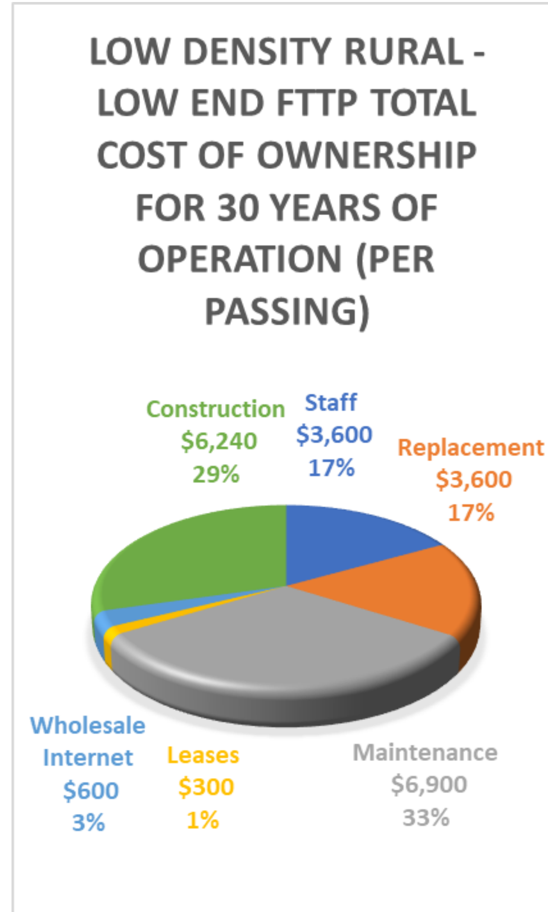


Figure 75: Low density rural – low-end FTTP total cost of ownership (30 years, per passing)



Low density – high-end FTTP cost analysis

Figure 76: Low density rural – high-end FTTP capex (per passing)

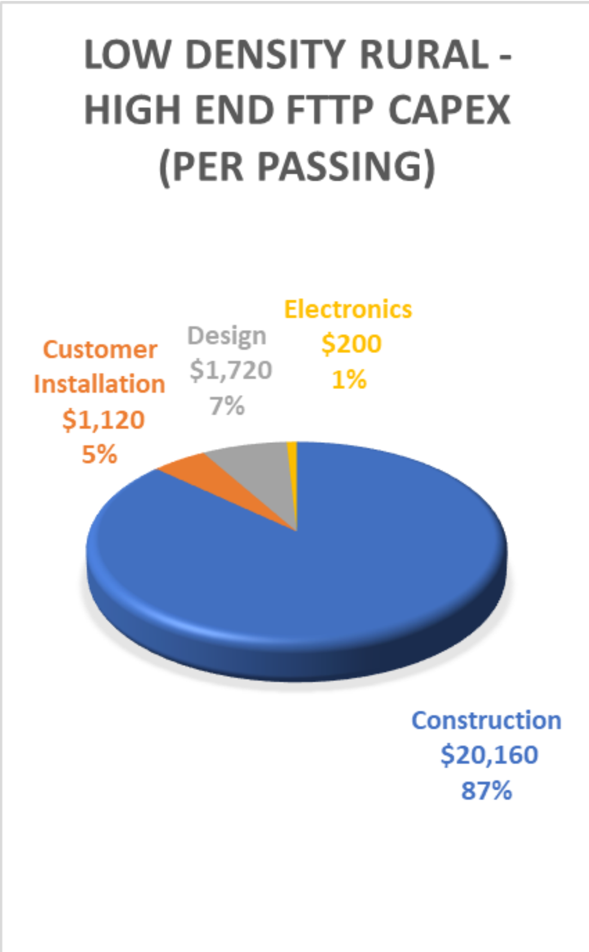


Figure 77: Low density rural – high-end FTTP annual opex (per passing)

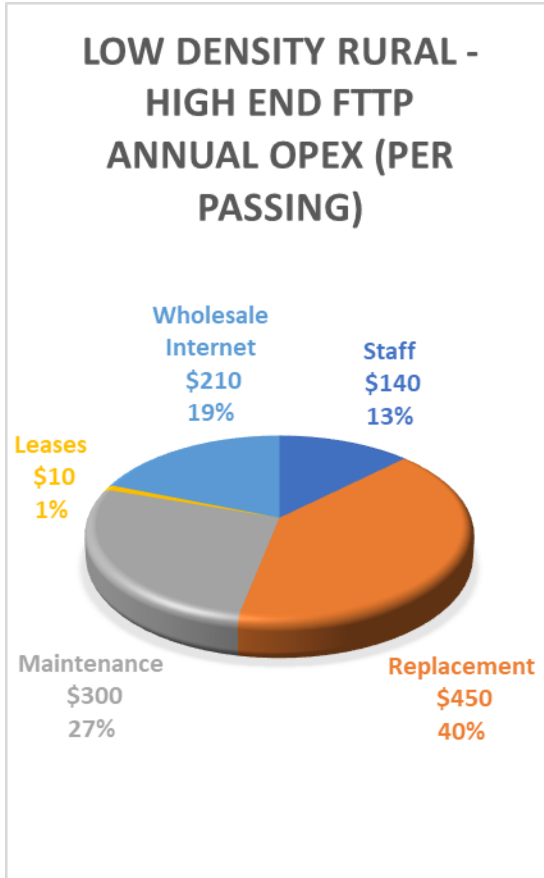


Figure 78: Low density rural – high-end FTTP total cost of ownership (30 years, per passing)

Very low density – low-end FTTP cost analysis

Figure 79: Very low density rural – low-end FTTP capex (per passing)

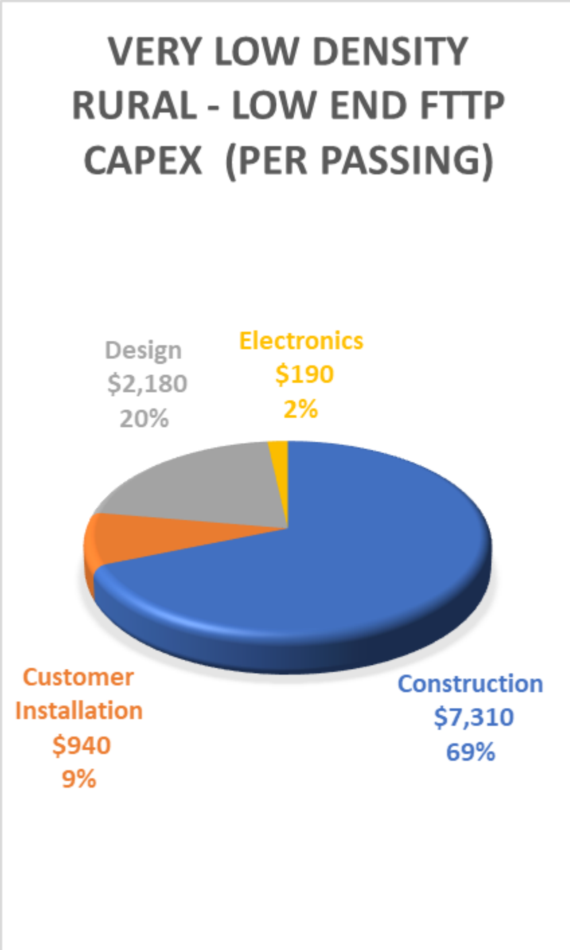


Figure 80: Very low density rural – low-end FTTP annual opex (per passing)

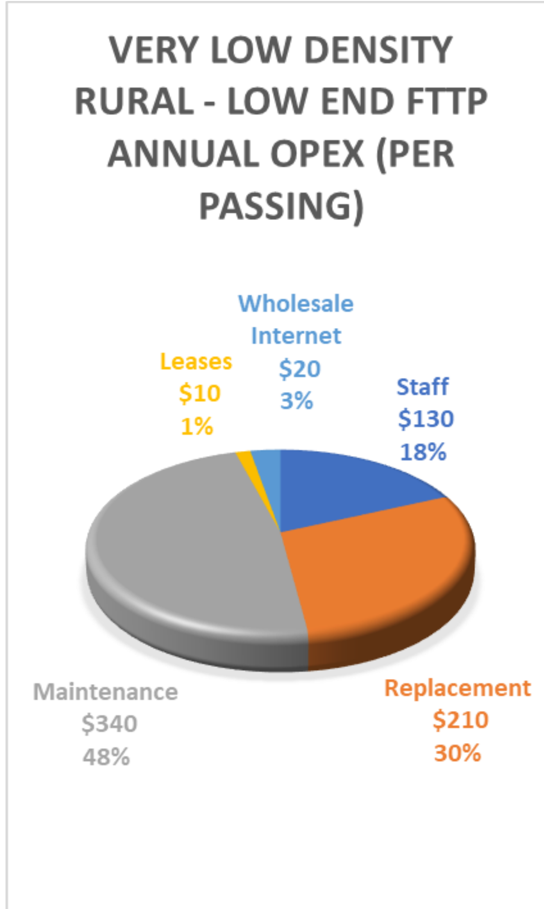
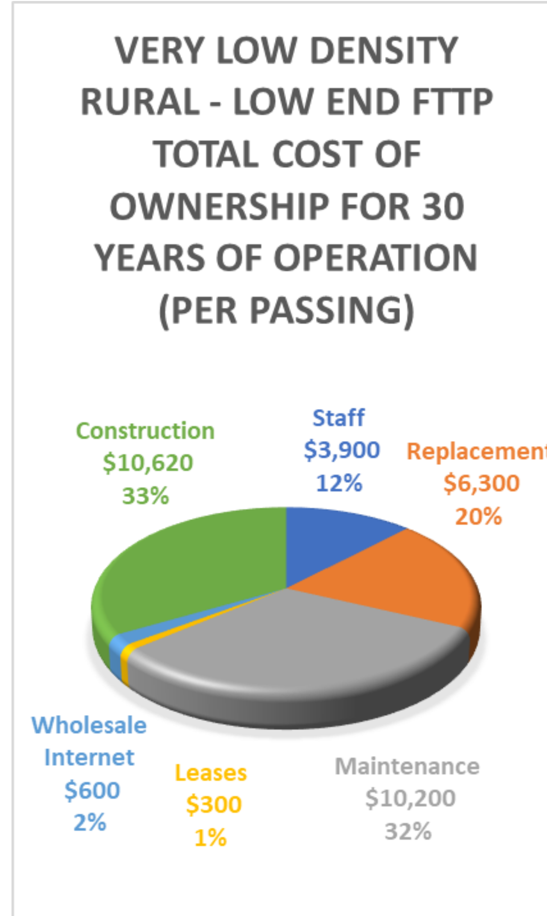


Figure 81: Very low density rural – low-end FTTP total cost of ownership (30 years, per passing)



Very low density – high-end FTTP cost analysis

Figure 82: Very low density rural – high-end FTTP capex (per passing)

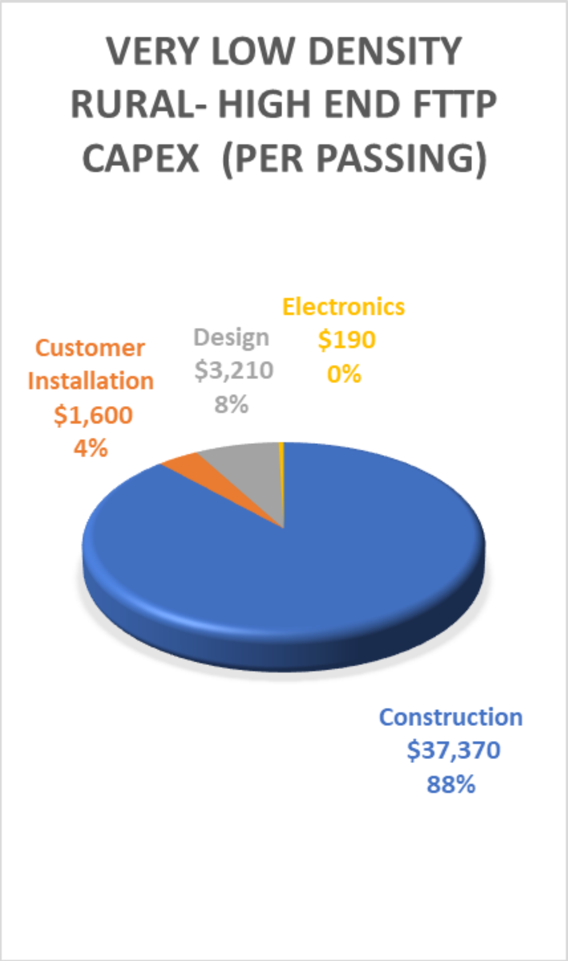


Figure 83: Very low density rural – high-end FTTP annual opex (per passing)

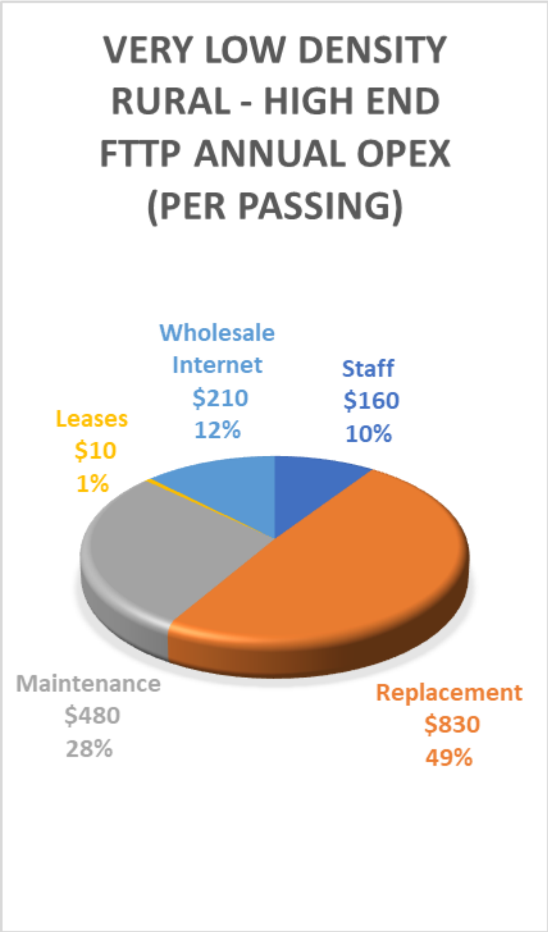
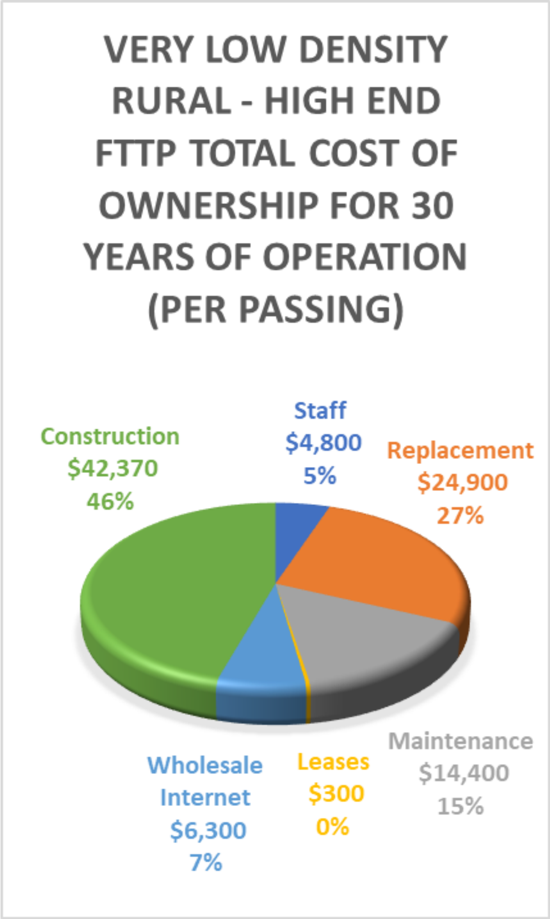


Figure 84: Very low density rural – high-end FTTP total cost of ownership (30 years, per passing)



BENTON INSTITUTE for BROADBAND & SOCIETY

Broadband Delivers Opportunities
and Strengthens Communities