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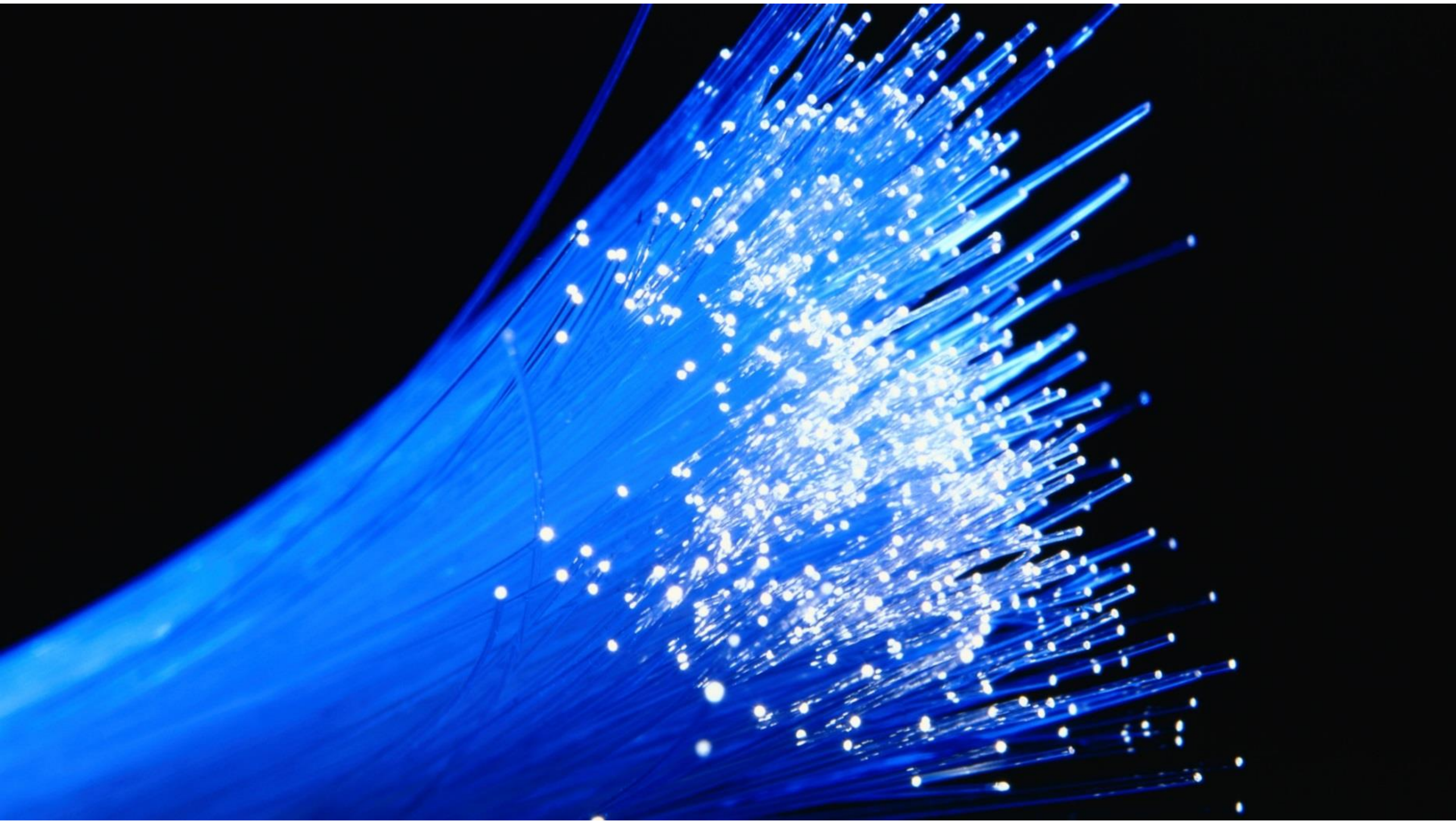

Broadband Factors for Last-Mile Connectivity

Prepared for the California Public Utilities Commission

December 2021

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Contents

Figures

Tables

1 Executive Summary

Senate Bill 156 requires the California Public Utilities Commission to report on the locations, routes, technical performance characteristics, network design, regeneration points, interconnection points, tie-ins, and other considerations that would increase the attractiveness and usefulness of California's planned statewide open-access middle-mile broadband network for last-mile commercial internet service providers (ISP).

To inform that report, the CPUC engaged CTC Technology & Energy to research and write this independent report addressing:

- Fiber and conduit specifications (Section 2)
- Construction considerations (Section 3)
- Variables affecting predicted fiber lifecycles (Section 4)
- Open-access middle-mile service models (Section 5)
- Last-mile service providers' technical and operational requirements (Section 6)
- Capacity growth expectations (Section 7)
- Benefits achieved by open-access middle-mile networks (Section 8)
- Middle-mile implementation considerations and network parameters (Section 9).

This document presents considerations based on best practices and industry standards regarding network design and technical criteria, for evaluation by the CPUC as it develops its report under SB 156. Where possible, the analysis includes considerations from the public comments filed with the CPUC in the relevant proceeding. These comments represent a variety of stakeholder perspectives and provide input into a wide range of issues—including network design and capacity planning, community and stakeholder engagement, socioeconomic development, and industry practices.[1]

[1] These comments are in the record of the CPUC's rulemaking R.20-09-001 and are publicly available on the CPUC website, https://apps.cpuc.ca.gov/apex/f?p=401:57:0 (accessed December 14, 2021).

1.1 Last-mile provider and user requirements should inform the standards and specifications for the open-access fiber

The intent of the middle-mile network is to support last-mile service—primarily by enabling providers, anchor institutions, and tribal entities to connect to, and interconnect with, the middle-mile network itself and with other networks.

Open-access middle-mile networks generally make some combination of conduit, dark fiber, lit fiber, internet, and colocation services available to last-mile providers in the service of public policy priorities. Section 5 discusses each of these open-access models and the considerations for providing a menu of options and prioritizing their implementation. Open-access policies and models intend to deliver benefits—such as increased competition, lower transport costs, increased reliability, innovative business strategies, and increased access to interconnection points—to last-mile providers in different scenarios and circumstances. Therefore, meeting the technical requirements of last-mile service providers will be critical to the success of the middle-mile network. Section 6 of this report identifies technical standards and requirements that last-mile providers will have for physical access (e.g., interconnection points, access to key routes) and access to network and application services (e.g., dark fiber, lit services, wavelengths) from competing providers.

Taken together, a statewide network that meets these requirements will provide last-mile service providers, anchor institutions, and tribal entities access to comparable levels of broadband service as if they were adjacent to a major data center or internet meet point.

1.2 Ensuring sufficient long-term capacity is a guiding principle

SB 156 requires the relevant state agencies to use a long-term planning horizon for the design, build, and use of this state asset.[2] Precision in such specifications is difficult, particularly in a state as large and varied as California, so the guiding principle—for the state, as it is for the industry and other statewide network planners—is to build capacity that will meet forecasted future needs wherever feasible.

This report discusses the factors that network planners consider as they determine the amount of capacity to construct for a use case that extends at least 30 years. Section 7 discusses specific considerations for a capacity growth outlook. It is a good industry practice to perform a market sounding to ascertain the specific demand for network and application services along a given route, as well as using best professional judgement about future needs, in order to strike the best balance between network capacity and costs.

[2] For example, the operator of the middle-mile network is directed to consider offering lease terms for access to dark fiber of "no less than 20 years." SB 156 (2021), Section 3, page 9 (Govt. Code Sec. 11549.57).

The growth in broadband demand among residential users since the start of the pandemic illustrates the ways in which last-mile capacity requirements may grow over time. But capacity requirements will encompass more than just growth in current households' bandwidth requirements.

The cost of living in many of the state's current population centers, for example, could lead to housing construction in areas that currently have low population densities. Automated vehicles, 5G wireless deployment, and other technological advances will create new demand for bandwidth in the state, and the continued growth in distributed energy generation and the use of smart grid technologies could increase the energy sector's bandwidth needs as well. Network design evolution, including increased demand for bandwidth and computer power at the edge of a network, closer to end users, will also create the need for robust infrastructure in more varied locations. And economic development efforts in the decades to come—paired with technological advances that are not even envisioned—likely will lead to enterprise demand for bandwidth in new places, and at potentially unforeseen levels.

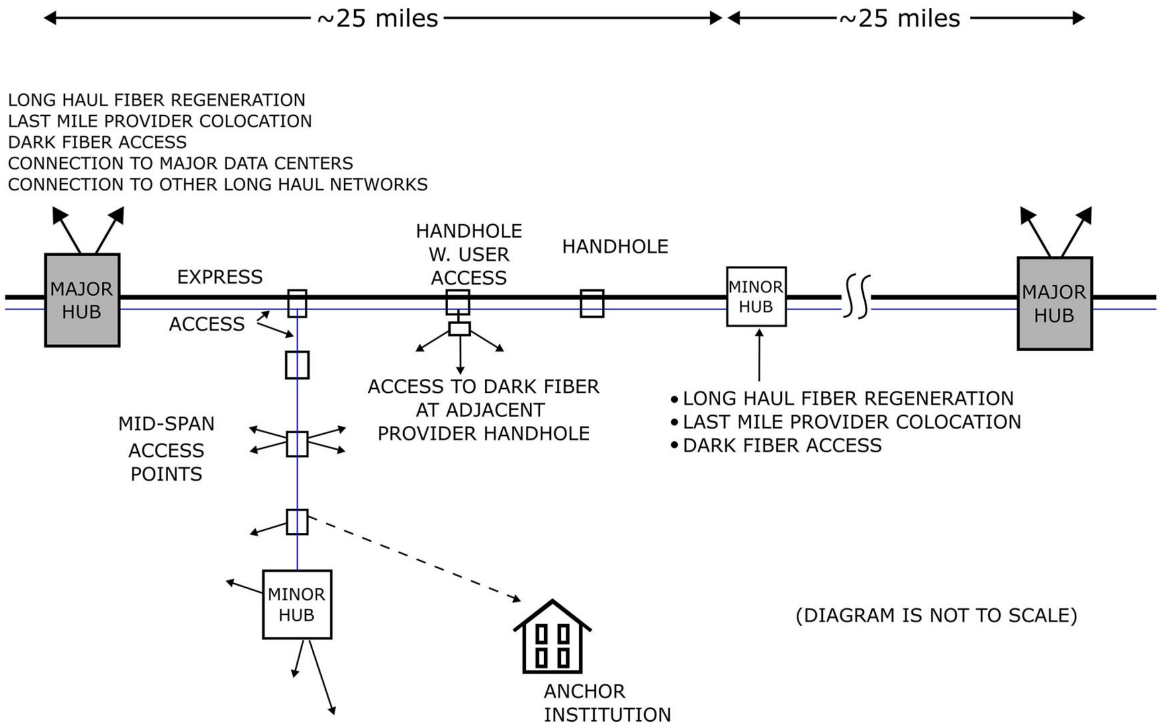
For these reasons, industry standards indicate that building more, not less, capacity is the best practice.

1.3 Industry best practices inform recommended fiber, conduit, and other technical specifications

The report supports its recommendations with a review and analysis, in Sections 2, 3, and 4, of key technical specifications for fiber technology and characteristics, conduit facilities, underground and aerial construction, network interconnection points, and fiber depreciation and reliability.

This report recommends a network model (Figure 1) and technical standards that the CPUC can use to analyze the sufficiency of existing middle-mile infrastructure and to recommend parameters for state-funded construction, possible leasing arrangements, and other approaches to address the need for middle-mile access throughout the state.

Figure 1: Proposed middle-mile network architecture concept



These recommendations are discussed in detail in Section 9 and summarized here:

- **Design with flexibility and scalability in mind:** Fiber and conduit technology is always evolving, so network design parameters should be flexible and forward-looking to allow the incorporation of new technology to enable improved performance and capacity while supporting cost and operational efficiencies. To the extent these improvements also extend the useful life of infrastructure, those improvements should be included in financial forecasting and depreciation calculations.

- **Select fiber types and strand counts that will meet projected capacity and performance requirements:** A statewide middle-mile network that aims to support most transmission standards ranging from 1 Gbps to more than 400 Gbps over distances of potentially up to hundreds of miles should comprise conduit, fiber type and strand counts to accommodate the needed capacity, latency, reliability, application, and cost requirements.

  Two fiber cables—an express cable interconnecting hub facilities and an access cable interconnecting field locations—can provide the needed capacity and flexibility. Based on industry standard practices and comments from service providers, ***express cables should have at least 288-count fiber, and in major routes where many routes aggregate near major cities and aggregation points (e.g., San Jose, Los Angeles), 432-count or 864-count should be considered.*** The higher counts will be needed in places where multiple

288-count routes join on the way to the locations in the cities, similar to how interstate highways in metropolitan areas need more lanes than rural interstates.

Access fiber cables should be sized based on the likely demand for fiber along the route between the hub locations—based on the density of potential last-mile provider connection points, anchor institutions, and other users, such as wireless providers and connections for future applications such as connected vehicles. In general, ***288-count access fiber should accommodate an average 10-count of fiber connections per mile and should accommodate most anticipated needs for local connections***—although in areas where many last-mile providers may connect, or a last-mile provider may know in advance it needs a large count locally, the network may want to consider a higher count.

For cables of 288-count or higher, ***ribbon cables are preferable*** as the strands are just spliced through at handholes, and the cost and complexity of splicing is reduced. (See Section 9.1.1 for more details).

Both the express and access fibers should be of G.652D type. Using G.652D fiber will provide the needed performance and have the advantage of enabling the middle-mile network to standardize on a single type of fiber, reducing complexity and costs.

- **Install sufficient conduit to meet anticipated long-term use cases:** Conduit capacity should enable the cost-efficient addition of fiber cable in the future, if and when additional capacity is required.[3] Conduit counts should reflect factors such as the interest of other providers for conduit capacity, and whether the right-of-way is restricted or closed to future construction (i.e., freeways).

  As a starting assumption, the open-access middle-mile network plan should assume the construction of ***two 2-inch conduits for immediate and near-term future use, as well as two to six additional ducts for longer-term future growth***. Duct counts might vary depending on location (e.g., metro versus rural) and business opportunities. Potential conduit duct leases should ideally be determined in the planning stage and factored into the total duct count.

- **Ensure adequate interconnection and colocation opportunities:** Hub facilities and handholes should be placed at intervals proscribed by the physical limitations of the network's electronics, fiber, and conduit. They will play an essential role in enabling interconnection and colocation by last-mile service providers and other users. ***In addition to regularly spaced hub site access, field access points should be in handholes at the end***

[3] Use of aerial fiber deployment on poles and other above-ground facilities can also be part of the design consideration, but the suitability must be carefully analyzed to take into account both benefits (ease of access, shorter time to market) and costs (limited pole access, reliance on competitors, exposed to the elements).

of freeway ramps, at the edge of the right-of-way outside of other major roads, and on utility poles in areas where cables are on poles.

The locations for these interconnection points should be determined based on industry best practices, technical specifications, regulatory requirements, and input from local stakeholders that might rely on this network. Furthermore, the suggested dual-conduit design allows flexible and secure addition of new access points wherever a handhole exists, after the network is complete.

- **Many factors are important to consider in making the determination as to when to build and when to lease existing fiber.** Because the middle-mile network comprises many miles, and there already are many miles of high-capacity fiber in many parts of the state, ***it is important to consider whether and where to lease fiber through long-term IRUs as an alternative to construction***. While IRUs would allow the state to control the network in a way that largely mimics ownership for a finite period of time, IRUs differ from true ownership of the underlying fiber asset in a number of important ways.
- **Consider what type of value-added services might expand the network's benefit to last-mile service providers.** The planning process for California's middle-mile network should include analysis of technical considerations and the business case to determine if the middle-mile network operator, or a vendor selected through a competitive procurement, should offer value-added services. The availability of these services at affordable rates and non-discriminatory terms for smaller, competitive last-mile providers should be one factor in determining whether offering such services will help deliver on the goals of the middle-mile network.

2 Elements of Passive Fiber Optic Infrastructures

At its most basic level, a fiber optic middle-mile network comprises fiber optic cables and, for underground construction, conduit. For each component, the operator must choose among different types and sizes of materials and different capacities (e.g., fiber counts).

2.1 Fiber strand classifications and capabilities

Optical fiber is broadly divided into two categories: multimode and single-mode fibers. High-capacity middle-mile networks extending over long distances are composed of single-mode fibers. Due to the inherent bandwidth and distance limitations of multimode fibers, multimode fiber primarily is used in campus network buildouts and rack interconnections within IT data centers and is being phased out in most of these cases by single-mode fiber.

2.1.1 Parameters for measuring fiber characteristics

The differences among fiber types are in variations of light propagation and wavelength characteristics, which are achieved by material compositions defining the refractive index profile across the fiber core and cladding. The four main parameters that capture optical characteristics of a single-mode fiber are attenuation, chromatic dispersion, polarization mode dispersion, and cut-off wavelength:

- **Attenuation** is the measure [dB/km] of loss of light within the fiber. Data sheets typically specify attenuations for wavelengths of common use (e.g., 1310 nm, 1490 nm, 1550 nm, and 1625 nm). Signal attenuation in single-mode fiber is lower than in copper telephone lines or coaxial cable broadband networks, allowing signal paths of about 25 miles without regeneration, using widely available, off-the-shelf equipment.
- **Chromatic dispersion** (CD) occurs as a consequence of the inherent wavelength-dependency of the refractive index of glass; it is measured as a coefficient [ps/nm/km]. Because the refractive index is inversely proportional to the propagation speed of light, CD introduces time delay variations within the optical signal spectrum—leading to a broadening of the transmitted pulses to a point where the pulses overlap and are not discernable by the receiver. The effect becomes linearly more pronounced with fiber length and is more critical for high-bitrate optical signal pulses. While it is less important in campus and last-mile networks with shorter distances and lower speeds, CD becomes a serious factor in middle-mile networks where signals must travel over long distances. When combined with the need for high capacity—above 10 Gbps—middle-mile networks require either fiber specifically made to counteract CD, or the use of CD-compensating electronics.

  High-capacity, wide-channel, dense wave-division multiplexing (DWDM) systems require a certain amount of added dispersion, because CD plays an important role in the suppression of nonlinear optical effects like four-wave mixing (FWM).[4] High-capacity transmission systems increasingly incorporate coherent transmission techniques[5] with DWDM.[6] The signal processing circuitry of coherent detection provides the advantage of enabling longer link lengths and electronically compensating for the effects of CD.

- **Polarization mode dispersion (PMD)**, like CD, introduces signal distortions over the length of the transmission path and is therefore potentially a distance- and data-rate-limiting factor in middle-mile and long-haul networks. The PMD coefficient characterizes the propagation speed dependency on the state of the light polarization [ps/sqrt(km)]. A perfectly circular waveguide with uniform refractive index has no PMD. Due to slight eccentricities of the fiber geometry and stress-induced refractive index variations, the pulse propagation speed varies with the state of polarization along the fiber. Unlike CD, PMD is less predictable and therefore difficult to counteract. Low PMD values are preferable.
- **Cut-off wavelength** defines a wavelength barrier for the use of the fiber. Operation below the cut-off wavelength should be avoided. It leads to multimode wave propagation with the inherent disadvantage of multipath dispersion akin to multimode characteristics. Cut-off thresholds above 1310 nm restrict the communications capacity potential of the fiber.

2.1.2 Single-mode fiber categories

The International Telecommunication Union has published standards for six single-mode fiber categories denoted as ITU-T G.652, G.653, and on up to G.657.[7] Most ITU standards include two or more subcategories (e.g., G.652A, G.652B, G.652C, G.652D), specifying variations from the original standard. Vendors' products carry their own brand names; their specification sheets typically refer to compliance with the ITU standards. The actual performance of any product within its category may vary among vendors due to proprietary fabrication techniques and may also exceed the minimum specifications set by the standards organization.

Besides the optical specifications, the ITU standards also encompass fiber dimensions and mechanical parameters, such as centricity tolerances, diameters, and minimum bend radii.

Table 1 highlights the main optical characteristics of a sample of single-mode fiber classifications—which are described in more detail in Appendix A.

[4] "What is four wave mixing (FWM)," Nov. 11, 2018, https://www.technopediasite.com

[5] Coherent Transmission Explained in Simple Terms (neophotonics.com),

[6] https://foa.org/tech/ref/appln/coherent.html

[7] International Telecommunication Union, https://www.itu.int/rec/T-REC-G/en (accessed December 14, 2021).

Table 1: Optical characteristics of single-mode fiber classifications

Fiber Type	G.652D	G.654E	G.655E	G.656
Effective Field Mode Diameter (µm)	8.6-9.5	11.0-15.0	8.0-11.0	7.0-11.0
Cut-off wavelength (nm)	1260	1530	1450	1450
Attenuation (dB/km)	~0.35 @ 1310nm ~0.25 @ 1550nm	< 0.23 @ 1550nm	< 0.35 @ 1550nm < 0.4 @ 1625nm	< 0.35 @ 1460nm, <0.35@ 1625nm
Chromatic Dispersion (ps/nm/km)	0 @ 1310nm, ~17 @ 1550nm	17-23 @ 1550nm	>9, <13	~1 @ 1460nm, 13@ 1625nm
Wavelengths of Use	1310nm, 1550nm, 1625nm	1550nm	1550nm -1625nm	1460nm-1625nm
Typical Applications	Metro Networks, CWDM	High Bandwidth Systems, Submarine, and Back Haul	Long Haul Systems, DWDM	Long Haul Systems with partial CDWM, DWDM

A statewide middle-mile network that aims to support transmission standards ranging from 1 Gbps to more than 400 Gbps over distances of potentially up to hundreds of miles may ideally be comprised of a combination of fiber types.

G.652 fibers are the most deployed fibers to date due to their versatility and relatively low cost. It is estimated that 80 percent to 90 percent of all fibers in operation today are of this class. The more expensive G.655 versions (about 25 percent more costly than G.655) are a distant second in terms of sales volume.[8]

G.652C and G.652D provide a contiguous range of operation from 1310 nm to 1625 nm. Therefore, they also support the full complement of coarse wavelength division multiplexing of 18 channels between 1260 nm and 1565 nm.

The high chromatic dispersion of G.652 fibers in the wavelength bands above 1550 nm, however, poses a challenge for links operated at high bitrates—and may require more frequent regeneration, with shorter spacings, to offset this problem. The need for regeneration would increase over time as the bitrates on the fiber increase.

This drawback is remedied with the G.655 class of fibers, which are optimized for transmissions of high-speed, short pulse intensity, modulated signals as well as for the support of DWDM systems over long distances. The benefit of these fibers comes with a trade-off: a limitation on the optical spectrum that can be used. G.655 fibers are only suitable for wavelengths above 1550

[8] Private communication with Corning Carrier Sales representative on December 5, 2021.

nm as the cut-off wavelength is shifted beyond the 1310 nm region. Therefore, 1310 nm-range optics are incompatible with G.655 fibers.

For short-haul network implementations of up to 25 miles, G.652D fibers will meet end users' requirements without the need for regeneration. Span lengths of up to 50 miles are possible with G.652D fibers using long-haul 100 Gbps pluggable[9] optics based on DWDM and coherent transmission principles as well as intensity-modulated systems with electronic CD compensation.

The development of fiber optic transmission media is ongoing. As new products prove their viability in laboratories, standards specifications are amended or added to the standards family collection. Many recent developments provide an indication of what may be just beyond the horizon. For instance, some recent vendor product specifications for G.652 fibers now meet the minimum standards requirements of the G.657 class, including high bend tolerance suitable for use in conduits with sharp directional changes. Progress has also been made in the research of multicore fibers[10] (which pack two or four fiber cores into a standard-size cladding) and hollow core fibers,[11] as well as in the development of technologies supporting their integration in operational systems.

2.2 Fiber optic cable types and capacities

Fiber strands are bundled in cables that are available in various packaging forms. The industry broadly distinguishes between two types of fiber cables: loose tube cables and ribbon cables. Both types come in several variations of the protective layer composition, tailored to certain environmental factors.

As an example, armored cables are often a choice when additional mechanical protection is indicated. The armor is a corrugated, flexible steel tape wrapped around the fiber bundle underneath the outer cable jacket. A typical use case would be aerial construction where wildlife, such as squirrels, pose a problem. Armored cable typically is not used in underground construction.[12]

2.2.1 Loose tube cables

Loose tube cables contain fibers in bundles of 12 strands, with a total strand count ranging from 12 up to several hundred. These tubes in turn are arranged around a central stress member of steel or dielectric material. Stress members absorb the longitudinal force on the cable during and

[9] J. J. Maki, Evolution of Pluggable Optics and What is Beyond, OSA Technical Digest (Optical Society of America, 2019), paper Th3.2, https://doi.org/10.1364/OFC (accessed December 14, 2021).
[10] Yoshinari Awaji et.al., Optical Fiber Communications (sixth ed.), 2013.
[11] Jeff Hecht, "Hollow-core optical fiber may have a bright future," Laser Focus World, April 14, 2020, https://www.laserfocusworld.com/fiber-optics/article/14170019/hollowcore-optical-fibers-may-have-a-bright-future (accessed December 16, 2021).
[12] Communications with CEO of VerTek, LLC construction company and director of outside plant at Altice USA.

after the cable installation. Hollow spaces between the inner tubes are filled with water-blocking granulates or gel as barriers for water intrusion into the inner tubes. The outer sheath consists of a rugged material that protects the fiber bundles from the environment, including damaging UV light, mechanical wear, physical lateral pressure, and water penetration.

2.2.2 Ribbon cables

In contrast to loose tube cables, the tubes in ribbon cables are filled with strips of 12 or 24 bonded fiber strands. The number of ribbons within a cable can vary from typically 96 up to thousands.

The use of ribbons in lieu of loose fibers raises the strand-packing density possible within a tube—meaning a given tube can accommodate higher fiber counts. Using ribbon technologies, more than 3,456 fibers can be placed into cables of less than 1.3-inch cable diameter. Some vendors offer cables with as many as 6,912 strands.[13] Ribbon cables are primarily, but not necessarily exclusively, chosen in deployment scenarios where the bulk of the fibers originate and terminate in the same locations. Ribbon cables are advantageous for deployment efficiency reasons as highlighted in Section 3.3.

2.3 Conduit options and sizing

Conduits or ducts serve the primary purpose of protecting the cable from the outside environment, such as water, chemicals, and above all mechanical force, which can have a detrimental impact on the performance and longevity of fiber media. They are used for underground construction, in subway systems, in utility companies' deployments, for raceways within buildings, and other applications.

It is a standard best practice to construct underground fiber optic cables in conduit. Placing fiber in conduit, as opposed to directly burying it under the ground, also makes it easier to maintain or upgrade the fiber, because it can be pulled out and replaced. Conduit also allows in many cases for more fiber to be added later, as well as enabling conduit capacity to be constructed for future use without new excavation.

2.3.1 Conduit materials

For new underground construction, conduits made of flexible and pressure-resistant high-density polyethylene (HDPE) are commonly used. In contrast to rigid PVC conduits that find application for indoor cable placements (but which are not allowed in California), HDPE maintains its mechanical integrity and flexibility. HDPE conduits are available in standard sizes as large as up to 6 inches in diameter thus accommodating a myriad of cable deployment situations. They optionally have end-to end pull cords pre-installed to facilitate pulling the cable through the

[13] In 2018 Prysmian introduced the first 6,912-fiber cable for general availability, https://na.prysmiangroup.com/media/press-releases/PG-NA-first-to-produce-6912-fiber (accessed November 29, 2021).

conduit as well as greased inner walls to reduce friction during the cable installation process. The industry also offers conduits with ribbed inner walls to lower the friction and stress on the cable even further.

The conduit wall's thickness is a parameter that has to be determined by the location-specific environment it is placed in. Heavy ground loading, such as road crossings for example, require thicker conduit walls to withstand the pressure than free land deployments. The wall thickness is generally given as standard dimensional ratio (SDR). SDR values is defined as the ratio of the minimum wall size to the outer duct diameter. The industry publishes SDR recommendations for common deployment scenarios.[14] SDR ratings from 9 to 13 are recommended for placements with lateral or heavy surface loads (roadways), whereas an SDR rating of 15 (thinner walls) would be adequate for aerial construction under bridges or subway conduit systems where the conduits have little or no exposure to lateral forces.

2.3.2 Multi-duct construction for capacity building

To avoid the need for additional construction in the future and to protect the investment in trenching, several ducts for immediate use together with a number of spares are buried in the same construction cycle. Where four or more ducts are constructed, they may be laid vertically and horizontally in a duct bank.

A network planner must take many factors into account when sizing the duct and determining the count of duct. Most of the cost of building a fiber network is the labor cost, with materials often costing only 10 percent to 25 percent. Therefore, it is well worth taking the opportunity to add many years of capacity into any construction.

However, when conduit size and count grow, construction costs increase in other areas, including the need to use larger bores, the need to place larger handholes and manholes, the need to use more right-of-way, and increased challenge in navigating around rock and existing utilities. Recommended practices in planning are to determine:

1. The immediate need for capacity, such as the number of cables, the number of separate business entities placing cables, the need for security (which may call for separate conduit for some parties)

2. The potential for one or more entities to work in partnership with the middle-mile network, such as in a public-private partnership, and require conduit for a discrete network independent of the fiber middle-mile network

[14] Plastics Pipe Institute, Chapter 14 Duct and Conduit, https://plasticpipe.org (accessed December 10, 2021).

3. The potential for increased capacity demand in the coming decades for example, new classes of providers with unknown business cases—considering that the lifetime of the infrastructure is many decades, comparable to twice amount of time since the emergence of the commercial internet

4. The need for spare capacity if conduit is damaged

5. The size of conduit needed to accommodate the network's cables—even the largest cables will fit in a 2-inch conduit, which will also fit two cables as discussed below; smaller conduit will not necessarily fit all cable sizes

There are also ways to optimize capacity available from a single conduit. For example, A common duct can be subdivided to accommodate multiple cables of different diameters. The subdivision of conduit space affords the owner the flexibility of filling the space on a per need or per opportunity basis. Quite often only one cable is pulled in to meet the initial and forecast demand while leaving the remaining duct space empty for growth.

The use of innerducts is one of two commonly techniques to subdivide conduit space. Innerducts are made of the same material as the conduit. Conduits with innerducts typically have diameters of 2 inches or 4 inches (and, in rarer cases, up to 6 inches) containing several innerducts of different diameters, commensurate with the envisioned fiber cable sizes.

A relatively new alternative to rigid innerducts is to use low-friction polyester fabric sleeves, providing flexibility in combining cable sizes and a way to augment cables counts in older cable ducts with spare space. The sleeves are folded when unfilled. The sleeves conform to available spare duct space and allow to fill the space with cables of varying sizes up to area capacity of 85 percent. Sleeves can also be pulled into pre-occupied ducts to maximize duct capacity and the solution to augmenting capacity. As a practical matter, pulling a cable on top of another without a guide (i.e., sleeve) is not recommended because of potential cable entanglements in the installation process.

3 Construction Considerations

The decision on fiber cable construction type may be based on a number of criteria including regulatory restrictions, environmental factors, time-to-market issues, available budget, and cost.

3.1 Underground construction

Fiber optic cables can be installed as direct buried cables or laid into ducts. The former is a construction practice mostly applied in network access plants, in particular for fiber drops connecting a residential customer to the closest fiber splicing enclosure a few hundred feet from the home.

To ensure maximum life span, cables of high capacity are buried in the ground within conduits (also referred to as ducts), which is a two-step process. First, the empty conduits are installed between 3 feet and 4 feet below the surface, depending on regional rules,[15] through plowing, trenching, or directional boring. That depth range is an industry norm, deemed sufficient to avoid freezing and accidental damage by surface construction and street repair. The level of effort for the construction depends on the ground composition. Plowing is a fast conduit installation procedure that can be applied if the soil composition is loose and free of plastic-piercing material. Opening the ground and laying the conduits can be accomplished in one work cycle by plowing.

If rocks are present, the excavation of a trench is required. The rock material has to be removed and the trench has to be padded and partially backfilled with soft material, such as sand, to avoid damage to the conduit walls.

Conduit segments are in most instances shorter than the cable segments and therefore need to be cascaded to match the cable runs. To avoid the penetration of water and earth material into the conduit space, the ends are either butt-fused or sealed with compression fittings mounted over the joint.

Upon completion of the conduit construction the fiber cable is inserted into the tube by either a pulling or a blowing method.

3.1.1 Pull method

Pulling fiber through a conduit by means of a preinstalled cord appears to be the method of choice for many fiber contractors in the U.S. The specified maximum cable pull force provided by the cable manufacturer limits the achievable link segment's length; 2,000 feet to 4,000 feet are typical average numbers, but the distance could be much shorter if the route has bends with tight radii requiring higher pull forces due to the friction of the cable within the conduit. It is imperative

[15] Caltrans specifies a minimum depths of 42 inches in its right-of-way. "Incorporating Wired Broadband Facility on State Highway Right-of-Way, User Guide," Caltrans, May 25, 2018, https://dot.ca.gov/-/media/dot-media/programs/design/documents/wired-broadband-facility-user-guide--1-01_edition-a11y.pdf (accessed December 13, 2021).

that the conduits be clean and lubricated to reduce the tension on the cable during the installation process. In that context, the ratio of innerduct to cable diameter is important. Opinions and experiences may diverge across the industry. Best practice is for the conduit space to be about twice the size of the cable diameter.

3.1.2 Blowing or jetting method

Blowing (or jetting) technology allows the installation of longer fiber segments (i.e., beyond the limitations of the pull method),[16] thereby requiring fewer handholes spaced further apart. This is the case even for routes with multiple bends—which, in a network constructed with the pull method, would require shorter distances between handholes because the cable could not physically tolerate the pull force. The blowing technique was invented in the 1980s for challenging fiber placements. It has been further developed in the years since and is now considered the superior placement method for any cable type, including electrical power transmission lines.

Blowing fiber cables into ducts requires machines that feed (push) the cable forward while also blowing air into the conduit. The air flow forms an air cushion around the cable and drives the cable along with reduced stress and friction.[17] As a result, the blow method allows to install cables that fill up to 80 percent of the conduits cross sectional area. The achievable maximum section runs are notably longer than segments of pulled cables. Long continuous fiber sections are preferable to shorter ones because they reduce the number of splice points. Nominal lengths of 9,000 feet are conservative. To achieve longer continuous cable sections, blow stations can be cascaded and distributed along the conduit path. As examples of the capabilities of this technology, an article from 1991 by J. Griffioen should be referenced. A lab experiment demonstrated the feasibility of filling a conduit of 1,500-meter length within two minutes.[18] The same author announced the successful cable installation segment of 800 m with 36 right-angled curves at install speeds up to 60 m/min.[19]

The blow method is more economical as it requires fewer work hours to accomplish cable installation and reduces the number of splice points.

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[16] W.W, Griffioen: “Evaluation of optical fiber lifetime models based on the power law”; Optical Engineering 33(2), February 1994; https://doi,org/10.1117/12.152242

[17] In a variation of the blow principle water is injected into the conduit instead of air called floating. Using water reduces the weight of the cable on the conduit walls thereby reducing friction.

[18] W. Griffieon, G.J Prins, A radically new ultra-high-speed method for the installation of Cables in Ducts, Proc. 40th IWCS (1991)

[19] W. Griffieon, The installation of conventional fibre optic cables in conduits, J Lightwave Technology, Vol. 7 , No. 2 (1989) 27

3.2 Aerial construction

Construction of fiber on aerial utility poles, depending on the condition and capacity of the poles and the business arrangement with the pole owner, can in theory be done rapidly and relatively inexpensively. In practice, the need for license agreements with the pole owner (which may be a business competitor), limited space on poles, and the need to move existing utilities in a "make-ready" process can increase costs, delay construction, and make the construction process less predictable.

Another consideration is that there is less capacity for fiber on a utility pole than in a large conduit bank. Even in the case where there is space for a fiber attachment and the poles can structurally support the capacity, a cable attachment on a typical distribution pole can support at most two large fiber cables, compared to dozens of cables in a small or medium-sized conduit bank.

A decided benefit of aerial fiber plant is a significantly shorter restoration time in case of cable damage compared to underground plant—simply given the ease of access to a damaged aerial fiber as compared to the effort required to repair or replace an underground cable.

3.2.1 Deciding on suitability of aerial construction

Determining whether it may be suitable to use aerial construction to reduce costs and speed construction in selected areas (particularly for a large percentage of rural areas, less so along highways) requires a methodical process.

First, the middle-mile provider should analyze whether a route can provide value with reduced aerial fiber capacity as compared to the larger capacity available in underground conduit. For example, a planned route might have modest anchor institution needs and be in proximity to low-density communities, which last-mile providers could serve with relatively low fiber counts. A route that potentially is redundant to another middle-mile route might also not require as much fiber capacity as a singular route.

Second, the middle-mile provider should perform an analysis of the aerial plant's environmental threats and potential resilience, such as whether the pole line is in an area subject to mudslides or in a Tier 2 or Tier 3 fire-threat area[20]

Next, the middle-mile provider should survey the aerial pole lines along the planned middle-mile routes. The poles should be inspected for condition and capacity, and the outside plant engineer who surveys the route should estimate the make-ready and pole replacement costs that would

[20] "Fire-Threat Maps and Fire-Safety Rulemaking," CPUC, https://www.cpuc.ca.gov/industries-and-topics/wildfires/fire-threat-maps-and-fire-safety-rulemaking (accessed December 10, 2021).

be required for deployment of new fiber. The goal of the route survey should be to determine whether adding two large cables is feasible—and, if so, to estimate the cost.

Comparing that cost to the estimated cost of underground construction (fiber and conduit) will provide a high-level sense of whether aerial construction would be feasible along that route. If so, the middle-mile provider should examine sample pole attachment agreements and have exploratory discussions with the pole owner or owners. For the operator, an "early win" might be possible if a pole owner has resilient poles (i.e., able to support new cables) and is able and willing to expedite the make-ready and pole replacement required over the planned fiber routes.

3.2.2 Aerial construction techniques

For a new provider of cable infrastructure, two options present themselves for aerial builds on utility poles. Assuming sufficient space is available, the traditional cable practice could be replicated that consists of attaching a messenger steel cable to the poles, which is used for lashing the fiber cable in a second work cycle. Future capacity augmentations with additional cables can be accomplished with overlashing. We recommend traditional strand-and-lash approach over use of figure-eight cables or self-supporting fiber cables, which cannot support overlashing and are less flexible and lower-capacity.

Where aerial builds are optimal, they tend to be significantly less costly than underground cable construction. In deployment scenarios with long, mostly straight sections, up to 20,000 feet of cable (limited by the size of standard cable reels) can be mounted in one piece. A crew of three workers can mount on average between 2,500 and 5,000 feet per day. Those numbers may vary from municipality to municipality depending on local construction and safety regulations.

3.3 Fiber splicing

In a middle-mile fiber network, individual strands connect from one piece of network electronics to another, sometimes dozens or hundreds of miles away. The strands are in cables containing hundreds of strands. However, each cable is in a reel only a maximum of 4 to 5 miles long, and therefore at the end of each cable the strands must be spliced to the strands of the next cable.

Furthermore, whenever a cable meets another cable—for example, a lateral cable to a building meets a backbone cable in the street—the strands in one cable need to be spliced to strands in the other cable to connect.

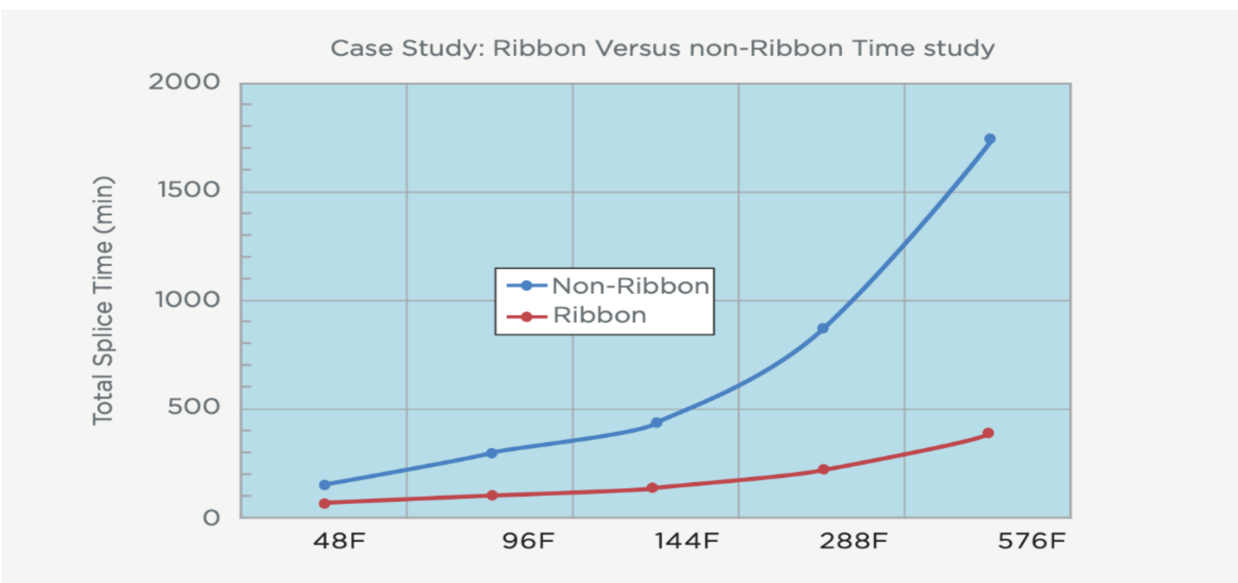
Splicing fiber to connect individual fiber segments in cascades is a critical procedure from the perspective of optical performance and from a mechanical integrity perspective. The process entails exposing individual fibers by removing the outer cable jacket of several feet, removing water blocking fill material end, dressing of the buffer tubes and eventually stripping the coating off the bare fiber strands. The fiber ends are cleaned and cleaved with precision to allow as a perfect butt joint of the two ends as possible. The quality of the joint as it relates to the added optical attenuation is to a high degree determined by the quality of the cleaved fiber facet.

Practically all single-mode fibers are fusion-spliced. Mechanical splices do not provide the durability of fusion splices. In fusion splicing, an arc heats the fiber ends and fuses the molten glass material on both sides together. Newer models of fusion splicers are highly automated and enable precise alignments of the fibers to achieve low-loss joints of less than 0.05 dB, a tiny fraction of the total loss over a middle-mile fiber route.

Subsequent to splicing, the fibers are placed in a splice tray, which in turn fits in an enclosure that must be sealed to prevent water intrusion. The cables have to be sealed as well to avoid longitudinal water penetration. Metallic stress members are now exposed and are required to be grounded.

Splicing fiber cables is a time-consuming and costly task that involves fiber organization, preparation of fiber ends, and stowing of the fiber joints in enclosures. Loose tube fiber cables require the technician to complete one splice at a time. In contrast, ribbon cables provide the advantage of greater splicing efficiency and lower costs. The technician's time and labor cost per splice are drastically reduced on ribbon cables because 12 fibers are fused and processed in every work cycle using a ribbon splicer. The estimated level of effort for splicing loose tube fiber cables compared to ribbon cables as a function of fiber count is illustrated in Figure 2.

Figure 2: Splice time comparison – ribbon vs. single fiber[21]



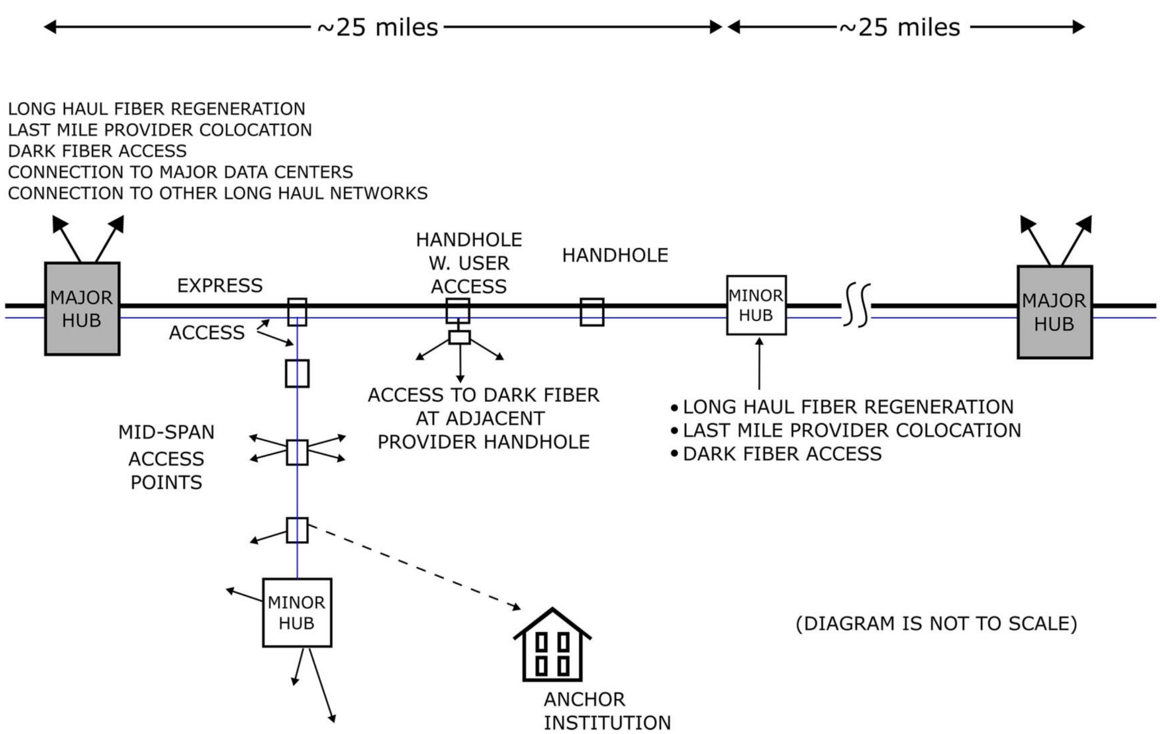
[21] Prasanna Pardeshi & Santosh Akundi, Ribbon Fiber Cable - A comparison with Non-Ribbon Cable, STL.Tech.

3.4 Location and specification of amplification, hub locations, handholes, manholes, and access points

Cable routes are dotted with fiber junction points that serve the purpose of joining individual fiber strands from two cables, cross-connecting fibers from different cables, or enabling the amplification of the optical signals. Those fiber route junction points are accommodated in handholes, manholes, vaults, or hub facilities.

The following figure illustrates these features of a middle-mile network; additional details are in Section 9.

Figure 3: Proposed middle-mile network architecture concept



3.5 Network end points

The end points of the network are interconnections with existing and future last-mile service providers. Service providers could be connected at hub facilities (as described in Section 9.1.4) or be directly connected to fiber in the right-of-way, and commenters in the middle-mile network proceeding have indicated interest in a wide range of flexible connection options.[22]

A network with sufficient capacity in fiber count will connect to last-mile service providers in the unserved areas but will also be able to accommodate other endpoints along the way, such as

[22] Sonic Telecom Opening, ALJ Supplemental Ruling, October 1, 2021, at p. 8-9; Central Coast Broadband Consortia Opening, ALJ Supplemental Ruling, October 1, 2021 at p. 5-6.

anchor institutions. It will also be able to connect to service providers using alternative models, such as wireless networking along the network route.

Where the middle-mile network is alongside a freeway, endpoints can be designed at the end of exit ramps, enabling last-mile providers and other users to connect last-mile fiber built to handhole locations away from the freeway.

Where the middle-mile network is alongside non-freeway collector roads, any handhole (or in the case of aerial plant, splice point on a pole) can be an endpoint, again with the last-mile provider or other user building its cable plant to that location.

Providers that connect in the right-of-way can lease or purchase fiber from the middle-mile provider back to a hub facility, where they can connect to middle-mile network electronics for internet service or other transport services. Alternatively, the providers could colocate their equipment at the hub and use their equipment in tandem with middle-mile network dark fiber.

4 Lifecycle of Fiber Cable Installations

From an investment standpoint, fiber assets have defined lifecycles. And, while decades of experience have demonstrated a typical lifecycle for the elements of fiber infrastructure, many variables can affect the reliability and longevity of installed fiber.

4.1 Financial depreciation standards

Useful lives of fiber assets such as underground conduit and fiber cabling have increased with technological advancements in telecommunications infrastructure. Improved fabrication processes and cable design modifications over the years have led to improved fiber reliability. Official standards and recommendations vary across sources for depreciation schedules; the minimum standard is 24 years for the useful life of underground conduit and 20 years for fiber cabling.

The Internal Revenue Service (IRS) releases an annual publication that documents cost-recovery mechanisms for business or income-producing property through deductions for depreciation. For 2020 tax returns, the IRS proposed a class life of 24 years for both underground conduit and cabling (asset class 48.14, "Telephone Distribution Plant").[23]

Similarly, the U.S. Department of Agriculture (USDA) releases regular notices establishing deprecation rates for telecommunications plant. Its Rural Utilities Service (RUS) administers rural utilities programs, which include management of all telecommunications programs. The 2020 report establishes a median useful live of 25 years for underground conduit and 20 years for underground fiber cable.[24]

The Federal Communications Commission (FCC) adopted depreciation ranges in Docket No. 98-137 dated December 17, 1999, which established a projected life of conduit systems between 50 and 60 years and underground fiber cable ("Buried Cable – Non Metallic") between 25 and 30 years.[25]

In 2012, the U.S. Government Accountability Office (GAO) conducted a study intended to examine proposed policies surrounding burying of conduit infrastructure in conjunction with federally funded highway construction projects. This audit states that "industry documentation

[23] "Publication 946: How To Depreciate Property," Internal Revenue Service, March 17, 2021, https://www.irs.gov/pub/irs-pdf/p946.pdf (accessed December 8, 2021).
[24] "Publication of Depreciation Rates," U.S. Department of Agriculture, Rural Utilities Service, Sept. 3, 2021, 2021-19018.pdf (govinfo.gov) (accessed December 8, 2021).
[25] "Report and Order in CC Docket No. 98-137," Federal Communications Commission, Released Dec. 30, 1999, https://docs.fcc.gov/public/attachments/FCC-99-397A1.pdf (accessed December 8, 2021).

estimates that the expected useful life of fiber cables is between 20 and 25 years and that the expected useful life of underground conduit is between 25 and 50 years."[26]

4.2 Fiber lifecycle predictions

There is a widely accepted assumption in the industry that the fiber in today's cables have a minimum lifespan of 20 to 30 years. Many financial models tend to be on the conservative side by assuming a depreciation schedule of 20 years. In 2008, Technology Futures, Inc. explained the depreciation being based on a combination of physical mortality, technological obsolescence, and loss of use due to competition.[27] The life expectancy of a carefully installed fiber cable may well far exceed 30 years, and conduit substantially longer.

Lifecycle estimates based on long-term statistics of deployed cable plant are scant, as fiber communications has a history of hardly 35 years. It is well known that early fiber links exhibited manufacturing flaws of fibers and cabling, requiring replacements of certain segments within a few years of operations. Notwithstanding early failures caused by mechanical damage, many aerial fiber strands deployed in late-1980s are still operational without any measurable service quality degradation.[28]

4.3 Factors contributing to early mortality

The physics and chemistry of fibers and cables have been extensively researched and modeled over the years by the manufacturing community and by independent institutions. The fundamental aging mechanisms of glass fibers and cable construct requirements are well understood at this time. The most dominant contributors to reduced fiber reliability have been identified to be water exposure and mechanical stress.

The impact of water and hydroxide migration into the fiber glass were recognized as short- and long-term issues from the early days of fiber production and deployments. Aside from leading to higher attenuation, water plays a significant role in corrosion processes at the fiber surface and the consequential weakening of the mechanical integrity of the fiber.

Mechanical stress and fatigue are also significant factors. By nature of the fabrication process, fiber cladding surfaces are dotted with minute surface imperfections. Surface irregularities are the initial starting points of cracks and the progressive mechanical weakening of the glass material. Any applied force – lateral, torque or tensile stress as would occur by applying pull force, pressure, twisting or bending beyond a specified and tolerated bend radius, promote crack

[26] "Planning and Flexibility Are Key to Effectively Deploying Broadband Conduit through Federal Highway Projects," Government Accountability Office, June 27, 2012, p. 4, https://www.gao.gov/assets/gao-12-687r.pdf (accessed December 8, 2021).

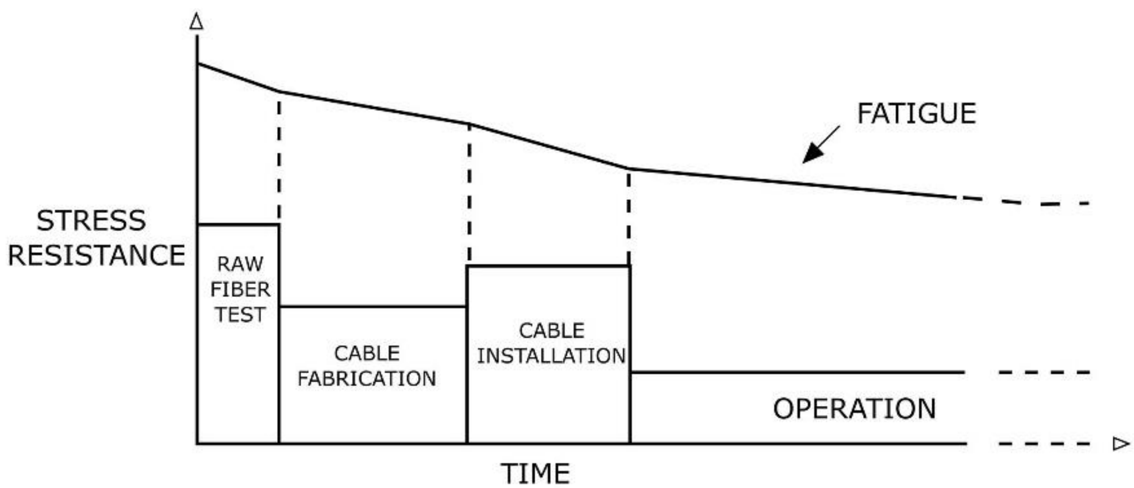
[27] Technology Futures, Inc. quoted in www.prweb.com/releases/2008/03/prweb751014.htm

[28] 1989 – 1992 Cablevision System, Inc. fiber deployments in backbone and access networks of a combined length of over 150 miles.

growth. Furthermore, intrinsic material tension caused during the fabrication process exacerbates the formation and growth of fractures within the glass leading to fatigue breaks. The likelihood of fatigue breaks is sharply raised by persistent fiber motion that could be caused by vibrations or cables swaying in aerial deployments.

Results of fiber material and production research indicate that fiber failures are probabilistic in nature. Discounting infant mortality, models suggest that failures rates are fairly constant and evenly distributed over a long period of time. Figure 4 illustrates qualitatively the main factors contributing to the fiber lifecycle.

Figure 4: Fatigue contributor to cabled fiber strands[29]



Starting with the fiber fabrication process, subsequent integrity proof integrity testing, which has the purpose of eliminating weak fibers from being included in the cabling process, followed by the mechanical stress during the fabrication and eventually during the installation, reduce the internal fiber strength even before it is put into operation. After installation the fiber failure rate is dominated by a stochastic aging process. The two parameters the cable owner has some degree of control over are stress factors as part of the installation process and the environment the cable is exposed to.

Production failure rates and life expectancy estimates are commonly withheld by vendors as proprietary information. Some models suggest a probability of 0.001 percent for any given mile of fiber in a life span of 20 to 40 years. In practical terms, the loss of some fiber strands within a cable can be expected. At the same time, fiber strands in carefully placed cables may well have a

[29] P. Van Vickle, Sumitomo Electric Lightwave

life expectancy far beyond 30 years. Some speculate that fiber strands located in vibration-free environments may maintain the required optical specifications for more than 70 years.

4.4 Environmental factor impact on fiber reliability

The decision on type of plant construction must include an assessment of potential risks that are beyond human control. For California specifically, natural disasters like forest fires, the potential impact of earthquakes, and flooding or mud slides should be evaluated.

In fire-prone regions, underground cables provide the best protection against heat damage. According to the analysis of H.K. Preisler et.al.[30] the soil temperature at 60 cm depth and lower is unlikely to exceed 60°C during wildfires. As fibers appear to withstand temperatures of up to 80°C [31] without any significant long-term degradation, underground cables are sufficiently protected from above-ground fires even in underground ducts buried in shallow trenches.

In seismic active regions, where major terrain movements or even frequent tremors have a high probability, telecommunications infrastructures are at risk of damage or destruction as evidenced by countless events around the world, regardless of build type. The 2019 earthquake in Southern California with a strength of 6.9 to 7.1 on the Richter scale reportedly caused 90 fiber optic cable failures across the fault line, many of which were attributed to pole displacements. Following the Great East Japan Earthquake and Tsunami in 2011, telecommunications institutions analyzed critical weaknesses of earlier infrastructure construction practices. An investigation by K. Sakaki et. al.[32] revealed that a relatively high failure rate was recorded of conduit-based segments with protective concrete on bridges and under buildings that lost their structural integrity during the quake. In a related study, Y. Yamazaki et. al.[33] investigated failure scenarios of underground conduits in urban environments. Simulations of earthquakes confirm observations that ground deformations cause conduits to compress, stretch or bend. Cables inside the conduits are then subjected to sudden tensile, or shear forces resulting in fiber strand or cable faults.

The orientation of the conduit with respect to the direction of the quake is an important factor as well. A proposed damage mitigation practice is the use of flexible joints that allow the conduits to expand and compress without exerting excessive force on the cable itself. Flexible corrugated

[30] H.K. Preisler et.al.: Modeling and risk assessment for soil temperatures beneath prescribed forest fires; Environment and Ecological Statistics 7, 239-25, 2000

[31] Y. Chen, K. Lewis, Beyond 85° C: Thermal Aging Impact on Optical Fiber with Corning CPC Coatings, June 2017, White Paper 4250, https://www.corning.com

[32] K. Sakaki, et.al., Protecting Telecommunication Services from Earthquake Damage, NTT Technical Review, Vol12, No.10, October

[33] Y. Yamazaki, et.al., Seismic Evaluation Technology for Underground Communication Facilities, NTT Technical Review, Vol6, Jan. 1, 2008

ducts engineered to withstand high compression forces have been developed and deployed in quake-prone regions and in areas where land subsidence are potential issues.

While there is no foolproof construction method that circumvents infrastructure damage by natural disasters, their impact can be mitigated by avoidance of routes through know across fault lines, as well as the use of redundant and diverse physical paths where possible, to maintain connectivity when a route is severed.

Consideration has been given to mitigation tactics that include the design of route diversity, mesh networking, dual facility entrances, and data center diversification.

4.5 Fiber break statistics and observations

Aerial fiber is more exposed to the elements, but experience indicates that underground fiber also is regularly damaged, including during unrelated construction activities. Building fiber in Caltrans rights-of-way can mitigate this risk, because it controls access to the right-of-way and fewer utilities are present on freeways and major roads than on city streets.

A study of cable failures in different plants between 1985 and 1998 by Bellcore and Alcoa Fujikura[34] alleges an over 20-fold-higher incident rate for underground cable breaks than for aerial builds based on observations on fiber routes with up to about 28,000 route miles of plant. As the study may not be representative of all cable infrastructure builds throughout the U.S., there is a consensus in the industry that underground construction is far from immune to destruction. Accidental cuts or dig-ups of underground cables by construction machines are reported by all cable service providers as common and frequent occurrences. Operators in England attribute up to 80 percent of cable failures in conduits to construction-related activities. Un-intended excavations of cable conduits have been determined to be the leading cause of inground cable failures, followed by worker errors in Japan.

Statistics for the U.S. are similar to the findings in Japan. According to statistics compiled by Bellcore & Alcoa Fujikura for a period 13 years from 1985 to 1998, 65 percent of cable breaks in underground ducts were attributed to excavation work, followed by 13 percent caused by worker errors. In 1992, MCI submitted a study of cable failures to the FCC stating that 64 percent of large outages were caused by excavations of which 47 percent were the result of planning or plan execution errors and 32 percent could be attributed to a lack of communication among involved

[34] Alcoa Fujikura LTD, Bellcore: Reliability of Fiber Optic Cable Systems, 2001.

parties.[35] Cables buried close in public rights-of-way like roadways can equally be at risk of damage by construction and maintenance activities.[36]

Most in-ground cable damage can be avoided because accidental cable destruction is the result of factors such as ignorance of existing underground infrastructure, lack of coordination between affected parties, lack of markers indicating the presence of fiber cables, poor documentation and availability of as-builts, and sheer carelessness.

It should also be noted that urban development can be a service disrupting factor to installed and operational infrastructure. Owners of cable systems are often required to relocate their plant if the existing infrastructure presents an obstacle to real estate developments or to utility upgrade projects.

Aerial plant is most vulnerable to damage by vehicular accidents, fallen trees, vandalism, lightning, wildfires, and wildlife. Fallen trees and accident-related outages lead the chart. While damage by wildlife, such as rodent bites, are generally less of a concern, they do happen and repair costs can be significant.[37] Also, vandalism and destruction by gun shots have been reported and cited as causes of severe outages.[38,39,40] Armored cables, although not often deployed due to their higher cost, effectively reduce the incident rate of cable failures and outages on segments of heightened physical damage probability.

[35] Dan Crawford: Fiber optic dig-ups: Causes and Cures; FCC Communications Security, Reliability and Interoperability Council, NRC 1992-1994.
[36] In October 2019, CenturyLink reported multiple damages to a buried trunk cable along Route 66 caused by posting of new road signs. The outage lasted 20hours, leaving thousands of customers of several carriers without service.
[37] In 2011 Time Warner had to replace about 50 miles of optical cable in Western New York that was damaged by squirrel bites.
[38] 1992 Cablevision lost connectivity in the Bronx, NY due to a shotgun-damaged aerial trunk cable.
[39] In 2015 the FBI reported three high capacity fiber cables were cut in San Francisco and Sacramento by acts of vandalism – the 11th attack that year.
[40] Just based on failed 911 calls, the FCC recorded over a thousand of malicious attacks on cable infrastructure in the years between 2007 and 2014 leading to severe service outages.

5 Open-Access Middle-Mile Service Models

Currently, many middle-mile providers compete with last-mile providers for enterprise, small business, and residential end user customers. A lack of transparent pricing makes it impossible to know whether these middle-mile providers are setting rates to disadvantage their last-mile competitors. The possibility of future rate increases or adjustments to service offerings or terms can disadvantage smaller last-mile providers and diminish the business case associated with new investments in last-mile networks.

Many states have found creative ways to make state-funded middle-mile communications infrastructure available in unserved or underserved areas on an open-access basis to achieve public benefits, including improving access to social services, improving reliability, lowering the cost of broadband services, and supporting a greater range of business models associated with last-mile network deployments. Additional benefits include transparent pricing and removing the potential of unaffordable middle-mile costs (or the potential for future rate increases) as a disincentive to last-mile investment. The achievements of other state open-access middle-mile networks are described in Section 8.

Some of these public-purpose middle-mile networks have grown out of research and education networks that date back to the earliest days of the internet, while others are more recent legislative initiatives specifically tasked with addressing middle-mile infrastructure gaps that hinder deployment of last-mile networks. Many states that have not explicitly chartered an open-access network still make some state-owned communications infrastructure assets available on a non-discriminatory basis through departments of transportation, public service, information technology or others.

Public-benefit middle-mile networking efforts emerge out of contexts specific to the state or region and develop unique business models that reflect the opportunities and restrictions set forth by the enabling legislation or relevant state statutes. Open-access middle-mile networks generally make some combination of publicly owned conduit, dark fiber, lit fiber, internet, and colocation services available to last-mile providers in the service of public policy priorities. In response to the numerous commentors who advocate for flexible service models, summaries of the network services that middle-mile network operators commonly provide are included below.

5.1 Defining middle-mile and open-access

The authorizing legislation, Senate Bill 156, states that the intent of the state's middle-mile network is "to provide an opportunity for last-mile providers, anchor institutions, and tribal entities to connect to, and interconnect with other networks and other appropriate connections to, the broadband network to facilitate high-speed broadband service…."[41] To meet this intent, this network must be designed to facilitate high-capacity service and meet the needs of last-mile providers, anchor institutions, and tribal entities.

To that end, the California Department of Technology's Middle-Mile Advisory Committee has defined **middle-mile** as "the physical mid-section of the infrastructure required to enable internet connectivity for homes, businesses, and community institutions. The middle-mile is made up of high-capacity fiber lines that carry large amounts of data at high speeds over long distances between local networks and global internet networks."[42]

SB 156 defines **open-access** as "equal non-discriminatory access to eligible entities on a technology and competitively neutral basis, regardless of whether the entity is privately or publicly owned."[43] Ensuring that access is "competitively neutral" helps to distinguish this state-funded network from existing middle-mile infrastructure owned by entities that may make fiber available for lease but do not offer access on a transparent, non-discriminatory basis through procedures such as publishing access rates or allowing adoption or opt-in of the terms and conditions of other contracts.

5.2 Creating opportunities for last-mile providers

The Legislature directed the CPUC to identify the "design, technical, business, and operational considerations that would increase the attractiveness and usefulness"[44] of the middle-mile network for last-mile providers. The California Department of Technology, through its Middle Mile Advisory Committee, has identified as a guiding principle that the state's open-access middle-mile network will "[p]rovide affordable, open-access, middle-mile broadband infrastructure to enable last-mile network connectivity throughout the state."[45]

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[41] SB 156 (2021), Chapter 112, July 20, 2021, Section 3, at p. 2, (Govt. Code Sec. 11549.52(a)); See, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220SB156 (accessed November 29, 2021); SB 156, Section 3, at page 5 (Govt. Code Sec. 11549.52(f)) the defines the "statewide open-access middle-mile broadband network" as the broadband infrastructure funded by Item 7502-062-8506 of the Budget Act of 2021, see SB 129 Budget Act of 2021. (2021–2022)," p. 337, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220SB129 (accessed November 29, 2021).

[42] Middle Mile Advisory Committee, "Middle-Mile Broadband Initiative FAQ," California Department of Technology, https://cdt.ca.gov/middle-mile-advisory-committee/middle-mile-faq/ (accessed November 29, 2021).

[43] SB 156 (2021), Section 3, at p. 5, (Govt. Code Sec. 11549.50(f)); See, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220SB156 (accessed November 29, 2021).

[44] SB 156 (2021), Section 3, at p. 7, (Govt. Code Section 11549.54(f)(1)(B)); See, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220SB156 (accessed November 29, 2021).

[45] Middle Mile Advisory Committee, "Middle-Mile Advisory Committee; Roles and Responsibilities," California Department of Technology, https://cdt.ca.gov/middle-mile-advisory-committee/middle-mile-roles-and-responsibilities/ (accessed November 29, 2021).

The state's open-access middle-mile network can improve the business case and create opportunities for new investment in last-mile networks and improved service delivery in important ways:

- **Lowering the price to last-mile providers of middle-mile transport services**. In less populated areas, where the economics of last-mile deployment are already challenging, the cost of backhaul to a major aggregation point can erase a network's profits.[46] Unlike in urban areas where transport cost per Mbps have steadily declined over time, transport costs in many rural markets have remained steady, and even increased in some areas, making it difficult for a last-mile provider to keep up with exploding demand for bandwidth.[47] Bringing the cost of transport, internet, and colocation services in rural areas in parity with what a provider would pay for such services in a major metropolitan area will lower rural providers' operating costs, thereby improving the case for new investment in last-mile networks in underserved areas.
- **Improving middle-mile service offerings and terms for last-mile providers.** In markets with numerous middle-mile providers, competition forces providers to regularly reinvest and upgrade their networks' capacity and offer users robust service-level agreements.[48] In areas without competition, providers are more likely to push equipment to its full useful life and have limited service offerings with less favorable service-level agreements. Higher capacity, more reliable middle-mile service allows a last-mile service provider to deliver a better user experience over its last-mile infrastructure. Furthermore, in less

[46] Sonic Telecom Opening Comments on ALJ Ruling, October 1 2021, at p. 6. For more examples of the impact high-cost middle-mile service can have on the return on investment associated with last-mile deployments, see the discussion in FCC filings related to middle-mile services in Alaska, where smaller providers have argued for years that the incumbent's monopolistic pricing of middle-mile services make the economics of last-mile deployment impossible. Outside of major population centers, middle-mile prices have remained steady over time, despite federal support for the incumbent's upgrade to its middle-mile infrastructure. Jeannette Lee Falsey, "For rural Alaska broadband, the 'middle mile' is everything," *Anchorage Daily News*, March 18, 2017, https://www.adn.com/features/business-economy/2017/03/18/for-rural-alaska-broadband-the-middle-mile-is-everything/ (accessed December 10, 2021). Even an economic model that the incumbent middle-mile provider submitted to the FCC estimated that costs for middle-mile services would constitute 84 percent of the total operating costs of last-mile networks in some areas: https://ecfsapi.fcc.gov/file/60002060979.pdf; see also: https://www.neca.org/docs/default-source/wwpdf/public/71614arc.pdf (accessed December 10, 2021).

[47] For example, see Yurok Tribe Opening Comments, September 3, 2021, at p. 6. *See also:* Mono County Opening Comments, September 3, 2021, at p. 4 (service costs in rural areas are higher and gaps in middle-mile exist); SANDAG Opening Comments, September 3, 2021 at p. 7, 12; Race Communications Opening Comments, September 3, 2021, at p. 3; Coachella Valley Assoc of Governments Opening Comments, September 3, 2021 at p. 3; LCB/SVI Opening Comments, September 3, 2021 at p. 5.

[48] Mono County comments, September 3, 2021, at p. 4; Coachella Valley Assoc of Governments Opening Comments, September 3, 2021 at p. 3, 4; LCB/SVI Opening Comments, September 3, 2021 at p. 5.

competitive markets, multi-decade contract terms may be unavailable, increasing the risks associated with investing in long-lasting last-mile infrastructure.[49]

- **Addressing the risks for last-mile providers associated with reliance on a single middle-mile provider.** Last-mile providers in areas where only a single operator offers middle-mile services often have no choice but to negotiate contract terms for access to middle-mile services with a company that competes for the same last-mile customers.[50] With limited competition and a lack of price transparency, the last-mile provider has minimal leverage in negotiations. Even if the middle-mile operator initially offers reasonable rates and terms, there is always a risk that evolving business models, market consolidation, or shifting shareholder priorities could cause service offerings or rates to become less favorable in the future.[51] Ensuring rural last-mile providers in California will have reliable access to affordable middle-mile services reduces the risk associated with building a business that relies so heavily on the willingness of a single company (i.e., the middle-mile provider) continuing to offer reasonable terms.[52]
- **Creating colocation facilities that foster interconnection and growth.** In areas that lack an existing carrier-neutral traffic aggregation point, some type of colocation facility will be required to make middle-mile services available locally.[53] These facilities could be provided by the middle-mile operator itself, by local jurisdictions willing to host meet-me-centers, or by private providers willing to agree to certain neutral-host conditions. Last-mile providers will be looking for disaster-hardened infrastructure with affordable power and rack space and the ability to interconnect with others on site.[54]

In order to deliver on its goal of enabling last-mile connectivity to support access to high-speed broadband for a variety of end users in unserved and underserved areas, the state-owned middle-mile network should strive to ensure that comparable service levels, terms, and rates are available throughout the state, regardless of how far a user may be from a major metropolitan area.

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[49] Sonic Telecom Opening Comments on ALJ Ruling, October 1, 2021 at p. 6.
[50] In the past, the FCC forced ILECs to provide certain middle-mile services to CLECs, but recently the FCC eliminated these unbundling and resale requirements. Many commentors note that this will make it more difficult to rely on ILECs for middle-mile services in the future. See for example, Sonic Telecom Opening Comments on ALJ Ruling, October 1, 2021 at p. 4.
[51] California Community Foundation Opening Comments, September 3, 2021 at p. 3-4.
[52] Sonic Telecom Opening Comments on ALJ Ruling, October 1, 2021 at p. 4.
[53] Central Coast Broadband Consortia Opening Comments, September 3, 2021 at p. 10; Rural County Representatives of California, Opening Comments September 3, 2021 at p. 5.
[54] Telephone conversation with Joe Freddoso, former President and CEO, MCNC, December 2, 2021.

5.3 Dark fiber service models

Access to dark fiber on the state-funded middle-mile network was the service most-commonly requested by public commenters. Dark fiber is understood to be a fiber segment without any electronics on either end. The dark fiber provider meets the last-mile service provider or other user at a fiber patch panel with connectorized fibers. The user is free in its choice of electronics, transmission formats, and bandwidth utilization of the fiber capacity. Network traffic management is solely the user's responsibility. It is also the user's responsibility to extend its network to the dark fiber access point.

Dark fiber is offered as point-to-point links. However, at the user's request the service provider may concatenate, or string together, several individual links, sometimes through the inclusion of third-party assets, to create a network topology of the user's choice.

Dark fiber may be preferred over lit services for many reasons:

- It offers the most control over security and privacy of the network
- It offers scalability to full fiber capacity
- It offers the most reliability and network availability
- It provides users with the greatest network control, and independence from third parties
- It offers low latency for mission-critical applications
- It provides a dedicated link between network elements
- It can use proprietary transmission protocols
- It can offer route diversity
- It can offer cost advantage over alternative solutions

Public comments from last-mile providers such as Sonic, South Valley Internet, and Race all discussed the importance and benefits of dark fiber access to their business models.[55] IP service providers (e.g., cable multiple-system operators, telcos) tend to build backbones interconnecting regionalized traffic aggregation points with dark fiber. In addition to "traditional" last-mile providers, data-intensive companies like Facebook, Google, and Microsoft are prime examples of dark fiber users. They lease dark fiber to complement their own fiber builds to interconnect their data centers. And mobile wireless providers prefer dark fiber to connect their facilities to their aggregation points, and their aggregation points to the backbone.[56] As discussed below, users

[55] Sonic Telecom Opening Comments ALJ Supplement Ruling, October 1, 2021 at p. 9-10; Race Telecommunications, September 3, 2021 at p. 2; South Valley Internet, September 3, 2021 at p. 3.
[56] "Dark Fiber Networks Market Size, Market Share, Application Analysis, Regional Outlook, Growth Trends, Key Players, Competitive Strategies and Forecasts, 2020 To 2028," *Research and Markets*, October 2020.

typically choose dark fiber if strong capacity growth is anticipated, reliance on third party operations is undesirable, latency reduction is a priority, or the cost of a dark fiber lease is favorable to the business model.

5.3.1 Common dark fiber user profiles

Common users of dark fiber include:

- **Large ISPs and wireless operators:** Regional and national service providers operate backbones that bridge markets for both internet services and TV programming. Backbones of mid-sized cable multiple-system operators are at (or have already exceeded) the 10 Gbps mark, looking to grow the capacity to 40 Gbps or 100 Gbps. Large, "premier" providers of internet services to communities need high-capacity links with IP transit companies or with internet peering partners.
- **Mid-sized ISPs:** For small service providers that generate traffic below 10 Gbps, lit services are more economical than dark fiber. However, data service consumption is on the rise at a compound annual growth rate of 26 percent to 30 percent.[57] Within 10 years, mid-sized ISPs will reevaluate the cost of lit services against dark fiber options that provide scalability to bandwidths only limited by the selected transmission hardware.
- **Anchor institutions:** Anchor Institutions, first and foremost government agencies, healthcare facilities, and education institutions are prime users of dark fiber. For government agencies one of the most compelling criteria is data security and complete control of the data flow. Healthcare institutions are increasingly adopting cloud applications for the storage and exchange of patient records and image evaluations. Uptime and scalability are critical performance factors in this business model. Odessa Medical in Texas, a twenty-eight-building healthcare operation, moved to a dark fiber infrastructure to avoid outages and bandwidth bottlenecks that had occasionally interrupted their mode of operation with third party service providers.[58] Future applications of telemedicine and virtual reality assisted procedures will further drive the need for bandwidth, reliable service, and short transmission delays.
- **Data centers:** As the number of data centers, especially smaller sized edge data centers, keep growing, this business sector will drive the need for more fiber routes and fiber connections for years to come. New applications associated with the Internet of Things (IoT), artificial intelligence, and cloud computing make edge computing (i.e., decentralized computing) compelling. While the efficiency of large data centers may not

[57] Cisco Visual Networking Index: Forecast and Trends, 2017 – 2022, https://twiki.cern.ch/twiki/pub/HEPIX?TechwatchNetwork/HtwNetworkDocuments/white-paper-c11-741490.pdf (accessed December 15, 2021).

[58] Brad Shook, IT Director at Odessa Medical, interviewed by Kate Gerwig, TechTarget.

quite be achievable, decentralized data networks have the advantage of being collectively more fault tolerant. It can be expected that regional data centers will play an increasingly important role in data processing moving forward.

- **Banking, financial services, and insurance (BFSI) institutions**: The banking, financial services and insurance industry relies heavily on highly available network interconnections between branch offices, data centers, and headquarters. The added security through a dedicated fiber infrastructure, and the unique control of the bandwidth usage and applications, makes this industry a prime potential user of dark fiber leases. In 2019 an unnamed bank moved its backbone to dark fiber. In another example, Provident Bank, based in New Jersey,[59] worked with a national fiber connectivity provider to consolidate networking across 34 branches, based in part on a dark fiber infrastructure.
- **Large enterprises:** Enterprises with multiple production, office, or retail sites have shown an explosive demand for networking capacity, and often have the IT expertise in-house to light their own fiber networks when that is the most cost-effective networking strategy.
- **Entertainment industry:** Many broadcasters have shifted from satellite content distribution to fiber-based networks on a regional basis. Media production companies heavily clustered in the surroundings of Los Angeles are already making use of dark fiber connections for collaboration and exchange of production elements.

5.3.2 Dark fiber pricing and lease structures

Dark fiber is generally priced on a per-strand, per-mile basis for a set term. Usually, the lease price is for fibers on an existing fiber network, and the user is charged the incremental cost to connect its facility via lateral construction to the closest access point on the existing fiber route. Additional fees are also assessed for colocation, any necessary building entry, and rack space. Some entities also charge an upfront fee to cover administrative costs.

Dark fiber pricing varies among markets and, even in the same market, among carriers. Pricing is route-specific, location-specific, and often based on proprietary data that carriers do not share with competitors or even potential users without a nondisclosure agreement. Pricing and structures vary greatly based on region, population density, volume, availability of alternate providers, cost structures and other factors. Each fiber owner will price dark fiber based on its individual goals and objectives, as well as the factors affecting commercial pricing in general: market competition in that location; market demand in that location; and the cost of building in that location.

[59] "Improving efficiency with a network that meets its targets: Provident Bank," Crown Castle, https://www.crowncastle.com/case-studies/provident-bank (accessed December 14, 2021).

The communications industry in the U.S. has developed a range of dark fiber lease structures over the decades of fiber deployment and operations. These structures are used by entities that own or use fiber, including public, private, and cooperative entities. The structures serve a variety of goals, including those related to accounting and tax treatment, but for purposes of this analysis, the structures involve an interplay of two critical elements: first, length of fiber lease and, second, cost. The longer the term, the lower the per-period cost, giving the user an effective discount in return for a long-term commitment—and (in the case of a long-term indefeasible right of use, or IRU) an upfront payment.

Upfront payment plus maintenance. Dark fiber is generally leased through an IRU for a term of 10 to 30 years, though a twenty-year term is most common. To purchase an IRU, the user pays a substantial upfront fee, generally calculated based on number of fiber strand miles leased. The user will also pay an annual recurring maintenance charge that is calculated based on route miles, not strand miles.

The upfront payment usually covers the entire term of the IRU, while the maintenance and colocation portions of the contract are variable or change based on predetermined measures, which allows for cost adjustments (modest in the case of maintenance) based on industry trends or inflation.

For the fiber owner, the benefit of this model is that it produces a substantial inflow of funds early in the IRU term. On the other hand, the model will not result in recurring annual revenues over the long term, beyond a portion of the cost of maintenance.

Per annum or per month pricing. This structure is used primarily for shorter-term commitments, which benefits a user that prefers a shorter-term financial obligation, has shorter-term needs for access to dark fiber, or that cannot pay a large upfront IRU fee. This type of structure could also benefit the fiber owner because it offers the flexibility of a shorter commitment and the chance to increase prices over time or lease to other users on different terms. In addition, it may increase the number of potential dark fiber users by lowering the initial costs (though net pricing over the term of the lease is usually higher than in the upfront payment model over the same period).

5.4 Lit fiber service models

Small and medium-sized service providers, as opposed to large ISPs and enterprise data centers, are more likely to want lit services in the middle-mile to enable them to cost-effectively deliver last-mile services while minimizing their investment in high-capacity, long-haul network equipment. For these smaller providers, lighting middle-mile fiber themselves may add significant operating costs and increase operational complexity. Purchasing lit solutions is likely to be more cost-effective for providers generating less than 10 Gbps of traffic.

Lit, or "managed," service options, which are described in Section 6.3, include managed wavelength (DWDM) and carrier Ethernet. DWDM over the middle-mile can offer the last-mile service provider a clear, dedicated channel with a committed bit rate. On the other hand, an Ethernet service sends data packets though multiple shared switches and/or routers. This can diminish performance over a lengthy circuit and reduces the predictability and consistency of the service, as well as the provider's ability to have visibility of the performance of the link. DWDM connections tend to cost more per Mbps than an Ethernet link, but offer lower latency, and added control, reliability, and security.

A small, local ISP focused on using the open-access middle-mile network to satisfy unmet demand in their own community will likely need to keep up front costs minimal and will not generate enough traffic for dark fiber to be the most economical solution. Mid-sized competitive providers often seek a mix of middle-mile services. They may try to secure dark fiber or more expensive wavelength service for their primary backhaul connections, and then purchase smaller lit Ethernet circuits to other aggregation points to add resiliency and surge capacity to their network.

To meet the needs of last-mile providers that have a variety of sizes and business models, and to facilitate growth and expansion into adjacent markets, industry practices in middle-mile networks are for there to be carrier Ethernet services in increments from 1 Gbps up to 40 Gbps and DWDM services of at least 10 Gbps, and up to 400 Gbps.

5.5 Internet service models

In addition to dark fiber and lit transport services, many open-access middle-mile network providers offer their own brand of internet services, with speeds commonly ranging from 10 Mbps to 100 Gbps, and often including IPv4 and IPv6 addressing, Border Gateway Protocol (BGP) support, and some type of distributed denial of service (DDoS) protection.[60] These services leverage the scale and redundancy of the public infrastructure to offer resilient, low latency, and bulk-priced internet bandwidth—reducing the need for smaller last-mile providers to obtain costly dedicated long-distance transport connections to major aggregation points where backbone IP providers are available and where capacity may be more available and affordable.

The scale of major middle-mile networks allows operators to develop peering relationships with ISPs and content and cloud service providers. Peering relationships and local content caches can improve the quality of service and reduce the amount of IP transit that the middle-mile provider needs to purchase. MCNC and Merit Network both report being able to pass 80 percent to 90 percent of the traffic generated on their networks to networks with which they have peering

[60] "Network Services," *NoaNet*, https://www.noanet.net/products/network-services/ (accessed December 14, 2021); "Connectivity; Internet," *MCNC*, https://www.mcnc.org/our-solutions/connectivity/internet (accessed December 14, 2021).

relationships.[61] Traffic that passes to a peer is traffic the provider does not have to pay to pass to an IP transit provider; these operators are able to pass the savings on to their users in the form of lower rates.

5.6 Conduit lease models

A conduit lease involves leasing access to empty conduit or innerduct. Maintenance costs are typically bundled into the lease fee. Conduit leasing has been offered by some states, municipalities, and telecommunication providers, but is not as prevalent as dark fiber—in part because sale or lease of conduit hands off a large percentage of the total capacity on a route, significantly more than individual fiber strands, and therefore should be done strategically. In some cases, a conduit lease is granted in exchange for access to rights-of-way or other assets. For example, the Utah Department of Transportation has grown a statewide conduit network by building a core conduit network and trading excess conduit capacity for routes throughout the state—expanding the state's networks and minimizing the long-term level of construction in its rights-of-way.

Conduit pricing varies across markets depending on the demand for interconnectivity within the region, much like dark fiber pricing. Typically, rates are based on the size and length of the conduit on a price per foot per annum for a multi-year term. Pricing can also be broken down based on the percentage of occupancy of inner ducts within the conduit.

Constructing some conduit capacity for lease or trade should be considered as a means of supporting future business models and as a means of using trades to cost-effectively expand the middle-mile network beyond its initial routes—for example, to reach urban colocation points and data centers outside the Caltrans right-of-way, or to connect to neighboring cities outside the state, such as Reno, Las Vegas, and Phoenix.

5.7 Colocation service models

The network can offer colocation space for last-mile providers and other users to place servers and other equipment inside hub buildings. A last-mile service provider can place equipment in the hub to interface with lit services provided by the middle-mile network or other networks with a presence in the hub facility. As the number of users at a hub site grows, a site built with affordable power and room to grow can attract other networks to it, thus further enhancing the value to last-mile providers.

Major streaming providers, content delivery networks, cloud service providers, and edge computing services may seek to extend their networks to the site in order to pass traffic more

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[61] Telephone conversation with Joe Freddoso, Former President and CEO, MCNC, December 2, 2021 and telephone conversation with Joe Sawasky, President and CEO, Merit Network, December 2, 2021.

efficiently to local last-mile providers.[62] Additionally, providers can connect their equipment to the middle-mile network to use dark fiber connections for their own interconnections, or to provide their own middle-mile services over the fiber. Colocation can occur both in hub buildings constructed as part of the middle-mile network, or it could occur at carrier-neutral aggregation points along the routes.

Much like in larger data centers, last-mile providers tend to request colocation service in smaller traffic aggregation points as a single rack, half rack, or full rack, and sometimes request a fixed or bundled rate for power consumption on site.

[62] Telephone Conversation with Reid Fishler, Senior Director, Hurricane Electric, December 1, 2021.

6 Requirements of Last-Mile Service Providers

Information infrastructure is in many ways similar to the road system, which is made up of local roads, arterial roads, collector roads, and freeways. Collector roads and freeways are characterized by high traffic volume and by myriad on/off ramps providing many traffic routes between local roads.

The middle-mile fiber network is analogous to the collector road and freeway systems. In a rapidly changing technological environment, wireless and wired last-mile service providers require flexibility in middle-mile route options and interconnection points.

As described below, large and small last-mile providers, as well as anchor institutions and other potential users of the network, have a wide range of needs. It is a good industry practice to perform "market sounding" to ascertain the specific demand for network and application services, as well as using best professional judgement about future needs, to strike the best balance between network capacity and costs.

It is also important to note that, once the network is built, it is costly to modify the fundamental design, such as conduit count and hub spacing. And, as discussed in Section 9.3, many statewide middle-mile networks are intentionally built with excess capacity on some routes, to enable swaps that could expand the network without the cost of new construction.

6.1 Interconnection

Last-mile service providers will, as a fundamental requirement of using open-access middle-mile fiber, need to connect along routes or at hub sites. Diverse interconnection points are critical to ensuring that the middle-mile network will meet the needs of a wide range of last-mile providers and other users.[63]

Many last-mile providers operate systems in many geographically dispersed regions throughout counties and states. For reasons of operational efficiencies, they connect their regional hubs and headends to backbones that terminate at their core network, where OSS/BSS systems, content distribution points, and internet gateways are located. The core network sites in turn rely on data paths leading to various content origination points, cloud application servers and internet access points.

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[63] The CPUC received many public comments discussing the importance of building in multiple interconnection points throughout the network, especially to connect key network hubs, colocation areas and other "meet up" points. The comments noted that placing a priority on interconnection will satisfy statutory goals and increase the "attractiveness and usefulness" of the network to commercial providers. SANDAG Opening Comments, September 3, 2021 at p. 11-12; Race Communications Opening Comments, September 3, 2021 at p. 5-6; Central Coast Broadband Consortia Opening Comments, September 3, 2021 at p. 10; LCB/SVI Opening Comments, September 3, 2021 at p. 9; Yurok Tribe Opening Comments, September 3, 2021 at p. 9-10.

To achieve service availability of 99.99 percent of time, broadband providers seek to build mission-critical links with route redundancy to two or more geographically diverse interconnection points.

6.1.1 Physical access 24/7

Interconnection points of any type (handholes, manholes, hub facilities) need to be accessible at all times. Outages, even service impairment scenarios, may necessitate emergency reconfiguration of the traffic routing schemes and fiber re-splicing to be performed at any intersection of the network. Furthermore, periodic equipment and network maintenance is typically scheduled for hours between midnight and early morning hours. Therefore, interconnection points used by last-mile service providers should not be in locations where they may have limited or restricted access.

6.1.2 Connection in right-of-way along route

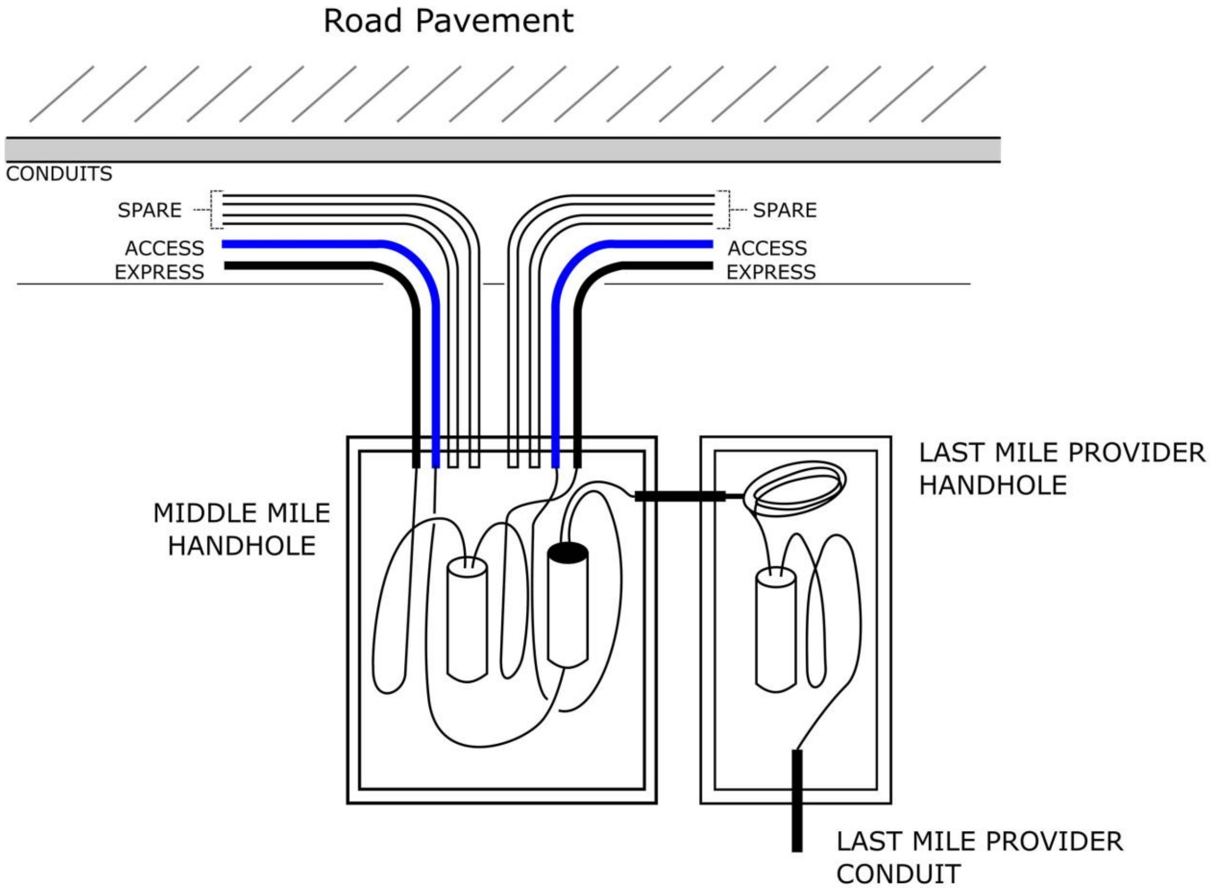
In addition to interconnections at various hub sites close to population centers and businesses, last-mile providers should have the option to meet the middle-mile provider at midspan points. However, Caltrans prohibits last-mile service providers from connecting fiber in the right-of-way—so interconnections at locations other than hub sites will require placement of access points at the edge of the right-of-way.[64]

As evidenced by public responses to the middle-mile project,[65] there is a strong demand from service providers for closely spaced fiber access points along the cable routes. Road intersections as well as highway on/off ramps are strategic locations for handholes because they often coincide with crossings of other communications facilities. By nature of cable infrastructure construction techniques, handholes are required in intervals of a few thousand feet and can be used for midspan access by dark fiber users. Handholes should be sized in accordance with anticipated user access requests. It is recommended that handholes for middle-mile provider splicing and user access be physically separated as illustrated in Figure 5 for reasons of security and damage-avoidance of the middle-mile infrastructure. The last-mile provider would install its own handholes, or the middle-mile provider would build it as part of service installation.

[64] "Incorporating Broadband Facility on State Highway Right-of-Way, User Guide," Caltrans, May 25, 2018, https://dot.ca.gov/-/media/dot-media/programs/design/documents/wired-broadband-facility-user-guide--1-01_edition-a11y.pdf (accessed December 15, 2021).

[65] Sonic Telecom Opening Comments on ALJ Supplemental Ruling, October 1, 2021; Coachella Valley Association of Governments Opening on ALJ Supplemental Ruling, October 1, 2021 at p. 6-7; Central Coast Broadband Consortium Opening Comments on ALJ Supplemental Ruling, October 1, 2021 at p. 5-6.

Figure 5: Sample handhole showing last-mile provider connection to access fiber



In locations off the state highway and road system, different rules apply. If sections are aerial construction, fiber access could be provided at or near utility poles in locked, aboveground fiber splice cabinets.

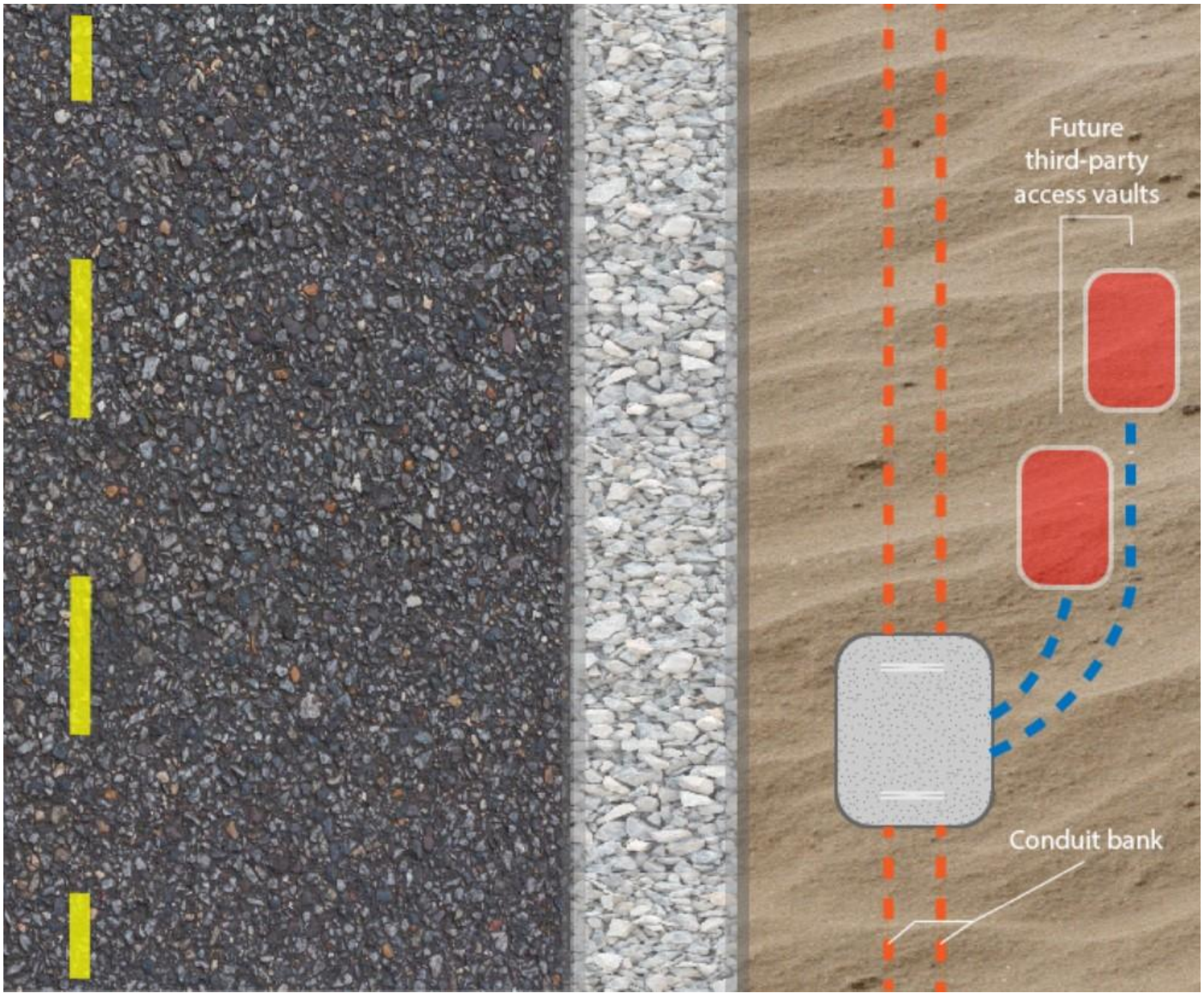
Construction in the rights-of-way of highways and state roads is subject to construction regulations issued by Caltrans.[66] As a general rule Caltrans will not allow handholes or any facilities that may require maintenance in the rights-of-way interstates, freeways, and "access controlled" highways. Exceptions are made for government entities under certain conditions and design deviation approvals on a case-by-case basis.[67] Handholes and hub facilities that are accessed by third parties such as last-mile service providers should be on municipal, county, or

[66] See, California Department of Transportation (Caltrans), Rights of Way Manual (July 2021), retrieved from https://dot.ca.gov/programs/right-of-way/right-of-way-manual; Caltrans Broadband User Guide (May 2018) https://dot.ca.gov/-/media/dot-media/programs/design/documents/wired-broadband-facility-user-guide--1-01_edition-a11y.pdf; Caltrans Broadband FAQs (May 2020) https://dot.ca.gov/-/media/dot-media/programs/design/documents/broadband-faqs-a11y.pdf

[67] Caltrans Broadband User Guide (May 2018), Section 5.2.

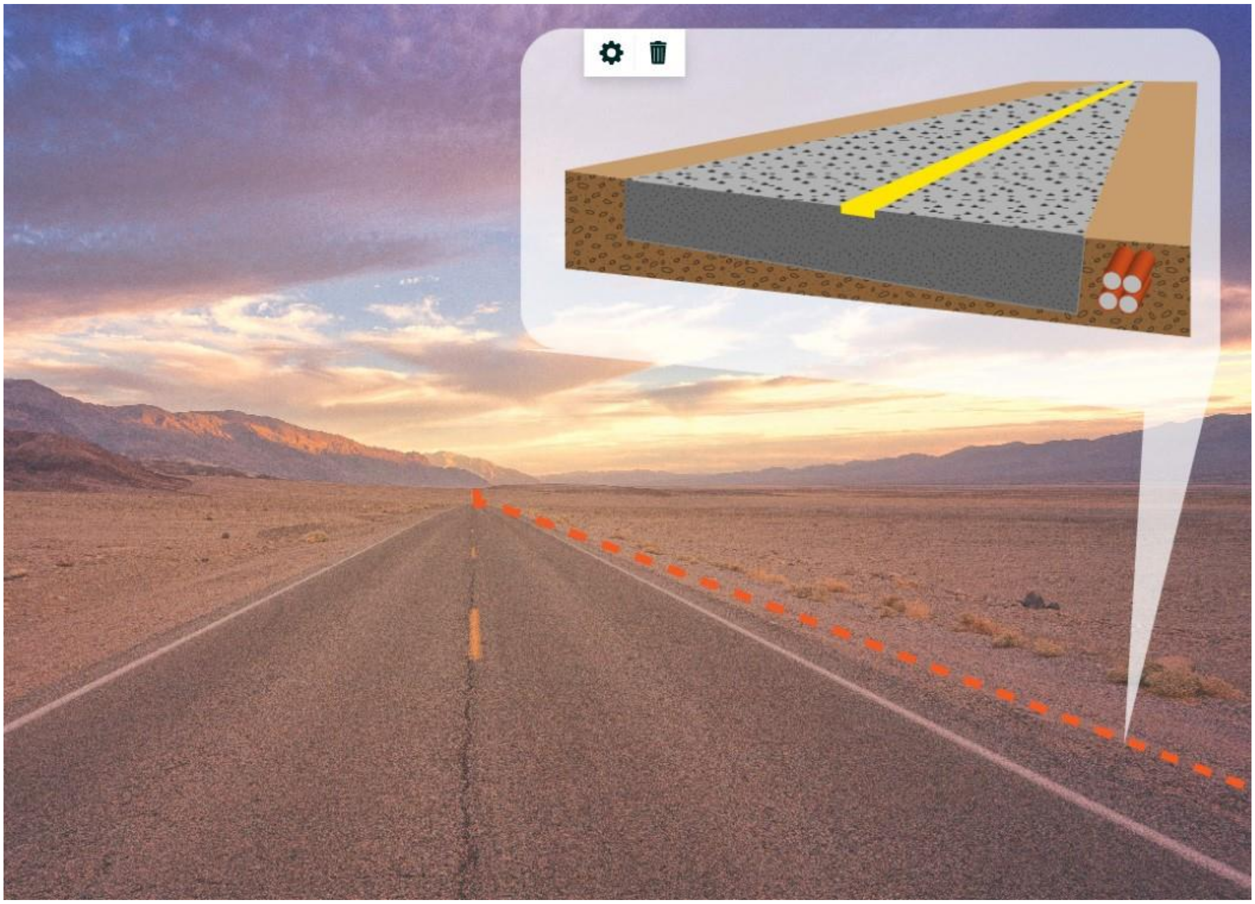
private property. Maintenance-free handholes operated by the middle-mile provider, such as in Figure 6, would be allowed to be placed in the rights-of-way.

Figure 6: Last-mile provider handholes adjacent to the middle-mile handhole



In the fiber it currently operates, Caltrans does not share its conduits, ducts, or fiber strands with broadband providers. It does, however, allow joint builds of conduit space and supports colocation of broadband conduits in its own communications trenches. Figure 7 illustrates conduit in the right-of-way.

Figure 7: Middle-mile conduit bank in Caltrans right-of-way



6.2 Access to key locations and routes

Last-mile service providers will need access to data centers and carrier exchange points, as well as routes out of the area (e.g., to other states) to interconnect with their backbone infrastructure.[68]

6.2.1 Data centers and interconnection points

ISP business models rely on solid interconnections with content providers and the internet at large. Interconnection exchange points are meet-points for carriers and service and content providers. ISPs' links to the internet can be implemented via IP transit providers, which typically have a presence at data exchange points or via peering links to individual private or public entities whom they trade significant traffic with. Peering is the preferred internet networking as it is structured as a settlement-free agreement between the partners. It is quite common for larger

[68] As discussed above, several public comments discussed the need for robust interconnection capabilities, See for example, Race Communications Opening Comments, September 3, 2021 at p. 6.

ISPs to have many peering arrangements specifying meet-points at data centers, at carrier exchange hotels, or even at mid-span hub locations.

The broadcast and content production industries have shifted their distribution model from a satellite to terrestrial fiber-based delivery system, requiring the establishment of points of presence in data centers and carrier hotels.

ISP operations show trends of a paradigm shift. New builds and network upgrades are increasingly implemented with virtualized network functions and cloud-based processing, thereby replacing purpose-built hardware in hubs and head-ends. Associated real time network management and data processing are cloud-computing processes that are consolidated in data centers remote from the service areas. This new model of disaggregated network functions necessitates robust communications links between all geographically dispersed network element functions.

6.2.2 Routes to other states

The proposed California open-access middle-mile network reaches the border to neighboring states in several locations, which present potential business opportunities with other carriers or other state-sponsored fiber initiatives. Fiber links across state lines have been built and operated by telcos, ISPs, and long-distance fiber providers such as Zayo or Crown Castle. As the need for more fiber from the public sector continues, CPUC has an opportunity to capitalize on this state asset. Connectivity providers regularly complement their fiber routes through partner companies on a per-need basis.

For instance, Truckee is less than 40 miles from The Citadel, a data center operated by Switch in Reno. Another fiber interstate interconnection point for California's middle-mile network is conceivably at Blythe. Blythe is the halfway point of a roughly 450-mile middle-mile route connecting Phoenix with Los Angeles. The possibility to extend middle-mile connectivity to those locations could be explored with private and public entities. Two potential business models include IRUs (i.e., offering conduit space or fiber strands to commercial service providers) and collaboration with ISPs and carriers on planning joint construction of data center backhaul service.

6.2.3 Cable landings

Cable landing stations terminate fiber at large data centers and carrier exchange service providers. The barriers to entry for a new cable landing station are high due largely to the cost and timeframe associated with environmental impact assessments, forcing new submarine cable projects to continue relying on existing stations, despite unfavorable terms. According to a private communication with Hurricane Electric, an IP transit and internet backbone provider, many landing stations are privately owned and competitors are prevented from interconnecting directly to the landing stations to avoid price erosion. [69]

In recent years submarine cables have been significantly financed through consortia of users requiring large amounts of bandwidth and dominated by content providers. More than 65 percent of subsea traffic in 2020 reportedly stemmed from international content providers.[70] Facebook, Amazon (AWS), Google, and Microsoft top the chart. They lease capacity and sell off or lease excess bandwidth to other industries, mostly through large carrier exchange operators.

As an example, AWS closed an IRU-based dark fiber deal with Telxius for one pair of dark fiber on the MAREA, a 200 Tbps submarine cable connecting Spain with Virginia.[71] Telxius, as the 50 percent stakeholder of the submarine assets, claimed three pairs of fiber for future use, leaving only four pairs for general international traffic. The data stream aggregation onto the remaining fibers is managed and controlled by a few large-scale colocation facilities and data centers.

According to a statement from Equinix,[72] the business model is evolving from a proprietary model (i.e., the undersea cable company controls the entry and egress from the crossing) to one in which the content providers and service providers terminate their services at carrier-neutral facilities near the undersea crossing.

NJ Fiber Exchange (NJFX) located in Walls, N.J., largely agrees with Equinix's outlook. NJFX's assessment of the landscape concludes that there is a definite need for carrier-neutral submarine access that facilitates connectivity and cross-connects where multiple industry segments can efficiently aggregate their traffic. NJFX is currently the only cable landing station that offers colocation space as a tier-3 carrier-neutral cable landing station in the U.S. They count upwards of 70 customers that extend their networks with dark fiber and/or lit service. The list of carriers colocated with NJFX include Zayo, Verizon, and Lumen, among many others.

Therefore, the emerging industry standard would be for the state middle-mile network to terminate at a carrier-neutral aggregation point near undersea cable crossings, and this approach is of interest to service providers in the state.[73]

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[69] Telephone conversation with Reid Fishler, Senior Director, Hurricane Electric, December 1, 2021.

[70] D. Swinhoe., "Submarine cables find new impetus under hyperscalers," Data Center Dynamics, November 23, 2021, https://https://www.datacenterdynamics.com/en/analysis/submarine-cables-find-new-impetus-under-hyperscalers

[71] W. Qiu, AWS Acquires a Fiber Pair on MAREA Cabe System on IRU Basis, January 21, 2019 https://www.submarinenetworks.com (accessed December 14, 2021).

[72] A. Vaxmonsky, New Subsea Cable Architecture Are Carrying the World's Traffic, http://blog.equinix.com/blog/2020/03/16/new-subsea-cable-architecures-are-carrying-the-worlds-traffic

[73] Yurok Tribe Opening Comments, September 3, 2021 at p. 9 (encourage interconnection with high speed cable landing in Eureka).

6.3 Access to network and application services

As discussed in Section 5, different open-access service models can support the connectivity needs of last-mile service providers and other users of the middle-mile fiber. These include not just dark fiber, but also managed services and wavelengths.

6.3.1 Dark fiber

Broadband service providers prefer to have as much control over their network as possible, and the large providers are the most likely to have a business and technical model where they use dark fiber and manage their own infrastructure. Generally, the large providers operate and manage a significant portion of their own infrastructure. In comparison to lit services, dark fiber does not require additional intermediary electronic equipment at the hand-off points; therefore, closing gaps with dark fiber makes sense from an operations point of view. More importantly, as discussed above in Section 5, the increasing need for bandwidth makes dark fiber economically more compelling than lit services depending on the user's data needs.

Dark fiber is for the most part offered as an unmanaged service. This means the user is responsible for the operation end-to-end, which includes the monitoring of the optical attenuation and identification of any fiber breaks. In recent years, companies leasing dark fiber have started to monitor their leased fiber assets by means of automated periodic testing of the transmission characteristics by means of Optical Time Domain Reflectometers (OTDR) on unused strands within the cable. Statistically, locating a cable break consumes upwards of 70 percent of the restoration time without OTDR surveillance. Integrated OTDRs allow the operator to instantly identify the precise location of a cable break and dramatically reduce the repair time.

An industry standard practice would be for the middle-mile provider to monitor all routes, including any routes where it only had dark fiber, by conducting continuous OTDR surveillance of a spare strand. If the middle-mile provider operates a lit services on the route, monitoring those services can suffice.

6.3.2 Managed services

In terms of lit fiber services, the fiber strands and terminating equipment, as well as the "cloud" routing network between end points, are infrastructure operated by a middle-mile provider.

Lit services include point-to-point links as well as point-to-multipoint links allowing the last-mile service providers and other users to build private and secure virtual home networks extending geographically over a metro area and beyond. The signal path between any two last-mile service provider access points travels through an interconnected network of routers and switches that are entirely under the middle-mile service providers' control and management. The lit fiber provider connects with the last-mile provider or other user's electronic equipment via standardized opto-electronics interfaces—typically pluggable optics—with fixed bitrates that range from as low as 1 Gbps, 10 Gbps, 40 Gbps up to 100 Gbps (today). Almost all interfaces are based on Ethernet and internet protocol (IP) standards.

Many carriers also support traditional SONET telecom transmission formats, such as 2.4 Gbps OC-48, although the demand for SONET and ATM connectivity has been in decline in recent years giving way to IP and Ethernet transport technologies, and the industry standard is not to include legacy services in developing a new network.

Therefore, a service contract or a service-level agreement between the two parties should list terms of committed information rates (minimum guaranteed and peak data rates) to set mutual expectations for service-level performance.

From a cost perspective, as discussed in Section 5, lit services are favorable to leased dark fiber for extended link lengths of lower capacity. Furthermore, lit services provide the user with networking flexibility and ease of operation, which may be important for smaller carriers or along secondary routes. Links can be turned up relatively quickly once the equipment is installed in the access locations. Changes to the network configuration, including speed upgrades can easily be accomplished in cooperation with the service provider. The management of the inter-facility network is the service provider's responsibility.

6.3.3 Wavelength services

Wavelength services, also known as managed wavelengths, have many similarities to dark-fiber in terms of privacy and latency. The proliferation of DWDM systems, which are cornerstones of high-capacity links today, is expected to continue. A carrier operating DWDM allocates one or several optical channels of the DWDM grid to the last-mile service provider or other user. For enhanced security, the optical channels may be equipped with optical encryption ensuring privacy against neighboring traffic traversing the same fibers.

Wavelength service plans are tied to standard speed tiers with tiers from as low as 1 Gbps up to 400 Gbps. The bitrate and interface options are dependent on the operators' DWDM systems and their interface specifications.

While wavelength services are by nature point-to-point links, some carriers, such as Crown Castle and Zayo also configure their networks to form ring configurations for path diversity traffic aggregation.

The difference between dark fiber and wavelength service is that the wavelength service is a service provisioned by the provider's electronics over the fiber, as opposed to the fiber itself. The service depends on the operation of the provider's DWDM platform and must be added and dropped at the provider's DWDM multiplexer at a hub facility.

In contrast, a last-mile service provider using dark fiber is completely independent of any electronics other than its own. The dark fiber user has end-to-end control of all signals on the fiber. There are also capital and operational costs for both the DWDM multiplexer and the optics to connect the last-mile service provider.

On a network where dark fiber is plentiful and inexpensive, many last-mile service providers will opt for dark fiber over a managed wavelength service for these advantages of control and independence. In a scenario with plentiful dark fiber, the main advantage of wavelength solutions is that, for long distances, the middle-mile provider often bundles the service with amplification at the hub facilities, and the last-mile provider will not need to have its own amplification equipment at intermediate hub facilities.

6.4 Access to multiple competing providers

The availability of competition in the middle-mile creates market dynamics favorable to last-mile network users. Besides having the leverage of competition, last-mile service providers can diversify reliance on third-party service partners to avoid outages in their service domain that result from system failures beyond their control.

6.4.1 Diversity and resilience

It is common for private enterprises and last-mile service providers to seek connectivity from multiple fiber connectivity companies for separate, independent paths to the same location. Uptime is one of the most important attributes of a resilient network design. The existence of fiber routes outside the enterprise's footprint is a consideration when weighing which connectivity provider is best suited to ensure diversity in a manner that provides service availability even in scenarios of major disruptive events, such as earthquakes or floods.

Highly redundant systems and networks are configured to tolerate at least one path or location failure without any service degradation. Even higher-level redundancy is achievable with meshed network topologies that allow fast rerouting of traffic and establish optimal connectivity over available network nodes.

6.4.2 Reduced costs

Access to open-access middle-mile fiber can reduce the costs for last-mile service providers. The degree to which access to middle-mile will reduce costs will depend on many factors, including route distances, the presence of third-party service providers, and content providers at interconnection points. In order to contain the cost of operation for the last-mile provider, a middle-mile provider should aim to place geographically dispersed access points in the form of handholes and hub sites that provide ease of construction for the last-mile provider. Likewise, industry practice is to build middle-mile fiber to interconnection points such as regional data centers and carrier hub locations.

6.4.3 Ongoing product evolution

In addition to reducing costs, open-access middle-mile fiber—as in other competitive environments—can enable product evolution and innovation that might not otherwise occur. For example, the availability of new middle-mile fiber in areas that previously were poorly connected can spur the development of smaller data centers closer to end users.

6.5 Minimum technical standards

Last-mile service providers will require that the middle-mile network and the services offered over the middle-mile network meet minimum technical standards in terms of capacity, security, and availability—which are key parameters for ensuring their own operations. Furthermore, all interconnection specifications for electronics and fiber optic elements have to be standards compliant and supported by the telecommunications industry at large.

6.5.1 Capacity

Lit services are generally available at fixed rates and on standard interface opto-electronics. The data rates range from as low as 1 Gbps up to 100 Gbps. Also, the data rates for wavelength services are generally different from Ethernet transport due to greater networking and traffic flow complexity of the latter, which makes it more difficult to provide the service at higher speeds.

- Wavelength services at a minimum support 10 Gbps interface with upgradeability to 40 Gbps and 100 Gbps.
- Ethernet data rates at the lower end are 1 Gbps but may be raised to 10 Gbps or 40 Gbps as a point-to-point service, depending on the provider's offerings. Ethernet point-to point may also be provided over DWDM at information rates of 50 Gbps to 100 Gbps.

Traffic management is essential to ensuring that lit Ethernet users' service levels are met in accordance with their contracts. The user's signal path traverses a mesh of switches and routers between end points. Any network element along the path can potentially be a choke point leading to congestion.

Last-mile providers will need to scale and upgrade transmission services within the existing fiber architecture. As bandwidth demand rises on the user side, the middle-mile capacity has to keep pace. A last-mile service provider that starts with a pair of 10 Gbps connections may require 100 Gbps as more customers adopt the service and as demand for new services increases.

For lit services, the supported interface speeds and pluggable optics models will need to expand over time. The provider's core routing and switching architecture will have to be grown in lockstep with the core network and edge traffic and the throughput offers to the user. Middle-mile Ethernet and DWDM equipment chassis may have a five- to 10-year lifetime, but the optical cards and interfaces will need to be upgraded more frequently.

6.5.2 Security

All service providers and anchor institutions will need assurance of data privacy on every element of the network and protection from a third party's unauthorized access to network management functions. For some industry segments, security takes the highest priority over any other aspects of the network service. Federal government agencies typically scrutinize network solutions for vulnerabilities and set forth restrictive rules of operations procedures for the provider.

Security measures span all network domains from design, construction details, operational procedures, and IT functions. Essential security practices include:

- Unattended hub sites are secured with key locks and access code security for both the building and surrounding grounds. Security cameras must be installed outside and inside the facility to deliver live feeds to the network operations center.
- Major hub sites are staffed with concierge desks logging visits and providing escorts though the facilities. Those without on-site staff will require middle-mile network staff to provide escorts.
- Middle-mile provider owned equipment as well as colocated equipment must be installed in locked cages or cabinets.
- Fiber access points such as handholes, and sidewalk cabinets must feature lockable doors or bolted lids on underground handholes and vaults. Easily accessible doors on outdoor cabinets are alarmed.
- Critical outside plant work and fiber splicing is supervised or audited.
- Lit services are provisioned with encryption techniques to render eavesdropping ineffective.
- Access to network management functions is restricted to authorized personnel and safeguarded by the industry's up-to-date intrusion prevention standards.

6.5.3 Availability

Documented availability of conduit, fiber, and third-party service offerings are important decision parameters for last-mile providers as they weigh their interconnection options.

In terms of dark fiber, if the last-mile provider decides to design a network that includes dark fiber middle-mile facilities, it will rely on accurate and transparent information on cable routes and fiber splice points to avoid unintended single-point-of-failure implementations.

Lit service availability can be captured and specified in several ways, including long-term or average availability. Short-term (time-specific) availability may be tied to use cases and therefore specified separately.

Average network availability is typically expressed in percentage of time. A general benchmark is 99.99 percent uptime for hosted applications and network connectivity ISPs seek to achieve on their last-mile service. A middle-mile provider, from the ISP point of view, needs to meet or exceed that target. Machine-to-machine applications require tighter margins of 99.999 percent or better. Depending on the end user's sensitivity to lost minutes of service, network availability may be spelled out in more granular terms in service-level agreements. As averages only reflect cumulative periods of degraded service but not specifically event durations, time limitations of service impacting disruptions may be a key metric as well.

Data service agreements can be structured in various ways. For example, best effort services, as the lowest quality service, make no warranties for throughput or attainable bitrates regardless of the interface electronics capabilities. More commonly users opt for a tier of service that commits the carrier to provide a minimum throughput and permits the data rate to temporarily peak up to a set burst rate. Data latency and timing variations in information arrival are equally relevant user key metrics that are governed by the service contract.

7 Capacity Growth Outlook

There are continuing trends toward increased and critical reliance on internet connectivity across all sectors. Cloud computing in data centers, the Internet of Things (e.g., security camera and data analytics), and networks of wireless access points supporting automated vehicular traffic are a few of the drivers for more densely meshed data networks and for higher transmission capacity requirements on every link, including those farther out to the edge.

According to market research, the global dark fiber industry is projected to expand yearly by 9 percent until 2028[74] while other research suggests growth of 12 percent up to 2026.[75] KBV Research[76] estimates that 68 percent of these investments will be made on long-haul dark fiber, 32 percent in metro-type fiber infrastructure.

Some fiber connectivity companies report that between 50 percent and 60 percent of all service agreements are on dark fiber leases today.[77] This strong market growth is in part attributed to the increasing dependence on reliable and robust internet connectivity of application hosting companies, service providers and data centers.

7.1 Commercial demand

Much of the current and expected future growth in commercial demand is fueled by relatively recent paradigm shifts in the industry. IT departments of larger enterprises have traditionally relied on in-house data centers that required huge capital investments. The remote data center model offers the advantage of "grow as you go" capability, but requires high capacity and secure, robust data transmission capabilities outside of in-house networks.

Multi-tenant data centers form eco-systems that make cloud storage, cloud computing and application hosting a compelling case with reduced capital expenditures and operating cost.

According to a data center survey in 2019,[78] 63 percent of enterprises still operate their own data center infrastructure. But 36 percent of that group acknowledged that they are deciding whether to upgrade their infrastructure in the coming years or to leverage third-party data center facilities.

Data centers and their service domains are evolving, too. A new demand for edge computing is on the rise to support the emergence of highly interactive services with low latency requirements

[74] Brand Essence Market Research and Consulting Pvt Ltd, September 7, 2021.
[75] Business Wire, Research and Markets, May 12, 2021.
[76] KBV Research, Market Research Report, March 2021.
[77] Private conversation with VP of Operations at FiberLight, on Texas markets.
[78] Penny Jones, "The trends driving the multi-tenant data center and services industry in 2020," 451 Research, LLC, January 28, 2020, https://go.451research.com/2020-mi-trends-driving-multi-tenant-datacenter-service-industry.html (accessed December 10, 2021).

(e.g., support of automated vehicles and Internet of Things). As discussed above, there is also a predicted need for smaller scale data centers that are situated closer to the user, and new middle-mile capacity may accelerate the emergence of those centers in California. Last-mile providers will benefit from the growth of edge data centers that will drive the demand for local and intermediate distance fiber connectivity, creating a cycle of supply and demand that will support local economies and data storage growth.

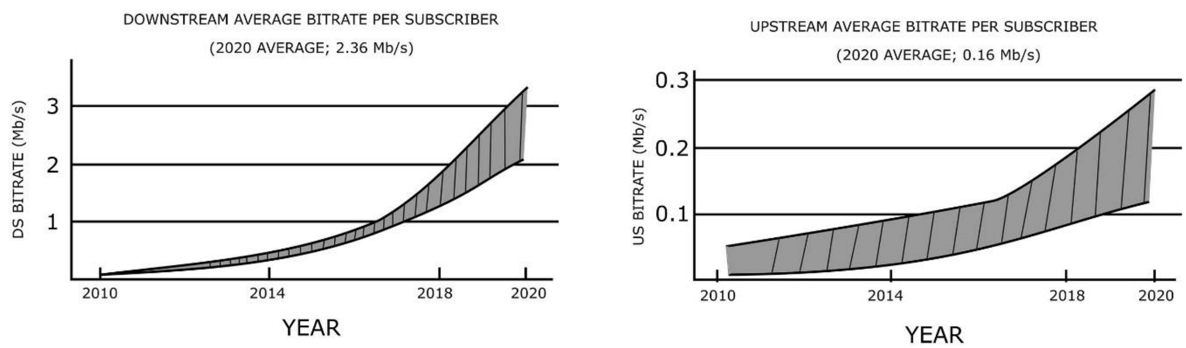
7.2 Residential and small business growth

The incumbent broadband providers consider residential customers and small businesses together as one service class. Restaurants, travel agents, remote office locations with small staffing would be examples of commercial enterprises that qualify as small businesses. The service delivery technology, on-premises networks, and bandwidth usage between small business commercial customers and residential customers are materially the same or very similar, especially as more Californians do telework, distance learning, and telemedicine from their homes.

It is to the advantage of the ISPs, when planning capital investments, to have a blend of residential and small businesses on their last-mile segments as the network utilizations of the two customer categories complement each other. Residential bandwidth demand is relatively low during regular business hours but builds up in the late afternoon to reach its peak during late evening.

Capacity estimates and forecasting for residential and small business market segments have been consistent and predictable over the past 15 to 20 years. The figure below illustrates the range of average upstream and downstream data rates at peak time (evening hours) recorded and reported by four independent cable ISPs for residential data service. The data flow is characteristically asymmetrical because of the underlying consumption behavior of residential subscribers. The downstream traffic per household has been increasing at a fluctuating compound annual growth rate of 25 percent to 40 percent over the past decade and reached an average bandwidth between 2 Mbps and 3.3 Mbps in 2020 (Figure 8).

Figure 8: Average subscriber downstream (DS) and upstream (US) data rates per subscriber



Over the years, several technological innovations and service options have contributed to the steady increase in bandwidth demand. Growing use of the internet as an information retrieval vehicle and graphics-rich internet content were drivers of bandwidth in the earlier years, widespread streaming of entertainment over the internet has been the cause of the surging demand in recent time. Furthermore, the average number of internet-connected devices per household has increased from two devices 15 years ago to over 10 in 2020.[79] While it may be difficult to forecast at what point in time the residential demand will plateau, one can speculate that the next major demand surge might be fueled by virtual reality-based communications applications and increases in connected home devices. By extrapolation of past usage, we estimate the average household quite possibly will consume an average of 100 Mbps during prime usage hours within 15 years, up from 2.3 Mbps in 2019.

This increased usage drives capacity demands by last-mile providers. A local ISP serving 10,000 households would engineer its backbone capacity to peak demand that occurs between 8:00 pm and 11:00 pm with 90 percent of subscribers showing some degree of internet activity. At this time, 9,000 out of 10,000 subscribers generate 2.5 Mbps, which equates to a minimum bandwidth requirement of over 20 Gbps capacity on the backbone. By the time the per-subscriber bandwidth has risen to 100 Mbps, the anticipated aggregated bandwidth would amount to 900 Gbps. Last-mile providers will consider changes to network architecture and the content distribution model with the goal of containing costs related to expensive backhaul. These last-mile providers will use tools to mitigate these costs such as local caching and a higher degree of fiber mesh networking.

7.3 Anchor institutions

Similar to businesses, anchor institutions such as schools, hospitals, government offices, law enforcement facilities, and community centers will benefit from networks between their

[79] " Average number of connected devices residents have access to in U.S. households in 2020, by device," Statista.com, March 2020, https://www.statista.com/statistics/1107206/average-number-of-connected-devices-us-house/ (accessed December 16, 2021).

locations, where synergies and the need for data-heavy collaboration exist. Different types of anchor institutions have their own types of requirements:

- Government agencies at the federal, state, and local levels continue to expand their networks to affiliated offices to more efficiently meet their internal communications needs and deliver services. Network connections to these agencies are often implemented with dark fiber or wave services for added security against unauthorized access.[80]
- Hospital groups have been in a process of transformation from independent care givers to digitally integrated care networks. They have shifted their mode of operation from manual paper record keeping to electronic systems that permit rapid retrieval of patient records and real-time sharing of x-ray images across different locations.

  Virtual care and multimedia-assisted telehealth over internet connections are rapidly becoming elements of public care practices. The facilities' dependence on reliable, highly available network connections will become even more important as telemedicine and virtual reality-assisted applications for medical procedures are predicted to gain wide-spread adoption. Many health care groups are regionally interconnecting their clinics with dark fiber to ensure sufficient capacity and service availability.

  The adoption of advanced communications, instrumentation, and diagnostic tools in the medical field will also rely on robust interfacility networks of high capacity.[81]
- The education sector has been undergoing significant changes through the incorporation of tools and resources made available on the internet. Remote lectures and the extensive use of collaborative applications are no longer a vision of the future but have been accelerated and intensified through the need to meet basic educational goals in the face of a global pandemic.

  The formation of regional and even statewide education consortia in support of bandwidth needs are well under way. Schools can collectively draw many of the same benefits as commercial enterprises in terms of cost efficiencies, economies of scale, and

[80] See, for example, public comments by SANDAG discussing the use of middle-mile capacity to support public safety and connection of government offices. San Diego Association of Governments Opening Comments, September 3, 2021 at p. 7, 13.

[81] "Best practices in the ANSI/TIA-1179 Healthcare Facility Telecommunications Infrastructure standard recommend that healthcare networks support a minimum of 10 Gb/s speeds in most areas, with 40/100 Gb/s in the healthcare network data center core": "The Need for Speed in Healthcare Networks," *Ciena; Application Note,* 2017, https://media.ciena.com/documents/The_Need_For_Speed_In_Healthcare_Networks_AN.pdf (accessed December 12, 2021).

content synergies. The sharing of resources such as internet access links, digital libraries, and human resources increase operational efficiencies while reducing overall costs.[82]

7.4 5G in rural areas

The evolution of wireless cellular technology and the use of fiber for radio tower connectivity and backhaul have been advancing hand-in-hand, increasing demand for reliable, high-capacity middle-mile infrastructure. For the low to moderate data speeds supported by 2G and 3G services, copper-based TDM circuits had a useful role.

With the advent of the first generation of 4G LTE, offering bitrates of up to 12 Mbps and serving 4,000 devices per square kilometer (about 0.4 square mile), fiber connectivity became the backhaul transport medium of choice. 5G operating in new spectrum bands, including 24 GHz millimeter wave, promises peak connection speeds between 1 Gbps and 10 Gbps per user, thus driving significant increases in the demand for both middle-mile fiber and fiber to individual antennas.

Propagation models of the 24 GHz spectrum expected to be used in built-up areas indicate a densification of radios from one per square mile typical for LTE technology to about 40 micro cells per square mile for 5G in urban, suburban, and small-town areas, with the density varying in rural areas between these numbers.

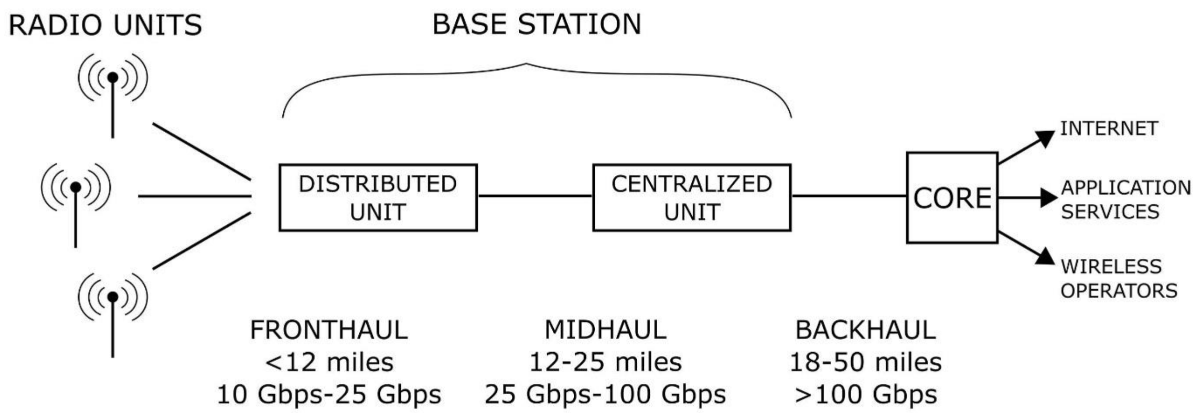
The anticipated 5G revolution will drive the demand for fiber much further than LTE has. There is an industry-wide consensus that the success of 5G deployment is intertwined with the availability of high fiber counts.[83, 84] The widely adopted build concept for 5G radio access network (RAN) is based on a distributed model, which comprises clusters of radios being connected to a baseband unit via fronthaul fibers (Figure 9, below). The baseband unit's function is logically and physically split into a distributed radio-facing unit and a control unit located in a regional data center, miles away from the radio antennas. The control unit of the baseband, in turn, is connected via backhaul links to the operator's core network.

The tight timing constraints between the individual functional elements of the architecture require low-latency fiber connectivity, and the sheer number of deployed network elements will be the determinant for fiber count. Based on architectural design concepts, the midhaul section

[82] "Median bandwidth per student [in schools facilities] has increased nearly five-fold since 2015, and by 37.6 percent [between 2019 and 2020]:" "2020 Executive Summary," *Connect K-12,* November 2020, https://connectednation.org/wp-content/uploads/2020/11/Connect-K12_final.pdf (accessed December 12, 2021).
[83] The Thales Group, 5G technology and networks, April 5, 2021.
[84] Kirsten Queen, "5G and fiber: two big reasons why 5G technology needs fiber," CenturyLink, February 8, 2021, https://discover.centurylink.com/2-reasons-5g-technology-needs-fiber.html (accessed December 12, 2021).

may require 10 times the fiber count of the backhaul section.[85] A middle-mile provider is poised to play a pivotal role in the 5G buildout by facilitating midhaul and backhaul fiber connections.

Figure 9: Next-generation 5G radio access network build concept



Intensive preparations for 5G rollout are well under way. Everstream, a “business-only” fiber company, announced early 2021 plans to add more than 2,000 miles to its infrastructure in the Midwest, in part to facilitate the connection of 2,000 5G macro towers, each served with a capacity of 100 Gbps.[86] Verizon stated that its aggressive plans to build fiber had been key in the support of their 5G rollout plans.[87] If 5G delivers on the promise of high capacity and proves to be suitable for real time vehicle control, the need for dedicated fiber in midhaul and backhaul driven by capacity and low latency requirements will rise dramatically.[88, 89, 90]

[85] G. Brown, New Transport Network Architectures for 5G RAN, Heavy Reading, white paper produced for Fujitsu, https://www.fujitsu.com (accessed December 10, 2021).
[86] Mike Robuck, “Everstream gears up to support 5G with fiber builds in 7 Midwest markets,” *Fierce Telecom*, January 12, 2021, https://www.fiercetelecom.com/telecom/everstream-gears-up-to-support-5g-fiber-builds-7-markets (accessed December 12, 2021).
[87] Verizon 2020 earnings call noted in Fierce Telecom article: Mike Robuck, “Verizon CEO: Fiber build out is paying off for more than 5G,” *Fierce Telecom*, January 30, 2020, https://www.fiercetelecom.com/telecom/verizon-ceo-fiber-build-out-paying-off-for-more-than-5g (accessed December 15, 2021).
[88] FiberLight’s Chief Executive officer Mac Dyman quoted in RCR Wireless News article: Catherine Sbeglia, “‘You’re assuming fiber is there:’ The less-talked about roles of fiber in 5G networks,” *RCR Wireless News*, March 24, 2021, https://www.rcrwireless.com/20210324/5g/youre-assuming-fiber-is-there-the-less-talked-about-roles-of-fiber-in-5g-networks (accessed December 15, 2021).
[89] Jon Baldry, “5G Is Rapidly Approaching, What Must Cable MSOs Do To Capitalize On This Business Opportunity,” SCTE Expo, October 22–26, 2018, https://www.nctatechnicalpapers.com/Paper/2018/2018-5g-is-rapidly-approaching (accessed December 10, 2021).
[90] “Verizon to Aggressively Deploy Dark Fiber for 5G Backhaul,” Zacks Equity Research, August 15, 2017, https://www.zacks.com/stock/news/227993/verizon-to-aggressively-deploy-dark-fiber-for-5g-backhaul (accessed December 10, 2021).

8 Benefits Achieved by Open-Access Middle-Mile Programs

Open-access middle-mile infrastructure platforms are used around the world and throughout the U.S., and many have as their mission to improve broadband access in unserved and underserved areas. Each middle-mile project must be tailored to fit the unique needs of the community it serves. However, the best-practices discussion below demonstrates that with the right mix of infrastructure, service offerings, and transparent and competitive pricing, these projects can reduce the upfront infrastructure costs and ongoing operating demands associated with operating a last-mile network in an unserved or underserved area.

Examples of successful international projects include projects in some of the smallest European countries that have had to expand their public infrastructure out of necessity. Estonia, with support from the European Agricultural Fund for Rural Development, has built the Estonian Wideband Infrastructure Network (EstWin) consisting of more than 4,400 miles of open-access middle-mile fiber nationwide, with the goal of addressing the urban-rural digital divide throughout the country. Once it was completed, 90.8 percent of households in urban areas had internet connections in 2019, while 89.6 percent of those in rural areas did.[91]

Lithuania has seen similar success with its Rural Area Information Technology Broadband Network (RAIN), winning the 2015 European Broadband Award in the socio-economic impact and affordability category for the second phase of its network implementation.[92] Some countries with state-owned telecommunications companies, like South Africa[93] and Brazil,[94] have allowed these companies to knit together fiber assets from state-owned electric, pipeline, and rail companies, and install new fiber in public rights-of-way, in order to create a nationwide open-access fiber backbone.

Other countries with less existing communication infrastructure have received loans from the Export Import Bank of China to build new, publicly owned fiber backbones, including Uganda's

[91] "Freedom on the Net 2020: Estonia" Freedom House, https://freedomhouse.org/country/estonia/freedom-net/2020 (accessed December 20, 2021).
[92] "Improving broadband access in rural Lithuania," *European Commission; EU Regional and urban development; Regional Policy; Projects,* November 2, 2018, https://ec.europa.eu/regional_policy/en/projects/lithuania/improving-broadband-access-in-rural-lithuania*,*
[93] "Who we are," *Infraco,* https://infraco.co.za/ (accessed December 12, 2021).
[94] Daniel Arnaudo, "Brazil, the Internet and the Digital Bill of Rights," *Igarape Institute*, April 2017, https://igarape.org.br/marcocivil/assets/downloads/igarape_brazil-the-internet-and-the-digital-bill-of-rights.pdf (accessed December 12, 2021).

National Transmission Backbone (NTB)[95] and the Dorsale à Fibre Optique Nationale of Guinea.[96] Additionally, in places like Sweden,[97] Iceland,[98] Ireland,[99] and New Zealand,[100] federal, regional, and municipal authorities have created open-access last-mile fiber-to-the-premises networks.

In the U.S., states and regional agencies have tasked open-access middle-mile programs with using publicly owned communications assets in the service of public policy priorities, such as reducing connectivity costs and improving service quality for anchor institutions and last-mile providers.[101] Some of these networks, like Merit in Michigan and MCNC in North Carolina, have interconnected higher education institutions since the earliest days of the internet, and evolved to offer a range of networking services to anchor institutions and last-mile providers. Many more, including the Maryland Broadband Cooperative (MdBC), the Mid-Atlantic Broadband Communities Corporation (MBC) in southern Virginia, NoaNet in Washington, and Project THOR in northwest Colorado are more recent creations, chartered specifically to address gaps in middle-mile infrastructure in rural areas.

The organizational structures and business models of each of these networks reflect their unique histories, chartered purpose, and the opportunities and restrictions afforded them in state statutes and regulations. Yet, these projects can offer important guidance and input for new broadband offices and state authorities that are starting down the same road toward building an open-access middle-mile network.

8.1 Affordability is a key element of successful open access middle-mile networks

Services over the State's middle-mile network should be priced in a way that is affordable for last-mile service providers. To that end, the affordability of middle-mile network services is an important consideration for network planners. Many of the State's future last-mile users—which may be ISPs or other kinds of entities organized to address broadband gaps around the State—

[95] Uganda's NTB offers a cautionary tale as the project has largely failed to achieve its stated goals in part because of the use of lower capacity G-652 fibers: "Implementation in crisis: How can the National Transmission Backbone Infrastructure be realized?" *The Republic of Uganda, Ministry of Finance, Planning and Economic Development; BMAU Briefing Paper,* May 2015, (accessed December 12, 2021).

[96] "Construction du Backbone National à Fibre Optique," *Ministere Des Postes, Des Telecommunications et De LEconomie Numerique,* https://mpten.gov.gn/construction-du-backbone/ (accessed December 12, 2021).

[97] Masha Zager, "Municipal Fiber in Sweden," *Broadband Communities,* December 1029, https://www.bbcmag.com/community-broadband/municipal-fiber-in-sweden (accessed December 12, 2021).

[98] Reykjavik Fibre Network, http://www.reykjavikfibrenetwork.is/ (accessed December 13, 2021).

[99] "About Us," *Open Eir*, https://www.openeir.ie/about-us/ (accessed December 13, 2021).

[100] "Ultra-fast broadband roll-out, New Zealand," *Institution of Civil Engineers,* https://www.ice.org.uk/what-is-civil-engineering/what-do-civil-engineers-do/ultra-fast-broadband-roll-out-new-zealand (accessed December 12, 2021).

[101] For a summary of many of the middle-mile initiatives undertaken in other states, see: The Advanced Communications Law & Policy Institute at New York Law School Reply Comments, September 21, 2021 at p. 3.

will rely on this infrastructure because it will be a tool by which they can viably address the market opportunity represented by broadband gaps in the State. But those gaps will not become market opportunities in the absence of affordable middle-mile services. Affordable middle-mile service is thus one critical element of ensuring last-mile deployment is viable.

Many of the new last-mile providers may be public entities. They will have entirely different economics than commercial entities. And the smallest ISPs among them will depend on affordable pricing that make their initiatives viable.

Affordability cannot be specified in the same way as a technical element like conduit size or fiber count, but it can become a guiding factor for the State's network. Experience in other states with open-access middle-mile networks illustrates best practices (and hurdles) to achieving that goal.

In Maryland, for example, middle-mile pricing over the open-access component of the state-owned fiber network has been sufficiently affordable for small ISPs, non-profit entities, and local governments that the middle-mile network infrastructure has been extensively utilized and has created last-mile opportunity and activity throughout the state. (See Section 8.2.2 and 8.2.3.) In contrast, in Massachusetts, pricing was quite frankly set too high by the state's partner; in our observation, the resulting under-utilization of the state's MassBroadband 123 middle-mile network was one of the primary challenges of that initiative.[102]

8.2 Accomplishments of open-access middle-mile programs in other states

Experience demonstrates that open-access middle-mile programs can lower costs and other barriers to last-mile service provision, while also delivering operational benefits such as increased network resiliency.

8.2.1 Improving service quality and lowering costs for anchor institutions

State-supported research and education networks have been providing middle-mile transport services for institutions of higher education since long before the world wide web was invented.[103] Some have expanded their reach to serve a broad range of anchor institutions including K-12 schools, libraries, and health care facilities.

These middle-mile networking efforts often impact the price anchor institutions pay for bandwidth. An anchor institution located in an area where the only connectivity option is a copper-based T1 line may be paying well over $500 per month for a 1.5 Mbps service. Once an

[102] "Construction, Turnover Complete on New 1,200 Mile Fiber Backbone for Western and Central Massachusetts," Massachusetts Broadband Institute, News Release, February 18, 2014, https://broadband.masstech.org/press-releases/construction-turnover-complete-new-1200-mile-fiber-backbone-western-and-central (accessed December 27, 2021).

[103] "About; History," *Merit Network,* https://www.merit.edu/about/history/ (accessed December 14, 2021); Who we are; History," *MCNC,* https://www.mcnc.org/who-we-are/history (accessed December 14, 2021).

anchor institution can secure a fiber connection to a state middle-mile backbone, it often ends up paying less for a more reliable connection with many times the capacity.

In California, CENIC has a long history of finding cost-effective ways to connect institutions of higher education, K-12 schools, and libraries to the California Research and Education Network (CalREN) backbone, supporting ongoing and reliable access to the bandwidth they need at a recurring price they can afford.

Even in cases where the middle-mile network does not directly serve anchor institutions, the availability of the open-access middle-mile network can help bring down the cost of last-mile services by lowering the costs associated with transport service to a major aggregation point where bandwidth is most affordable and direct connections to major content and cloud service providers are available. On the western slopes of Colorado, Project THOR makes transport service available to both public and private sector users at community-hosted Meet-Me-Center. Project THOR charges $1.30 per MB for private-sector partners and $1.02 for public sector partners. Previously middle-mile providers in the area were charging roughly double that rate.[104]

8.2.2 Lowering barrier to entry for last-mile providers

With the right service offerings and competitive pricing, open-access middle-mile infrastructure can substantially reduce the upfront infrastructure costs associated with building a new last-mile network in an unserved or underserved area.

Without open-access middle-mile fiber, new entrants are often forced to purchase middle-mile transport and colocation services from incumbent telecommunications or cable companies, which may be in direct competition for last-mile customers. In some unserved or underserved markets, the reliable, high-capacity middle-mile transport services a new entrant would seek may not be available at all. Even if such services are available and an incumbent provider initially offers reasonable rates for colocation and middle-mile transport services, the threat of future rate increases may be enough to deter the new entrant from investing in a last-mile buildout, even if demand is there and some state or federal funding support is available.

As soon as high-quality, competitively priced middle-mile service becomes available, providers find ways to use it to bring service to the places in the community that are most starved for bandwidth. If the barriers to entry are sufficiently low, a new provider may emerge right from the community. This has happened in communities across the state of Washington thanks in large part to the services and support that NoaNet, the state's open-access middle-mile network. Once NoaNet connected the Jamestown S'Klallam Tribal facilities in Blyn to fiber, the tribe's economic

[104] Tamara Chuang, "Internet service in western Colorado was so terrible that towns and counties built their own telecom," *The Colorado Sun*, April 16, 2020, https://coloradosun.com/2020/04/16/internet-service-western-colorado-rural-broadband-nwccog-sb152/ (accessed December 12, 2021).

development authority established its own last-mile service provider, Jamestown Networks (JNET), connecting the tribe. JNET focuses on connecting tribal, government, commercial, and other anchor institutions, such as schools, libraries, and hospitals. Thanks to NoaNet, JNET has been able to minimize its own investment in infrastructure, while still expanding its reach well beyond its local community. Today, JNET serves more than 60 schools and 40 tribal, government, and commercial customers.[105]

The state of Washington has a number of public utility districts (PUD) that have invested in open-access last-mile infrastructure. Open-access middle-mile and last-mile fiber has helped create a thriving ecosystem of retail ISPs. Many of these retail providers operate without any fiber infrastructure of their own, and can still deliver high-quality services to a growing pool of users connected to open-access last-mile fiber across the state, as seen in the ISP and service location counts of some of the larger PUD last-mile networks: 10 ISPs are using the Chelan County PUD network to serve more than 16,000 homes; five ISPs are using the Kitsap County PUD network to serve more than 1,000 homes; five ISPs are using the Mason County PUD network to serve hundreds of homes; 13 ISPs are using the Grant County PUD fiber network to serve more than 70 percent of the community; and 12 ISPs are using the Benton County PUD network to serve area businesses and homes.[106]

Even in areas where last-mile fiber is still scarce, access to NoaNet network services makes it relatively simple to create a fiber-fed, fixed wireless ISP that provides reliable broadband service in areas that previously only had DSL or satellite internet. A version of this story took place in Skamokawa, Washington, at the mouth of the Columbia River. In fall of 2017, after camping in the area, Steve Carson and his wife got the urge to buy a home that was for sale in Skamokawa but needed a way to get reliable internet to be able to keep their businesses going. Steve ran an IT firm, and learned that NoaNet fiber ran right nearby, but state statutes prevented them from serving a residential customer. Steve began talking to neighbors and discovered enormous demand for better internet service. He invested in some fixed wireless equipment and launched Skamokawa Internet Services less than a year later. [107] The company continues to add additional transmitter sites to offer service in new areas. When the pandemic forced the area into lockdown in early 2020, Steve had already expanded the network to be able to offer reliable broadband

[105] Customer Spotlight: Jamestown Networks," *NoaNet*, February 22, 2021, https://www.noanet.net/insights/case-studies/customer-spotlight-jamestown-networks/ (accessed December 12, 2021).
[106] "Dark vs. Lit Fiber: The Importance of Open-Access Broadband," *NoaNet*, September 1, 2021, https://www.noanet.net/insights/dark-vs-lit-fiber-the-importance-of-open-access-broadband/ (accessed December 12, 2021).
[107] "Customer Spotlight: Skamokawa Internet Services," *NoaNet*, November 19, 2020, https://www.noanet.net/insights/customer-spotlight-skamokawa-internet-services/ (accessed December 12, 2021).

service to almost 100 of his neighbors.[108] The availability of open-access middle-mile services from NoaNet makes small last-mile networks like Skamokawa Internet Services more economically feasible, and capable of delivering a customer experience that satisfies the growing residential and commercial demand for bandwidth.

For municipalities and counties that are interested in working with the private sector to address broadband coverage gaps, open-access middle-mile services can help improve the underlying economics of public private partnerships. As a member of the Maryland Broadband Cooperative (MdBC), Charles County was able to leverage the competitively priced middle-mile services MdBC offered in its area as it sought a private provider to work with to bring fiber service to unserved parts of the county. The county was able to form a partnership with a local ISP, ThinkBig Communications, in 2020 that guarantees that unserved rural areas will get ubiquitous fiber-to-the-premises deployments. In return for ThinkBig's deployment commitments, the county made a grant to the company and served as applicant to a state broadband funding program that unlocked additional funding for ThinkBig.[109] The County was able to get ThinkBig to agree to providing rates and service levels in line with those offered in the Washington, D.C., metropolitan area, which would have been an unreasonable request to make of a provider had MdBC's competitively priced transport service not been available in the area.

Similarly, in Colorado, the resilient network architecture and competitively priced middle-mile transport services offered through Project THOR helped Summit County secure a partnership with ALLO Communications to bring fiber-to-the-premises service to the area.[110]

Open-access middle-mile networks can also serve as a building block that larger competitive last-mile providers can use to efficiently expand their networks into new territories. Not long after Highline, a rapidly growing competitive fiber provider, had won much of the Rural Digital Opportunity Fund support available in Michigan's upper peninsula, the company announced it would be purchasing dark fiber and wavelength services from Merit's open-access network to expedite its buildout. Merit President and CEO Joe Sawasky noted that, "Considering that hundreds of thousands of Michigan residents still lack access to basic broadband service, this collaboration with Highline Internet using our open-access dark fiber and dark wave services

[108] "Happy New Year," Skamokawa Internet Services, January 28, 2021, https://skamokawa.net/new/happy-new-year/ (accessed December 14, 2021).
[109] Charles County Government, "$2.9 Million Broadband Grant Awarded to Charles County," thebaynet.com, May 20, 2020, https://www.thebaynet.com/articles/0520/29-million-broadband-grant-awarded-to-charles-county.html (accessed December 9, 2021).
[110] Lindsey Toomer, "Fiber optic network projects expand across Summit County." *Summit Daily*, July 6, 2021, https://www.summitdaily.com/news/local/fiber-optic-network-projects-expand-across-summit-county/ (accessed December 9, 2021)

represents a crucial next step in our common goal to facilitate equal fiber broadband internet access to everyone in need—regardless of geographic location."[111]

8.2.3 Creating opportunities for existing service providers

A lack of affordable backhaul in an incumbent provider's existing network footprint limits the service offerings that last-mile networks can deliver. A cable provider may not construct hundreds of miles of its own fiber to connect to its more remote hybrid fiber-coaxial (HFC) networks, but with the availability of open-access fiber in the area, these providers can leverage the competitively priced middle-mile services to upgrade their network capacity and improve service options. As a member of the Maryland Broadband Cooperative, for example, Comcast has been able to leverage open-access dark fiber to help upgrade its service offerings in parts of Maryland's rural eastern shore where the company did not have its own fiber.[112]

Similarly, in North Carolina, Zayo and Crown Castle used dark fiber IRUs from MCNC to fill in gaps in their networks and extend their services into more communities across the state. The high-capacity backbone also helped boost demand for higher-capacity last-mile services among anchor institutions, improving the revenue opportunity for the last-mile providers MCNC relies on to connect anchor institutions to its North Carolina Research and Education Network (NCREN). When a telehealth consortium formed in the state, MCNC began serving many of the state's rural healthcare facilities. The healthcare facilities would specify their capacity needs for last-mile circuits and MCNC would help negotiate with a local last-mile provider. Gaining access to a backbone with abundant capacity drove demand for higher capacity last-mile circuits. Then-CEO of MCNC, Joe Freddoso, monitored the consortium members' evolving requirements and found that 95 percent had upgraded to a larger circuit within five years of being connected to NCREN.[113]

8.2.4 Adding resiliency to the communications system

Public-purpose middle-mile infrastructure can also improve the resiliency of communication systems. In northwestern Colorado, the incumbent provider had single fiber routes into many of the western slope communities, and the towns suffered frequent service disruptions. The Northwest Council of Governments (NWCOG) came together to form Project THOR, a middle-mile backbone ring that interconnects meet-me centers in each of the participating jurisdictions and provides transit service back to an internet exchange point in Denver.

The network was designed specifically to improve resiliency and reliability in the area and it has contributed to a reduction in the number and length of network outages. When a mudslide cut

[111] "High Capacity Fiber Internet Service Expedites Connectivity in Michigan's Upper Peninsula through Highline Internet," *Merit; News*, August 2, 2021, https://www.merit.edu/news/high-capacity-fiber-internet-service-expedites-connectivity-in-michigans-upper-peninsula-through-highline-internet/ (accessed December 9, 2021)

[112] Telephone conversation with Drew Van Dopp, President and CEO and Tyler Patton, Senior Vice President of Public Affairs, *Maryland Broadband Cooperative*, December 1, 2021.

[113] Telephone conversation with Joe Freddoso, former President and CEO, MCNC, December 2, 2021.

a major fiber route in Glenwood Canyon, it took critical Colorado Department of Transportation (CDOT) equipment offline. Project THOR's resilient ring architecture quickly provided needed support, as CDOT later explained: "[Project THOR] jumped in and provided CDOT with backup bandwidth so that we could get our devices, cameras and weather station west of the 123.5 [mile marker] up and running so we could get better situational awareness."[114]

Communities adjacent to Project THOR's jurisdictions have also benefited from the resiliency that Project THOR brings to the area's communication infrastructure. In October 2020, the Cameron Peak and East Troublesome fires threatened the fiber routes in Estes Park, placing the community's communications system at risk. NWCOG's Regional Broadband Program Director, Nate Walowitz, established a new fiber route into Estes Park originating from a hospital already connected to Project THOR in Granby. Stringing together existing fiber from multiple public and private providers, the new route was established in under 48 hours, and created a ring for a resilient link between Estes Park and Fort Collins to its east.[115]

In 2017, the Washington Department of Emergency Management worked with NoaNet to help upgrade the state's 911 public safety answering points to next-generation 911 (NG911). As of spring 2020, the entire state's 911 system had migrated from circuit-switched connections to NoaNet's resilient fiber backbone. The upgrade has already improved 911 call routing and response times. Seeing this improvement, counties in the state have now begun to upgrade their 911 systems to enable next-generation 911 services, like text-to-911 and livestreaming from emergency events, to help prepare first responders.[116]

8.2.5 Building sufficient capacity for current and future use

The Utah Department of Transportation (UDOT) operates approximately 2,700 miles of conduit and fiber in interstates and other highways in its right-of-way, including a resilient ring covering major corridors around the state. While UDOT constructed approximately 1,000 miles of conduit, it constructed sufficient conduit capacity to trade with commercial providers on other routes and traded its excess conduit to expand its mileage almost threefold.

UDOT conduit is used for internal communications and operations, including CCTV, variable message sign connections, and management of traffic signals and other devices. UDOT is in the process of planning and deploying connected vehicle applications. The conduit is also used for

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[114] Kelli Duncan, "Project THOR a hidden hero in reopening of Glenwood Canyon", *Vail Daily,* August 16, 2021, https://www.vaildaily.com/news/project-thor-a-hidden-hero-in-reopening-of-glenwood-canyon/ (accessed December 12, 2021).
[115] Tamara Chang, "Spurred by the threat of wildfires, an Estes Park broadband project moved at the speed of light," *The Colorado Sun*, November 9, 2020, https://coloradosun.com/2020/11/09/fires-estes-park-broadband-emergency-communication/ (accessed December 12, 2021).
[116] "A Safer Washington with Next-Generation 911," *NoaNet; Case Studies,* October 27, 2021, https://www.noanet.net/insights/a-safer-washington-with-next-generation-911/ (accessed December 9, 2021).

the state's government and public safety network and to provide connectivity for service providers serving locations throughout the state.

The number of conduit varies by route but is a minimum of eight in each build. UDOT has had instances where the conduit has been insufficient and it increased capacity by installing microduct in the conduit. UDOT has found that the commercial providers, including AT&T and CenturyLink, prefer their own conduit over fiber lease arrangements so that they can manage their own fiber installation and splicing.

For UDOT, recent conduit construction costs have ranged from $184,000 per mile on I-84 to $204,000 per mile on I-70, for projects over 100 miles each. Construction techniques have varied over the routes, including saw-cutting and boring. The highest costs were in mountainous areas where saw-cutting was required. Design principles include fiber access vaults every half-mile for transportation communications, and regeneration facilities spaced up to 50 miles apart.[117]

8.3 Lessons learned

Staff and former staff from Merit, MCNC, Project THOR, UDOT, and MdBC have identified lessons learned in terms of construction, operations, and business model approaches through the execution of their respective middle-mile networking projects.

8.3.1 Construction

- **Use merit-based system to award construction contracts.** After the first fiber construction crew that MCNC used took longer and cost more than initial estimates, MCNC began to split new fiber builds into phases, and assigned the first phase across multiple construction crews. MCNC then selected the crew that met the specified quality standards at the lowest cost per mile and in the appropriate time frames in the first phase to complete the second, larger phase of construction.[118]
- **Perform construction and business development tasks in parallel**. When MdBC was chartered, the enabling legislation placed restrictions on fund allocation. The cooperative could fund construction-related expenses, including hiring construction and project managers; however, their funding could not be used to hire operations and business development staff until later into the project. This restriction interfered with the group's community relationships and ability to build relationships with the last-mile carriers that would have driven increased demand for middle-mile infrastructure to improve the availability of service and ultimately benefit the end users in the community.[119]

[117] Videoconference discussion with Lynne Yokum, Fiber Optics Manager, Utah Department of Transportation, January 13, 2021.

[118] Telephone conversation with Joe Freddoso, Former President and CEO, MCNC, December 2, 2021

[119] Telephone conversation with Drew Van Dopp, President and CEO and Tyler Patton, Senior Vice President of Public Affairs, Maryland Broadband Cooperative, December 1, 2021.

- **Put in more strand count and conduit than you think will be necessary**. MdBC learned the value of consistently putting in a higher strand count along a route than may initially seem necessary. After its initial construction, MdBC finds that it is already running low on available strands in some of its most popular routes and has also found more demand for dark fiber than it was expecting along some of its remote routes. Today, even along one-lane highways, the cooperative has a practice to never install fiber with less than 48 strands, and more often will only build with 96 strands or more.[120] UDOT's experience is another example of the need to build in excess capacity and it has adopted a practice to construct a minimum of eight conduits on any interstate route. Yet, UDOT has found that this count is still sometimes insufficient.

8.3.2 Operations

- **Dedicate resources to cultivating relationships with carriers.** Last-mile service providers will be critical partners in achieving the state's middle-mile networking goals. Last-mile service providers will be willing to incorporate the publicly owned infrastructure as a building block to extend their networks into unserved or underserved areas if they have a trusted point of contact within the operator of the middle-mile network. The network operator staff should understand the last-mile "language" and be responsive to the last-mile provider needs such as service and maintenance requests, as well as any complaints or suggestions the last-mile service providers may have. Dedicating staff time to cultivating relationships with last-mile service providers will create efficiencies and expedite the process to connect carriers with the network, as well as create a feedback loop that can help the state adjust its policies to maximize the impact of the middle-mile network.[121,122]

- **Use interconnection agreements to drive responsiveness.** The state can leverage access to its middle-mile services to improve transparency and help make last-mile providers more responsive to the communities they serve. Interconnection agreements contain clauses that require last-mile providers to report key network performance indicators, like network uptime, incident response times, oversubscription rate, and other data that can provide local and state officials a more nuanced understanding of the level of service that the last-mile service provider is delivering to its customers.[123]

[120] Ibid.
[121] Ibid.
[122] Videoconference discussion with Lynne Yokum, Fiber Optics Manager, Utah Department of Transportation, January 13, 2021.
[123] Telephone conversation with Joe Freddoso, Former President and CEO, MCNC, December 2, 2021.

8.3.3 Business model

- **Seek ownership of underlying assets as much as possible.** Although many middle-mile providers build some sections of their networks through the lease of dark fiber or lit circuits from existing providers, there is general agreement that owning the underlying asset is critical to reach long-term financial sustainability and to meet the needs of last-mile providers and other users. Joe Sawasky, the founder of Merit, completed a multi-dimensional analysis that looked at the full cost of fiber ownership over the useful life of the asset compared with IRUs and leased circuits; he found that, even with the cost of fiber maintenance and refreshing equipment, fiber ownership offered enormous savings over time.[124] With limited funding available in its early stage, Project THOR has been forced to rely on lit circuits from Lumen for many connections in its backbone ring, but they are hoping to use federal infrastructure dollars to replace all of these with their own fiber, or long-term IRUs, in order to decrease the operating costs that must be covered by participating jurisdictions.[125]

- **Offer lit services to meet the needs of smaller providers.** Some of the open-access middle-mile networks that started from state research and education networking efforts have been restricted from providing lit services to last-mile providers. For example, Merit can only offer dark fiber and wavelength service to last-mile providers, and MCNC can only lease dark fiber. Although private providers can use the dark fiber to offer their own lit services, to make the cost of list services competitive, there must be sufficient demand in the local market. These middle-mile providers have found that not being able to offer the lit fiber services to smaller last-mile providers has limited the ability of these networks to reduce the barriers to entry in unserved or underserved areas.[126]

- **Use internal accounting and market research to inform rates.** Middle-mile providers generally use two key data sets to inform their rate structures. If available, providers can consider current market pricing charged by private providers for comparable services in nearby markets. To develop this database internally, Merit Networks conducts an annual service and rate review of its competitors in order to allow network administrators to understand whether their current rates are above, below, or in line with market pricing.[127] The second consists of the full cost that the middle-mile provider incurs to deliver the service, including setting aside funds to periodically refresh network electronics. While a middle-mile provider may intentionally set rates somewhat below current market pricing to encourage competition or reduce barriers to last-mile deployments, failing to fully

[124] Telephone conversation with Joe Sawasky, President and CEO, Merit Network, December 2, 2021.
[125] Telephone conversation with Nate Walowitz, Regional Broadband Program Director for the NWCOG, December 1, 2021.
[126] Telephone conversation with Joe Freddoso, Former President and CEO, MCNC, December 2, 2021.
[127] Telephone conversation with Joe Sawasky, President and CEO, Merit Network, December 2, 2021.

recover associated costs can place a middle-mile provider in the position where it must identify additional funding sources when network components reach the end of their useful life.[128] A middle-mile provider with public funding sources or a statutory mandate to serve certain areas of the state, also must factor those considerations into the rates they charge for access.

- **Offer professional and value-added services to complement network offerings.** Many middle-mile programs offer a suite of professional services that complement the network service offerings and help last-mile providers, local jurisdictions, and anchor institutions make the most of what the middle-mile network can offer. For instance, NoaNet offers technical consulting, engineering, business planning, grant writing, construction management, installation, and maintenance services.[129] This has helped local jurisdictions to leverage the middle-mile infrastructure to address local public policy priorities and has lowered the barriers of entry to a point where even very small last-mile providers can quickly make use of NoaNet's network while keeping operating costs and complexity minimal. Merit is primarily focused on serving anchor institutions and offers professional services that these types of network users may not have in house, such as assistance with network engineering tasks and network security and integrity support services.[130]
- **Consider channel sales mechanism to get more carriers using the network.** "Channel partners," effectively serve as brokers for providers of fiber and other connectivity services (including data center space). These channel partners make it more efficient and effective for fiber owners to market their assets to many potential buyers. MCNC selected one such partner through a competitive process to help market its available dark fiber. The partner receives between 5 and 15 percent of the contract amount, depending on the contract size and where the lead originated.[131]

The projects discussed above experienced success and encountered barriers on a variety of core issues including network design, business development, service quality, network resiliency, and needs assessments. By gathering a library of resources from existing projects and input from those with actual experience of last-mile providers' needs and business models, the CPUC will have data, perspective, and content to support its own recommendations and decision making.

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128 Telephone conversation with Joe Freddoso, Former President and CEO, MCNC, December 2, 2021.
129 "Network Services," NoaNet, https://www.noanet.net/products/network-services/ (accessed November 29, 2021).
130 ''Professional Service,'' Merit Network, https://www.merit.edu/community/community-services/proserve/ (accessed December 12, 2021).
131 Telephone conversation with Joe Freddoso, Former President and CEO, MCNC, December 2, 2021.

9 Middle-Mile Implementation Considerations

This report uses the California Department of Technology's Middle-Mile Advisory Committee definition of "middle-mile" as a guide for its analysis and recommendations: "the physical mid-section of the infrastructure required to enable internet connectivity for homes, businesses, and community institutions. The middle-mile comprises high-capacity fiber lines that carry large amounts of data at high speeds over long distances between local networks and global internet networks."[132]

An open-access, middle-mile network architecture, composed of segments spanning from long-haul routes to short-range connections, must be designed in a fashion that will be resilient and will meet the needs of a wide cross-section of end users, including last-mile service providers, anchor institutions, and enterprises. Understanding necessary conduit and fiber counts, in particular, is critical to ensuring there will be adequate fiber at each location and that the network's capacity will be sufficient to meet long-term demand.

The following sections recommend technical standards including the characteristics of cables and components, fiber optic technical specifications, and the size and scale of the middle-mile network's conduit and capacity.[133]

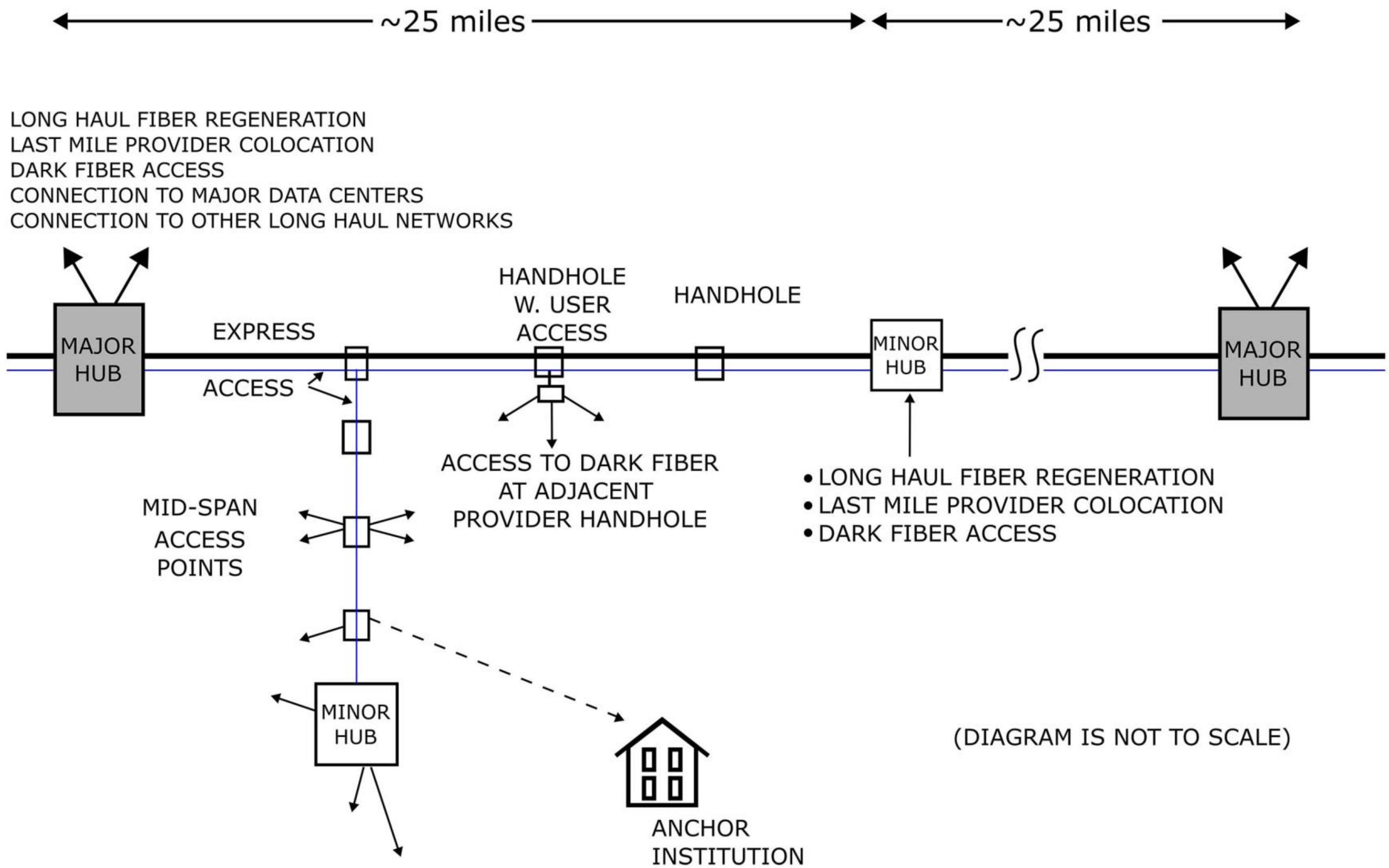
9.1 Network design and capacity

Figure 10 (below) and the sections that follow illustrate a recommended, basic configuration template for middle-mile conduit and fiber—with the understanding that, given California's variations in such key factors as population density and topography, the application of the model will be variable.

The proposed core network is designed as a tiered transport network that carries high-capacity communications between major hub locations and provides access for last-mile service providers and local traffic. The design is structured such that traffic from any access point can be merged on to the "highway" while also supporting plentiful, flexible local connections for last-mile providers and anchor institutions.

[132] Middle Mile Advisory Committee, "Middle-Mile Broadband Initiative FAQ," California Department of Technology, https://cdt.ca.gov/middle-mile-advisory-committee/middle-mile-faq/ (accessed November 29, 2021).
[133] See Section 2 for an overview of the elements of fiber network infrastructure; Section 3 for a discussion of construction considerations; and Section 6 for details on the requirements of last-mile service providers.

Figure 10: Proposed middle-mile network architecture concept



As illustrated in the figure above, the recommended open-access middle-mile fiber network architecture includes two categories of fiber:

1. **Express fiber and conduit** connects hubs with high-capacity links operating at speeds up to multiple terabits per second (Tbps)—multiple thousands of Gbps. Express fiber and conduit is only accessed at hub facilities and is not accessible at handholes or any outdoor locations.
2. **Access fiber and conduit** provides fiber access at major hubs, minor hubs, and handholes along the cable path. This infrastructure can directly connect last-mile service providers, closed-loop community-based networks, anchor institutions, and potentially commercial users.

In this model, two fiber cables run in separate conduit in parallel along highways and state roads: one cable (express) that is dedicated to longer-distance connections and one cable (access) used to connect locations between the hub facilities, back to those facilities.

The express fibers interconnect major hubs located in or near data centers, business hubs, or data carrier exchange points (i.e., carrier hotels). Access fibers then interconnect with express cables at major and minor hubs sites.

Access fibers can directly connect to last-mile service providers and other users along the route. Those fibers are accessible in the hub facilities, where they can interconnect with express fibers through equipment at the hub facilities or through direct fiber cross-connects.

Regeneration electronics (repeaters) are housed in hubs spaced on average 25 miles apart. There are major and minor hubs, which differ in scale depending on last-mile provider need, the number of providers that connect or have electronics at the location, and whether the hub sits at a major geographic intersection point in the network.

A hub is a small-scale central communications facility built to central office specifications in terms of security, power, rack space, and other operational requirements. The hubs facilitate fiber connections between express and access fibers, data aggregation from access fiber strands, and colocation for users' equipment. Hubs can serve as access points for user-built dark fiber terminations.

The 25-mile spacings between hubs ensure that the middle-mile network can support the standard 1310 nm and 1500 nm optical equipment commonly used today; fibers powered by long-haul optics can also be accommodated, and will only need to be regenerated or amplified at every two or three hub spacings. (See discussion in Section 2.)

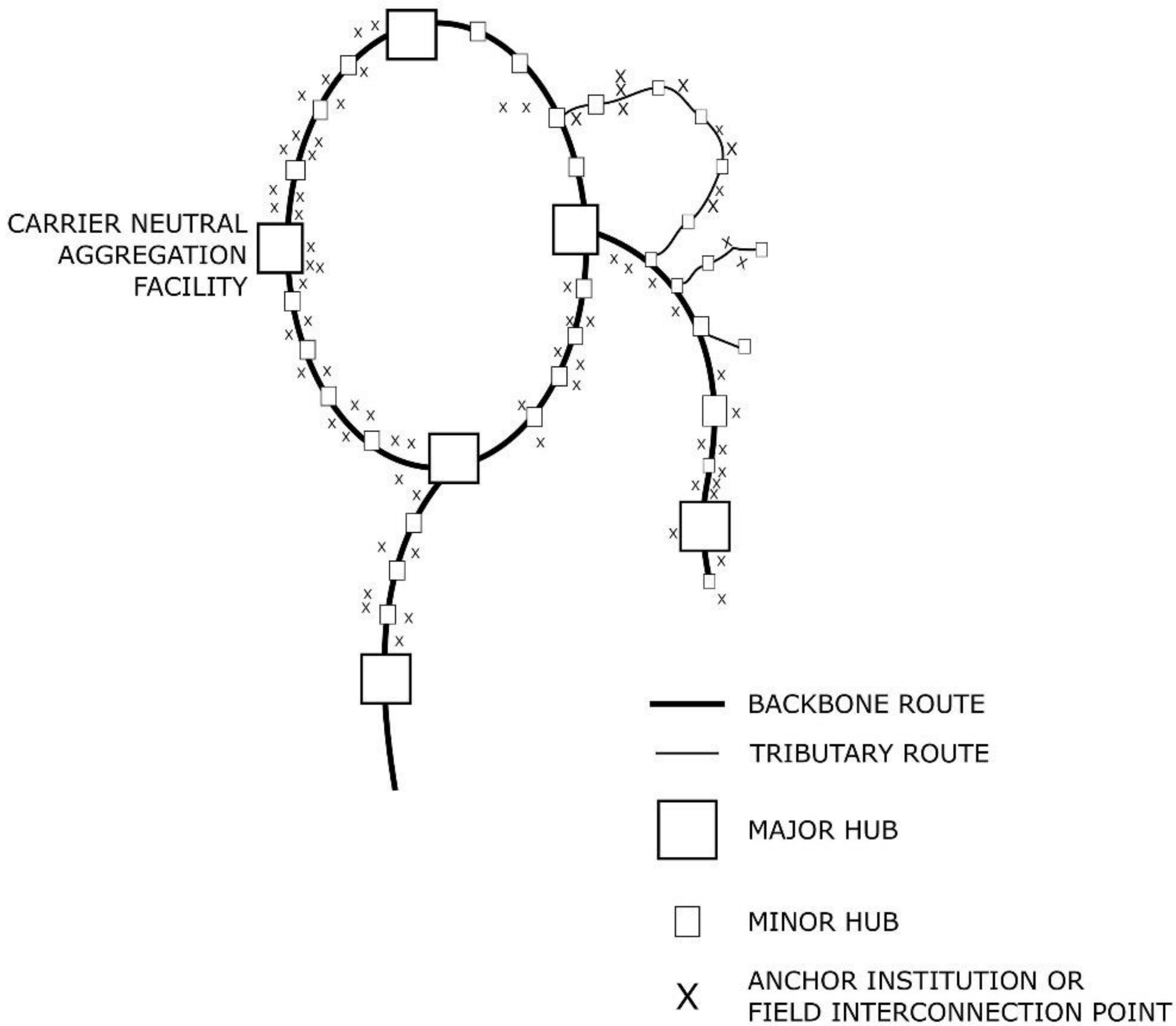
Due to the 25-mile spacing of these hubs, any local fiber branch-off point along a route will always be within about 12.5 miles of the closest express fiber interconnection point.

As discussed above in Section 6, many last-mile providers and other users will find value in a middle-mile network where they can connect flexibly at multiple access points. This architecture can enable a provider to "pick up" fiber spur connections along a route without having to build many miles to a hub facility—reducing the cost to serve isolated locations.

Access points may be at the end of freeway ramps, at the edge of the right-of-way outside of freeways, and on utility poles in areas where cables are on poles. The locations for these interconnection points should be determined based on industry best practices, technical specifications, regulatory requirements, and input from local stakeholders that might rely on this network. Furthermore, the dual-conduit design allows flexible addition of new access points wherever a handhole exists, after the network is complete.

The figure below depicts a logical diagram of a middle-mile section implementation. The backbone, consisting of express fiber cable and access fiber cable, passes through hub sites along the route. The network is designed as a ring architecture that facilitates redundancy and path diversity. Last-mile service providers, anchor institutions, and other users are provided many meet-point options at handholes and hub sites. Tributary fiber links that are access cable spurs or that are constructed by other service providers are interconnected with the middle-mile backbone access cable at mid-span meet-points and hub sites.

Figure 11: Logical diagram of a middle-mile section implementation



9.1.1 Fiber capacity and type

Express fibers interconnect urban environments with a high density of media and content-producing companies, banking operations, data centers, research facilities, and other users that require high capacity. It is industry practice to place no fewer than 288-count fiber strands for middle-mile routes on major roads. For cables of 288-count or higher, ribbon cables are preferable as the strands are just spliced through at handholes, and the cost and complexity of splicing is reduced.

Both the express and access fibers should be of G.652D type. This standard is in many ways comparable to the G.652 “SMF-28” garden-variety fiber used for decades by most of the industry, but the G.652D version has reduced attenuation to accommodate middle-mile distances and capacity needs. G.652D fiber also enables the middle-mile network to use electronics that support the standard 1310 nm and 1550 nm electronics as well as high-capacity dense-wave-division multiplexing (DWDM) electronics.

Express fibers need to be capable of carrying traffic of terabit scale, and these speeds are generally provided using DWDM systems, where many separate high-speed signals are simultaneously carried in the same strands.

Some in the industry have advocated use of more costly G.655 LEAF fiber[134,135] (Appendix A) which can accommodate wider spacing of regeneration facilities. However, while G.655 is used frequently in undersea links, on terrestrial links the trend has been to move away from G.655 and use G.652 fiber, and instead amplifying the signal electronically.

Using G.652D fiber will also have the advantage of enabling the middle-mile network to standardize on a single type of fiber, reducing complexity and costs.

The needed fiber count will vary by route, depending on the density of population and potential connection points along the route, as well as whether the route connects from unserved areas to major internet aggregation points.

Public comments on the level of adequate fiber count vary. Some comment that existing fiber inventory will carry the capacity demand of tomorrow because the evolution of transmission technologies will drive the bandwidth per fiber ever higher.[136] While that statement may be true, it does not address the rapidly increasing demand for diverse fiber routes and other needs for excess capacity.[137] Lumen proposes a fiber count of 432 per cable. Verizon suggests cables with 864 fibers[138] for highly developed urban areas.

Express fiber strands will carry the lit services operated by the middle-mile provider, as well as strands sold or leased to competing middle-mile providers and those sold or leased to last-mile providers who prefer dark fiber for their long-distance routes. Based on comments from service providers and typical fiber counts constructed by private sector middle-mile providers, express cables should have at least 288-count fiber, and in major routes where many routes aggregate

134 Central Coast Broadband Consortium, Opening comments Sept.9 2021, Middle-Mile Ruling 2 -Public Comments.
135 Corning brand of G.655-compliant fiber: "Corning LEAF Optical Fiber," Corning, https://www.corning.com/optical-communications/worldwide/en/home/products/fiber/optical-fiber-products/leaf-fiber.html (accessed December 10, 2021).
136 CVIN Opening Comments, September 3, 2021 at p. 10-11 (criteria should not be about fiber count, but about the operational capacity of the facility; AT&T Opening Comments, September 3, 2021, at p. 15 (cannot forecast future capacity needs just based on fiber count, capacity is always in flux); California Broadband Cooperative Opening Comments, September 3, 2021 at p. 6.
137 LCB/SVI Opening Comments, September 3, 2021 at p. 10; Yurok Opening Comments, September 3, 2021 at p. 10 (add fiber and conduit capacity for future-proofing, route redundancy for outage, breakage, and natural disaster).
138 Lumen Opening Comments, September 3, 2021 at p. 6; Verizon Opening Comments, September 3, 2021 at p. 11.

near major cities and aggregation points (e.g., San Jose, Los Angeles), 432-count or 864-count should be considered. The higher counts will be needed in places where multiple 288-count routes join on the way to the locations in the cities, similar to how interstate highways in metropolitan areas need more lanes than rural interstates.

Access fiber demand is more analogous to the arterial road handling local traffic. Access fiber cables should be sized based on the likely demand for fiber along the route between the hub locations—based on the density of potential last-mile provider connection points, anchor institutions, and other users, such as wireless providers and connections for future applications such as connected vehicles. In general, 288-count fiber should accommodate an average 10-count of fiber connections per mile and should accommodate most anticipated needs for local connections—although in areas where many last-mile providers may connect, or a last-mile provider may know in advance it needs a large count locally, the network may want to consider a higher count.

It is preferable that network design and capacity planning estimate a high future demand for both express and access fiber because:

- Fiber material costs are relatively low
- Splicing costs for ribbon cable do not increase substantially with fiber count (Section 3.3)
- Almost any size cable can fit in a 2-inch (or even a 1.5-inch) conduit

In the long run, underestimating the fiber count may prove costly, requiring new rounds of fiber installation. While underestimating fiber needs can generally be remedied through fiber augmentations in reserve ducts, doing so is an inefficient use of conduit, and also reduces the middle-mile network's ability to trade excess conduit for conduit on other routes.

9.1.2 Conduit capacity

Decisions about the number, type, and size of the conduits to install along various routes will have significant implications on a middle-mile network's long-term capabilities. Conduit is the foundational real estate of a middle-mile fiber network. Multiple conduits installed in a bank is an efficient way to build capacity, packing the most capacity in the least space and helping the right of way owner both in economical use of space and in creating capacity for current and future use, as opposed to having many separate construction projects by separate service providers. Multiple conduits also provide the ability for individual providers to have their own conduit and to be entirely responsible for their own cable installation and splicing, providing an added level of security and resilience for those providers.

A middle-mile network should include conduit that is divided to address three use cases:

1. Immediate use by the network operator – this is conduit sized for the operator's current capacity requirements
2. Future use by the network operator – this is empty conduit that will be held in reserve until the operator needs to pull more fiber for future use; it is sized for the operator's projected future capacity requirements
3. Immediate or future use by the network operator as a leasable asset – this is conduit that might be leased immediately or might be held in reserve until the operator identifies a lessee

The amount of conduit needed along a given middle-mile route will depend on key factors including whether the route is a main or tributary route; whether the route traverses urban or rural areas; how much capacity is required overall; and how many different entities are expected to use the conduit.

In an open-access model in which the operator wants the ability for flexible implementation by many parties with existing and future business models, the conduit requirement will thus tend to be higher than in a deployment planned by an operator with a narrower use case. That said, the conduit sizing decision must also take into consideration the incremental cost of the additional conduit and installation, as well as the progressively larger handholes and manholes needed to accommodate larger conduit counts.

As a starting assumption, the open-access middle-mile network plan should assume the construction of two 2-inch ducts for immediate and near-term future use, as well as two to six additional ducts for longer-term future growth. Duct counts might vary depending on location (e.g., metro versus rural) and business opportunities. Potential conduit duct leases should ideally be determined in the planning stage and factored into the total duct count.

The additional conduit capacity will also vary based on the sensitivity of the right-of-way. For example, Caltrans may want to open the right-of-way along a freeway only once for conduit construction, and the conduit count should cover future use—UDOT practices call for at least eight conduit in a freeway (Section 8.1.5). Conduit count may be lower in an area where the right of way owner is more flexible about future excavation, or where expressed demand is less.

The rationale for 2-inch conduit is that it allows the spacing of handholes to a maximum of 4,000 feet (based on the limitation of the conduit reels available from manufacturers). Larger duct sizes significantly reduce the handhole spacing (half the diameter reduces the distance to 750 feet), thus raising the cost of construction.

A 2-inch duct also provides flexibility for fiber cable sizing. On the high side, newer cables with up to 6,912 fiber strands can be pulled in. Alternatively, 2-inch ducts can accommodate two fiber cables of 288-strand capacity.

A bank of 2-inch duct costs only 10 to 15% more than the same bank, using 1.5-inch duct, including labor and materials, assuming 70% trenching and 30% directional boring.

Because 2-inch duct strikes a balance between large conduit requiring large bores and more complex handling, and smaller ducts that potentially limit the cable size, it is a "go to" size for many service providers and will fit most needs.[139]

9.1.3 Handhole spacing

Handholes need to be placed at every point along underground construction where the ends of individual cable sections meet, roughly every 2,000 to 4,000 feet if the cable is pulled into the conduit. Jetted cables would conservatively double the maximum spacings between handholes. Their primary function is to house the splice cases and protect them from the environment. They also provide access to entities connecting to the network—for example, the middle-mile network may place an additional handhole containing the fiber strands that are leased by a last-mile service provider or a wireless provider, adjacent to the middle-mile network handhole. The last-mile wireline or wireless provider builds its own fiber to that handhole and performs its own splicing—thereby being able to perform all access and maintenance without coming into contact with the rest of the middle-mile network.

Handholes are mostly prefabricated enclosures made of polyethylene, fiber glass or concrete placed below ground with bolted covers at or just below the surface. For additional security the covers may be recessed further and covered with earth mass or pavement material that surrounds the handhole. The size of manholes is dependent on the number and size cables that intersect at that location. Typically, pass-through splicing handholes may be 17" x 34" x 24" deep, whereas intersecting high count fiber cables with cross fiber splicing may require the space of a 36" x 48" x 36" enclosures to provide sufficient space for larger splice cans and coiling of the end tails of the cables.

9.1.4 Hub facilities

A fiber hub is a building or cabinet that facilitates the cross connections of many fiber paths. An all-passive fiber hub consists of patch panels and fiber management trays for the operator's assets and for the user fibers that interconnect with the providers' strands. An active hub is a standalone central-office type facility. Active hubs may be operated as staffed or unstaffed

[139] Discussion with Pineland Telephone Cooperative, October 21, 2021.

facilities. In either case provisions have to be made for 24/7 accessibility. (See Appendix C for a sample hub specification.)

In the middle-mile context, a hub is more likely an active hub. A hub facility is equipped with fiber termination panels and demarcation racks for clear delineation of ownership and maintenance responsibilities between the (middle-mile network) operator and the last-mile service provider or other user. Hubs typically house the service provider transmission equipment for traffic aggregation and re-routing, amplification of pass-through optical signals and circuit amplification and regeneration of signals on long haul links. Last-mile providers or other users place their equipment in lockable cabinets or cages in a designated rented space within the hub facility.

An alternative to a dedicated middle-mile hub, if it exists in proximity to the middle-mile route and the unserved areas, is an existing carrier-neutral exchange location. The middle-mile network could place its equipment and fiber terminations in this facility and have the same functionality.

The locations of service hubs are strategically chosen based on criteria that include potential vulnerabilities to human intrusion, fire, building damage, and flooding. The availability of reliable power from the grid is an essential factor of consideration. Above all, the hub has to allow for ease of new aerial or underground construction to the facility. Hubs are ideally situated at points of backbone fiber intersections that have provisions for diverse traffic routing with dual building entrance possibilities.

Hubs can be established in a variety of building settings. It is common to use telecommunications central offices, secure spaces in office buildings, or even prefabricated huts for that purpose. Modular huts are particularly suitable for locations that require flexibility for scaling and expedient deployment. Hubs with electronic equipment must conform to a set of telecommunications industry standards, which include the availability of standby power in case of power grid failures, AC and DC power plants backed up by automatic power generators, temperature control (HVAC), fire-suppression systems, and premises access security. Hub locations usually serve as meet-points for last-mile service providers and other users, so they must have provisions for securing users' colocated racks of equipment, such as fiber management panels and electronics. ISPs and enterprise users typically occupy one to two racks. The colocation footprint requested by content providers and carriers, however, may extend over several racks.

9.1.5 Signal amplification and regeneration

For an open-access middle-mile architecture that aims to accommodate a broad spectrum of last-mile providers and other users, the spacing of hub locations may be determined by the range of optics that the middle-mile and last-mile service providers commonly use. Because optics for wavelengths at 1310 and 1550 nm with bitrates at 40 Gbps and 100 Gbps commonly have ranges of 25 miles without amplification, hub spacings should be spaced by that distance.

For long-haul links in unpopulated areas, there will be few last-mile service providers and other users accessing the fiber in the areas, so greater hub spacings should be contemplated. In these use cases the distance limitations of longer-range optics, capable of transmitting reliably up to 50 miles on G.652D fibers, can serve as a guideline for hub spacings.

Signal amplification and signal regeneration become relevant in long-haul networks where low signal levels and mounting dispersion raise receive errors. The industry distinguishes between three types of corrective methods that can be applied to maintain signal integrity:

- 1R: reamplification of the signal alone
- 2R: reamplification and pulse shaping
- 3R: reamplification, pulse reshaping, pulse retiming (also known as regeneration)

The complexity of electronics and cost rise with the level of regeneration type—1R being the least complex. 3R is technically the most complex method of restoring signal integrity, which is used predominantly in interstate and transcontinental links exceeding 600 miles.

For the vast majority of terrestrial applications, 1R and 2R are applied by means of optical amplification with erbium-doped amplifiers or Raman amplification.[140] They are universally applied for intensity modulated and for DWDM systems because of their simplicity and low cost. A typical gain of about 20 to 24 dB with an erbium-doped amplifier extends the reach after every amplification stage to more than 60 miles.

Depending on fiber type, intensity modulated systems also require dispersion compensation at certain distance intervals. Dispersion compensation is part of 2R as it reshapes the pulses to their original forms. Dispersion can be compensated for by integrating a piece of fiber with negative dispersion coefficient that contracts the widened pulses or more commonly today with the help of circuitry that is part of the receive and retransmit electronics. The intervals at which pulse reshaping must occur is dependent on bitrate, wavelength and on the fiber in use.

Aside from fiber transmission systems employing DWDM and coherent detection for high capacity (>100 Gbps) over intermediate and long distances, the transmission market is dominated by pluggable optics.[141] Pluggable optics are small factor, interchangeable interface

[140] https://www.techopedia.com, What is erbium-doped fiber amplifier; https://www.cisco.com, Practical Aspects of Raman Amplifier, March 5, 2018, Document ID 212834

[141] J. J. Maki, Evolution of Pluggable Optics and What is Beyond, OSA Technical Digest (Optical Society of America, 2019), paper Th3.2, https://doi.org/10.1364/OFC.

devices inserted directly into electronic equipment such as routers and switches. The specifications of pluggable optics run the gambit from 1 Gbps, 10 Gbps, up to over 100 Gbps and distance ratings from about 6 miles up to 50 miles.

9.2 Acquiring fiber through irrevocable right of use (IRU) agreements

There are some circumstances in which last-mile needs can be met through leasing middle-mile fiber through long-term IRUs as an alternative to construction. However, while IRUs would allow the state to control the network in a way that largely mimics ownership for a finite period of time, IRUs differ from true ownership of the underlying fiber asset in a number of important ways. The following factors are important to consider in making the determination as to when to build and when to lease existing fiber.

Time to market is a consideration but must be balanced with capacity requirements and long-term economics. Dark fiber leases or IRUs combined with additionally constructed fiber routes can effectively shorten the construction period under certain circumstances. The "build where you must, lease where you can" strategy as proposed by the TPA and others is an expedient way to extend connectivity to remote unserved or underserved areas.[142] However, the term length of such leases will be a fraction of the useful life of fiber and conduit assets, and although leasing may appear to offer cost savings in the short term, the cost of leasing is likely to be higher over the long run. Furthermore, the availability of sufficient strands of dark fiber to satisfy projected capacity requirements in areas of need is not guaranteed and adding capacity through new fiber construction at a later date will be more costly per mile than during the initial buildout, where the state will benefit from economies of scale.

Additional funding may be necessary to maintain the capacity of the state-owned network when dark fiber leases expire. The decision to lease capacity on an existing network must be made with an understanding that there is no guarantee that the leasing provider will make these assets available again under similar terms once the initial lease expires. Network planners should scrutinize the terms of the initial lease and analyze the level of current or planned transport competition in the area; planned growth and bandwidth demand in the area; anticipated technology evolution over the course of the initial lease that may expand capacity of the current facility; and other elements that could impact long-term costs. This concern is also true for lit services. Lit services are bandwidth-limited—and subject to price increases over time—so using available lit services as a tool for building capacity is an inherently limited approach.

Renewal of dark fiber leases is subject to market pricing and therefore not aligned with the state's objective of building an open-access network providing long-term, affordable, and non-

[142] CENIC Opening Comments, September 3, 2021 at p. 2-3; SANDAG Opening Comments, September 3, 2021 at p. 10-11; Race Communications Opening Comments, September 3, 2021 at p. 4-5; CVIN Opening Comments, September 3, 2021 at p. 9.

discriminatory broadband connectivity opportunities to all. If lease rates increase, the network operator may be forced to pass these added costs along to network users. Leased dark fiber business models also do not scale in capacity for middle-mile providers, because the cost per strand is likely to be higher in the leased portion of the network than in the newly constructed portion. If the state's network operator runs out of capacity on a leased portion, it can try to lease additional strands, but even if more strands are available for lease, the costs associated with the lease will eclipse the cost associated with new construction well before the leased portion has the strand count the network would have had available had the state pursued new construction.

Dark fiber leases are subject to availability, and the state risks being left with stranded assets if a lessor elects not to renew a lease. There is never a guarantee that an IRU offered today will be offered again tomorrow, much less when the IRU expires and the state is forced to negotiate a new contract with the provider. Market conditions, increased demand for lit services, and shifting business models can all impact a provider's willingness to offer an IRU on a given route. During the telecom bust of the early 2000s, many state research and education networks (REN) increased capacity and extended their networks through fiber IRUs. By the time those IRUs expired, a decade or two later, the fiber market had experienced consolidation, and fiber owners no longer offered dark fiber products. Control over any portion of the state middle-mile network runs over IRUs will return to the lessor at the end of the contract term, at which point the state would be required to build new fiber in that route, pay another provider to construct the route and provide an IRU, or purchase lit services, all of which would be costlier than constructing the route as part of the initial network build.

High-strand-count IRUs may not be available. Even where providers are willing to offer dark fiber leases and IRUs, they will likely be reluctant to provide an IRU for the full number of strands that the state would put in during new fiber construction. Having a limited strand count at its disposal on leased routes will reduce the ability of the state network operator to offer dark fiber services on some portions of the network, reducing the value that the network can deliver to last-mile providers. Even if a provider were willing to provide a very high count IRU, the total cost would likely exceed the cost of the state building the fiber itself.

IRUs limit the ability for terms of use to evolve over time. An IRU will define the terms of access and use that the state network operator can offer to its last-mile customers over the leased portion of its network. An IRU may place limits on how the state network operator and its last-mile providers can access and use the leased fiber strands. Even if the state is able to obtain terms that satisfy the needs of every operator today, technologies and business models will continue to develop. The state will likely need to update the terms of its dark fiber leases over the years in order to meet the needs of an evolving industry, but it will not have the same flexibility to do so on the leased portion of its network as it does on the sections where it owns the underlying fiber assets.

For these reasons, IRUs are not a substitute for the capacity or flexibility the state can gain through new fiber construction. Wherever possible, the middle-mile network should be comprised of fiber owned by the state. Although constructing fiber may have a higher upfront cost on a given route than an IRU for the specific count of fiber the network expects to use, constructing fiber will prove more cost-effective in the long run and will deliver a more valuable asset that is better equipped to deliver on the public policy goals laid out in SB 156.

IRUs should therefore be considered primarily as a short-term solution to expedite the process of delivering urgent open-access middle-mile services to communities with the greatest need in the immediate moment, such as in cases where last-mile providers are ready to activate service prior to the completion of middle-mile construction. Ideally, however, new fiber construction will be the most efficient and effective way for the state to deliver on the goals set out in SB 156.

9.3 Building capacity through swaps and trades

Achieving this goal will require construction of middle-mile fiber infrastructure—but it could also include leasing existing middle-mile fiber in some cases, as discussed above, or trading or swapping conduit or fiber infrastructure in one area for comparable infrastructure elsewhere in the state.

Determining how much infrastructure to build (and where), and how much infrastructure to swap, is a key concern of commenters—and will require consideration of many factors.

Fiber swaps can provide a cost-effective way to add route redundancy and extend the reach of the state-owned network. Intentionally adding excess strand count to all new build areas would create an asset the state could use for fiber swaps with other providers; that approach would add route redundancy and resiliency for both the provider that makes the swap and the last-mile providers using the state-owned network. As in the case of the UDOT middle-mile network, if excess conduit is built, the Caltrans-constructed network can be a seed network that, over years, can greatly expand its route without additional construction, if conduit is swapped. UDOT was able to almost triple its conduit mileage relative to what it constructed, simply through conduit swaps.[143]

[143] Videoconference discussion with Lynne Yokum, Fiber Optics Manager, Utah Department of Transportation, January 13, 2021.

For example, excess conduit in major Caltrans corridors may be swapped for conduit belonging to local governments or commercial providers who have conduit in important locations outside the Caltrans right-of-way, such as to data centers and cable landing sites.

Excess conduit capacity can also be a valuable long-term asset. Building spare conduits beyond the immediate need was supported by many public comments, especially at challenging, high-cost construction sites.[144] Excess conduit capacity provides the middle-mile operator the flexibility to build fiber at a later date or lease the conduit space to privately owned telecommunication carriers. Excess conduit constructed as part of the middle-mile network can be particularly valuable in a swap if it is in high-value right-of-way such as freeways, where it is less likely to be impacted by accidental digging than other conduit, and where Caltrans may restrict or forbid future construction by other providers.

The state-funded middle-mile network will have to span across both urban and rural communities. Many commenters assert that state-funded middle-mile construction should focus on remote unserved and underserved areas where construction costs have been an impediment for the private sector to achieve a positive return on investment. Some also comment that metropolitan areas are fiber-rich, and do not warrant further fiber construction at this time.[145] On the other hand, many commenters, including ISPs and independent providers, stress the importance of having network interconnection options at major carrier-neutral interconnection points.[146] As most of these carrier hotels are centrally located within business hubs of metro areas, such as One Wilshire in Los Angeles, the middle-mile architecture will need to be extended through metro areas. Obtaining paths through metro areas via fiber or conduit swaps should be prioritized since these areas will have the highest per mile construction costs, and highest likelihood of having sufficient capacity to satisfy future demand.

Fiber and conduit swaps should be evaluated on a case-by-case basis and pursued only where the state determines such a trade will be in the interest of the last-mile providers using the state-owned infrastructure.

9.4 Operational costs

The middle-mile network will need to be operated and managed, and the types of needed operational activities will depend on the types of services it offers. The lower possible operational cost will be the cost of the network operating solely as a dark fiber network. In that scenario the

[144] SANDAG Opening Comments, September 3, 2021 at p. 12-13 (partnering with Caltrans and County to deploy additional conduit along state route highway); Race Communications Opening Comments, September 3, 2021, at p. 7 (recommending four 2-inch conduits for excess capacity); Verizon Opening Comments, September 3, 2021, at p. 11.

[145] Charter Fiberlink/Time Warner Opening Comments, September 3, 2021, at p. 14-15.

[146] See, for example, California Community Foundation Opening Comments, September 3, 2021 at p. 9, 16; Central Coast Broadband Opening on ALJ Supplemental Ruling at p. 6.

cost will include fiber utility location and repair, and operation of a network operations center, and maintenance and operation of hub sites, and cost of easements.

Adding the cost of lit services increases the operational costs. Adding the requirements of the dark and lit fiber services, a middle mile network will have the following operational cost elements:

Colocation – Costs associated with the placement of equipment in facilities, as well as physical connections with other providers.

Commodity internet capacity and transport – Purchase of wholesale bandwidth and corresponding transport costs.

Core network electronics maintenance – Maintenance associated with core network electronics deployed during construction phases. Replacement cycles fall between 7 and 10 years for enterprise, decreasing to 5 to 7 years as the network gets closer to the customer.

Distribution electronics maintenance – Maintenance associated with distribution electronics deployed during construction phases. Replacement cycles mirror that of core network electronic equipment, with consideration that distribution electronics typically reside closer to the customer.

Facilities – Cost of renting or leasing, utilities, and similar operational costs.

Fiber maintenance and repair – Cost of maintaining and repairing fiber cable and conduit.

Insurance – Required cost typically driven by network size and cost and generally calculated as a percentage of capital expenditures.

Legal and regulatory – Costs driven by various regulatory landscapes, number of customers, and the types of products and services being offered.

Maintenance for fiber used under indefeasible rights of use ("IRU") – Annual contributions toward maintenance paid by a dark fiber IRU lessee to the lessor based on a number that is contractually defined.

Marketing and advertising – Costs driven by customer acquisition goals and available marketing mediums.

Network connections and splicing – Incremental cost associated with connecting last-mile providers and other users to the network.

Network Operations Center ("NOC") services – Cost for an internal or contract 24/7 operations center at which network performance is closely monitored, ISP (customer) complaints are received, and maintenance teams are dispatched. The NOC ensures that the middle-mile provider can meet its service level obligations to the last-mile service providers by making sure that any performance problems are avoided or detected immediately.

Operational Fees – Pole attachments, rights-of-way and other fees associated with delivering service.

Personnel – All personnel related expenses including staffing, employee benefits, training, travel, and licensing. Staffing levels are typically driven by one of either the number of customers served or by network miles. Most positions outside of customer support staff are directly influenced by the amount of network miles. In early years, a more manual and precise approach should be exercised to keep staffing agile and appropriate.

Professional services – Costs incurred for the following:

- Internal systems and support – Cost for the platforms and technical support associated with provisioning work orders, billing and invoicing systems, as well as integration with other internal applications
- Construction – Expenses associated with the outsourcing of any part of the construction or installation phase
- Other professional services – General consulting and accounting are among other professional services related to operations

Underground locates – Costs incurred locating and flagging fiber cables and conduit.

A more detailed model can estimate for different scenarios the yearly costs and will be the sum of fixed network costs, such as the NOC and central staffing, and costs that scale with the mileage of the network, the number of connected last-mile service providers and anchor institutions, and the number of customers of the last-mile providers.

9.5 Value-added services

Middle-mile networks can deliver value-added services that expand their benefits. Just as the presence of the physical infrastructure reduces costs for ISPs, these services lower barriers for last-mile service provision.

As an example, NoaNet, the statewide, open-access middle-mile network created by public utility districts in Washington State, delivers internet, Ethernet, transport, colocation, software-defined wide area networking (SD-WAN), private cloud, access control and surveillance and voice over IP (VoIP) services.[147]

Merit offers many of these value-added services as well, and also offers direct layer 3 peering and cloud connections to all of the major cloud platform providers. Merit also offers a full range of security services, including a threat scanner, firewalls, DDoS protection, and cyber education training, to support anchor institutions in securing their networks.[148]

The planning process for California's middle-mile network should include analysis of technical considerations and the business case to determine if the middle-mile network operator, or a vendor selected through a competitive procurement, should offer these value-added services. The availability of these services at affordable rates and non-discriminatory terms for smaller, competitive last-mile providers should be one factor in determining whether offering such services will help deliver on the goals of the middle-mile network.

One service option that deserves consideration is end user implementation support for access to the middle-mile meet-points. Telecommunications carriers and ISPs that have construction resources in-house are not likely to ask for assistance. However, anchor institutions with limited construction expertise would benefit from end-to-end project management provided by the owner. Zayo, as an example, offers dark fiber building-to-building connectivity that includes renting or constructing fiber extensions from their fiber access points to users' locations.

[147] "Network Services," NoaNet, https://www.noanet.net/products/network-services/ (accessed November 29, 2021).
[148] ''Professional Service,'' Merit Network, https://www.merit.edu/community/community-services/proserve/ (accessed December 12, 2021).

Appendix A: International Telecommunication Union Standards for Single-Mode Fiber Categories

The International Telecommunication Union has published standards for six single-mode fiber categories denoted as ITU-T as G.652 to G.657. The following sections briefly describe each standard.

G.652 fibers

G.652 with subcategories A, B, C, and D, are the most-widely deployed fibers world-wide. The original fiber class G.652 A, standardized in 1985, is characterized by a distinct attenuation peak at 1383 nm caused by water inclusion in the glass. Subsequent fabrication modifications (B, C, and D variants) led to drastic reductions of the water absorption peak and slightly improved attenuation across the range from 1310 nm to 1625 nm, making them versatile and universally useable fibers.

A characteristic of G.652 fibers is a zero-dispersion value at 1310 nm, favorable to pulse-coded signals at that wavelength. The same transmission technology operating at 1550 nm, however, is met with the disadvantage of very high chromatic dispersion of over 15 ps/nm/km. As a result, high data rate transmissions over longer distances become challenging for intensity modulated systems. In those circumstances a method of signal reshaping is required to restore the original signal integrity. Alternatively, the effect of dispersion can be at least partially corrected through the integration of fiber elements with negative dispersion reversing pulse broadening.

In newer fiber constructions, G.652D version has displaced the now outdated G.652A fiber version.

G.653 fibers

The primary objective of this standard was to minimize CD for the 1550 nm band by shifting the zero-dispersion point into the band and by flattening the dispersion curve over the C-band. This class of fibers is also referred to as “dispersion-shifted” and “dispersion-flattened.” As practical system performances revealed that zero dispersion is a negative attribute for DWDM due to four-wave mixing impairments, G.653 has been less commonly deployed.

G.654 fibers

G.654 fibers are made of pure silica, which reduces the optical attenuation to sub-0.2 dB per kilometer. In addition, G654 fibers are designed with enlarged effective optical field diameter with respect to the standard G.652 fiber, which permits to couple more light power into the fiber therefore extending the spacing of regenerators. As a consequence of the larger field diameter the wavelength cut-off is shifted from 1260 nm to 1530 nm, which limits its use to the 1550 nm range. Typical application use cases of this fiber are long-haul terrestrial and submarine links.

G.655 fibers

G.655-compliant fibers, also known as NZDSF (Non-Zero, Dispersion-Shifted Fibers) are an engineering compromise to satisfactorily meet the requirements of both intensity modulation and DWDM technologies. The dispersion zero-point is shifted close to the C-band, thus reducing the effective dispersion in the C- and L-bands. The dispersion values are sufficiently high to suppress FWM in DWDM systems and low enough to control pulse broadening in pulse modulated links.

G.655 type fibers were in high demand after their introduction around the year 2000. Their primary application was in long haul networks. Corning's G.655 version, branded as "LEAF" fiber,[149] recorded the company's second-highest sales volume. The demand for G.655 terrestrial applications has waned because of major technological advances in electronic dispersion compensation in recent years, which substantially mitigate the signal degradation associated with CD. Corning's LEAF fiber currently accounts for less than 5 percent of all fiber sales.[150]

G.656 fibers

Due to an enlarged effective mode area and sub-0.2db/km attenuations, G.656 fiber have emerged as a standard for wideband communications across the C and L-band that facilitate the support of Raman amplification. Raman amplification is predominantly applied in very long spans of hundreds of miles, submarine links being a prime example.

G.657 fibers

G.657 fibers feature reduced bending losses at tight bending radii. Their optical characteristics are materially similar to those of the G.652 family. However, they are designed for space constrained installations as one would encounter in access networks and especially in-building distribution raceways and customer premises. Specifications for several subcategories have been published. The G.657/B3 variant is the most bending tolerant fiber allowing radii as small as 5 mm without significant loss of light.

[149] "Corning LEAF Optical Fiber: Product Information," Corning, https://www.corning.com/media/worldwide/coc/documents/Fiber/LEAF%20optical%20fiber.pdf (accessed December 17, 2021).
[150] Private communication with Corning Sales, December 5, 2021

Appendix B: Fiber Testing Standards

Fiber cables are specified and tested to industry norms issued by Telcordia and Insulated Cable Engineers Association, Inc (ICEA). For outside plant construction, cables are required to be compliant with ICEA 640[151] and Telcordia's GR20 standards that describe test procedures and required specifications primarily related to mechanical stress and temperature tolerance. In addition, cable materials must comply with fire regulations and standards set forth by the Underwriter Laboratories, LLC (UL) and the National Fire Protection Agency, NFPA. In-building and outside plant cables adhere to different fire rule sets. In-building cables are typically plenum-rated, which refers to a cable insulation with high fire resistance and low smoke development.

Table 2 lists the cable test types and parameter values as per ICEA 640/GR 20 requirements. The tests have the objective of eliminating early failures due to manufacturing faults.

Table 2: Excerpt of cable test requirements performed by manufacturers

Test Type	ICEA640 &GR20 Requirements
Tensile strength	600 pound-feet installation, 180 pound-feet installed
Compressive strength	2.2 kN
Impact resistance	4.4 N-m
Cable twist	+/- 180^{o} ,10 Cycles
Cable bending	20x outer cable diameter
Temperature cycling	-40^{o}C to + 70^{o}C
Cable aging	-/+ 85^{o}C over 7 days

The most relevant tests in relation to installation procedures and handling are tensile strength, cable twist, impact resistance, and cable bending. Exceeding those parameter values may result in diminished life expectancy of the products. (For more details on fiber lifecycles, see Section 4.)

The specifications of vendors' products typically list a subset of the above-mentioned parameters but reference compliance with further industry standards as illustrated in Table 3.

Table 3: Example of a vendor specification sheet

Property	Specification
Maximum tensile strength during installation	600 pound-feet
Maximum service load	180 pound-feet
Minimum bend radius	20x outer cable diameter
Compression resistance	124 lbf/in
Temperature range	- 40^{o}C to + 70^{o}C
Compliance	ICEA 696/RoHS/FT4-UL1666/NFPA 502

[151] ICEA S-87 640-2006: Standard for Optical Fiber Outside Plant Communications Cable

Appendix C: Minimum Specifications for Network Hubs (Huts) Along Cable Routes

Depending on environmental situations, hub facilities may have to be built with special consideration of location-based risk factors. Standalone hubs are available for protection from ballistics, fire, and the impact of earthquakes. For deployment in regions of elevated tremor and quake probability, hardened facilities specifically designed to withstand ground movements are highly recommended.

The installed hubs and related subcomponents have to meet these minimum specifications:

- Compliance with national and local code
  - Interior dimensions of at least 10 feet (width) x 12 feet (length) x 10 feet (height), larger dimensions are required for designated colocation facilities.
  - Structural walls and ceiling components consisting of precast, minimum 5000 PSI, steel reinforced concrete
  - Support a floor equipment load of minimum 500 PSF
  - Support a roof live load of 100 PSF
  - Building code-recognized fire rated for 2 hours
  - Withstand wind speeds of 150 MPH when secured to proper foundation
  - Bullet resistance per UL752, Level 4 (.30-06 at 15 feet)
  - Foundation comprised of a level, concrete pad with steel reinforcement
  - Two underground cable entry points for communications cable shall be provided, each equipped to support six 2-inch conduits

- Interior finishing and cable accessory specifications:
  - Space for colocated equipment cages or lockable rack cabinets (2 feet wide, 2 feet deep, 6 feet high), one per user
  - One wall-mounted, painted plywood board (4 feet x 4 feet x ¾-inch thick) for common telecommunications and other wall-mounted accessories
  - Cable ladders having a width of 12 inches and a total length of approximately 22 feet ceiling/wall mounted to provide 8 feet of clearance to the floor

- Cooling and heating system specifications:
  - Two 5-ton (redundant), self-contained HVAC units with 5 kW heat strips be wall-mounted to the shelter, designed to be weather-proof, rodent-proof, and tamper-proof
  - Each HVAC unit fed from separate circuit breakers in the main distribution panel

- Electrical system specifications:
  - Main distribution load center providing a minimum of 20 positions, consisting of the main distribution panel, breakers, lug box, and related components for 200A, 120/240v, single phase electrical service
  - UL 1449 Type 1 SAD/MOV surge protection
  - Minimum of four duplex, 20 Amp wall-mounted receptacles
  - 35 kW diesel electrical generator
    - Minimum 140 gallon sub-base fuel tank
    - Automatic transfer switch

- Lighting specifications:
  - 4-foot, two-bulb fluorescent fixtures with acrylic lens covers (minimum four)
  - 150 watt exterior lighting fixture with photo-cell and motion sensor control

- Alarms and fire protection systems:
  - The shelter shall be equipped with the following monitoring and alarm features:
    - High temperature
    - Low temperature
    - Power grid disruption
    - Generator activation
    - Air conditioner failure
    - Primary power failure
    - Door opened/closed
    - Fire and smoke alarm
  - Inert gas fire suppression system (FM-200, or equivalent)
  - Door locks and identity badge access
  - Camera surveillance indoor and outdoor (perimeter)
  - Fenced-in premises with badge access

Figure 12: Hub layout with colocated user equipment

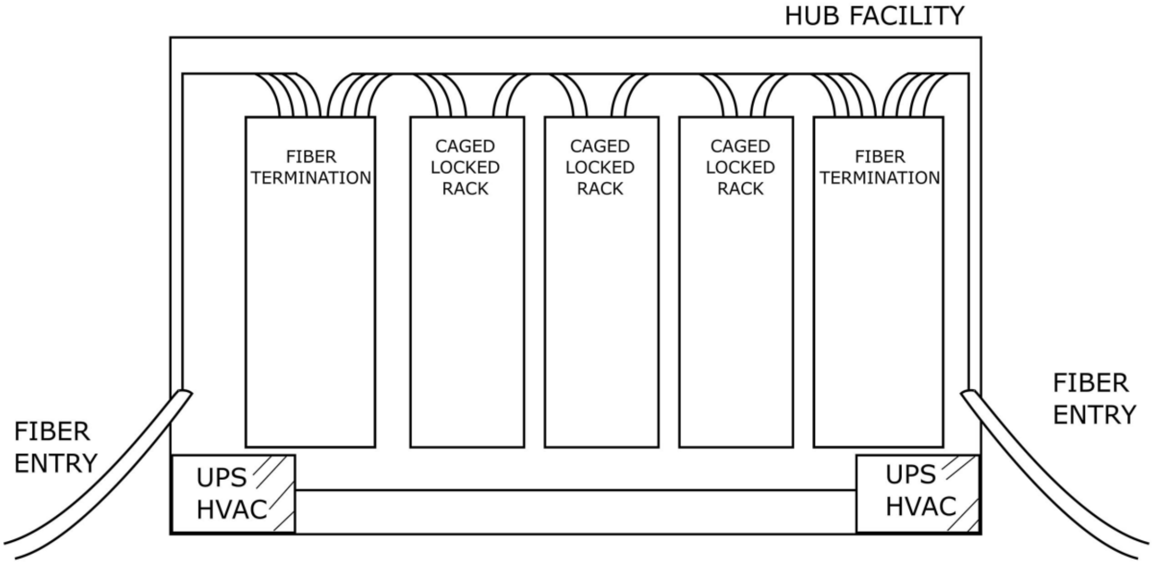


Figure 13: Hub facility for regeneration (no colocation)