IV. NETWORK ECONOMICS

The United States has a diversity of both wired and wireless broadband networks which provides the vast majority of Americans with choices as to their broadband providers: most homes have a choice between wired broadband provided by a telephone network or a cable network. Telephone and cable networks were originally built for and funded by voice and video services respectively; but now, through upgrades, both are able to provide high-speed broadband to much of the country. Large investments in these networks are being made to further increase speed and capacity in the most profitable areas of the country. In addition to wired networks, there have been significant investments in wireless networks to provide broadband terrestrially via mobile and fixed wireless networks or via satellite. Like wired broadband, mobile broadband is likely to be provided over a network originally built for a different purpose—in this case mobile voice. Strong 3G mobile broadband adoption from smartphones, data cards and netbooks has driven operators to commit to large-scale upgrades to their wireless data networks using new 4G technologies. These new 4G technologies (WiMAX and LTE) can be used to provide broadband in higher speed mobile networks, fixed wireless networks and even hybrid fixed/mobile networks. Due to high costs and low capacity, satellites have primarily targeted customers in remote areas without other broadband options, but recently developed high-throughput satellites may change this.

BASIC NETWORK STRUCTURE

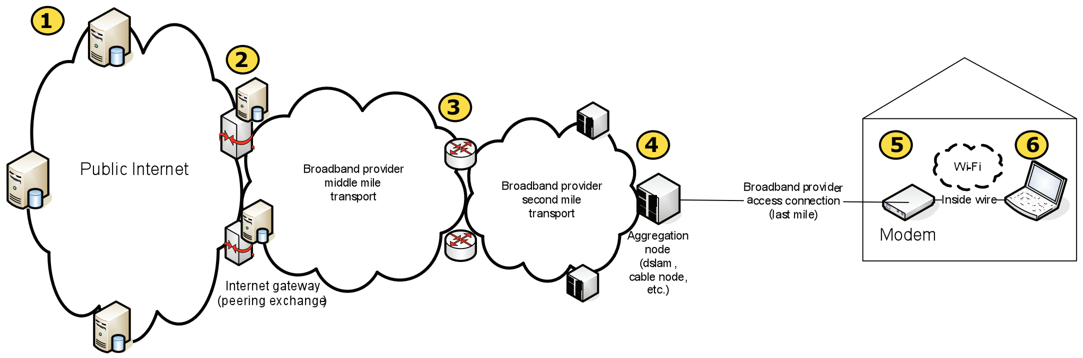
Exhibit 4-A is a diagram of the different portions of a broadband network that connect end-users to the public Internet. Starting at the public Internet, (1) content is sourced from various geographies and providers, data flow through the first peering point of the broadband provider (2), through the "middle mile" aggregation point (3) and "second mile" aggregation point (4), before being transported over either a wired or wireless "last mile" connection to the customer modem (5), which can either be embedded in a mobile device or standalone customer premise equipment (CPE), in the case of a fixed network. Once inside the premises broadband is connected to a device (6) through either wired or wireless connections (e.g. WiFi).

LAST-MILE TECHNOLOGY COMPARISON

We model the deployment economics of DSL/FTTN, FTTP, HFC, Satellite and 4G fixed wireless technologies. Each technology is modeled separately using detailed data and assumptions. Our model shows that fixed wireless and 12,000-foot-loop DSL have the best economics in delivering 4 Mbps down- and 1 Mbps up-stream to the unserved areas of the country.

Fixed wireless networks have favorable economics in most unserved areas, as the high fixed costs of wireless towers are amortized over many customers. In the least dense areas, particularly in mountainous terrain, however, there are few customers per tower and wired technologies are more economically efficient. Among wired networks, 12 kilofeet (kft) DSL has the best economics while still meeting the National Broadband Availability Target because it requires the least amount of network replacement/building. Although satellite capacity is

Exhibit 4-A:
Basic Network Structure



DEFINITIONS

① **Public Internet content:** Public Internet content that is hosted by multiple service providers, content providers and other entities in a geographically diverse (worldwide) manner

② **Internet gateway:** Closest peering point between broadband provider and public Internet for a given consumer connection

③ **Link between second mile and middle mile:** Broadband provider managed interconnection between middle and last mile

④ **Aggregation node:** First aggregation point for broadband provider (e.g. DSLAM, cable node, satellite, etc.)

⑤ **Modem:** Customer premise equipment (CPE) typically managed by a broadband provider as the last connection point to the managed network (e.g. DSL modem, cable modem, satellite modem, optical networking terminal (ONT), etc.)

⑥ **Consumer device:** Consumer device connected to modem through internal wire or Wi-Fi (home networking), including hardware and software used to access the Internet and process content (customer-managed) limited by the number of satellites, and latency can be an issue for some applications, the fact that costs are not dependent on population density makes it an attractive option for serving the most remote areas of the country. We model FTTP, HFC and 3-5 kft DSL as well, and even though the performance and revenue opportunities are better with these technologies, they have unfavorable economics in areas with low population density relative to the other technologies mentioned, due to the high fixed costs of building or replacing large parts of the network.

In order to accurately model each technology, we need to understand both the technical capabilities as well as the economic drivers. First, we determine which of the network technologies could meet end-user speed requirements. Then, we collect detailed cost data required to accurately model the build of a network with the required network capacity. Finally, we determine the incremental revenues that could be generated from each technology.

Network Capabilities

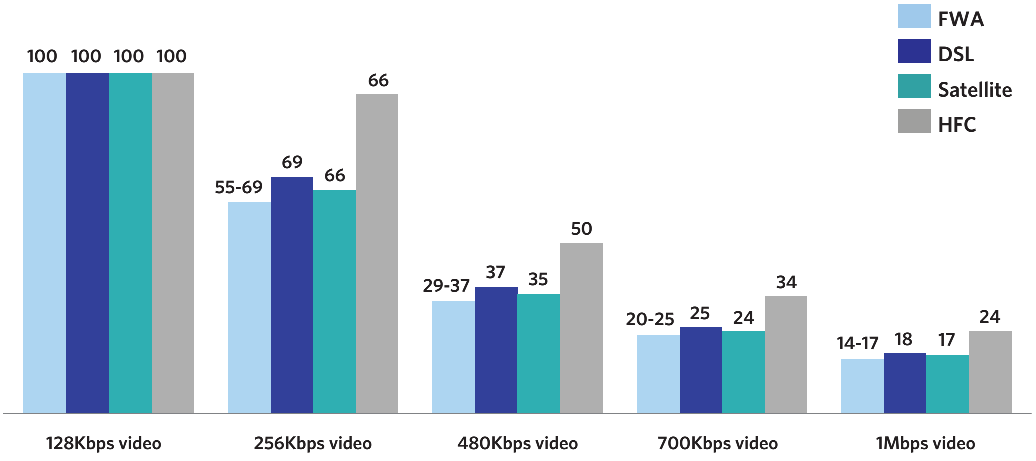
The National Broadband Availability Target is download speeds of 4 Mbps and upload speeds of 1 Mbps. As we shall see in later sections, we dimension the DSL/FTTN, HFC, FTTP, fixed wireless and satellite networks in our network model to meet the National Broadband Availability Target. Further, the sustained data rate capabilities of the networks are comparable.

For example, we compare the streaming capacities of the DSL, wireless, HFC and satellite networks as modeled in our analysis in Exhibit 4-B. For each of the cases, we consider a fully subscribed network, i.e., a network with the maximum prescribed subscriber capacity at the aggregation point nearest the end-users (a cell site in the case of wireless, a DSLAM/backhaul for DSL and a spot-beam for satellite). The details for each technology will be presented in following sections. For this analysis we assume the following: for wireless, a network of cell sites with 2x20MHz of spectrum, each with 650 subscribers;[1] for DSL, a network with about 550 subscribers[2] being served by a Fast-E second-mile backhaul link.

The exhibit shows the percentage of subscribers in each network that can simultaneously experience video streams of various rates. Thus, for example, we estimate that 29-37% of the wireless subscribers in the cell site can simultaneously enjoy a 480 kbps video stream.[3] For DSL and next-generation satellites, those numbers are 37% and 35%, respectively. So, each of the networks as dimensioned has comparable capabilities. We note that the capacity of an under-subscribed or under-utilized network will, of course, be higher. Thus, for example, if we used a Fast-E backhaul to serve a single 384-port DSLAM, then nearly 55% of subscribers can simultaneously enjoy a 480 kbps video stream.

However, the methods by which each technology can expand to meet growing capacity demand in the last mile differ. For example, with DSL, increased demand can necessitate two types of capacity upgrades that have very different remedies. First, when speed needs for a given user exceed the loop length capabilities on a DSLAM port (unshared network portion), the DSLAM is extended closer to the user so that the shortened copper loop can provide higher speed. This will involve fiber extension, electronics upgrades and significant outside plant reconstruction and rearrangement. This can be a very costly

Exhibit 4-B:
Streaming Capacity of Modeled Broadband Networks[4]



Simultaneous streams in a fully subscribed network
Percent of subscribers of second aggregation point

process that involves many aspects of "new" construction, such as pole transfers/make-ready costs, fiber trenching and general overbuild of portions of the outside plant. And second, if the capacity expansion is a result of aggregate demand growth among the users sharing the second-mile backhaul of the network, and not the last mile, one only needs to upgrade DSLAM ports and increase backhaul capacity. Undoubtedly, this carries significant cost, but is relatively straightforward as it primarily involves electronics upgrades.

In the case of HFC, RF signals for data transmission are modulated onto coaxial cables and shared among all of the subscribers who are connected and active on the coaxial portion of the HFC network. Therefore, the last mile is a shared resource. One process for capacity expansion is cable node splitting, which involves electronics upgrades similar to DSL but often also requires significant outside plant reconstruction and rearrangement. Thus, it involves many aspects of "new" cable construction, such as pole transfers/make ready costs, fiber trenching and general overbuild of portions of the outside plant. While this process is not without significant cost and lead time, it is well understood and has been practiced for several years. In addition, there are a number of other often-used methods for increasing capacity as will be discussed in the HFC section.

Similarly, the last mile is shared in FTTP/PON networks. More precisely, optical signals are modulated onto fiber optic cables, which are then distributed to individual homes between the PON splitter and the home. Capacity expansion is again a matter of upgrading electronics either at the headend, home or both, and certainly requires rearrangement of PON splitters and other passive outside plant equipment but does not require a fundamental design and architecture change.

In the case of wireless communications, the primary shared resource in the last mile is the RF spectrum. Multiple wireless devices, such as mobile phones and wireless data cards, simultaneously transmit/receive over the same shared spectrum. In fact, an average cell site covers more than 4,000 people, often referred to as POPs or population.[5] As we will see later, the wireless networks that we model to deliver broadband will be capable of serving up to 650 homes per cell tower using a paired 2x20 MHz[6] of spectrum. Capacity expansion in the last mile typically involves using more spectrum or adding more cell sites or both.[7] Since wireless spectrum is a scarce resource, wireless capacity expansion can be expensive, involving many of the high costs of outside plant/tower construction, etc. (similar to wired technologies discussed above), unless the provider has adequate spectrum holdings. With adequate spectrum, however, capacity expansion is straightforward and relatively inexpensive. Spectrum needs in *unserved rural areas*—with low population densities—are expected to be limited. Given the amount of spectrum currently available and the additional spectrum likely to become available in the next several years,[8] we expect that capacity expansion in wireless should be relatively inexpensive in *these* areas.

Capacity expansion with satellites will ultimately involve launching additional satellites which are capable of providing more total bandwidth and higher spatial reuse of the available spectrum. New launches, however can cost up to $400 million and require potentially long lead times, as will be discussed later in this chapter.

All of the technology comparisons in this chapter are based on network builds that can meet the target, with an effective busy hour load assumption of 160 kbps (see later section on Network Dimensioning). A fundamental tenet is that the networks have been modeled such that users will receive an equivalent level of service and performance whether they are serviced by the fixed wireless 4G access network or a 12 kft DSL architecture.

Cost Comparison

Our model allows us to calculate the relative cost structure of different last mile technologies as a function of population density in unserved areas. As shown in Exhibit 4-C, the costs associated with all technologies are competitive in the highest densities and diverge as we move toward lower population densities. Note that Exhibit 4-C represents the present value of costs, not the gap associated with each technology.

HFC and FTTP costs are comparable and both are among the most costly in all densities. As one might expect, the cost of running a new connection to every home in low-density areas is very high. In effect, carriers face the cost of deploying a greenfield network in these areas.

Short-loop FTTN deployments (3,000- and 5,000-foot loops) realize some cost savings relative to FTTP from being able to avoid the last few thousand feet of buildout. These savings are particularly valuable in denser areas where operators are more likely to find more homes within 3,000 or 5,000 feet of a given DSLAM location. At the other extreme, in the least-dense areas, where a carrier might have only one customer within 3,000 feet of a DSLAM location, 3,000-foot FTTN is actually more expensive than FTTP; a fiber drop is less costly than a DSLAM. Longer-loop (12,000-foot) DSL is particularly low cost in higher-density areas, where the cost of a DSLAM can be amortized over more customers.

Wireless solutions are among the lowest cost solutions and wireless costs grow less quickly as density falls. As discussed in Chapter 3, and in more detail below, a major driver of wireless cost is cell size. The assumptions made about cell size in hillier terrain are larger drivers of cost than density; however, when ordering census blocks by density, as in Exhibit 4-C, this effect is averaged away and lost. More detail about the impact of cell size on cost is included later in this chapter.

Exhibit 4-C includes only costs, both capex and ongoing costs, and does not include revenue. Technologies that enable higher revenue could have lower investment gaps than costlier alternatives. Thus, it is possible that FTTP deployment could have a lower investment gap in some census blocks than FTTN or wireless. In addition, given the assumptions made about take rate and ARPU, wireless often will have a lower investment gap than a less-costly 12,000-foot-DSL solution.

However, as noted in Chapter 3, evaluating the economics of technologies over areas as small as a census block makes little sense. Counties or other service areas draw census blocks from across multiple densities. Therefore this revenue-driven advantage is muted when census blocks are aggregated into counties or other service areas and wireless and 12,000-foot-loop DSL are the lowest investment-gap terrestrial solutions overall.

TECHNOLOGIES INCLUDED IN THE BASE CASE

As seen in Exhibit 4-C, our model indicates fixed wireless and 12 kft DSL are the low-cost terrestrial solutions that are capable of delivering speeds consistent with the Broadband Availability Target in unserved areas. We will focus on those technologies and satellite across the next three sections, before returning to those technologies with higher deployment costs.

Wireless Technology

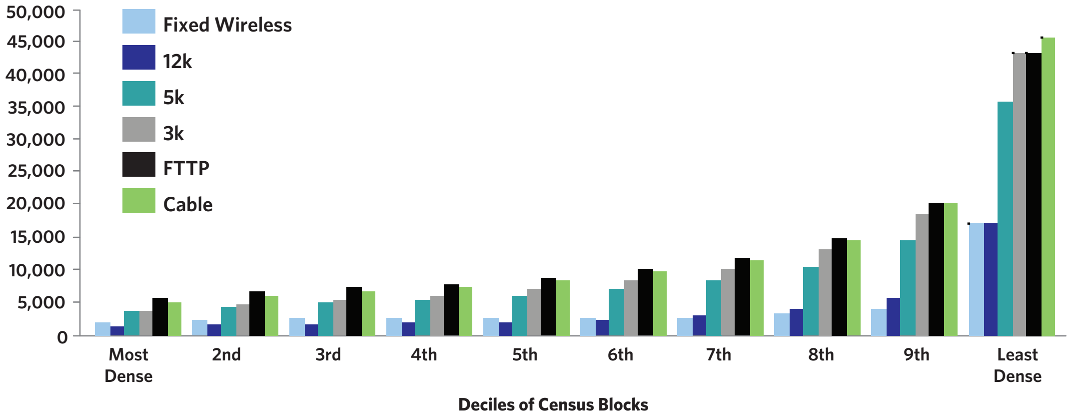
The first mobile networks were built when the FCC approved commercial car-phone service in 1946 but the first commercial cellular telephony service in the United States came in 1983 using AMPS technology. AMPS was an analog phone service that was still in use in some regions of the United States as recently as 2008. As wired communications started going digital in the 1980s, so did wireless telephony. In the 1990s there were four different 2G digital wireless technologies used in the United States: CDMA-based IS-95, TDMA-based IS-54 (often called Digital AMPS or D-AMPS), GSM and iDEN. Initially, these technologies provided voice services and some limited circuit-switched data services like SMS with peak data rates of 9.6 kbps.

CDMA and GSM became the predominant technologies in the United States, with more than 71% of subscribers in 2004.[9] For GSM, the first real step towards packet-based data services was GPRS, which was later replaced by EDGE. Even with EDGE, the average data rates were still only 100-130 kbps. The big step towards mobile broadband for GSM providers came with UMTS or WCDMA, a CDMA-based air interface standard; average user data rates were 220-320 kbps. Over time, the standards bodies created HSDPA for the downlink and HSUPA for the uplink, collectively referred to as HSPA today. User data rates of up to several Mbps became possible,[10] allowing GSM-family providers to offer true 3G service. See Exhibit 4-D.

Like GSM, CDMA rapidly evolved, first into CDMA2000 1xRTT which delivered peak data rates of 307 kbps and later into CDMA2000 EV-DO that is capable of delivering data rates of up to 3.1 Mbps.

There are two competing 4G standards that can be used in wireless broadband networks:[11] LTE, which is an evolution of the GSM family of standards, and WiMAX. Both of these technologies use OFDMA modulation instead of CDMA and, as such, are not backward compatible with either HSPA or EV-DO. The 4G technologies are only beginning to be deployed and adopted. In fact, LTE, one of the most anticipated

Exhibit 4-C:
Present Value of Total Costs for All Technologies in Unserved Areas[12]



Ordered by unserved housing-unit density

4G technologies, has yet to be commercially deployed in the United States as of the time of this writing, while WiMAX covers less than 3% of the population.[13]

Evolution of the Performance of Wireless Technologies

As wireless technologies have evolved, so have their performances. In a broad sense, with every evolution the industry has achieved higher peak throughputs, improved spectral efficiencies and lower latencies. Additionally, with 4G the wireless signal can be transmitted over wider bandwidths of up to 20MHz,[14] which further increases spectral efficiency and network capacity, while letting the user experience higher data rates. Additionally, 4G uses a native, all-IP architecture, thus benefitting from the technology and economic efficiencies of IP networks.

The most important dimension of performance—at least as far as capacity of the wireless network is concerned—is spectral efficiency, which is the number of bits/second that a sector can transmit per hertz of spectrum. As such, spectral efficiency drives average downlink data capacity of a cell site linearly. Exhibit 4-E shows the evolution of the average downlink and uplink data capacities of a single sector in a three-sector cell site for the GSM family of standards.[16]

Note that there is no known analytic form for Shannon capacity for a multi-user, multi-site wireless network today. However, one can estimate the Shannon limit for a single user on a single cell site. Further, scheduling efficiency gains from multi-user scheduling are well understood.[17] One can therefore estimate the capacity of a multi-user, multi-site network.[18] But, this estimate does not take into account potential future gains in wireless technology and networks from, for example, coordinated transmission of data to users from multiple cell sites. Nonetheless, this estimated limit suggests that gains in spectral efficiency—and the ability of networks to cheaply improve performance or capacity—will likely be limited in the future.

In fact, as illustrated in Exhibit 4-E, we estimate that the latest release of the LTE standard brings us to within 25% to 30% of the maximum spectral efficiency achievable in a mobile network. Going forward, improvements in spectral efficiency are likely to result from techniques that include the use of new network architectures and multiple-antennas.[19] Specifically:

- Multiple-antenna techniques, such as spatial multiplexing in the uplink and improved support for beamforming
- Network enhancements:
  - Coordinated transmission of data to users from multiple cell sites
  - Relays or repeaters to improve coverage and user experience at cell edges with low additional infrastructure cost
- Carrier or spectrum aggregation to achieve higher user burst data rates

The 4G network architecture represents an evolution as well. 3G networks, having evolved from legacy 2G architectures that were primarily designed for circuit-switched traffic, were hierarchical in design and included many more network elements. 4G, on the other hand, optimizes the network for the user plane and chooses IP-based protocols for all interfaces.[20] The result: a much simpler architecture with far fewer network elements. Not only does this reduce capex and opex for 4G networks relative to 3G, but it also means reduced network latencies; see Exhibit 4-F. The performance of TCP/IP, the Internet data transport protocol, is directly impacted by latency,[21] so that reduced latencies translate directly into improved user experiences.

BOX 4-A

Wireless Multiple Access 101

In any wireless network with multiple users, those users must share the wireless communication channel. Different technologies use different schemes for sharing the channel; these schemes are commonly referred to as multiple access schemes. One such scheme is Time Division Multiple Access, or TDMA, which divides the channel into multiple time slots, allocating each to one of many users. The users then communicate with the base station by transmitting and receiving on their respective time slots. TDMA is used in GSM/GPRS/EDGE as well as the eponymous TDMA IS-54 standard.

Another scheme is Code Division Multiple Access or CDMA. It uses *spread-spectrum* technology for sharing the physical communication channel between the users. More precisely, in CDMA, the signal to and from each user is modulated using a uniquely assigned code. This modulated signal on the assigned code is spread across far more bandwidth than the bandwidth of the data being transmitted. This allows multiple users to simultaneously transmit or receive communication signals on the channel, which are then separated at the base station using the codes. CDMA allows for greater spectral efficiency than TDMA where communication to each user takes place in a uniquely assigned time slot. All 3G technologies, EV-DO and UMTS/HSPA, use CDMA, as does IS-95 and CDMA 1xRTT.

Finally, in Orthogonal Frequency Division Multiplex Access or OFDMA, data transmission occurs on a set of orthogonal *sub-carriers* assigned to each user; the sub-carriers are then modulated and transmitted using conventional modulation techniques. OFDMA has emerged as the multiple access technique for 4G technologies.[15]

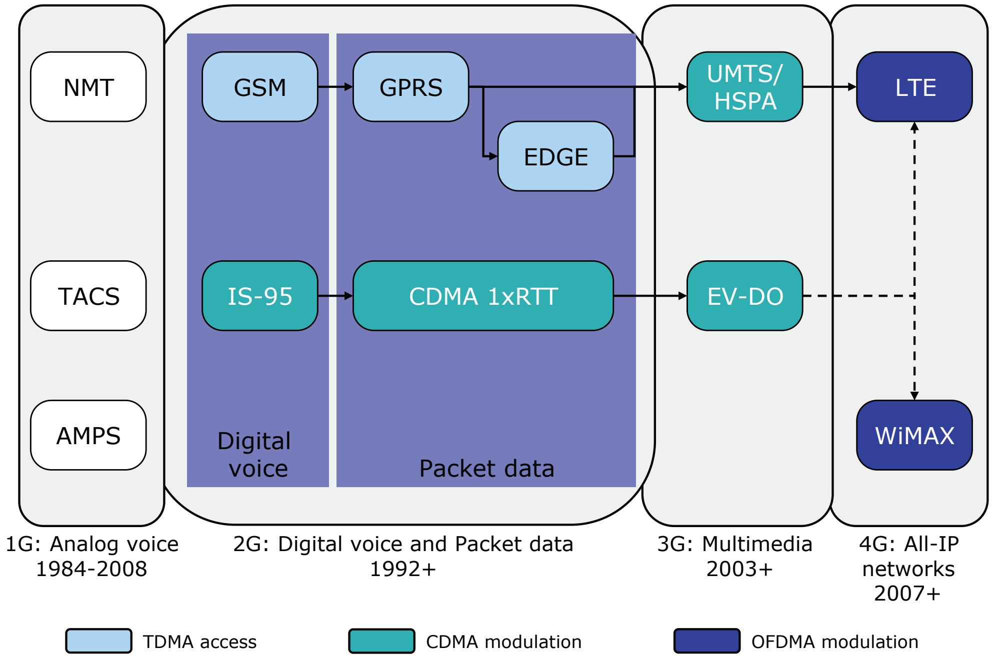


Exhibit 4-D:
Different Wireless Technology Families Have Evolved Over Time[22]

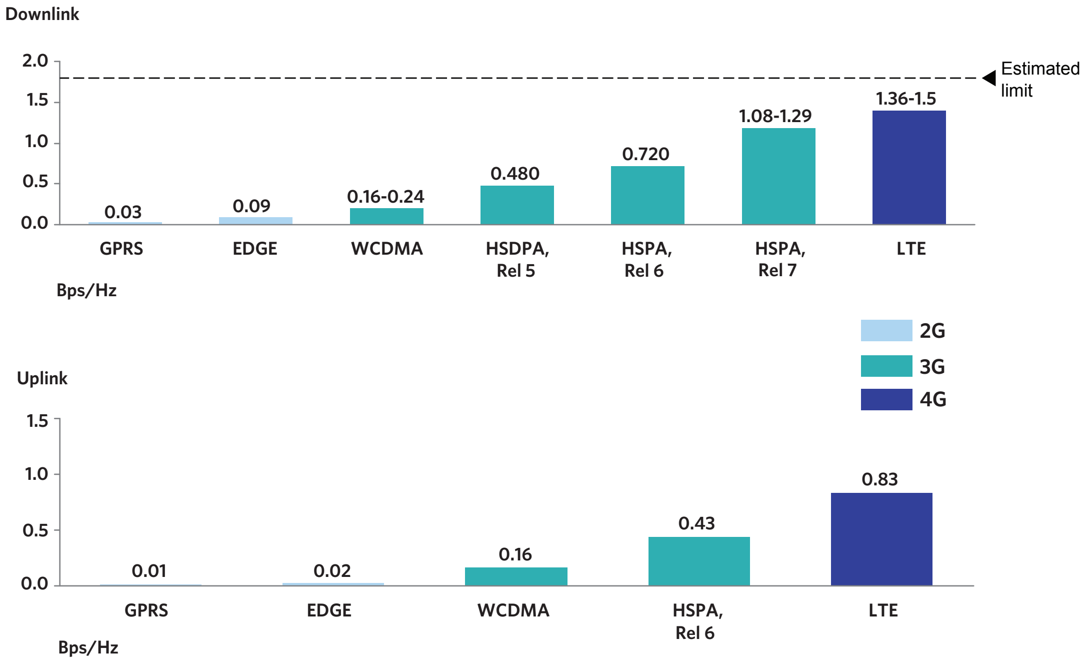


Exhibit 4-E:
Downlink and Uplink Spectral Efficiencies by Technology[23]

4G Deployment Plans

Exhibit 4-G shows projected 4G deployment plans for major carriers in the United States based on public announcements.[24] Verizon Wireless has the most aggressive deployment schedule for LTE. It plans to build out to 20 to 30 markets in 2010, extending to its entire EV-DO footprint by 2013—thus reaching more than 93% of the U.S. population.[25] AT&T has announced that it will be trialing LTE in 2010, then rolling it out commercially in 2011. Sprint plans to deploy WiMAX through its partnership with Clearwire. WiMAX has been rolled out in a few markets already and Clearwire announced plans to cover 120 million people by the end of 2010. With carriers in the United States and around the world making these commitments to deploy 4G, we expect it to have significant benefits of scale: a robust ecosystem, strong innovation and substantive cost savings.

Given the superior performance of 4G and the likely extensive 4G coverage by 2013, we shall limit our wireless analysis to 4G technologies in the rest of this document. Our goal is certainly not to pick technology winners, and we recognize that other wireless technologies, such as WiFi mesh, cognitive radios and even 3G, will be important parts of the broadband solution. However, these technologies are unlikely to deliver a cost-effective and reliable wide-area broadband experience consistent with the National Broadband Availability Target in unserved communities. To the extent these technologies offer appropriate service at comparable or lower prices, they will certainly play a role.

Fixed Wireless Access (FWA) Networks

By FWA networks, we refer to wireless networks that use fixed CPEs in addition to (or, possibly, even instead of) mobile portable devices. FWA solutions have been deployed as a substitute for wired access technologies. For example, FWA networks are being used commercially in the U.S. by Clearwire with WiMAX and Stelera with HSPA, and globally by Telstra

Exhibit 4-F:
Evolution of Round-Trip Latencies in Wireless Networks, in Milliseconds[26][27]

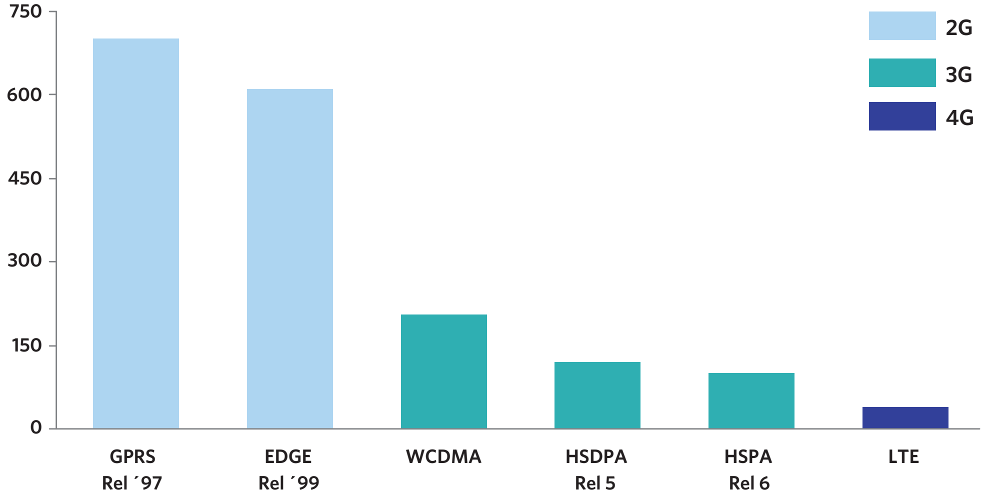


Exhibit 4-G:
Publicly Announced 4G Wireless Deployments

Technology	Companies	2009	2010	2011	By 2013
LTE	• Verizon • AT&T • MetroPCS • Cox		• Verizon (100MM) • AT&T (Trials)	• AT&T (start deployment) • Cox (start deployment) • MetroPCS (start deployment)	• Verizon (entire network)
WiMAX	• Clearwire/Sprint • Open Range • Small WISPs	• Clearwire (30MM) • WISPs (2MM)	• Clearwire (120MM)		• Open Range (6MM)

with HSPA. In addition to the larger providers, there are hundreds of entrepreneurial and independent Wireless Internet Service Providers (WISPs) who provide fixed wireless services to at least 2 million customers in rural areas, including many areas not covered by the national wireless companies.[28] Such deployments are particularly attractive in areas where wired competitors do not exist or have inadequate capabilities.

Fundamentally, FWA uses fixed CPE to deliver better performance by improving end-user signal quality. Examples of techniques that allow fixed wireless to provide superior performance compared to mobile broadband include:

- ➤ CPE techniques:
  - ➤ Using a higher power transmitter than would be possible with a battery-powered end-user device in order to improve the upstream data rate and/or increase the coverage area
  - ➤ Using large high-gain antennas along with external mounting to decrease building loss and further improve both upstream and downstream data rate and/or increase the coverage area
  - ➤ Placing the antenna in a favorable location to achieve line-of-sight or near line-of-sight to reduce path loss
- ➤ Base Station techniques: using stronger power amplifiers and multiple antenna techniques in order to increase the coverage area and/or capacity

These techniques are broadly applicable to most spectrum bands and to both 3G and 4G technologies. As such, generally speaking, FWA networks can support both fixed and mobile traffic, with fixed CPEs improving the performance of fixed service relative to mobile.

Our objective is to provide fixed broadband service to homes; so, we have used the performance characteristics of a FWA network in our network model. *In what is to follow, unless otherwise mentioned, the term wireless network will refer to a FWA network.*

Complexity of Analyzing Wireless Networks

It is important to recognize that a wireless network has several layers of complexity that are not found in wireline networks, each of which affect the user experience and, therefore, network buildout costs and the investment gap. For example, the location of the user relative to the cell site has a significant impact on data rates. More precisely, those at the cell edge, i.e., farthest from the cell site, will have much lower signal quality than those closer to it. And as signal quality drops, throughput drops as well; thus, at the cell edge a user may experience more than 60% degradation in data rates relative to the average experience within the cell.[29]

Another factor affecting user experience is the fact that wireless spectrum is shared by all the users in the cell. As a result, a user can experience significant variations at the same position in the cell depending on temporal changes in capacity demand (or loading).

There are other factors that lead to a heterogeneity of user experience. For example, the wireless signal itself undergoes different levels of degradation depending on terrain, user mobility and location (indoors vs. outdoors vs. in-car). Further, there is a wide range of end-user device types, which vary in their peak bandwidth capabilities, have different types of antennas, form factors, etc. Each of these factors can lead to a different user experience under otherwise identical conditions.

Consequently, analysis of the performance of wireless networks requires a statistical approach under a well-defined set of assumptions. We shall describe the assumptions behind the parameters we used in our wireless network model. However, it is possible that the parameters in an actual network deployment are different from those that we estimated. Improving the accuracy of our estimates would require a RF propagation analysis in the field—an extremely time-consuming and expensive proposition that is usually undertaken only at the time of an actual buildout. And even that approach will not always capture some effects, such as seasonal foliage.

Approach

Exhibit 4-H is a schematic that lays out our approach to analyzing the cost of the network buildout. The cost of the network, as shown, is driven by the number of cell sites required to deliver broadband service and the cost of building, operating and maintaining each cell site.

The number of cell sites required to serve an area is fundamentally dependent on capability of the technology. Using the performance of LTE networks, we dimension cell sites to deliver downlink and uplink speeds of 4 Mbps and 1 Mbps, respectively, in two steps:

- ➤ First, we ensure that the cell sizes are dimensioned to provide *adequate signal coverage*; i.e., absent any capacity limitations, the propagation losses within the coverage area are constrained and, therefore, the received signal strengths are adequate for delivering the target data rates. Our analysis indicates that the uplink requirement is the driver of coverage limitations.
- ➤ Next, once we have ensured adequate signal coverage, we ensure that each cell site has sufficient *capacity* to meet the traffic demand. We achieve this by constraining the maximum number of subscribers per cell site. As mentioned in Network Dimensioning, we only consider the downlink capacity requirements—and not the uplink—for our analysis.

Following that, we present the economics of a wireless network. In particular, we analyze the influence of factors like spectrum, terrain and downlink capacity on wireless economics. We also discuss in detail the factors that influence the cost of building and operating a cell site, namely tower lease/construction and backhaul for cell sites.

Dimensioning the Network for Coverage

The method of determining the maximum cell radius to ensure sufficient coverage in the modeled network is driven by three key factors (see Exhibit 4-I):

- Broadband rate targets and the corresponding link budgets: Link budgets allow us to calculate the Maximum Acceptable Propagation Loss (MAPL) of the transmitted signal such that the received signal quality is adequate for achieving the target data rates.
- Spectrum bands: The propagation characteristics of spectrum bands are different, thereby impacting cell radius.
- Terrain: It plays an important role in radio propagation. Simply put, mountains and hills block wireless signals; so areas with rougher terrain require smaller cell radii than areas with flat terrain.

Link Budgets

In order to deliver uplink speeds of 1 Mbps within 90% of the cell coverage area in a FWA network, the maximum acceptable propagation loss (MAPL) is 142 to 161 dB; see highlighted text in Exhibit 4-J. By contrast, the MAPL in a mobile environment is 120 to 132 dB. In other words, higher power CPEs with directional antennas placed in favorable locations in a FWA network yield gains of more than 20 dB over mobile devices.[30]

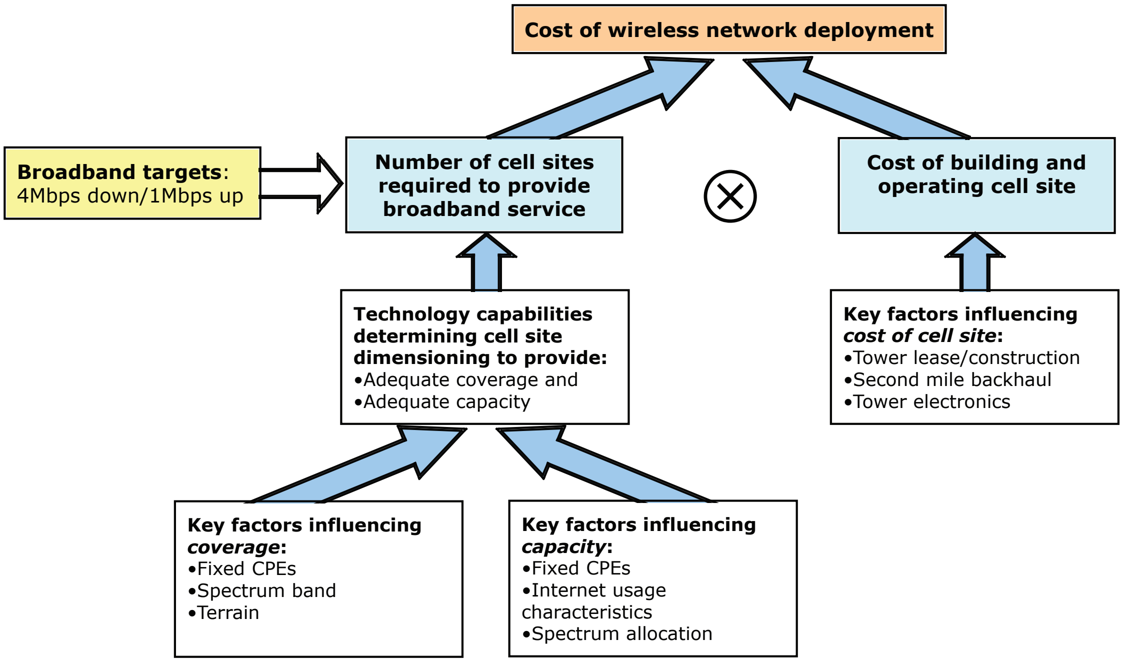
For our target data rates, it is the uplink that drives coverage limitations; i.e., the cell radius limits imposed by the uplink link budget calculation are smaller than the radii required to ensure adequate downlink received signal strengths. A cell radius small enough for a 200 mW handheld device or a 500 mW FWA device to deliver adequate signal strength to the base station is also small enough for a 40 W (macro) base station to deliver more than adequate downlink signal strengths.

Loosely speaking, unless the downlink and uplink requirements are more asymmetric than the power differential, the significantly higher power at the base station implies that adequate uplink coverage should result in adequate downlink coverage.[31]

Impact of spectrum bands

Cellular service today typically operates in one of several bands: from 700 to 900 MHz; from 1.7 to 2.1 GHz; and from 2.5 to 2.7GHz (see Chapter 5 of National Broadband Plan for details). Generally speaking, in this range of frequencies lower frequency signals suffer lower propagation losses and therefore travel farther, allowing larger cell sizes. Lower frequency signals also penetrate into buildings more effectively. Thus, for example, the Okumura-Hata model[32] predicts that the radius of rural cells in the 700MHz band can be as much as 82% greater

Exhibit 4-H:
Approach for Analyzing Cost of FWA Network



than in the PCS band for comparable coverage. In suburban areas this benefit is 105%, while in urban areas the improvement is greater than 140%. That makes lower frequency bands better suited for coverage and deployments in rural areas.

Terrain classification and maximum cell size

Terrain plays an important role in radio propagation, an effect that cannot be captured using propagation loss models such as the Okumura-Hata model.[33] Since mountains and hills block wireless signals, areas with rougher terrain require smaller cell radii than areas with flat terrain.

To account for this effect of terrain, we classified terrain into each of the four categories shown in Exhibit 4-K. More precisely, we used GIS data to classify each Census Tract (CT),[34] based on elevation variations across one square Km grids, into one of the four categories.

Exhibit 4-I:
Methodology for Determining Maximum Cell Radius for Coverage

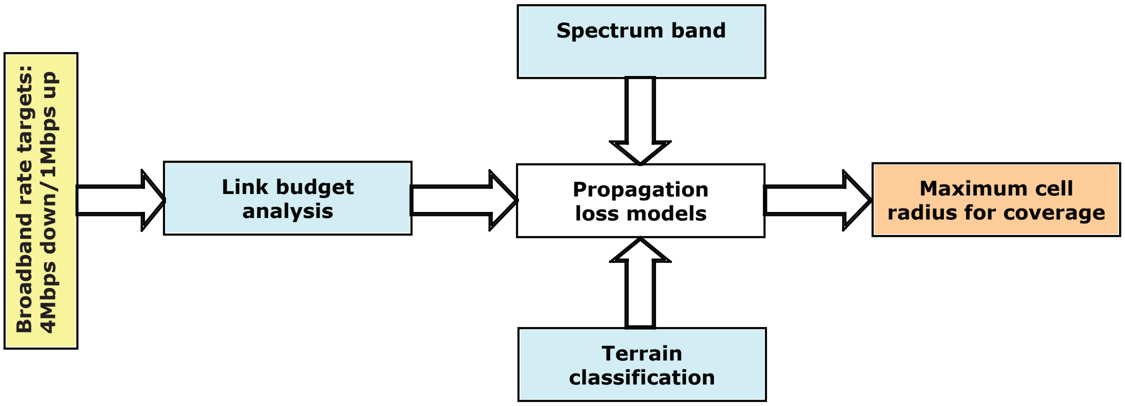
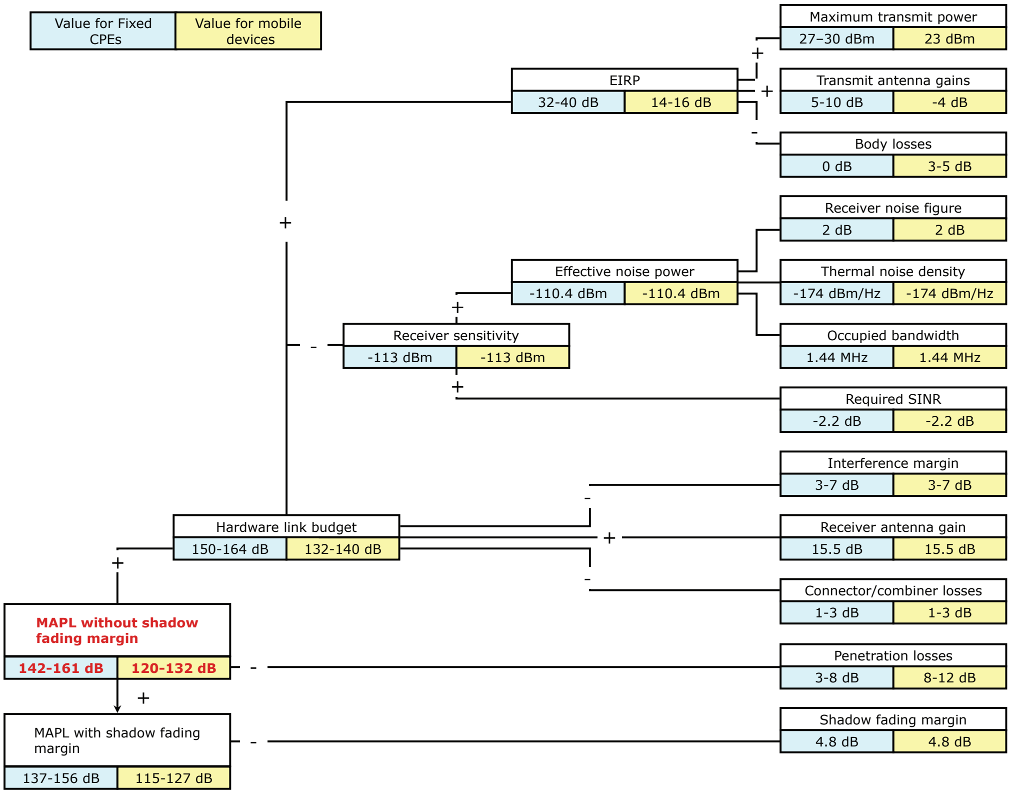


Exhibit 4-J:
Link Budget for Delivering 1.26 Mbps Uplink Speeds at 700MHz [35] [36]



Recall from the discussion of link budgets that the Maximum Allowable Propagation Loss (MAPL) for achieving our target broadband speeds is 142—161 dB. We use RF planning tools[37] (see Exhibit 4-M) to estimate the cell radius for each terrain type that will keep propagation losses within bounds.[38] More specifically, we choose the MAPL to be 140 dB, allowing for possible propagation losses due to foliage.[39] Areas in green in Exhibit 4-M correspond to areas with adequate signal coverage. The results of this analysis are shown in Exhibit 4-L for the 700MHz band.

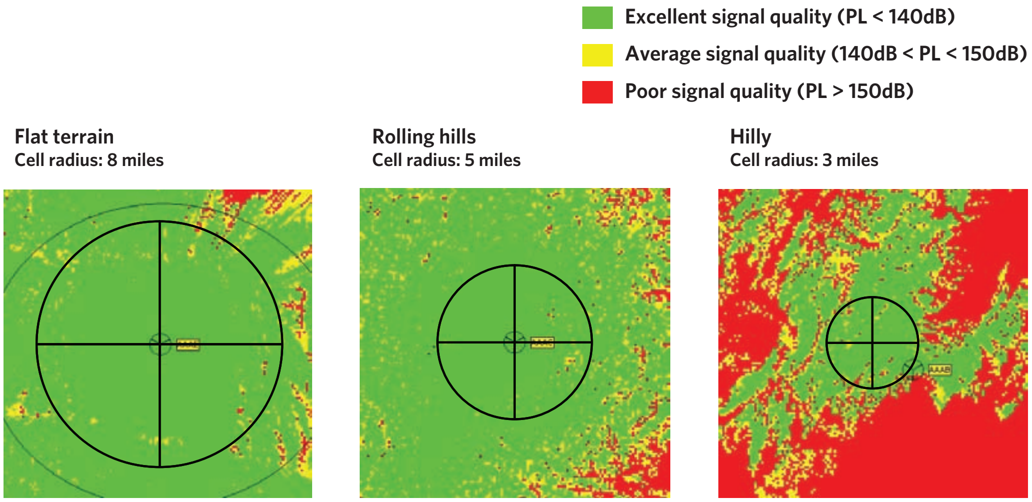
Exhibit 4-K:
Classification of Terrain of Census Tracts

Terrain type	Standard deviation (SD) of elevation (meters)	Examples
Flat	≤ 20	Topeka, Kan.; SD = 12 King City, Mo.; SD = 19
Rolling hills	20 to 125	Manassas, Va.; SD = 41 Lancaster, Pa.; SD = 45
Hilly	125 to 350	Lewisburg, W.V.; SD = 167 Burlington, Vt.; SD = 172
Mountainous	≥ 350	Redwood Valley, Calif.; SD = 350

Exhibit 4-L:
Maximum Cell Radius for Adequate Coverage in the 700MHz Band

Terrain type	Examples	Maximum cell radius (miles)
Flat	Topeka, Kan. King City, Mo.	8
Rolling hills	Manassas, Va. Lancaster, Pa.	5
Hilly	Lewisburg, W.V. Burlington, Vt.	3
Mountainous	Redwood Valley, Calif.	2

Exhibit 4-M:
Propagation Loss for Different Terrain Types at 700MHz[40]



Flat terrain
Cell radius: 8 miles

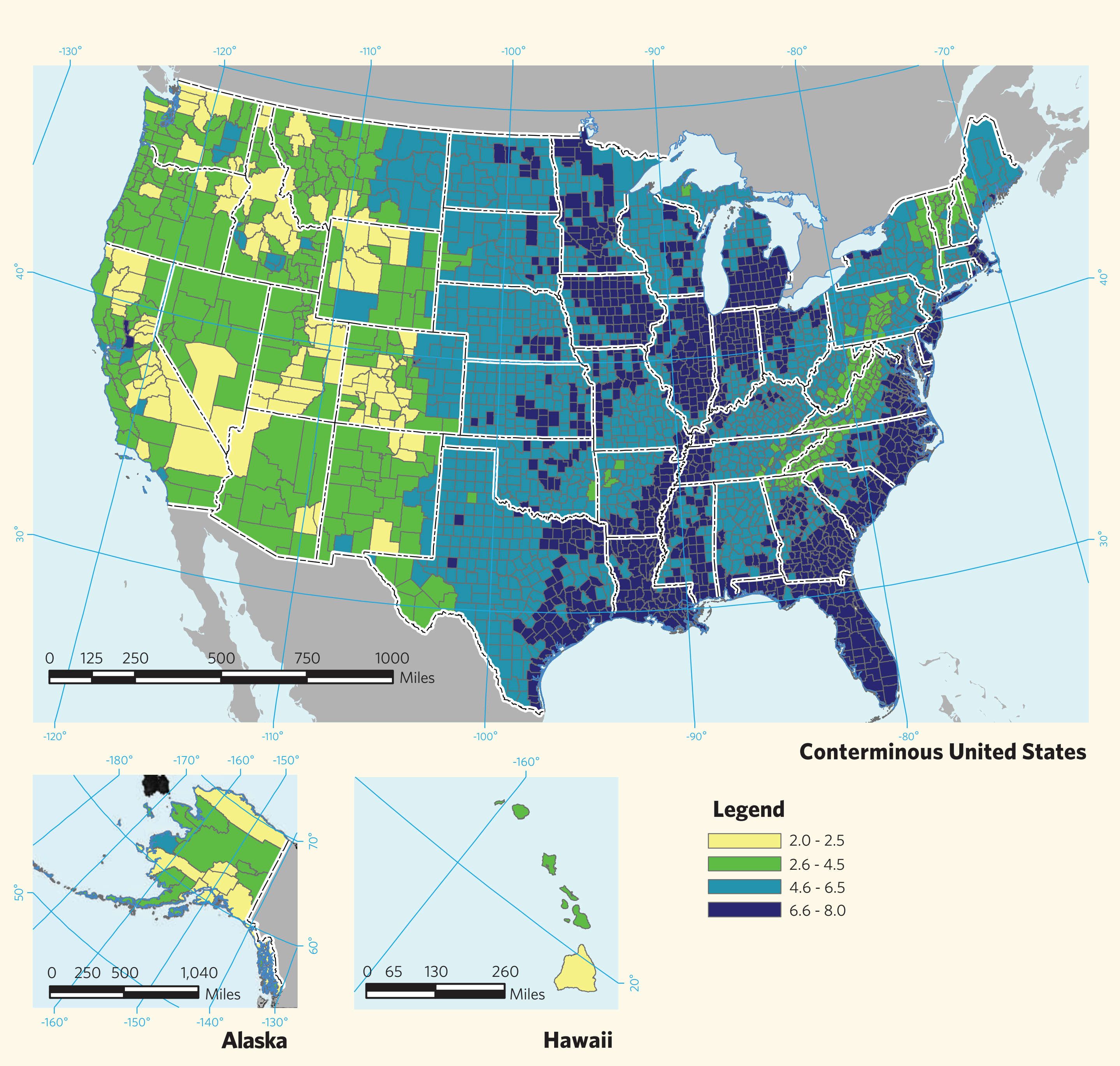
Rolling hills
Cell radius: 5 miles

Hilly
Cell radius: 3 miles

We show a terrain map of the continental United States in Exhibit 3-X; average cell radii for each county based on the classification in Exhibit 4-L for the 700MHz band are shown in Exhibit 4-N. Finally, Exhibit 4-O quantifies the number of households by the cell sizes required to provide adequate coverage to them. Note that only around 13% of housing units (HUs) are in hilly or mountainous areas.

Finally, the propagation characteristics of the spectrum band clearly impact coverage. But, spectrum availability does not play an explicit role in our analysis. Certainly the

Exhibit 4-N:
Average Cell Size in Each County (in miles)



aggregated uplink *capacity* at a cell site improves with spectrum, but the only way to increase the maximum achievable data rate for a *specific user* is to reduce cell size. In other words, site counts will increase if we increase the uplink data rate requirement; adding more spectrum will not alleviate the problem.

Dimensioning the Network for Capacity

Exhibit 4-P shows that subscriber capacity of the wireless network depends primarily on the following:

- Broadband requirements and traffic characteristics. The first represents the National Broadband Availability Target of 4 Mbps downlink while the latter is a characterization of the demand for network capacity, generated by the subscribers on the network (see also Network Dimensioning section).
- Spectrum allocation. Loosely speaking, if spectral efficiency of the air interface remains unchanged, capacity of the wireless network grows proportionately with spectrum allocation.
- Fixed CPE with directional antennas. Specifically, the improvement in signal quality and data rates resulting from using directional antennas at CPE.

We then use the performance of LTE networks to determine the maximum subscriber capacity of the FWA network.

Importantly, signal quality or Signal to Interference and Noise Ratio (SINR)[41] in the downlink is not significantly impacted by increasing the transmission power in cells that are not coverage (i.e., signal strength) limited. This is because signal attenuation depends on the distance from the transmitter, so that SINR depends on the distance of the user from the *serving*[42] cell site relative to the other interfering cell sites. So, if we increase transmission power of all cells similarly, both received signal power and interference power increase proportionately and the net improvement in SINR is small. Correspondingly, reducing the radius of all cell sites proportionately also has a relatively small impact on SINR distribution.

Requirements and Traffic Characteristics

Exhibit 4-Q shows our estimate of the maximum number of subscribers in a FWA cell site for different spectrum allocations.[43] This estimate includes the impact of directional antennas in fixed CPE as discussed below.

As noted in the section on coverage, cell radii are chosen to ensure that the signal quality is adequate for delivering 4 Mbps downlink and 1 Mbps uplink. However, since spectrum is a shared resource, we must ensure that the network is also capable of providing sufficient capacity to deliver these speeds. The approach to sizing the number of subscribers therefore is to first characterize network usage using the Busy Hour Offered Load (BHOL) metric; see Network Dimensioning for details. We assume the BHOL per subscriber is 160 kbps. Then, we use the performance of LTE networks to determine the maximum number of subscribers per cell site for different spectrum allocations such that users achieve the broadband-speed target 95% of the time when the BHOL is 160 kbps.[44]

Note that we achieve our target downlink data rate by limiting the maximum subscribers per cell site, which can be

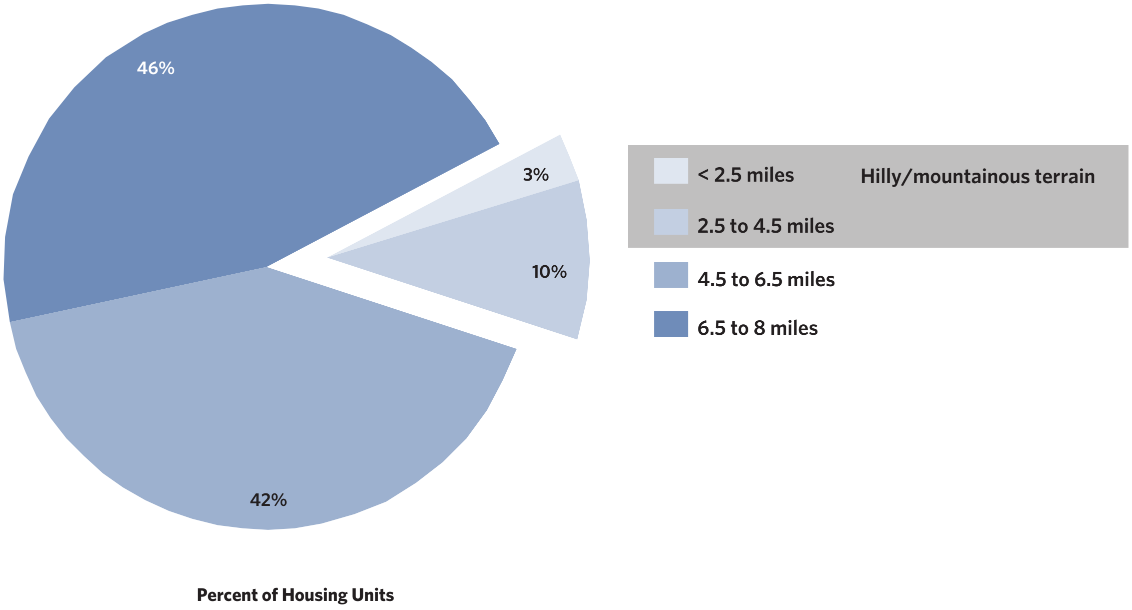


Exhibit 4-O:
Coverage of Unserved Housing Units by Cell Radius

interpreted to be a limit on cell size. But we remarked earlier that we cannot increase data rates by reducing cell size—a seeming contradiction. The resolution is that reducing cell size does not improve signal quality unless it results in a reduction in the number of subscribers per cell site. For example, the user-experience in two cells with 100 subscribers each will not be materially impacted if the cell radius of each is 1/2 km instead of 1 km. Since the load on the network will not change in either case, the utilization is unchanged as well. If we now introduce two additional cells into this hypothetical network, such that each cell has 50 subscribers, then we will see an improved user experience because fewer subscribers in each cell will imply reduced load in each cell. That, in turn, will reduce each cell's utilization and, thereby, improve signal quality and end-user data rates.

So, we cannot prescribe a maximum cell radius to achieve a target downlink data rate (because population density across geographies is not uniform). But we can limit subscribers per cell to achieve target speeds.

Fixed CPE with directional antennas

Using fixed CPE with directional antennas can result in more than a 75% improvement in spectral efficiency over CPE with omni-directional antennas.[45] More significant is the gain in data rates at the cell edge. We illustrate this in Exhibit 4-R. Specifically, the chart on the left shows the improvement in SINR distribution in the cell site when the network has CPE with directional antennas instead of omni antennas. For

Exhibit 4-P:
Methodology for Dimensioning Wireless Networks to Provide Adequate Capacity

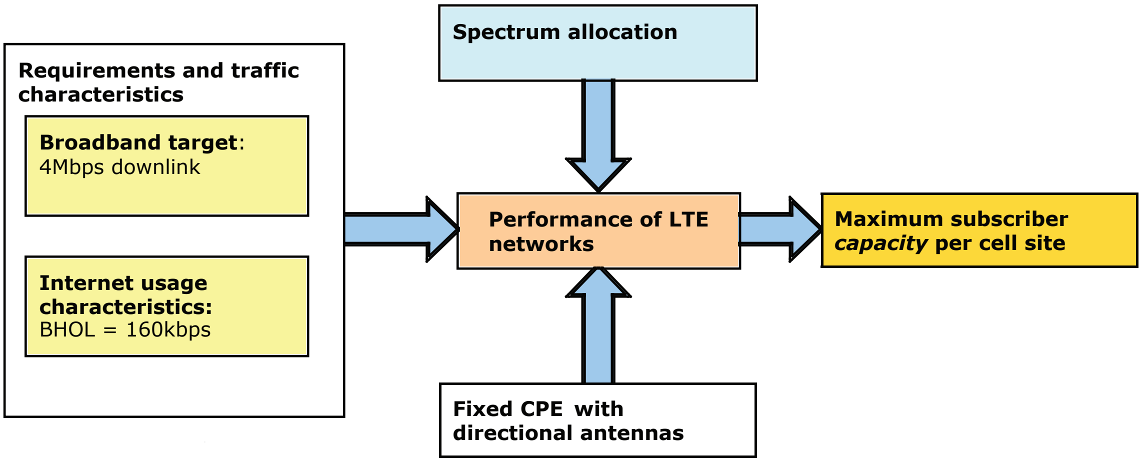
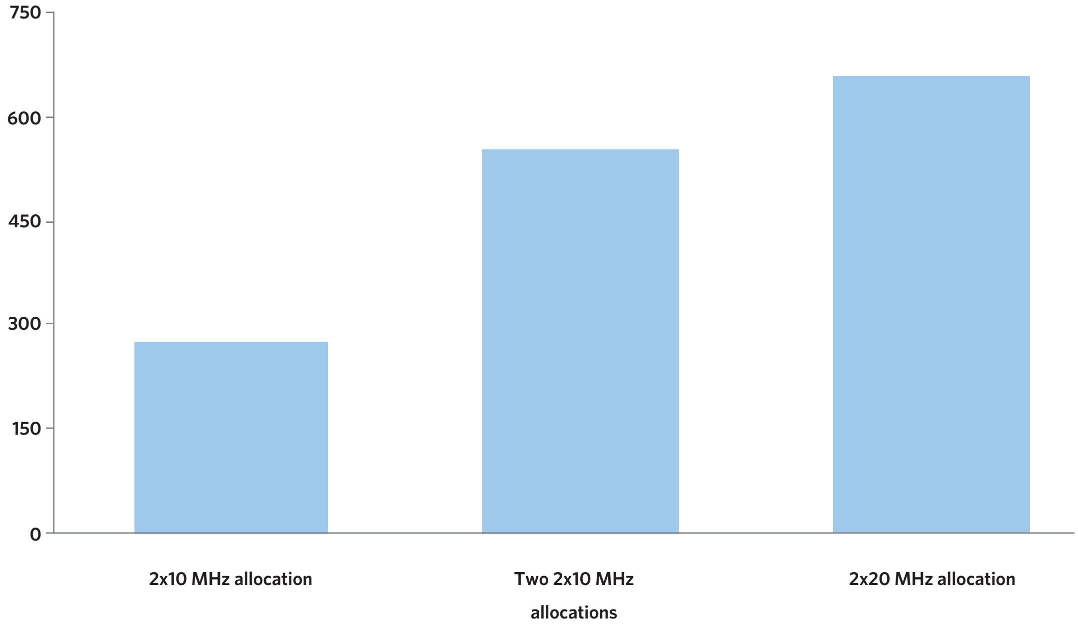


Exhibit 4-Q:
Maximum Number of Subscribers Per Cell Site in an FWA Network with Directional Antennas at the CPE[46]



example, nearly 35% of users in a network with omni antennas have a SINR of 0 dB[47] or worse. By contrast, less than 1% of the users in a network with directional antennas have a SINR of 0 dB or worse. The significant boost in signal quality is a result of (a) improved signal reception with the higher antenna gain of a directional antenna and (b) reduced interference due to the increased interference rejection possible with such antennas.

This improvement in SINR directly translates to better data rates. For example, if a CPE with an omnidirectional antenna experiences a data rate of ~3 Mbps, then a CPE with a directional antenna will experience an average of ~9 Mbps under otherwise identical conditions.

Spectrum allocation

We mentioned above that lower spectrum bands are better suited for coverage. Higher frequency spectrum, on the other hand, is better suited for capacity by deploying Multiple Input and Multiple Output, commonly referred to as MIMO,[48] solutions. This is because smaller antennas can be used at higher frequencies and multiple antennas can be more easily integrated into handsets constrained by form factor. As such, deployments in these bands can have higher spectral efficiency. That is not to say that MIMO cannot be deployed in the lower frequency bands; rather, MIMO solutions are more practical and cheaper in the higher bands.

In our model, we assume 2x2 MIMO,[49] which is easily implemented in the 700MHz band in a FWA network.

The importance of spectrum towards ensuring a robust mobile broadband future has been discussed at length in the Chapter 5 of the NBP. In this section, we discuss how spectrum availability impacts subscriber capacity. For convenience, we shall assume the propagation characteristics of the 700MHz band for this discussion.

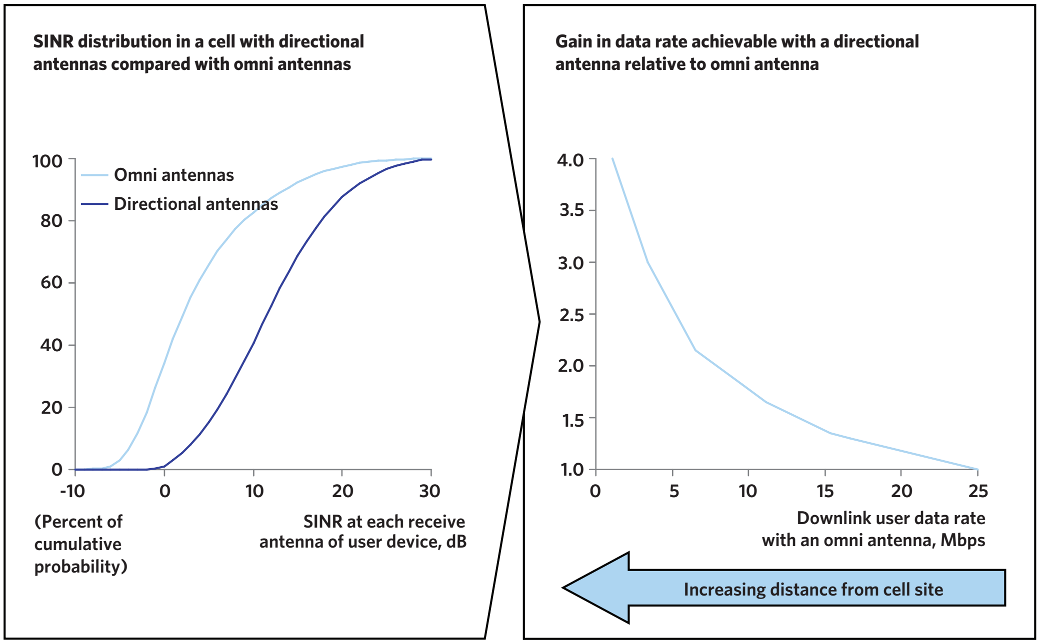
In Exhibit 4-Q, we saw that the capacity of a network with two paired 2x10MHz carriers[50] is twice that of a single 2x10MHz carrier. That should not be surprising. Interestingly, however, the capacity with a single 2x20MHz carrier is 20% higher than with two 2x10MHz carriers.[51] This is, in part, due to the better statistical multiplexing possible with the first option (using the wider carrier). Most of these gains will also be achievable with the second option once carrier/spectrum aggregation is introduced in the LTE standard.

Exhibit 4-S shows the spectrum needs in 2020 and 2030 for *coverage* cell sites in the unserved regions of the United States. Recall that coverage cell sites provide adequate downlink and uplink coverage (i.e., 4 Mbps/1 Mbps downlink/uplink speeds at the cell edge); however, depending on the number of households within the cell site, it may not have enough capacity to meet the traffic needs.

For our baseline model, we assume that 2x20MHz of spectrum is available per cell site. So, as the figure shows, in 2020, 94% of the *coverage* cell sites will also have adequate capacity. The remaining cells need techniques such as cell-splitting or 6-sector cell sites to increase capacity.[52] As the uptake continues to increase, the spectrum needs will also increase, as shown by the chart on the right.

This analysis is based on an average BHOL per subscriber of 160 kbps. Higher data usage than that will indeed increase spectrum needs. Still, the analysis shows that spectrum needs are

Exhibit 4-R: Impact of Directional Antennas at CPE on SINR [53][54]



relatively modest, due to three reasons. First, we used a FWA network, which has higher capacity than a mobile one. Second, the population density in the unserved regions is very low—less than 10 HUs per square mile. Consequently, the number of subscribers per cell site and the traffic demand per cell site are also relatively modest. Finally, the uplink coverage requirement of 1 Mbps resulted in a much higher cell site density than would otherwise be necessary, which further reduced the number of subscribers per cell site.

We end this discussion on spectrum availability by contrasting the difference in impact spectrum has on uplink and downlink dimensioning:

- ➤ In order to achieve a target *uplink* user data rate, we limit the maximum cell radius to ensure sufficient *coverage*. And while propagation characteristics of the spectrum band are important for our calculation of maximum cell radius, spectrum availability has little impact—the uplink signal received at the cell tower, not the availability of spectrum, is the limiting factor.
- ➤ In the *downlink*, on the other hand, we are limited by cell site *capacity*. We can either reduce the cell size to match subscriber demand with capacity, or we can add spectrum to the cell site, because more spectrum implies more capacity. The first option is more expensive, because the incremental cost of using additional spectrum at a cell site is smaller than the construction costs associated with cell-splitting if spectrum is available.

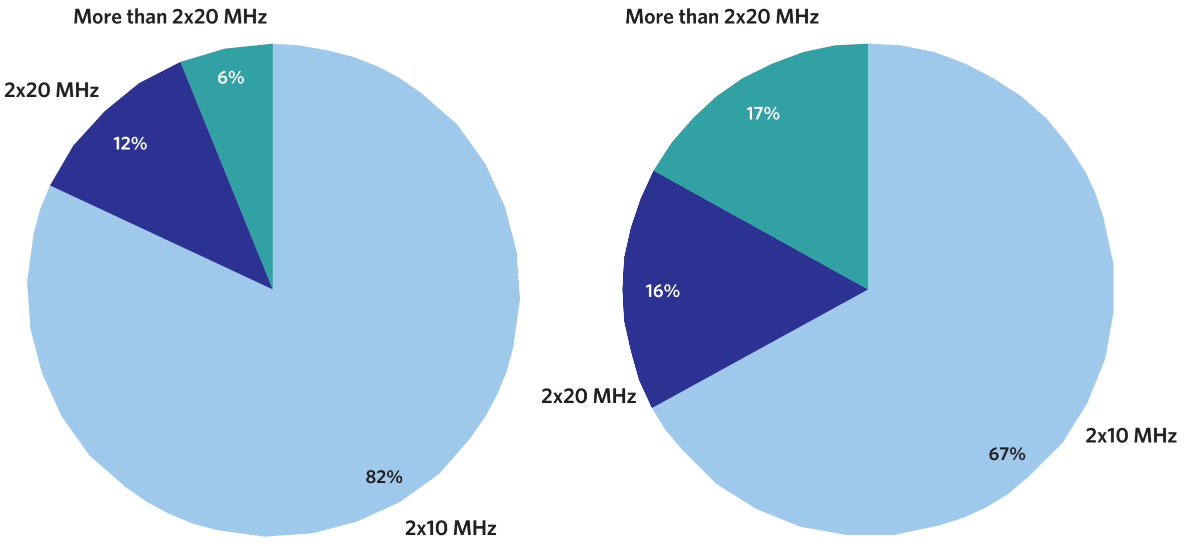
Therefore, the overall impact of spectrum availability on network buildout depends on the evolution of downlink and uplink usage characteristics. Specifically, let us consider two extreme scenarios:

- ➤ **Extreme uplink usage**: If uplink usage were to evolve disproportionately faster than the downlink, then the only way to dimension the network would be to reduce the cell size. In doing so, we reduce the number of subscribers per cell site. That, in turn, automatically reduces the downlink capacity needs per cell site so that spectrum plays a less critical role in the solution.
- ➤ **Extreme downlink usage**: If, on the other hand, downlink usage evolves disproportionately faster than the uplink, then availability of spectrum can significantly mitigate the need for additional cell sites. That, in turn, significantly reduces the cost of network capacity expansion.

Second-Mile Backhaul

A key requirement of wireless broadband networks is high-capacity backhaul, a need that will only grow as end-user speed and effective load grow. Today, even though 97.8%[55] of the U.S. population has 3G coverage, most cell sites are still copper fed. For example, Yankee Group estimates that more than 80% of cell sites are copper fed.[56] Further, Sprint Nextel noted that in its network, "most towers carry between one and three

Exhibit 4-S: Spectrum Needs for Cell Sites in 2020 and 2030, Based on BHOL of 160 kbps



Spectrum needs for cell sites, 2020
Percent of cell sites

Spectrum needs for cell sites, 2030
Percent of cell sites

DS-1s" and that "almost no towers have more than five DS-1s."[57] This is important because copper facilities will have inadequate speeds for a well-subscribed 4G cell site; so, without adequate upgrades, backhaul can quickly become the choke point of the network (see Exhibit 4-T). Additionally, both fiber and microwave avoid some of the reliability problems often found in dealing with copper-based backhaul. Said differently, dimensioning adequate backhaul is one of the key drivers for providing wireless broadband. As shown in Exhibit 4-T, for our purposes we need backhaul capacity that can only be provided by fiber and/or microwave.

In unserved areas, microwave point-to-point backhaul is a potentially attractive alternative to fiber for providing second-mile capacity at substantial cost savings relative to fiber. We assume that microwave allows high-capacity connectivity at a lower price by bypassing the need for a direct aerial or trench-based connection. For instance, a microwave link can provide speeds of up to 500 Mbps over a distance of 20 miles[58] at a typical equipment cost of roughly $50,000.[59]

By contrast, costs of new fiber construction depend heavily on the distance to an existing fiber network and whether the area has aerial plant available for connection. Costs can range from approximately $11,000 to $24,000 per mile for aerial construction and roughly $25,000 to $165,000 per mile for buried construction.[60] Many providers may prefer fiber regardless of the cost, especially in denser areas, because of its ability to provide higher capacity per link and its inherent reliability.

Overall, when compared with new fiber construction, and even with leased Ethernet links, microwave links can have a lower total cost for link distances greater than 1-2 miles.[61]

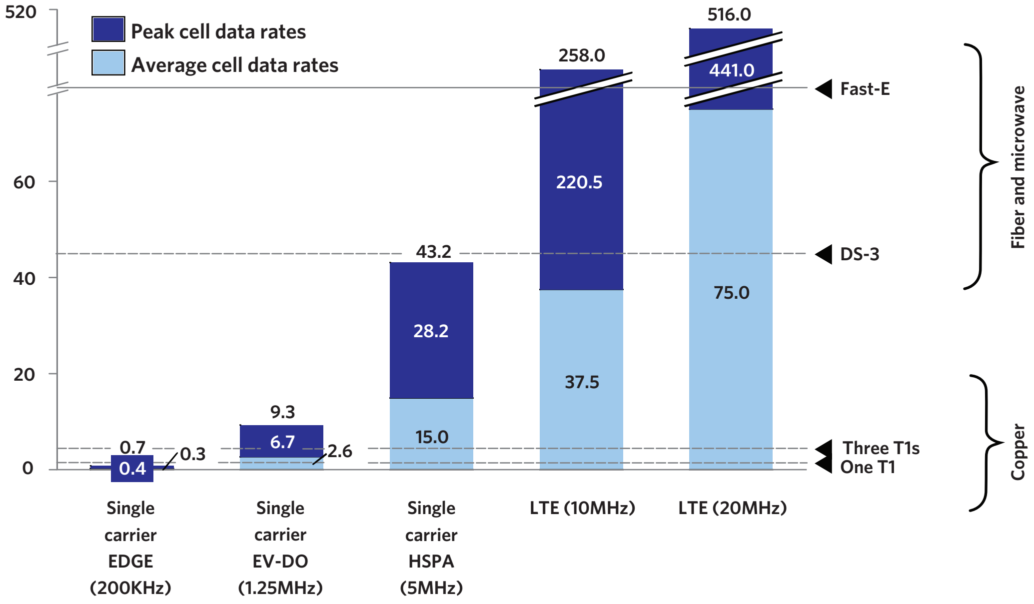
Ethernet over Copper (EoC) may also be part of the 4G-backhaul solution. We did not include EoC in our 4G-backhaul calculations for several reasons: first, as noted above, there is often a limited amount of copper available; second, the quality of that copper over the multi-mile distances in rural areas is unknown; and third, for new cell-site construction, where there are no existing backhaul facilities, carriers are likely to install fiber or rely on microwave.

Hybrid Fiber Microwave (HFM) backhaul architecture

Since microwave can be a cost-effective substitute for fiber, a Hybrid Fiber Microwave (HFM) backhaul architecture would yield significant cost savings in wireless networks relative to an all fiber network (see Exhibit 4-U). Specifically, as illustrated in the exhibit, in an HFM architecture some cell sites rely on microwave for backhaul, and only few cell sites are fiber-fed. The fiber-fed sites serve as backhaul "aggregation points" for the remaining cell sites. These remaining sites connect to the fiber-fed aggregation points using microwave links, sometimes using more than one microwave hop. For example, Cell site 3 is fiber fed, serving as an aggregation point for the backhaul needs of Cell sites 1 and 2. Further, Cell site 2 connects to Cell site 3 using one microwave hop, while Cell site 1 connects using two (via Cell site 2). Such HFM architectures are already being used by wireless service providers such as Clearwire, for example.[62]

Even though the microwave links now have reliability comparable with their wireline counterparts, an HFM network that uses a large number of hops can lead to concerns about

Exhibit 4-T:
Average and Peak Capacity of a 3-Sector Cell Site Relative to Backhaul Speeds, Mbps



reliability. To see this, observe in Exhibit 4-U that the loss of the microwave link between Cell sites 2 and 3 will also result in the loss of backhaul connectivity for Cell site 1. If each of these cell sites had a radius of 5 miles, then as much as 150 square miles would lose coverage through the loss of the single link. Clearly, then, this cascading effect can become particularly pronounced in a network that has a large number of hops. On the other hand, the more hops, the greater the potential for second-mile cost savings.

Our baseline model for FWA uses an HFM architecture with a maximum of four microwave hops.

In unserved areas, an HFM second-mile network architecture has cost advantages over a fiber-only network architecture. Microwave backhaul has two additional benefits, especially to service providers who do not already own fiber middle-mile backhaul assets. First, microwave can often be deployed faster than fiber. Second, in many territories, the owner of wired backhaul facilities could be a competitor in providing wireless service. In such cases, microwave backhaul offers an effective alternative to paying competitors for backhaul service.

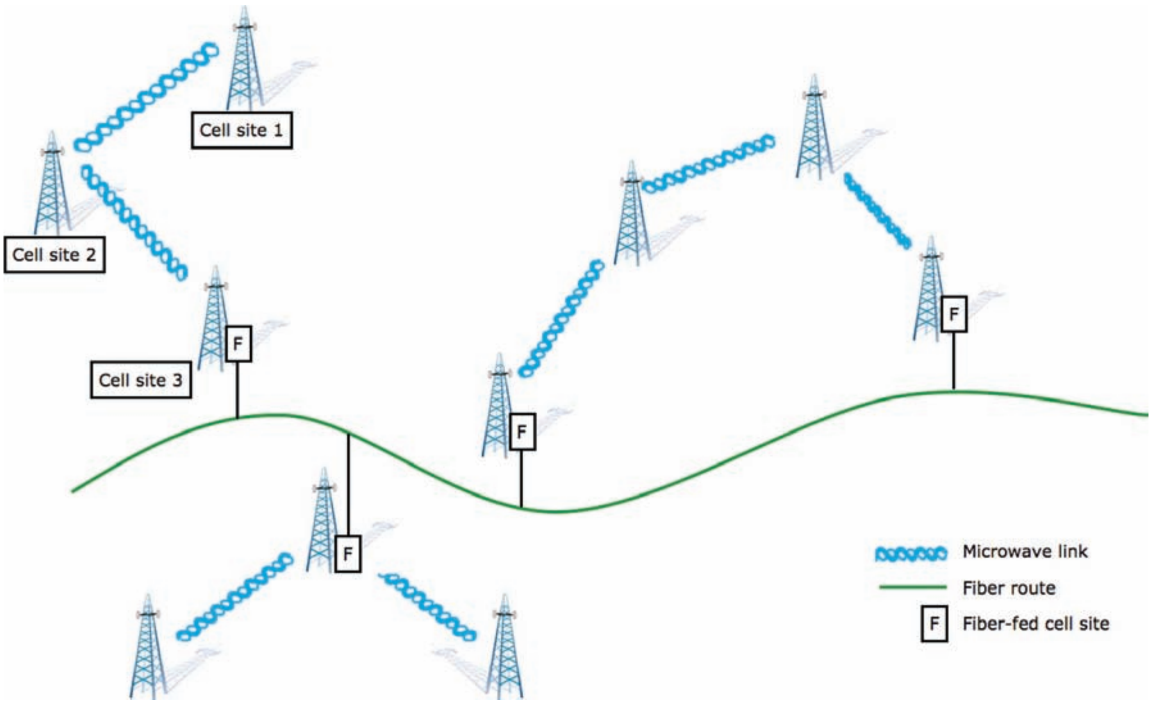
However, microwave backhaul also has two significant limitations. First, as noted earlier, microwave links have capacity limitations and cannot be used for very high-speed backhaul needs. Further, higher data rates require more spectrum. Since there is only a limited amount of spectrum available, carriers can only have a limited number of high-speed microwave links in a geographical area. Note that the NBP had a series of recommendations related to improving point-to-point backhaul solutions in Chapter 5.

The second limitation is a requirement for line of sight from one microwave tower to the next. In hilly or mountainous terrain, this may mean that a provider needs to add additional microwave relays even beyond the reduction in cell size described above, adding to costs. It may be the case that the same terrain issues drive up fiber costs as well, perhaps even more quickly, so this will not necessarily tip the balance toward fiber. But it will likely drive up backhaul costs overall. Further, in some cases the tower may need structural reinforcements to support a microwave antenna, which will drive up the cost of microwave installation.

So, even though an HFM architecture has significant cost advantages, fiber is expected to be the primary backhaul choice for service providers because it offers a scalable, future-proof backhaul solution.

Finally, a fiber-only architecture has one significant strategic advantage. As broadband needs continue to grow, fiber emerges as the only last-mile technology capable of meeting ultra high-speed needs. So, any solution that brings fiber closer to the home by pushing it deeper into the network puts into place an infrastructure that has long-term strategic benefits. On balance, therefore, we need to weigh this strategic benefit against the higher associated cost to evaluate the value of a fiber-only architecture over an HFM architecture.

Exhibit 4-U: Hybrid Fiber Microwave Backhaul Architecture for Cellular Networks



Economics of a Wireless Network

Exhibit 4-V shows the network elements that we modeled for FWA network cost analysis (see also Exhibit 4-A above). Specifically, in the last mile—the link from the cell site to the end-user—we model installation and operations costs, as appropriate, for the tower infrastructure, Radio Access Network (RAN) and other ancillary[63] equipment. We also account for the cost of the end-user CPE. In the second mile, which is the backhaul connection from the cell site to the second point of aggregation in the exhibit, we model the costs of installing microwave equipment and new fiber, as needed; see the Section on Middle Mile for details on backhaul network architecture.

Our network model, as shown in Exhibit 4-V, shows that the Investment Gap when using FWA networks in the 700MHz band for providing broadband to the unserved population in the United States is $12.9 billion (Exhibit 4-W). This funding gap is for the wireless buildout *only* and is not driven by the second least-expensive of a mix of technologies. For more details on our overall network modeling assumptions and principles, see **Creating the Base-case Scenario and Output** above.

Dependence on terrain type

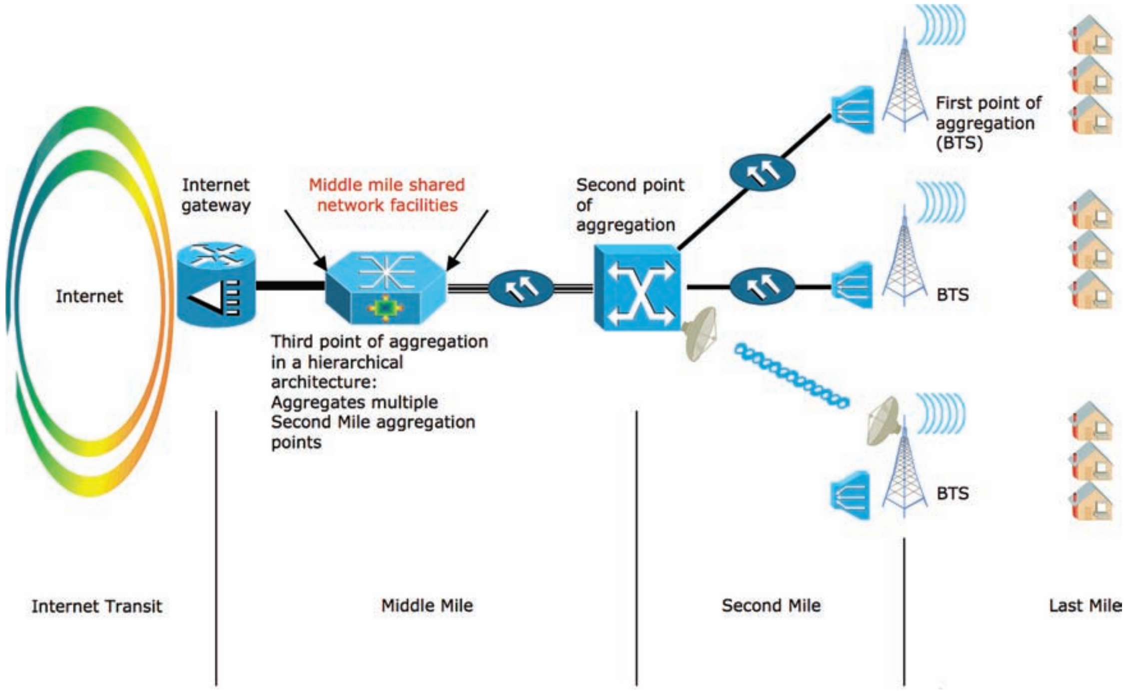
Recall that for our network model, we classify terrain into four types, choosing a different maximum cell radius for each. Exhibit 4-X shows the average investment (i.e. capex) per housing unit (HU) and Investment Gap per HU based on the underlying cell radius required. The smaller cell radii correspond to counties that are mountainous/hilly.

The exhibit shows that the cost of serving HUs in hilly terrain can be as much as 30 times higher on average than in flatter areas. This is in part due to the fact that smaller cell radii in hilly terrain mean that we need more cell sites, thereby driving up the cost; and, in part due to the fact that HU density is also lower in hilly areas. [64]

Our classification of terrain in Exhibit 4-K is based on a statistical analysis of terrain variation data. It is likely that in some instances our method will misclassify a census tract (CT). The only way to get an extremely accurate estimate of cell radius is to actually do a RF propagation analysis for each CT using tools such as those provided by EDX Wireless. That is extremely time-consuming and expensive. To range the impact of misclassification, we analyze the sensitivity of buildout costs and the investment gap to our terrain classification parameters.

Exhibit 4-Y illustrates the results from our sensitivity analysis. In addition to the FWA buildout costs and the FWA investment gap, we also show the overall investment gap for bringing broadband to the unserved using a mix of technologies. Note that the impact on the overall investment gap is less than 10%. This is because the overall investment gap is driven by the second least-expensive technology. More specifically, we find that the percentage of unserved HUs served by wireless drops from 89.9% in the baseline to 89.1% with the "very mountainous" classification in parameter C, thus explaining the relatively small impact terrain classification has on the overall investment gap.

Exhibit 4-V:
Illustrative Wireless Network Architecture



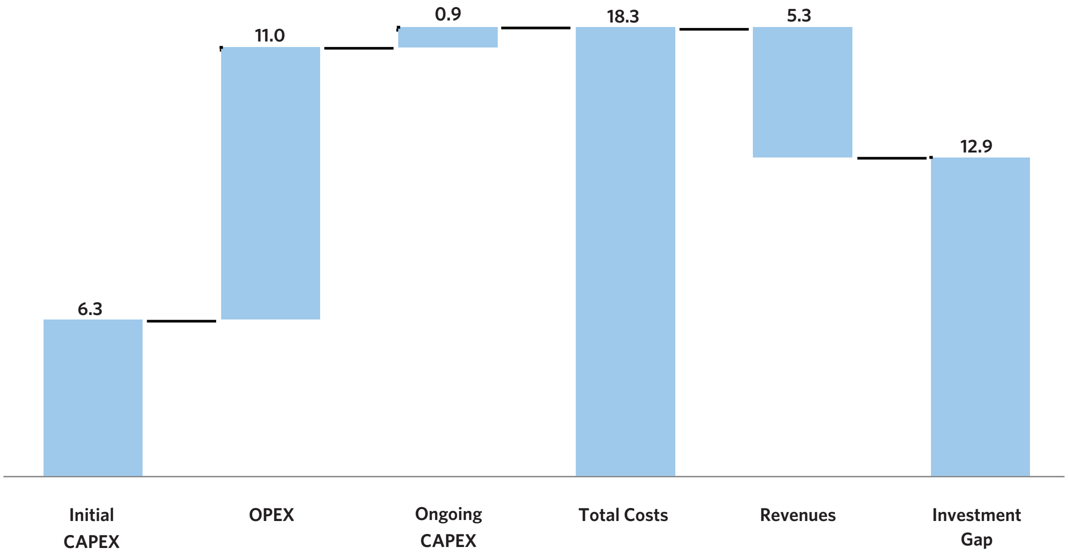
Dependence on downlink capacity

Since LTE is not commercially deployed yet, it is conceivable that actual downlink spectral efficiency and, consequently, subscriber capacity differ from that simulated. So, we analyze the dependence of wireless buildout costs and the investment gap to our subscriber capacity estimates as shown in Exhibit 4-Z. We note that the impact on costs as well as Investment Gap is negligible. Consequently, the impact on the overall Investment Gap—as determined by the cost of the second least-expensive network—is also small (not shown in chart).

Dependence on spectrum

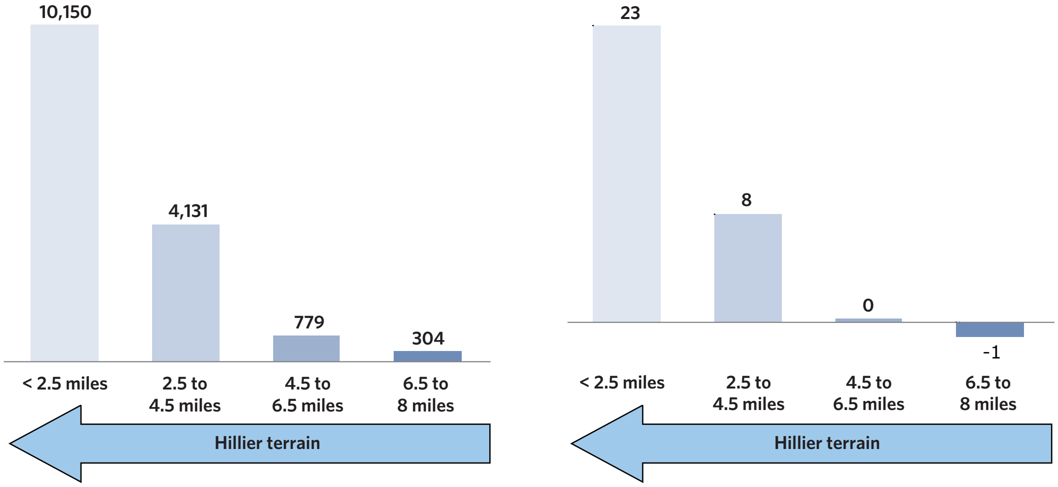
Our baseline model assumes a network deployment in the 700 MHz band. If, instead, we deploy the network in the PCS band, the

Exhibit 4-W:
Investment Gap for Wireless Networks



(in billions of USD, present value)

Exhibit 4-X:
Total Investment per Housing Unit (HU) and Investment Gap per HU by Cell Size



Total initial investment per HU by cell radii

(USD, present value)

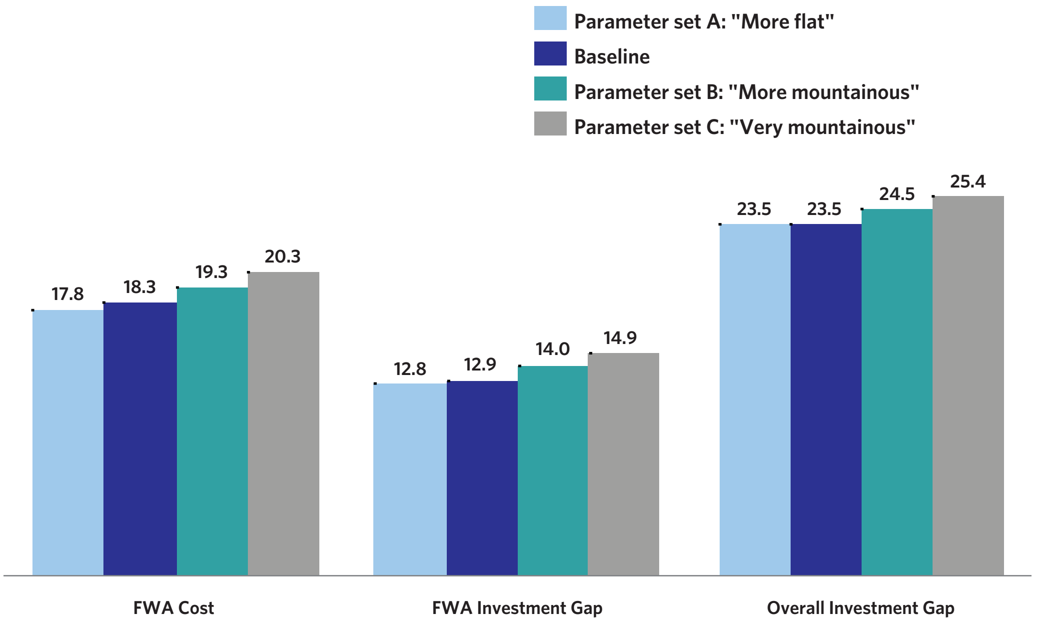
Investment Gap per HU by cell radii

(in thousands of USD, present value)

total cost of the FW deployment in counties with negative NPV is 96% greater. Further, the FW investment gap is 90% more. Note that this is a comparison of the FW investment gap only and not that of the overall investment gap. For this analysis, we use the following maximum cell radius for each of the four terrain types.[65]

Terrain classification	Maximum cell radius (miles)
Flat	5
Rolling hills	3
Hilly and Mountainous	2

Exhibit 4-Y:
Sensitivity of Investment Gap to Terrain Classification—Change in Costs and Investment Gap by Changing Terrain Classification[66]



(in billions of USD, present value)

Terrain type	Classification parameters based on Standard Deviation of elevation of CTs			
	Baseline	Parameter set A	Parameter set B	Parameter set C
Flat	≤ 20	≤ 25	≤ 20	≤ 20
Rolling hills	20 to 125	25 to 125	20 to 125	20 to 125
Hilly	125 to 350	125 to 350	125 to 300	125 to 250
Mountainous	≥ 350	≥ 350	≥ 300	≥ 250

Cost and gap shown for counties that have a negative NPV. The baseline classification is based on parameters in Exhibit 4-K. The remaining parameter sets alter the classification of flat and hilly terrains, as shown below. We highlight the changes in the parameters from the baseline for convenience.

Our baseline also assumes 2x20 MHz of spectrum availability. Exhibit 4-AA shows the economic impact of spectrum availability assumptions. Note that the lack of spectrum increases the cost of the buildout in unserved areas by nearly 5%. The cost impact is relatively small because 2x10 MHz of spectrum is sufficient for 82% of the cell sites (see Exhibit 4-S). The cost impact in areas with negative NPV is even smaller (less than 3%). This is because the cell sites in these areas are typically smaller, so that they also have fewer HUs in them (see Exhibit 4-X for the impact of cell radius on the Investment Gap), which reduces the spectrum needs for the cell sites. Consequently, the impact on the Investment Gap in these areas is also small.

We have not yet addressed the fact that no U.S. service provider currently has more than 2x10MHz of contiguous spectrum in the 700MHz band. But both Verizon Wireless and AT&T Wireless do have noncontiguous spectrum holdings of over 2x20MHz of spectrum across different bands. However, these bands will not all have similar propagation characteristics.

A common deployment strategy used in such situations is to use the lower frequency bands with superior propagation characteristics to serve households further away from the cell site. The higher frequency bands, which can have superior capacity through the use of MIMO techniques, are then reserved for serving those closer to the cell site. This ensures that each available spectrum band is efficiently used.

Cost per cell site

Exhibit 4-AB shows a cost breakdown of a wireless network for all unserved areas. Note that the cost of the network is dominated by last-mile and second-mile costs, which we shall refer

Exhibit 4-Z:
Sensitivity of Costs and Investment Gap to Subscriber Capacity Assumptions—Change in Costs and Investment Gap Under Different Downlink Capacity Assumptions

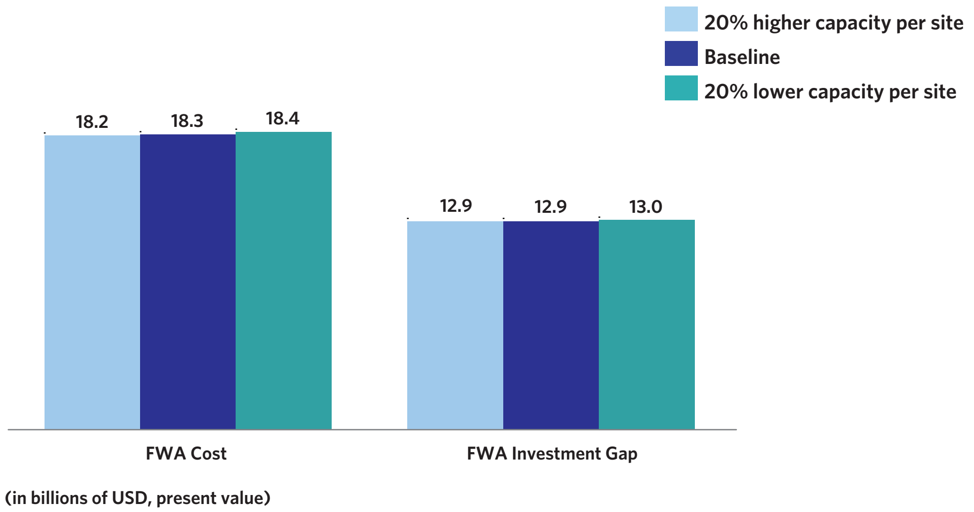
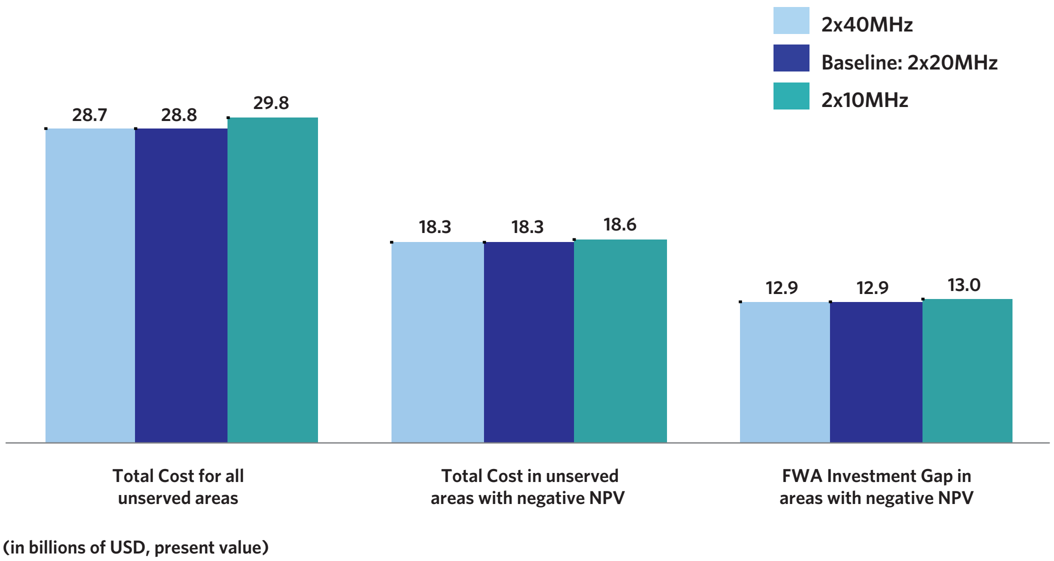


Exhibit 4-AA:
Impact of Spectrum Availability on FWA Economics—Change in FWA Costs and Investment Gap Under Different Spectrum Availability Assumptions



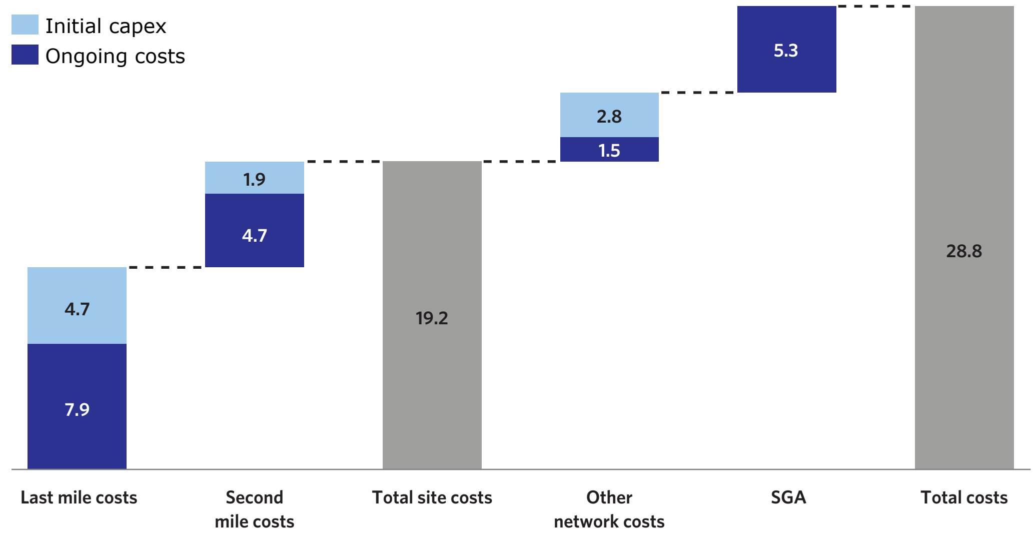
to as simply *site costs*; these account for more than 67% of the total costs. Exhibit 4-AC shows that tower construction/lease and second-mile backhaul costs constitute 68% of the cost of deploying, operating and maintaining a cell site.

Tower construction/lease costs comprise 34% of site costs. To model site costs appropriately, we create one set of hexagonal cells that cover the entire country for each analyzed cell-size (2, 3, 5 and 8 miles). These hexagonal cells represent the wireless cells. Each cell needs to contain at least one tower. To account for the fact that existing services imply existing towers, we turn to several data sources. First, we used the Tower Maps data set of tower locations.[67] For cells that do not include a tower site in that data set, we used 2G and 3G coverage as a likely indicator of cell site availability. Specifically, we assumed that the likelihood of a tower's presence is half the 2G/3G coverage in the hexagonal cell area. For example, a cell that is fully covered by 2G/3G service has only a 50% chance of having a tower site. In areas without a tower, we assume that a new tower needs to be constructed 52.5% of the time;[68] the remainder of the time we assume a cell site can be located on an existing structure (e.g., a grain silo or a church steeple).

In practice, the cost of deploying a wireless network in an area without any wireless coverage today should be higher because of the likely absence of any existing wireless network infrastructure that the provider can leverage. And, with our assumptions above, we capture that effect.

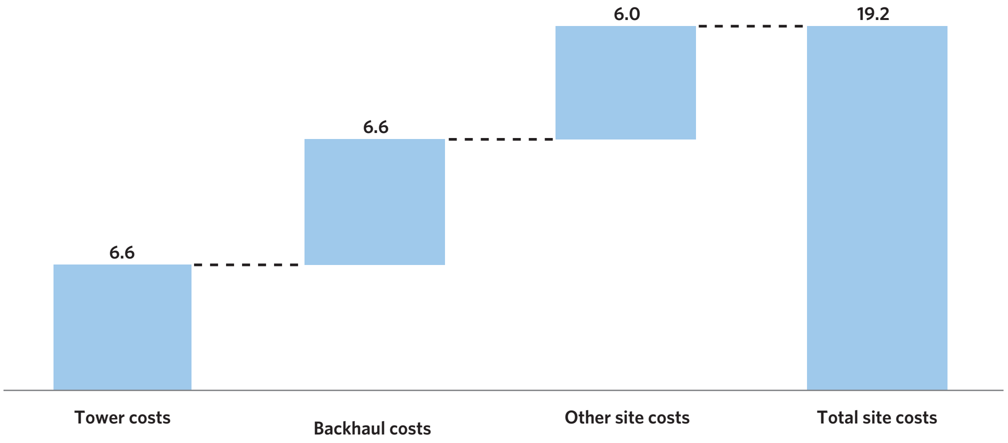
Our cost assumptions in the model indicate that the total 20-year cost of constructing and maintaining a tower is $350K to $450K. By comparison, the total cost of co-locating on an existing structure is only $165K to $250K. Further, our model

Exhibit 4-AB:
Cost Breakdown of Wireless Network Over 20 Years [69]



(in billions of USD, present value)

Exhibit 4-AC:
Breakdown of Total Site Costs for Wireless Network in Unserved Areas



(in billions of USD, present value)

shows that new tower construction is necessary around 15% of the time.

Second-mile backhaul

Our baseline model for the FWA network uses a Hybrid Fiber Microwave (HFM) backhaul architecture with limited microwave penetration. Specifically, we allow a maximum of four hops. Recall that a network architecture that allows a deeper microwave penetration will reduce network costs at the expense of a possible reduction in reliability. Recognizing this trade-off between reliability and cost, we analyze how a restriction on the number of hops affects the cost of the FW buildout and the investment gap. Specifically, we analyze two HFM architectures and compare them with a fiber-only network: (1) Very limited microwave penetration: an HFM network where we allow a maximum of four hops; and (2) Moderate microwave penetration: an HFM network where we allow a maximum of four hops.

In each scenario, we constrained the capacity of the microwave link to 300 Mbps. That limits our ability to daisy-chain microwave links, because the cumulative backhaul needs of all cell sites upstream of a link in the chain cannot exceed the capacity of that link. For example, returning to Exhibit 4-U, the capacity of the link between Cell sites 2 and 3 must be greater than the cumulative backhaul needs of Cell sites 1 and 2; otherwise, one of Cell sites 1 or 2 will require a fiber connection.

Exhibit 4-AD compares the initial investment for the three scenarios. We note that the cost of limiting the number of hops is small—less than 5% when we limit it to two instead of four. This is because most of the unserved regions do not constitute large contiguous areas and can, therefore, be served using a small cluster of cell sites. As a result, the limitation does not severely impact cost. In fact, in the scenario where we allow deep microwave penetration, more than 85% of the cell sites using microwave backhaul connect to a fiber-fed cell site in two or fewer hops.

Exhibit 4-AD:
Cost of an HFM Second-Mile Backhaul Architecture—Initial Investment with Different Second-Mile Backhaul Network Architectures

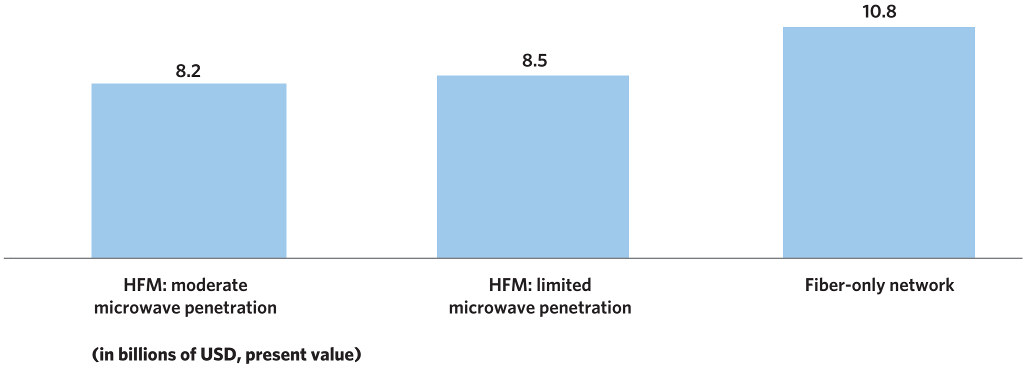


Exhibit 4-AE:
Cost Assumptions and Data Sources for Wireless Modeling

Parameter	Source and comments
Tower construction	Mobile Satellite Ventures filing under Protective Order
BTS	Mobile Satellite Ventures filing under Protective Order
Ancillary Radio Access Network	Mobile Satellite Ventures filing under Protective Order
Core network equipment	Mobile Satellite Ventures filing under Protective Order
Site operations	Mobile Satellite Ventures filing under Protective Order
Land Cover	http://www.landcover.org/data/landcover/ (last accessed Feb. 2010) Summary File 1, US Census 2000
Elevation	NOAA GLOBE system http://www.ngdc.noaa.gov/mgg/topo/gltiles.html (last accessed Feb. 2010)
Microwave radio	Dragonwave
Microwave operations	Level-(3) filing under Protective Order
Fiber installation, equipment, operations and maintenance	See cost assumptions for FTTP
Wireless CPE	Based on online price information available for different manufacturers

Conclusions

In order to engineer a wireless network to provide a service consistent with the National Broadband Availability Target, we use the uplink speed target and supplement it with terrain data to compute a maximum cell radius for four different terrain types. In the downlink, we calculate a maximum subscriber capacity per cell site.

A significant driver of variation in per site costs is tower availability and backhaul costs. For backhaul, a Hybrid Fiber Microwave (HFM) architecture results in a lower cost; but a fiber-only network does have the benefit of deeper fiber penetration.

Next, we conduct a sensitivity analysis of our model parameters and assumptions. Not surprisingly, spectrum availability and spectrum bands can have a significant impact on the cost the FWA network as well as the investment gap.

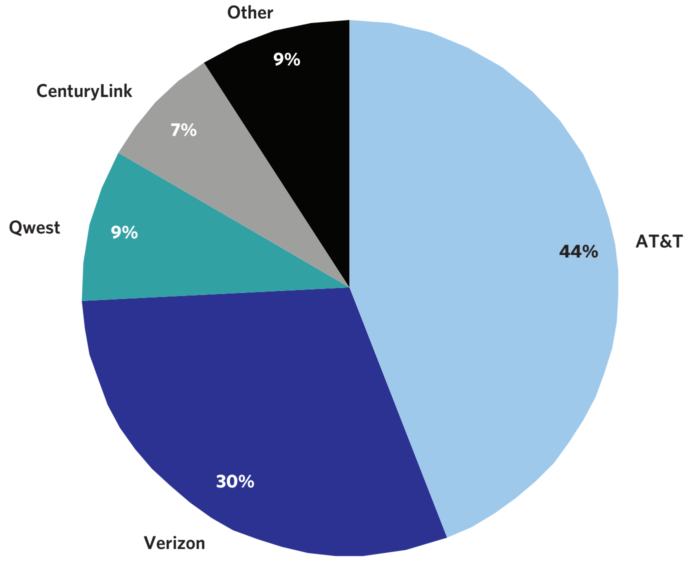
12,000-foot-loop DSL (Digital Subscriber Line)

Telephone networks have traditionally been two-way (or duplex) networks, arranged in a hub-and-spoke architecture and designed to let users make and receive telephone calls. Telephone networks are ubiquitous in rural areas, in part because local carriers have had the obligation to serve all households in their geographic area; this is known as the carrier-of-last-resort obligation. In addition, some telephone companies have historically relied upon implicit subsidies at both the federal and state levels to provide phone service. More recently, they have received explicit financial support through the federal Universal Service Fund (USF). The USF was designed to ensure that all households have access to telephone service at rates that are reasonably comparable to urban rates.

Thousands of independent telephone companies provided service in local markets. But when the telephone network was originally constructed, a single operator, AT&T, dominated it. In 1984, AT&T divested its access network into seven Regional Bell Operating Companies (RBOCs). Over time, the original seven RBOCs have consolidated into three: AT&T (formerly Southwestern Bell, Pacific Telesis, Ameritech, BellSouth and non-RBOC SNET), Verizon (formerly NYNEX, Bell Atlantic and non-RBOC GTE) and Qwest (formerly US WEST).

Exhibit 4-AF:

Breakout of Voice Line Ownership — Telco Consumer Telephone Access Lines Market Share (3Q 2009)[70]



Percent of United States lines

Numbers do not sum to 100% due to rounding.

Consolidation has occurred among smaller Incumbent Local Exchange Carriers (ILECs) as well, with many of them consolidating into CenturyLink, Windstream, Frontier and Fairpoint. Yet well over a thousand small ILECs remain. Today, there are more than 1,311 Telco operators,[71] but the three RBOCs own 83% of voice lines.[72] See Exhibit 4-AF.

The evolution of modern telephone company networks has required significant investments in network capabilities in order to offer broadband access. In the late 19th and early 20th centuries, these networks were built for plain old telephone service (POTS), which provides basic voice service between users over twisted-pair copper wires. These wires, or “loops,” were installed between the home and the telephone exchange office via an underground conduit or telephone poles. The basic telephone network architecture and service, originally designed for two-way, low frequency (~4 kilohertz, or kHz), all-analog transmissions with just enough capacity to carry a single voice conversation, are still used today by most homes and businesses. In fact, this network is the basis for the high-speed broadband service known as Digital Subscriber Line (DSL) offered by telecommunications companies.

With the advent of the modem, telephone networks were the first networks to provide Internet access. After all, millions of homes were already “wired” with twisted-pair copper lines that provided POTS. Initially, dial-up Internet used the same analog network designed for voice to deliver Internet access at speeds of up to 56 kilobits-per-second (kbps). To offer high-speed access, the network needed to be reengineered to handle digital communications signals and upgraded to handle the tremendous capacity needed for broadband data and broadcast transmissions. Although twisted-pair copper cables are capable of carrying high-capacity digital signals, the network was not optimized to do so. The large distance between a typical home and telephone exchange offices, as well as the lack of high-speed digital electronics, stood in the way of broadband deployments.

Steps to upgrade telephone networks for broadband:

- Invest in fiber optic cable and optic/electronics to replace and upgrade large portions of the copper facilities for capacity purposes
- Replace and redesign copper distribution architecture within communities to “shorten” the copper loops between homes and telephone exchanges
- Deploy new equipment in the exchanges as well as the homes (DSL equipment) to support the high capacity demands of DSL and broadband
- Develop the technology and equipment necessary for sophisticated network management and control systems

- Implement back-office, billing and customer service platforms necessary to provide the services common among telephone operators today

DSL provided over loops of 12,000 feet (12 kft) is a cost-effective solution for providing broadband services in low-density areas. In fact, it is the lowest cost solution for 10% of the unserved housing units. DSL over 12 kft loops meets the broadband target of a minimum speed threshold of 4 Mbps downstream and 1 Mbps upstream, and the backhaul can easily be dimensioned to meet the BHOL per user of 160 kbps.[73] Since DSL is deployed over the same existing twisted-pair copper network used to deliver telephone service, it benefits from sunk costs incurred when first deploying the telephone network.

Capabilities

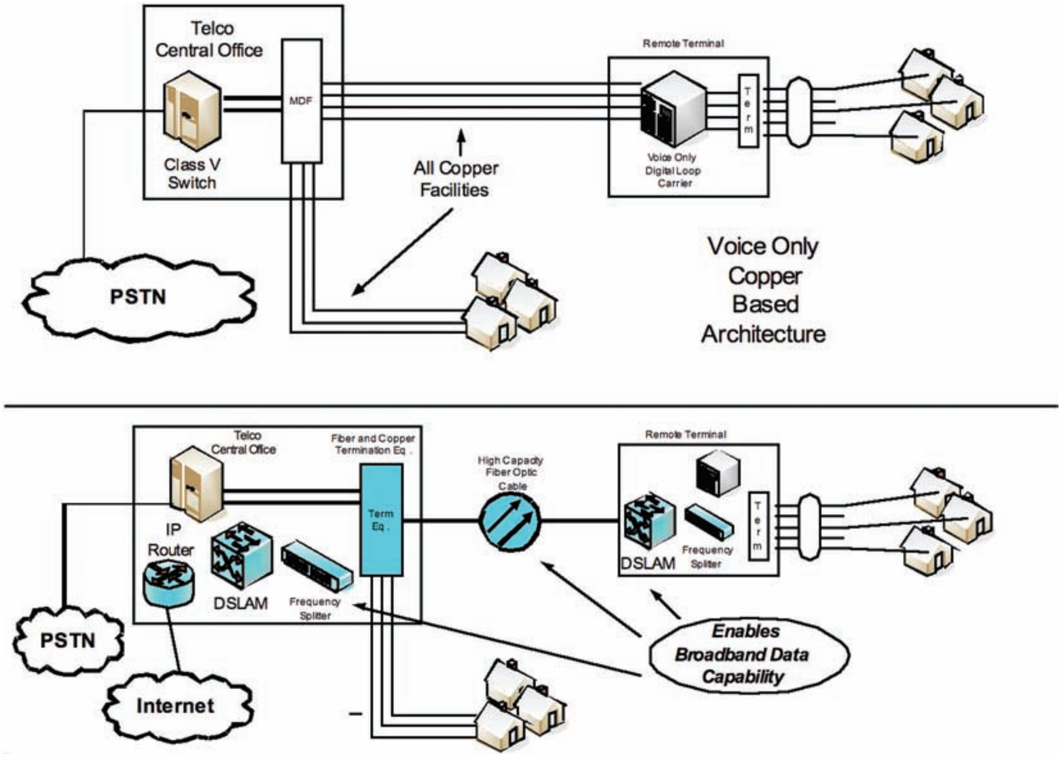
DSL over loops of 12,000 feet typically uses ADSL2/ADSL2+ technology, which was first standardized in 2005 and which uses frequencies up to 2.2 MHz. As ADSL2+ over 24AWG gauge wire provides rates of 6 Mbps downstream and 1 Mbps upstream, the technology meets the speed requirements for broadband service of 4 Mbps down and 1 Mbps up. Figure 4-AH illustrates how loop length affects speed for ADSL2+.

The technology can perform 1 Mbps upstream on 12 kft of 24 AWG twisted-pair copper loops.[74] In this case, 24 AWG wire is assumed with no bridged taps. Performance with 22 AWG wire, which is often used in rural areas, would yield higher bitrates, while use of 26 AWG wire would yield lower rates.

In order to provide faster speeds than those listed above, DSL operators can bond loops and continue to shorten loop lengths. The bonding of loops can be used to multiply the speeds by the number of loops to deliver rates over 30 Mbps if sufficient numbers of copper loops are available. [75] The performance improvements that can be achieved by shortening loops from 12 kft to 5,000 feet or 3,000 feet and replacing existing technology with VDSL2 are discussed in the DSL 3-5 kft section below. Shortening loops requires driving fiber closer to the end-user; while costly, it could provide much faster speeds that could serve as an interim step for future fiber-to-the-premises (FTTP) deployments. Investment in 12 kft DSL ,therefore, provides a path to future upgrades, whether the upgrade is to 5 kft or 3 kft loops or FTTP.

For the small-to-medium enterprise business community, copper remains a critical component in the delivery of broadband. Ethernet over Copper (EoC), often based on the G.SHDL standard, is a technology that makes use of existing copper facilities by bonding multiple copper pairs electronically. EoC can provide speeds between 5.7 Mbps on a single copper pair

Exhibit 4-AG:
Telco-Plant Upgrades to Support Broadband



and scale up to 45 Mbps, or potentially higher, by bonding multiple copper pairs. Though middle and second mile connectivity of 100 Mbps is likely necessary, bonded EoC technology can serve as a useful and cost-effective bridge in many areas. Moreover, the embedded base of copper plant is vast—one market study shows that more than 86% of businesses today are still served by copper.[76] Although service providers may prefer to deploy fiber for new builds, existing copper likely will be part of the overall broadband solution, particularly for last- and second-mile applications, for the next several years.

In addition to bonding and loop shortening, marginal speed improvements and increased stability of service levels with ADSL2+ can be achieved through the use of Level 1 dynamic spectrum management (DSM-1).[77] DSM-1 is physical layer network management software that enables reliable fault diagnosis on DSL service. This advancement is available today and may increase bit-rates by up to 10% on ADSL2+.[78] Additionally, DSM-1 helps to ensure stability and consistency of service such that carriers can reach the theoretical 4 Mbps even at high take rates within a copper-wire binder.

We model a 12 kft DSL network that meets the speed and capacity requirements defined in the discussion of 4Mbps downstream requirement in Chapter 3. As outlined in the network design considerations below, we note network sharing in DSL networks does not start until the second mile. The modeled ADSL2+ technology exceeds the speed requirement and includes costs associated with loop conditioning when appropriate. In addition, the modeled build ensures that second and middle-mile aggregation points are connected to the Internet backbone with fiber that can support capacity requirements.

A fundamental operational principle for DSL is that all of the bandwidth provisioned on the last-mile connection for a given end-user is dedicated to that end-user. Unlike HFC, Fixed Wireless, and PON, where the RF spectrum is shared among multiple users of that spectrum and thus subject to contention among them, the last-mile DSL frequency modulated onto the dedicated copper loop and associated bandwidth are dedicated. Sharing or contention with other users on the network does not occur until closer toward the core of the network, in the second and middle mile, where traffic is aggregated (see Exhibit 4-AI). This second- and middle-mile network sharing still occurs in all other access network technologies as well. The “sharing” concept is introduced in detail in the capacity planning discussion in the Network Dimensioning section below.

The ADSL 2+ standard is widely deployed today in telco DSL networks and is assumed to be the minimum required to achieve 4 Mbps downstream and 1 Mbps upstream. The last mile access network ADSL2+ is defined in ITU-T Recommendation G.992.5[11]. The technology provides rates of 6 Mbps downstream and 1 Mbps upstream on the longest loops of a Carrier Serving Area (CSA) (3.7 km or 12 kft of 24 AWG twisted-pair copper loop), with much higher rates attainable on shorter loops.[79]

We perform our analysis and cost calculations based upon a maximum 12 kft properly conditioned copper loop. Loop conditioning costs are applied to those loops that have never been conditioned to offer DSL. For example, if the statistical model showed any DSL speeds for a given census block, we do not apply the loop-conditioning cost since we assume it had already occurred. We believe that only about 1 million homes nationwide have DSL available at a speed below the 4 Mbps

Exhibit 4-AH: Downstream Speed of a Single ADSL2+ Line as a Function of Loop Length[80] (24 AWG)

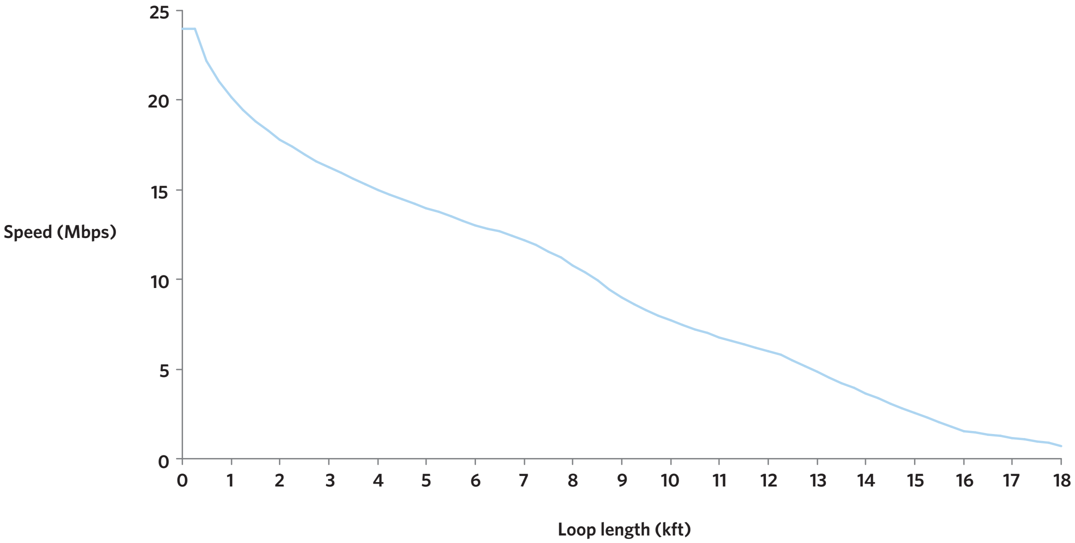


Exhibit 4-AI:
DSL Network Diagram

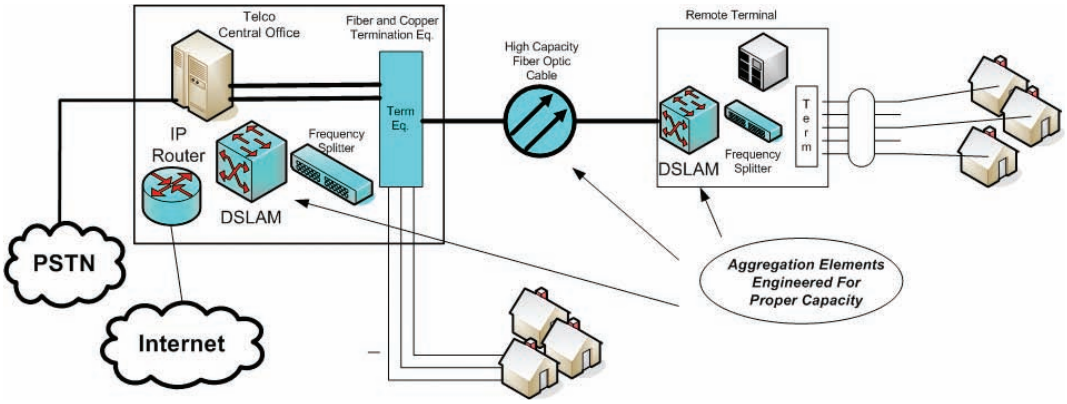
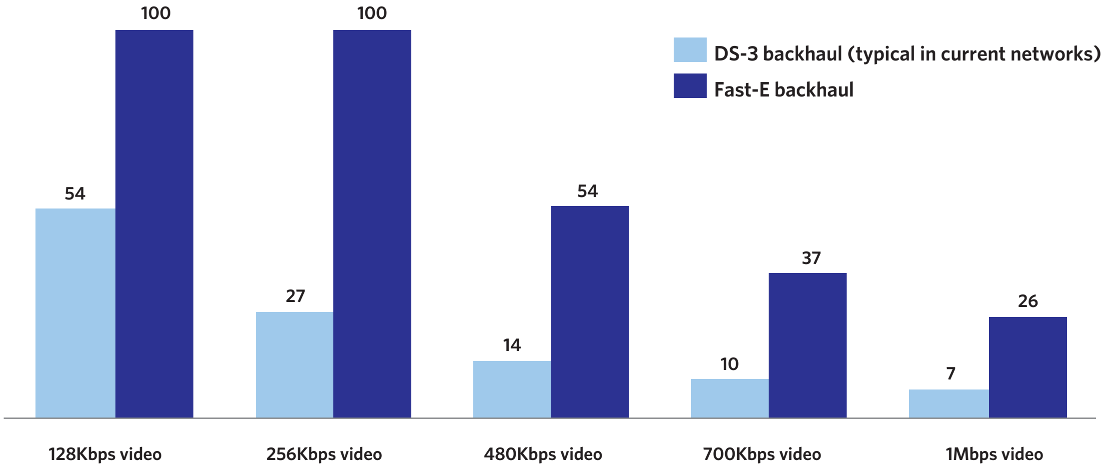
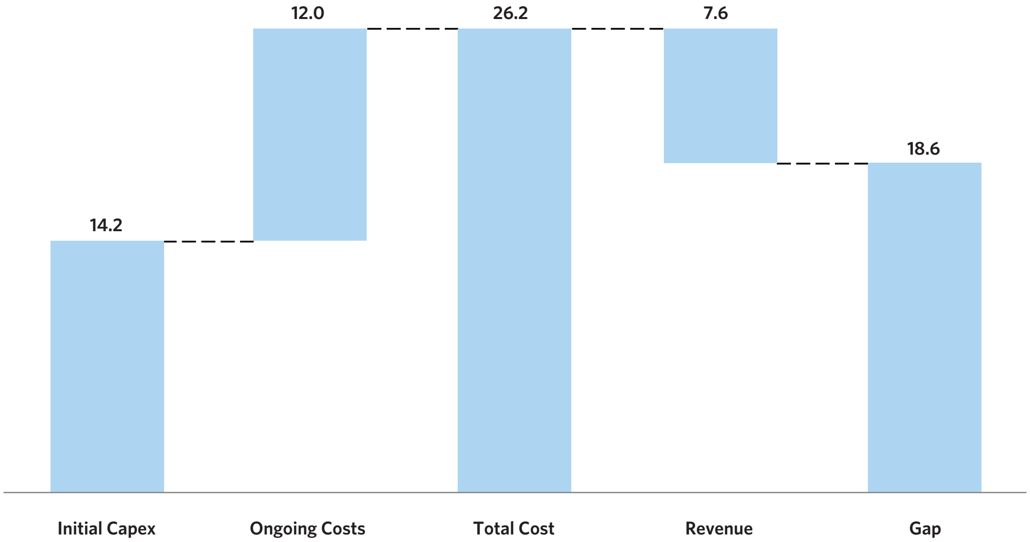


Exhibit 4-AJ:
Capacity of a DSL Network—Simultaneous Streams of Video in a DSL Network[81][82]



Percent of subscribers, 100% = 384

Exhibit 4-AK:
Economic Breakdown of 12,000-foot DSL



(in billions of USD, present value)

target speed. In the remaining areas, comprising about 6 million housing units, the model includes loop-conditioning costs.

We model the ADSL2+ access network such that DSLAMs are connected to the central office and other middle- and second-mile aggregation points using fiber optic-based Ethernet technology that provides backhaul capacities more than sufficient to meet a 4 Mbps down and 1 Mbps up end-user requirement. Moreover, we calculate the estimated average BHOL per user to be 160 kbps. A typical DSLAM serves between 24-384 subscribers. Since Ethernet-based backhaul provides a minimum of 100 Mbps (a.k.a. Fast-E) bandwidth, scaling to as much as 1 Gbps (a.k.a. Gig-E), the middle- or second-mile aggregation point has sufficient backhaul capacity required to support 4 Mbps down and 1 Mbps up. The resulting capacity of such a DSL network dimensioned with a Fast-E backhaul is shown in Exhibit 4-AJ.

In a DSL network with fewer subscribers, as will be the case in rural areas with low population density, the fraction of users who could simultaneously enjoy video streams of a given data rate would go up proportionately. The dimensioning discussed above is in contrast to the capacity of the network with conventional backhaul provisioning of ~1 Mbps in the shared portions of the network for every 14.5 users.[83]

Economics

The economics of the DSL network depend on revenues, operating costs and capital expenditures. Using granular cost data from DSL operators and vendors, the model calculates the gap to deploy 12 kft DSL to unserved markets as $18.6 billion. Exhibit 4-AK shows the breakout among initial capital expenditure, ongoing costs and revenue.

Initial Capex

Initial capital expenditures include material and installation costs for the following: telco modem, NID, protection, aerial or buried copper drop, DSLAM, cabinet, ADSL2+ line card,

Exhibit 4-AL: Data Sources for DSL Modeling

Material Costs	Source
Telco Modem	Windstream filing under Protective Order
For port sizes of 24 - 1,008:	
DSLAM Unit	Windstream filing under Protective Order
Cabinet	Windstream filing under Protective Order
Allocated Aggregation Cost (CO Ear)	Windstream filing under Protective Order
ADSL2+ line cards	Windstream filing under Protective Order
Fiber optic cabling	FTTH Council
Aerial Drop	Windstream filing under Protective Order
Buried Drop	Windstream filing under Protective Order
NID	Windstream filing under Protective Order
Protection	Windstream filing under Protective Order
Copper cable (24 and 22 AWG)	Windstream filing under Protective Order
Drop terminal/ building terminal (DTBT)	Windstream filing under Protective Order
Feeder distribution interface (FDI)	Windstream filing under Protective Order
Material Labor Costs	
FDI Splicing and Placing labor cost	Windstream filing under Protective Order
DTBT Splicing and Placing labor cost	Windstream filing under Protective Order
Telco Drop and NID labor cost	Windstream filing under Protective Order
Structure Labor Costs	
Duct, Innerduct and Manhole labor cost	Windstream filing under Protective Order
Loop Conditioning cost	Windstream filing under Protective Order
Poles. Anchor and Guy labor cost	Windstream filing under Protective Order
Buried Excavation labor cost under various types of terrain- normal, hardrock and softrock	Windstream filing under Protective Order

allocated aggregation cost, fiber cable up to 12 kft from the end-user, feeder distribution interface and drop terminal/building terminal, as well as the engineering costs for planning the network and the conditioning required on loops (i.e., the removal of load coils[84] and bridged taps[85]). For a detailed list of inputs into our model and the source for each, please refer to Exhibit 4-AL.

Ongoing Costs

Ongoing costs include: replacement capital expenditures required to replace network components at the end of their useful lives, network administration, network operations center support, service provisioning, field support, marketing and SG&A.

Revenues

Revenues are calculated by taking the Average Revenue Per User (ARPU)—which varies according to the level of broadband service/speed provided as well as whether the bundle of services provided includes voice, data and video—and multiplying it by the average number of users. For 12 kft DSL, only data ARPUs are used as incremental to voice, which is assumed present due to the fact that DSL technology utilizes twisted-pair copper wires originally installed and used for POTS.

Satellite

Broadband-over-satellite is a cost-effective solution for providing broadband services in low-density areas. In fact, it could reduce by $14 billion the gap to deploy to the unserved if the 250,000 most-expensive-to-reach housing units were served by satellite broadband. Satellite broadband, as provided by next generation satellites that will be launched as early as 2011, meets our Broadband Availability Target requirements by offering a minimum speed threshold of 4 Mbps downstream and 1 Mbps upstream and BHOL per user of 160 kbps.

Capabilities

Satellite operators are in the midst of building high capacity satellites that will dramatically augment the capacity available for subscribers in the next two years. ViaSat and Hughes, for example, plan to launch high-throughput satellites in 2011 and 2012, and offer 2-10 Mbps and 5-25 Mbps download-speed services, respectively. Upload speeds will likely be greater than the 256 kbps offered today, but no specific upload speeds have been announced. Since satellites are technically constrained by the total capacity of the satellite (>100Gbps), operators could change plans to offer customers at least 1 Mbps upstream even if it is not currently planned. Since the next-generation satellites will be able to offer 4 Mbps downstream and 1 Mbps upstream, satellite broadband meets the technological requirements for inclusion in the National Broadband Plan.

Technical limitations

Over the last decade, satellite technology has advanced to overcome some of the common drawbacks previously associated with it. Due to the properties of the spectrum band used for this service (Ku band downlink 11.7-12.7 GHz, uplink 14-14.5 GHz; Ka band downlink 18.3- 20.2 GHz; uplink 27.5-31 GHz), inclement weather can have an effect on service. However, the ability to dynamically adjust signal power, modulation techniques and forward error correction have all reduced degradation of service except in the most severe of weather conditions.

Since the satellites are in geosynchronous orbit nearly 22,300 miles above the earth, there is a round-trip propagation delay of 560 milliseconds associated with a typical PING (user to ISP and back to user). Recently, integrated application acceleration techniques, including TCP acceleration, fast-start and pre-fetch, have helped mitigate satellite latency for some Web-browsing experiences.[86]

Despite these technological advancements to improve the Web-browsing experience, the latency associated with satellite would affect the perceived performance of applications requiring real-time user input, such as VoIP and interactive gaming. Not only does this delay have a potentially noticeable effect on applications like VoIP, but it would also be doubled in cases where both users were using satellite broadband (e.g., if two neighbors, both served by satellite VOIP, talked on the telephone). Given that most voice calls are local, this could become a significant issue for rural areas if all calls must be completed over satellite broadband.

Spot beams

Broadband satellites use multiple spot beams to provide nationwide coverage. Spot beams use the same spectrum over and over in different geographies, providing more total throughput for a given amount of spectrum. The multiple re-use of frequencies across the coverage area for a satellite provider is similar to a cellular system that reuses frequencies in a "cell." Furthermore, because a spot beam focuses all its energy on a very specific area, it makes more efficient use of the available satellite power.

Nevertheless, a satellite's bandwidth to an end user is provided by and limited to the bandwidth of the spot beam covering that geographic area as well as the total satellite capacity. Therefore, potential network chokepoints for a satellite broadband network include total satellite capacity and spot beam bandwidth.[87] Each spot beam is designated over a section of the United States; once a spot beam is assigned to a certain geographic area, it generally cannot be re-allocated, shifted or moved to cover another area.

With its first leased satellite in 2005 and again with its own satellite in 2007, WildBlue found itself running out of capacity in high-demand regions.[88] In fact, ViaSat plans to aim bandwidth at exactly the same regions where WildBlue's capacity has run out.[89] Many unserved do not live in high-demand areas. These are among the factors that play a role in the capacity assumed available for broadband as discussed below.

Capacity

Providing sufficient capacity for a large number of broadband subscribers, e.g. all of the unserved, may prove challenging with satellite broadband. ViaSat and Hughes believe these next generation satellites have the capacity to serve as many as 2 million homes each;[90] ViaSat has stated on the record that its ViaSat-1 satellite will be capable of providing approximately 1 million households with Internet access service at download speeds of 4 Mbps and upload speeds of 1 Mbps.[91]

Treating satellite as a substitute for terrestrial service, however, requires that satellite be able to deliver service comparable to terrestrial options. Practically speaking, that means that satellite needs to support an equivalent BHOL per user.[92] We believe that the satellite industry could support more than 1.4 million subscribers in 2011 (note that this combines existing capacity with what is planned on being launched) and a total of more than 2.0 million subscribers in 2012 (after the launch of Hughes's next generation satellite, Jupiter). The picture becomes less clear, however, as we look to 2015, when the number of subscribers that current and planned satellites can support would decrease as demand per user grows. End-user demand has been growing at rates as high as 30% annually.[93]

We make certain assumptions in quantifying the number of subscribers that the entire U.S. satellite broadband industry could support with the launch of ViaSat-1 in 2011 and Jupiter in 2012. As there have been no commitments to launch new broadband satellites after 2012, we create a five-year outlook on satellite broadband capacity based on the following assumptions (see Exhibit 4-AM):

- ViaSat will launch a 130 Gbps satellite in early 2011.[94] A comparable satellite, Jupiter, will be launched by Hughes in 2012.[95]
- "Total Downstream Capacity" is 60% of "Total Capacity."
- "Total Usable Downstream Capacity" factors in 10% loss, which includes factors such as utilization and a potential loss of capacity from geographic clustering in which a non-uniform distribution of subscribers would engender certain spot beams to not be fully utilized.

Busy hour offered load (BHOL) assumption

Busy hour offered load, or BHOL, is the average demand for network capacity across all subscribers on the network during the busiest hours of the network. Understanding BHOL is critical for dimensioning the network to reduce network congestion. A more detailed discussion on BHOL can be found later in the Network Requirements section, but the basis for our assumption in satellite is explained here.

Suppose we want to dimension a network that will continue to deliver 4 Mbps. In order to estimate the BHOL for such a network in the future, we first note that average monthly usage is doubling roughly every three years, based on historical growth.[96] There is a significant difference between average usage and the typical user's usage with average usage heavily influenced by extremely high bandwidth users. Next, it becomes crucial to pick the right starting point (i.e., today's BHOL). As the mean user on terrestrial based services is downloading roughly 10 GB of data per month, busy hour loads per user for terrestrial networks translate to 111 kbps busy hour load, assuming that 15% of traffic is downloaded during the busy hour. Terrestrial-based services like cable and DSL experiencing busy hour loads of close to 111 kbps today form the "high usage" case in Exhibit 4-AN.

If we exclude the extremely high-bandwidth users, the average user downloads about 3.5 GB/month, which under the same assumptions for the busy hour would translate to 39 kbps busy hour load. The "medium usage" case in Exhibit 4-AN takes the 39 kbps as a starting point and grows to 160 kbps in 2015; it is this case that we use for our analysis of satellite as well as other networks. The "low usage" case assumes a user downloads 1 GB/month, which translates to 11 kbps; that is roughly what level of service satellite providers offer today of 5-10 kbps.[97] Using 11 kbps as a starting point, the "low usage" case applies the same growth rate as the medium and high usage cases. Exhibit 4-AN summarizes the three usage cases.

Exhibit 4-AM:
Available Satellite Capacity Through 2015

Year	2009	2010	2011	2012	2013	2014	2015
Total Capacity (Gbps)	35	35	165	295	295	295	295
Total Downstream Capacity (Gbps)	21	21	99	177	177	177	177
Total Usable Downstream Capacity (Gbps)	19	19	89	159	159	159	159

One reason why the BHOL-per-user might be lower for satellite: satellite operators' fair access policies, which are essentially usage caps, and a degree of self-selection in those who choose satellite-based broadband. However, in a world where users do not self-select into satellite, it is far from certain the extent to which these reasons will still be valid.

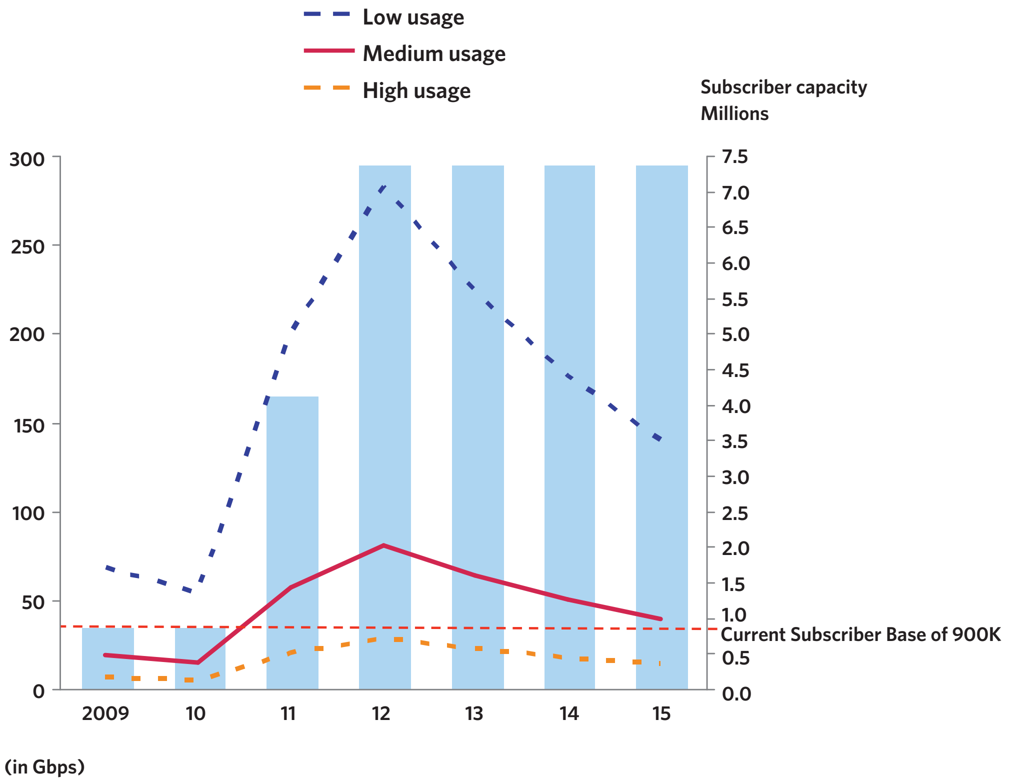
Using the above-mentioned assumptions under the "medium usage" case, the satellite industry could support nearly 1 million subscribers by 2015 (see Exhibit 4-AO). Note that each successive year, the satellites can support fewer subscribers due to the doubling of the BHOL every few years noted above. Each next-generation satellite can support approximately 440,000 subscribers using the usage forecast for 2015. Given that the satellite industry in the United States currently supports roughly 900,000 subscribers, this presents a potential difficulty in meeting the needs of the industry's current subscriber base, plus new net additions. If satellite broadband is offered at a level of service comparable to that of terrestrial broadband under the "medium usage" case and BHOL growth continues, satellite providers will need to devote significant incremental capacity to their existing customer base.

Since satellite providers today offer BHOL of between 5 kbps and 10 kbps,[98] our terrestrial-based BHOL assumptions would represent a marked increase in the service level of satellite providers. ViaSat has said on the record that its ViaSat-1 will support a "provisioned bandwidth" (a concept very similar to busy hour load) of 30-50 kbps.[99] However, satellite operators may not be planning for yearly growth comparable to historical terrestrial rates. Thus, despite the growth in satellite capacity between 2010 and 2012, the number of subscribers capable

Exhibit 4-AN:
Satellite Usage Scenarios[100]

Year	2009	2010	2011	2012	2013	2014	2015
Busy Hour Load (Kbps) @ 27% growth y-o-y							
Low usage	11	14	18	22	28	36	46
Medium usage	39	49	62	79	100	126	160
High usage	111	141	178	225	285	360	455

Exhibit 4-AO:
Satellite Capacity Based on Low, Medium and High Usage Scenarios



of being supported with our assumptions starts to fall quickly after 2012, absent additional satellite launches. Due to the limited capacity, we do not assume satellite in the calculation of the gap figure of $23.5 billion, but we have contemplated a case in which 250,000 of today's unserved subscribe to broadband over satellite.[101]

If satellite is used to serve the most expensive 250,000 of the unserved housing units, it will reduce the gap. Some 250,000 housing units represent 3.5% of all unserved, <0.2% of all U.S. households, and account for 57%, or $13.4 billion, of the total gap. Exhibit 4-AP shows the remaining gap if satellite is used to serve the most expensive census blocks containing a total of 250,000 subscribers.

The map in Exhibit 4-AQ identifies the location of the highest gap census blocks with a total of 250,000 housing units that we assume are served by satellite in Exhibit 4-AP.

Economics

Nearly all of the costs for satellite broadband are fixed and upfront with the development, construction and launch of the satellite. Each next-generation satellite costs approximately $400 million, which includes satellite construction, launch insurance and related gateway infrastructure.[102] Operating costs for a satellite broadband operator are typically lower than for a wired network provider. Because a single satellite can provide coverage for the entire country with the exception of homes on the north face of mountains or with dense tree cover, the cost of satellite broadband remains constant regardless of household density, which makes it a great option for remote areas.

However, due to the capacity constraints of each satellite, and the growth in use discussed above, satellite operators likely need to continue adding new satellites over time. Estimates of the initial capital expenditure to provide all 7 million of the unserved housing units using satellite broadband service are near $10 billion, including the cost of up to 16 next-generation satellites as well as the CPE and installation for each end-user, assuming the "medium usage" scenario. Timing may be an issue if satellite broadband were deployed as the only means of reaching the unserved, as a next-generation satellite takes approximately three years to build.[103]

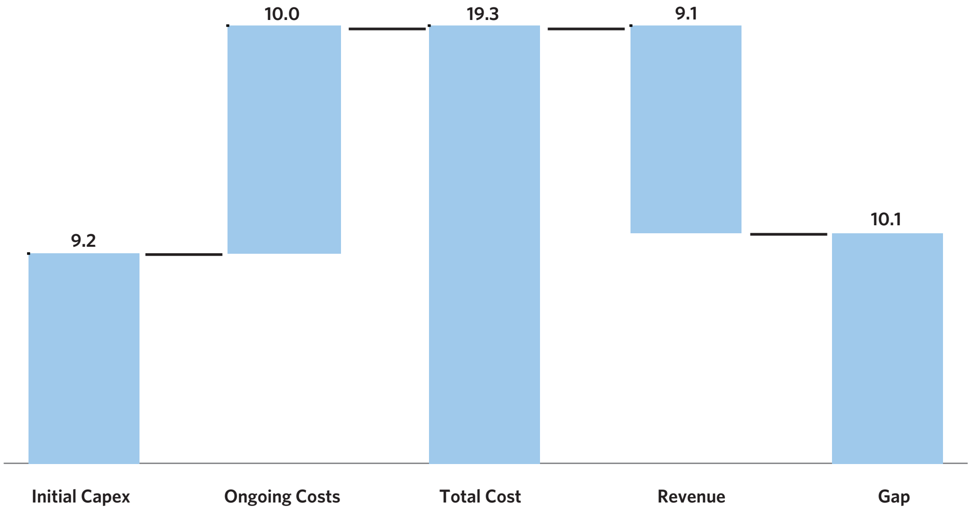
Additionally, with each satellite capable of supporting roughly 440,000 subscribers using our assumptions, satellite operators could be forced to potentially more than double their current monthly subscriber fees, which today range from $60-80 per month, in order to maintain the same return on investment as today.

The cost-per-subscriber is driven by the high up-front costs associated with building and launching a satellite. As capacity required per-subscriber increases, the number of subscribers that each satellite can support drops. That drop, in turn, means that there are fewer subscribers over whom to amortize high fixed costs. Thus the average cost-per-subscriber increases, creating less favorable economics over time or requiring higher monthly fees to be charged to the end-user as described above.

Even with greater efficiency of planned satellites like ViaSat-1 or Jupiter, which provide more capacity per launch, the average capex-per-subscriber will only grow with the increase in effective load-per-user. See Exhibit 4-AR, which shows the average capex per subscriber at various levels of monthly usage. The levels of usage correspond to the low, medium and high usage cases described above.

In Exhibit 4-AR, the capex of a satellite (including build, launch and insurance), the associated gateway infrastructure and the CPE is divided by the number of subscribers, depending on the usage characteristics. Note that the average cost calculation may in fact overstate the true cost of a given subscriber over the lifetime of the satellite.

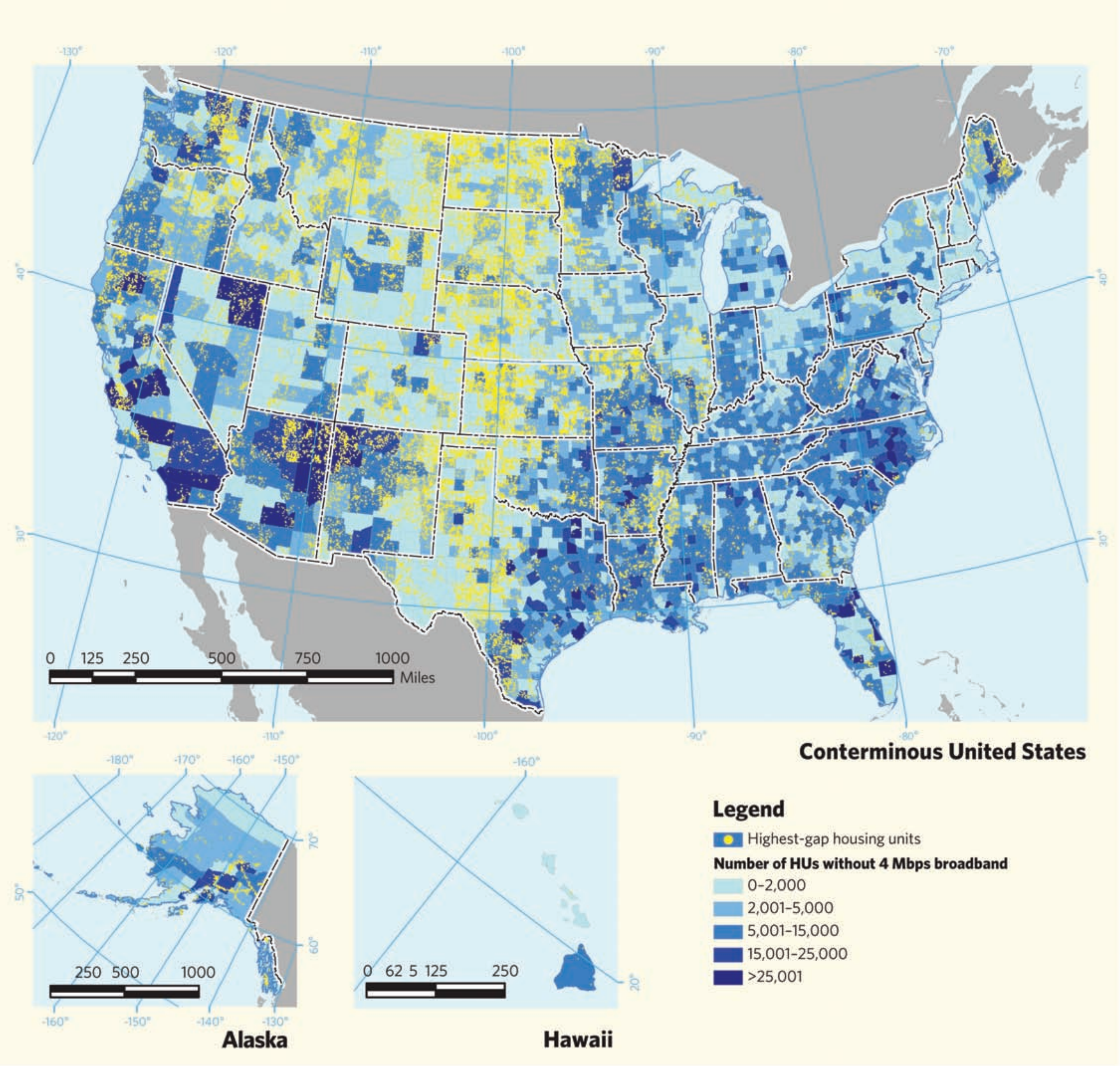
Exhibit 4-AP: Economics of Terrestrially Served if Most Expensive Housing Units are Served with Satellite[104]



Buy down

Due to the relatively high price of satellite broadband service, there may be a need for a subsidy of the monthly ARPU for those served by satellite broadband. Current ARPU for satellite broadband is generally $60-80 per month depending on speed tier, service provider and choice of whether to purchase CPE upfront or pay a monthly fee for it.[105] For illustrative purposes, assuming a starting point of $70 per month, end-user support to reduce the price to $35 monthly would cost $105 million annually (250,000 people x $35 difference in ARPU x 12 months).

Exhibit 4-AQ:
Location of Highest-Gap Housing Units

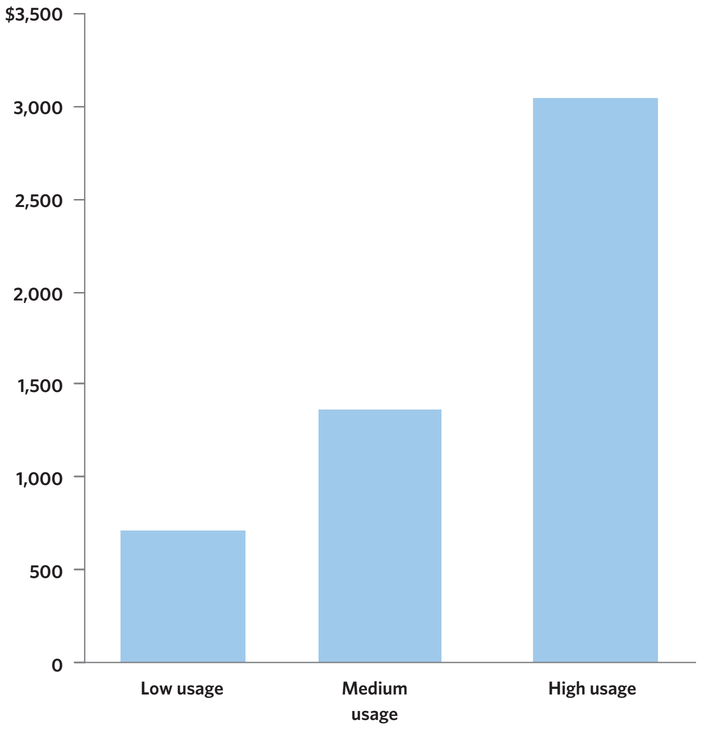


Over 20 years, discounting at 11.25% , the present value of this annual amount is over $800 million.

As discussed above, if satellite operators were to assume a higher use case to provide a level of service comparable to terrestrial providers and to double their price to ensure consistent return on investment (note that the ability to generate enough cash flow affects their ability to finance future satellites), the required subsidy would grow proportionately. Assuming a contemplated starting price of $120, the subsidy required would be $255 million annually (250,000 people x $85 difference in ARPU x 12 months) to yield an end-user price of $35. Over 20 years, the present value of this annual expenditure is roughly $2 billion.

Despite these challenges, we believe that satellite can still provide an economically attractive service for some, and that satellite providers can be an alternative to terrestrial providers, both wired and wireless. However, as we explain further in Chapter 3, uncertainty—principally about the optimal role satellite might play in the disbursement process—has led us to not explicitly include satellite in the base-case calculation.

Exhibit 4-AR:
Satellite Capex per Subscriber— Average cost/POP at Scale



TECHNOLOGIES NOT INCLUDED IN THE BASE CASE

Fiber-to-the-premises (FTTP)

Fiber-to-the-premises (FTTP) offers the greatest potential capacity of any of the technologies considered, making it the most future-proof alternative. The tradeoff for this is the additional construction cost incurred to extend fiber all the way to the premises, making FTTP the most capital-intensive solution considered. On the operational side, the extension of fiber enables the removal of all active components in the outside plant, providing FTTP with a substantial operational savings over competing technologies with active electronics in the outside plant.[106] However, in unserved areas in particular, these savings are insufficient to overcome the initial capital expenditure burden, making FTTP the solution with the highest lifetime cost and the highest investment gap.

Capabilities

There are three basic types of FTTP deployments: point-to-point (P2P) networks, active Ethernet networks and passive optical networks (PON). PON makes up more than 94% of the current residential FTTP deployments in the United States.[107] PON has the advantage of offering lower initial capital expenditure requirements and lower operating expenditures relative to P2P and Active Ethernet deployments, respectively. As such, our analysis utilized PON as the modeled FTTP network.

Exhibit 4-AS shows the capabilities of the varieties of PON currently in use in the United States.[108]

While the majority of homes currently passed by FTTP deployments in the United States are passed by BPON networks, more new deployments are utilizing GPON.[109] PON is a shared medium, meaning that a portion of the access network running between the headend and the passive optical splitter is shared among multiple end-users.

Typical PON deployments share a single fiber in the feeder portion of the access network among 32 end-users. See Exhibit 4-AT. For BPON, this yields a fully distributed downstream capacity of 19.4 Mbps and upstream capacity of 4.8 Mbps per end-user. For GPON, these capacities increase to 78 Mbps downstream and 39 Mbps upstream. As these speeds do not factor in any oversubscription, with a reasonable oversubscription of 15:1,[110] an operator with either a BPON or GPON deployment could easily offer its customers a product with download speeds exceeding 100 Mbps, far exceeding what we anticipate being required in the foreseeable future.[111] As such, FTTP clearly is a candidate from a capability standpoint for delivering broadband to the unserved.

Future PON architectures

PON architectures continue to evolve. The full standard for the next evolution of GPON is expected to be completed in June

2010, with deployments starting in 2012. It will offer download speeds of 10 Gbps and upload speeds of 2.5 Gbps and 10 Gbps, and it will be able to coexist on the same fiber as GPON. Deployments of the next evolution of EPON could even predate those of GPON, offering download speeds of 10 Gbps and upload speeds of 1 Gbps and 10 Gbps.[112] See Exhibit 4-AU.

Beyond these near-term standards, numerous long-term ideas are being presented. For example, Wave Division Multiplexing PON would replace the splitter with an arrayed wave guide and utilize a different wavelength for each end-user. This would effectively eliminate the sharing of the fiber in the second mile that takes place with existing PON varieties, enabling dedicated end-user capacities of 10 Gbps or more.

Exhibit 4-AS:
Capabilities of Passive Optical Networks (PON)

	BPON	EPON	GPON
Standard	ITU-T G.983	IEEE 802.3ah	ITU-T G.984
Bandwidth	Downstream up to 622 Mbps	Downstream up to 1.25 Gbps	Downstream up to 2.5 Gbps
	Upstream up to 155 Mbps	Upstream up to 1.25 Gbps	Upstream up to 1.25 Gbps
Downstream wavelength(s)	1490 and 1550 nm	1550 nm	1490 and 1550 nm
Upstream wavelength	1310 nm	1310 nm	1310 nm
Transmission	ATM	Ethernet	Ethernet, ATM, TDM

Exhibit 4-AT:
Passive Optical Network (PON) FTTP Deployment

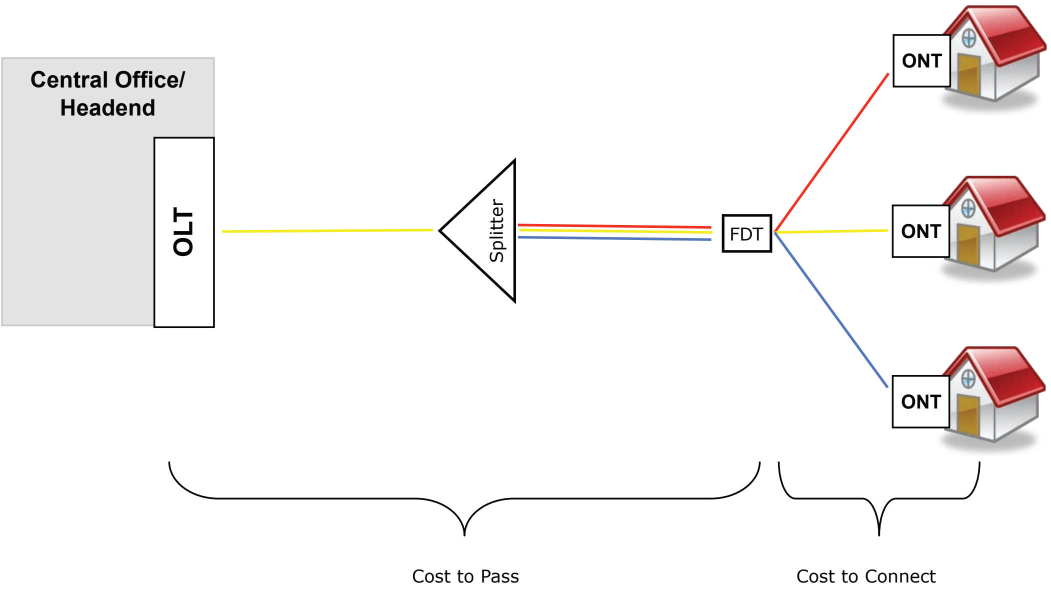


Exhibit 4-AU:
Future PON Architectures

	10G GPON	10G EPON
Bandwidth (upstream/downstream)	10/2.5 Gbps or 10/10 Gbps shared	10/1 Gbps or 10/10 Gbps shared
Positives	Compatible with existing GPON	First completed
Key challenges	10 Gbps upstream not viable for single-family units	10 Gbps upstream not viable for single-family homes; 1 Gbps upstream too little bandwidth

FTTP economics

To build FTTP to deliver broadband to the 7 million housing units that are classified as unserved (at a broadband definition of 4 Mbps download and 1 Mbps upload) would lead to an investment gap of $62.1 billion.

The initial capital expenditure averages out to be slightly more than $5,000 per premises. This initial capex value comprises two pieces: the cost to pass a premises and the cost to connect a premises. (These costs are detailed in Exhibit 4-AV.)

The cost to connect a premises is the smaller of the two charges, typically averaging about $650-$750/premises.[113] The cost to connect is entirely success-driven and consists of the installation of the fiber drop and equipment at the customer premises. Making up the bulk of the $5,000 initial capex cost of a FTTP deployment is the cost to pass a premises; this is the cost to build the fiber network distributed over the premises capable of being serviced by the network. Cost-to-pass is typically spoken of in terms of all premises passed by a FTTP deployment, but the more meaningful number is cost-to-pass per subscriber, which takes into account penetration rate. With fiber installation costs ranging between $10,000 and $150,000 per mile, depending on a variety of factors including deployment methodology, terrain and labor factors,[114] the cost to pass is highly sensitive to penetration rate and household density.

Using several data points provided by existing FTTP providers, we are able to establish the following empirical relationship between the cost-to-pass for a FTTP deployment and household density, using standard curve-fitting techniques[115] (see Exhibit 4-AW):

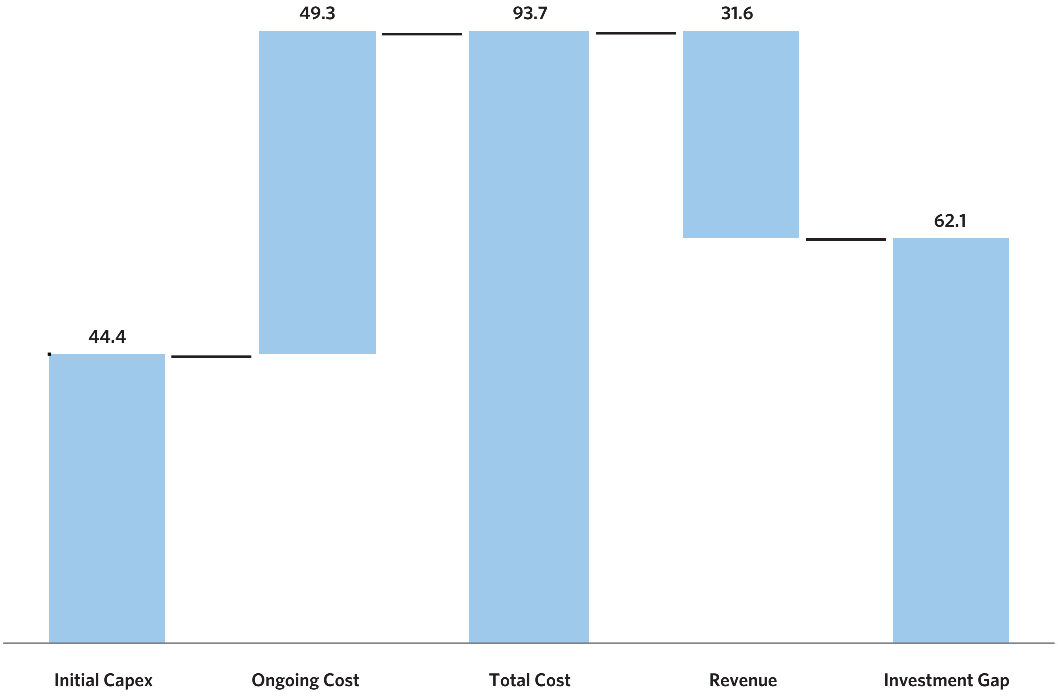
Cost per home passed = $\$701.59 * e^{(8.19/\text{Household density})}$

where Household density is in homes per square mile.

As one can see, the unserved segment starts to intersect the cost-to-pass curve just as the curve starts to steepen significantly. At about 10 households per square mile, the cost-per-premises passed is slightly less than $1,600. Halving the density to five housing units per square mile more than doubles the cost-to-pass, to more than $3,600. At this level, factoring in average broadband penetration of roughly 65% and including the cost to connect each premises yields a cost-per-subscriber in excess of $6,000. Due to the low densities of the unserved segment and given the current expectation of bandwidth demand over the coming years, even with an optimistic scenario for increasing broadband adoption, FTTP may be prohibitively expensive when alternative technologies can also meet bandwidth demands.

The final category of costs is one where FTTP holds a significant advantage: the cost-to-serve. By extending fiber all the way from the serving office or headend to the customer premises, an FTTP network eliminates the need for any active components in the outside plant. This can reduce ongoing maintenance and support expenditures by as much as 80% relative to an HFC plant.[116] However, on a monthly basis for a typical scale network deployment, this savings amounts to just a few dollars per subscriber, and as such is generally insufficient to offset the initial capital expenditure burden.

Exhibit 4-AV:
Breakout of FTTP Gap



FTTP Deployment

The cost information above can be displayed in a simple financial model that can be used to easily estimate the viability of a FTTP deployment in addition to the model that calculates the cost of the investment gap across the country. See Exhibit 4-AX.

First, consider cost per home passed. In this example, we use $850, a value that would cover roughly 80% of the United States. Factoring in a 40% penetration rate, a value taken from the high end of Verizon's publicly stated 2010 target rate for its competitive deployments,[117] we get a $2,125 cost-to-pass per subscriber. Adding in the cost-to-connect, inflated to account for churn and equipment replacement over the life of the network, we get a rough estimate of $3,225 total investment per subscriber. At this level, an operator could succeed with a monthly EBITDA of

Exhibit 4-AW:
Cost to Pass with FTTP by Density of Homes[118]

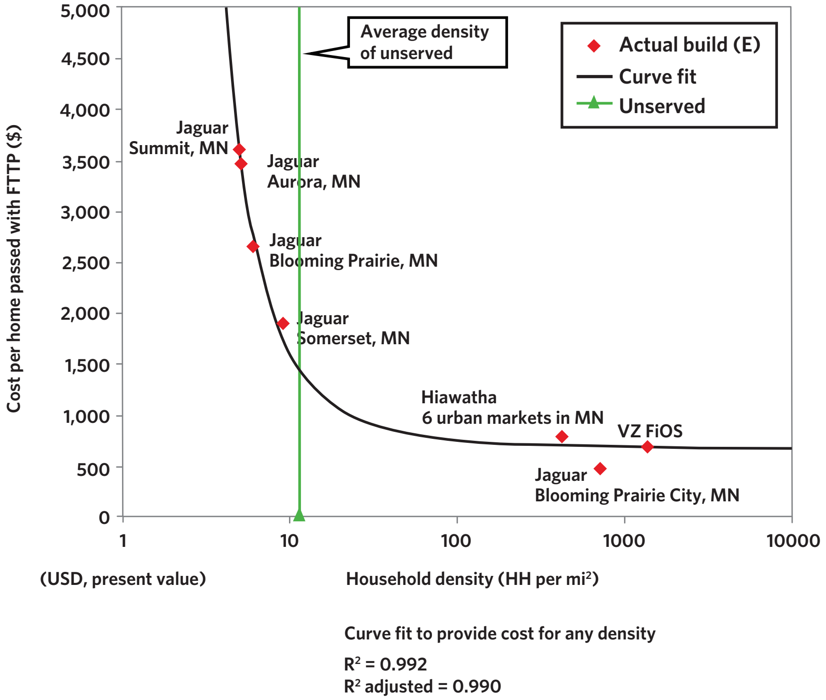
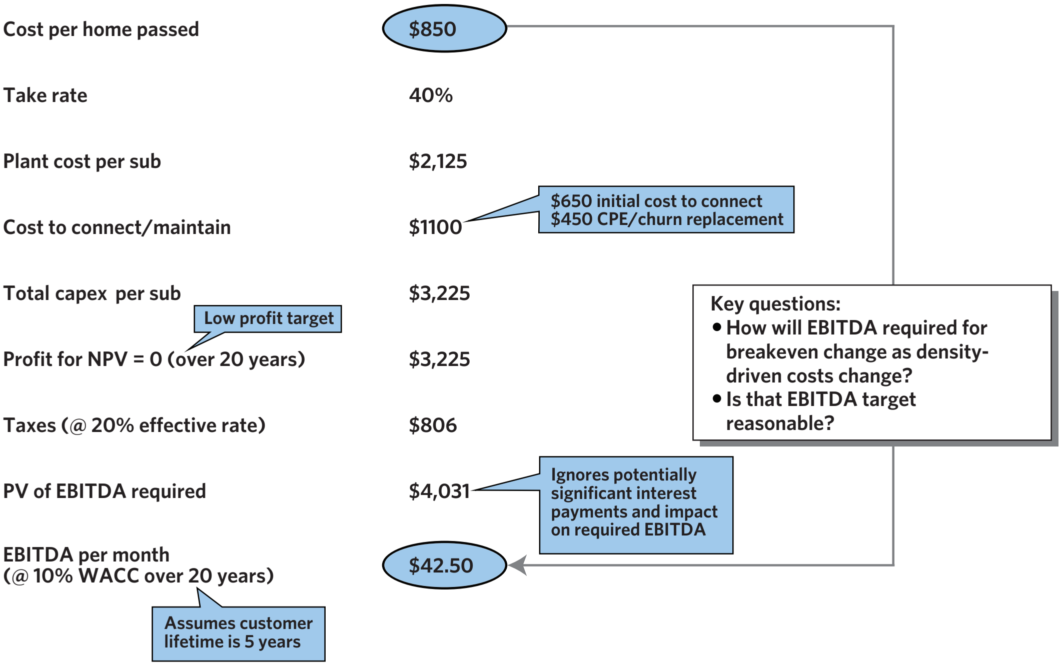


Exhibit 4-AX:
Simple Financial Model to Calculate Breakeven EBITDA for FTTP



Cost per home passed	$850
Take rate	40%
Plant cost per sub	$2,125
Cost to connect/maintain	$1100
Total capex per sub	$3,225
Profit for NPV = 0 (over 20 years)	$3,225
Taxes (@ 20% effective rate)	$806
PV of EBITDA required	$4,031
EBITDA per month (@ 10% WACC over 20 years)	$42.50

$650 initial cost to connect
$450 CPE/churn replacement

Low profit target

Key questions:
- How will EBITDA required for breakeven change as density-driven costs change?
- Is that EBITDA target reasonable?

Ignores potentially significant interest payments and impact on required EBITDA

Assumes customer lifetime is 5 years

$42.50/subscriber, a value that is roughly in line with estimates of margins for some of the largest providers in the country.

Next, we calculate the cost to deploy FTTP in each county in the country using the curve fit calculated in Exhibit 4-AW. Applying that cost to the financial model laid out in Exhibit 4-AX, one can calculate the EBITDA required for FTTP to break even in each county; the results are shown in Exhibit 4-AY. Note that a successful FTTP entrant would need to have roughly $38 in monthly EBITDA from each customer at the assumed 40% take rate to provide returns to capital in the denser half of the country.

It is important to note that for an incumbent, much of the revenue associated with a FTTP deployment cannibalizes its existing revenue. As such, an incumbent telco would only want to factor in the incremental revenue offered by a FTTP deployment, namely additional data revenue and video revenue. This has the effect of significantly reducing the viability of FTTP deployments currently for many incumbent providers.

Due largely to this cost structure, there have been few large incumbent providers overbuilding their existing footprints with FTTP. To date, the bulk of FTTP deployments have been driven by a single RBOC, Verizon, which has deployed FTTP in the denser, suburban and urban areas in its footprint, and by Tier 3 ILECs, CLECs, municipalities and other small providers. These providers have deployed FTTP in areas that are less densely populated than those of Verizon, but they have been able to largely replicate the RBOCs' cost structure by achieving an average penetration rate that is nearly double that of the RBOC (54% vs. 30 %).[119]

3,000 – 5,000 foot DSL

Despite providing faster broadband speeds than 12 kft DSL and being capable of delivering video services, DSL over loops of 3,000 (3 kft) feet or 5,000 (5 kft) feet has a higher investment gap when providing broadband services in low-density unserved areas. DSL over 3-5 kft loops delivers broadband speeds well in

Exhibit 4-AY:
Esitmated Monthly EBITDA Required to Break Even on an FTTP Build Across the Country[120]

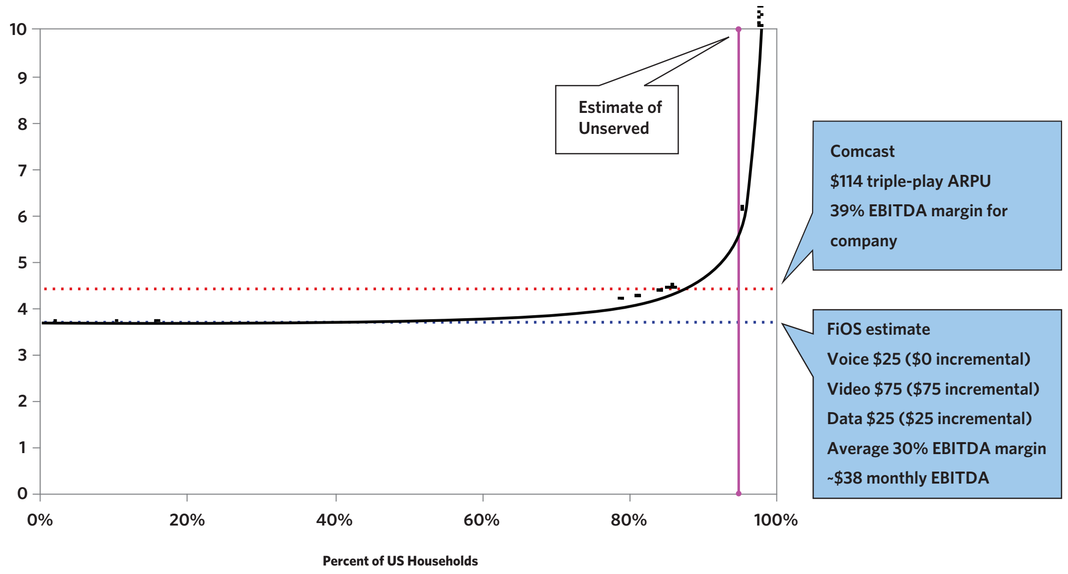


Exhibit 4-AZ:
Data Sources for FTTP Modeling

Item	Source
Optical light terminal (OLT)	Calix protective order filing
Fiber distribution hub (FDH)	FTTH Council
optical splitter	FTTH Council
Fiber drop terminal (FDT)	FTTH Council
Optical network terminal (ONT)	FTTH Council, Calix protective order filing
fiber optic cabling	FTTH Council
aerial placement	FTTH Council
buried placement	FTTH Council
operating/maintenance expenses	Hiawatha Broadband protective order

excess of the 4 Mbps downstream and 1 Mbps upstream target. However, due to the cost of driving fiber an additional 7,000 to 9,000 feet closer to the end user, 3 kft DSL and 5 kft DSL are more costly solutions than 12 kft DSL and, thus, have higher investment gaps than 12 kft DSL in all unserved markets.

Capabilities

DSL over loops of 3 kft or 5 kft typically uses VDSL2 technology, which was first standardized in 2006 and uses frequencies up to 30 MHz. While there may be some VDSL technology still being used today, many operators are replacing it with VDSL2. Therefore, we will examine the capabilities of VDSL2 technology at 3 kft and 5 kft.

VDSL2 can provide 35 Mbps downstream and 6 Mbps upstream over 3 kft loops, and it can provide 20 Mbps downstream and 2 Mbps upstream over 5 kft loops. As VDSL2 over 24 AWG wire provides rates well above 4 Mbps downstream and 1 Mbps upstream, the technology meets the speed requirements for broadband service. Exhibits 4-BA and 4-BB illustrate how loop length affects speed for VDSL2. Of course, speeds realized in the field are heavily dependent on plant quality, so

Exhibit 4-BA: Downstream Speed of a Single VDSL2 Line at Various Loop Lengths[121]

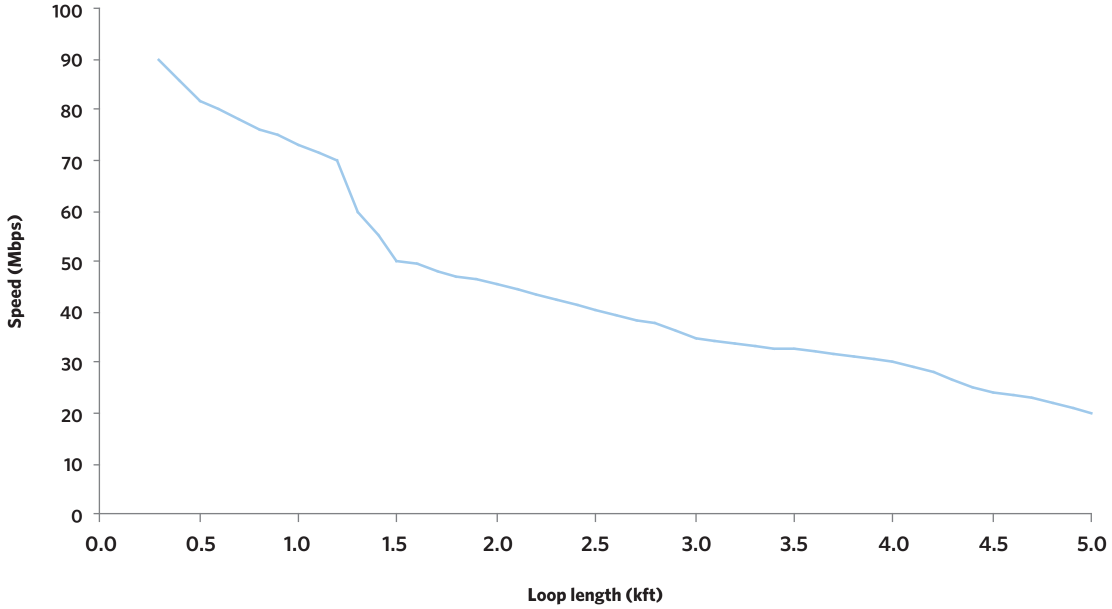
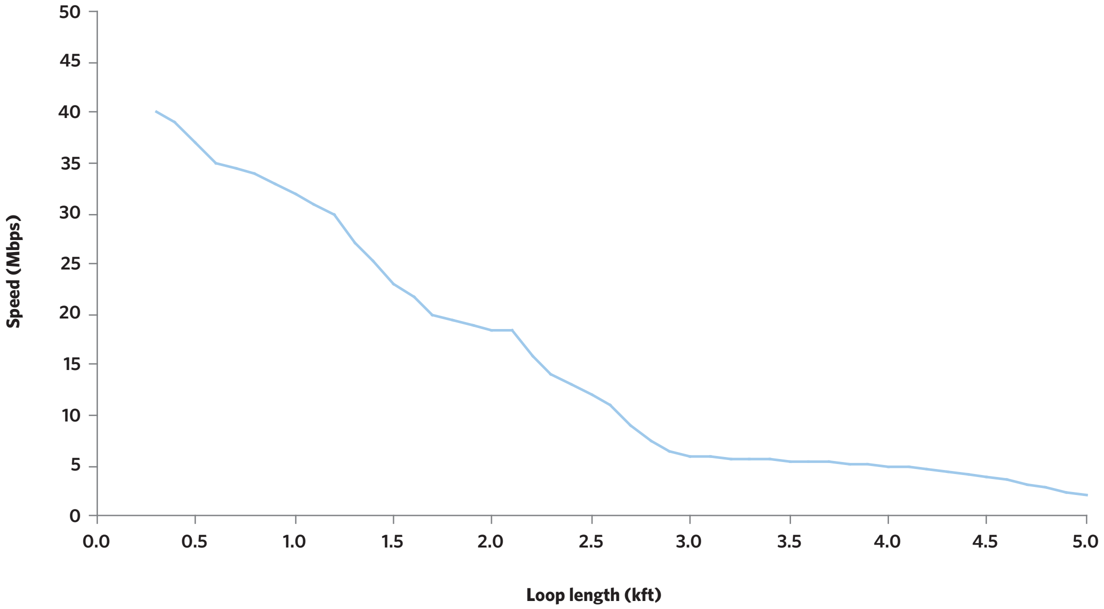


Exhibit 4-BB: Upstream Speed of a Single VDSL2 Line at Various Loop Lengths[122]



any degradation in the copper plant will lead to lower speeds for a given loop length.

In this case, 24 AWG wire is assumed with no bridged taps. Performance with 22 AWG wire, which is often used in rural areas, would yield higher bitrates, while use of 26 AWG wire would yield lower rates.

For VDSL2, performance can be improved through vectoring, bonding or a combination of the two. Vectoring, or Dynamic Spectrum Management level 3 (DSM-3), has shown improved performance in lab tests by canceling most of the crosstalk between VDSL2 lines sharing the same binder and is currently being tested in the field. The bonding of loops, assuming there are two copper pairs available, would enable the doubling of the speed achieved to the end-user. A combination of vectoring and bonding could produce downstream speeds over 300 Mbps if lab and field tests prove successful. Exhibits 4-BC and 4-BD illustrate the performance of bonded and vectored VDSL2.

Operators who have shortened loops from 12 kft to 3-5 kft and currently use VDSL2 technology have seen DSL technology offer faster speeds in the past decade.[123] Current and future

Exhibit 4-BC:
Downstream Speed of VDSL2 Variants[124]

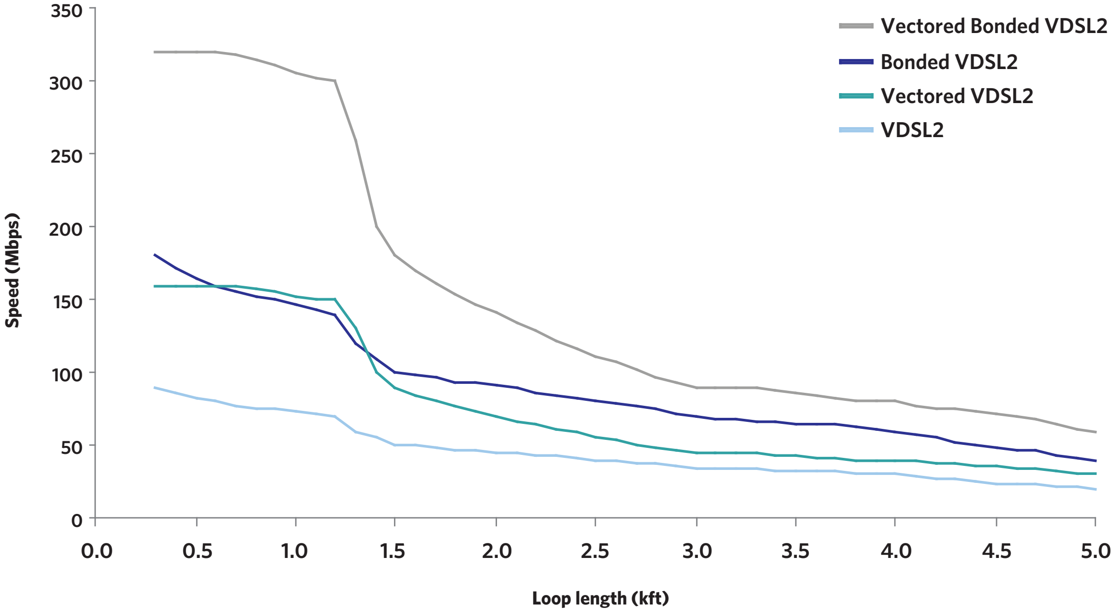
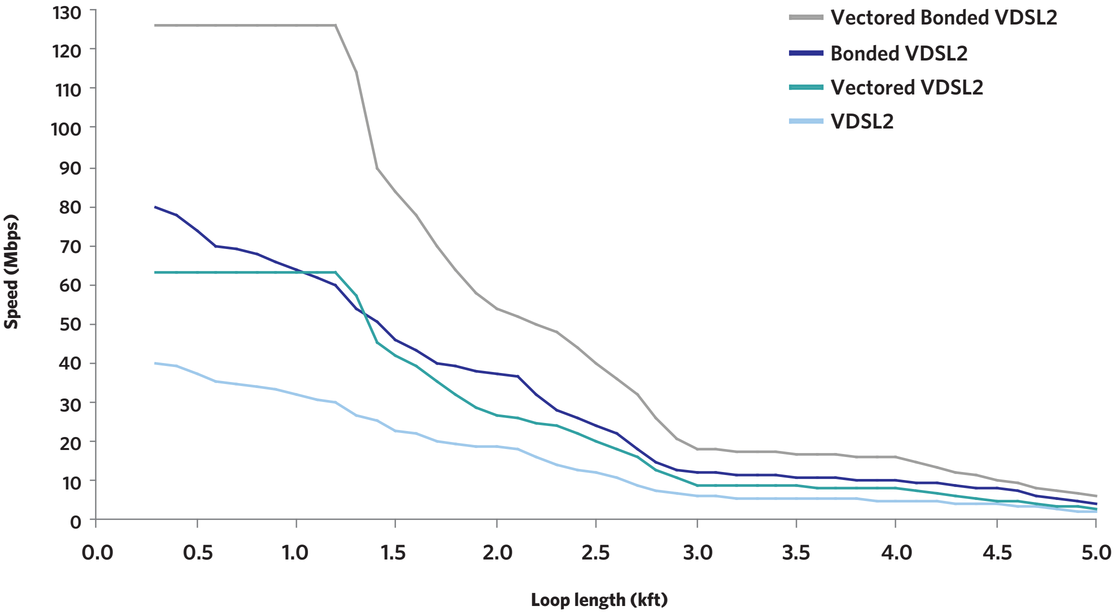


Exhibit 5-BD:
Upstream Speed of VDSL2 Variants[125]



technology improvements, such as the three levels of DSM, are likely to continue to improve speeds as well as the stability of the service provided. Further development of and investment in these improvements, along with bonding, are likely due to DSL's prevalence worldwide.

We model the VDSL2 access network in a similar fashion to the ADSL2+ network described (see above for details). In essence, we assume VDSL2 DSLAMs are connected to central office and other middle- and second-mile aggregation points with fiber-optic-based Ethernet technology providing backhaul capacities that are more than sufficient to meet the end-user requirement. Costs associated with loop conditioning are included when appropriate.

Economics

Like those of the 12 kft DSL network, the economics of the 3 kft DSL and 5 kft DSL networks depend on revenues, operating costs and capital expenditure. Using granular cost data from DSL operators, the model calculates the investment gap to deploy 3 kft DSL to unserved markets as $52.7 billion and the investment gap to deploy 5 kft DSL to unserved markets as $39.2 billion. The total gaps for 3 kft and 5 kft DSL are more than twice as costly as the respective number to deploy 12 kft DSL to the unserved, despite 3-5 kft DSL earning nearly 3x the revenue of 12 kft DSL because their ARPUs include video as well as data. The cost differential is mainly driven by the high cost of driving fiber closer to the end user, less so by the higher cost of VDSL2 technology versus ADSL2+ technology. The following waterfall charts show the breakout among initial capital expenditure, ongoing costs and revenue. See Exhibits 4-BE and 4-BF.

Initial Capex

Initial capital expenditures include material costs and installation for the following: telco modem, NID, protection, aerial or buried copper drop, DSLAM, cabinet, VDSL2 line card, allocated aggregation cost, fiber cable up to 3 kft or 5 kft from the end-user (respectively), feeder distribution interface and drop terminal/building terminal, as well as the engineering costs for planning the network and the conditioning required on loops (i.e., the removal of load coils and bridged taps).

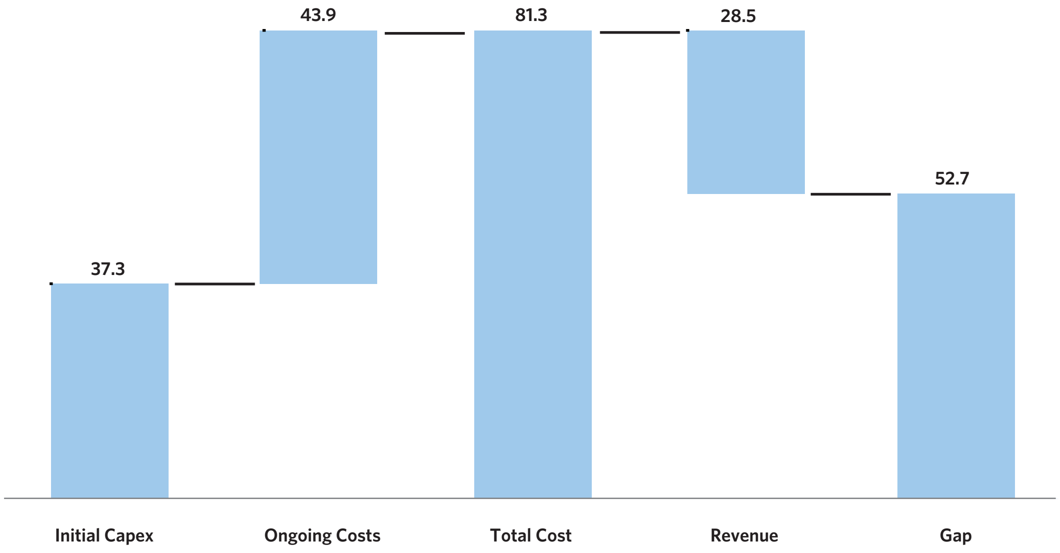
Ongoing Costs

Ongoing costs include replacement capital expenditure required to replace network components at the end of their useful lives, network administration, network operations center support, service provisioning, field support, marketing and SG&A.

Revenues

Revenues are calculated by taking the ARPU—which varies according to the level of broadband service/speed provided as well as whether the bundle of services provided includes voice, data and video—and multiplying it by the average number of users. For 3 kft and 5 kft DSL, data and video ARPUs are used as the incremental services to voice, which is assumed present due to the fact that DSL technology utilizes the twisted pair of copper wires originally installed and used for POTS. VDSL2's higher speeds at 3 kft and 5 kft could support both video and data, although not all real-world operators of VDSL2 choose to offer both services today. The addition of video revenue is not enough to compensate for the incremental investment required to drive fiber within 3 kft and 5 kft of the end user for the unserved.

Exhibit 4-BE:
Breakout of 3,000-Foot DSL Gap



Material and labor costs for 3 kft and 5 kft DSL are the same as for 12 kft DSL except for VDSL2 line cards, which are sourced from a Qwest filing under Protective Order.

15,000 foot DSL

DSL over loops of 15,000 feet (15 kft) is a very cost-effective solution for providing Internet access in low-density areas but fails to meet the Broadband Availability Target.

Capabilities

DSL over 15 kft loops typically uses ADSL2/ADSL2+ technology. ADSL2+ over 24 AWG wire provides rates of 2.5 Mbps downstream and 600 kbps upstream; therefore, the technology does not meet the speed requirements for broadband service under the Broadband Availability Target. Refer to Exhibit 4-AH in the 12 kft DSL section for a further understanding of how downstream speed varies with loop-length distance.

Hybrid Fiber-Coax Networks

The focus in this section will be on high-speed data connectivity provided by hybrid-fiber-coax (HFC), or cable, networks. We'll look first at the capabilities of HFC networks, then at the economics of these services.

Our analysis indicates that the capabilities of HFC networks far exceed end-user speed and network capacity requirements, as shown above and in the National Broadband Plan. Therefore, by

Exhibit 4-BF:
Breakout of 5,000-Foot DSL Gap

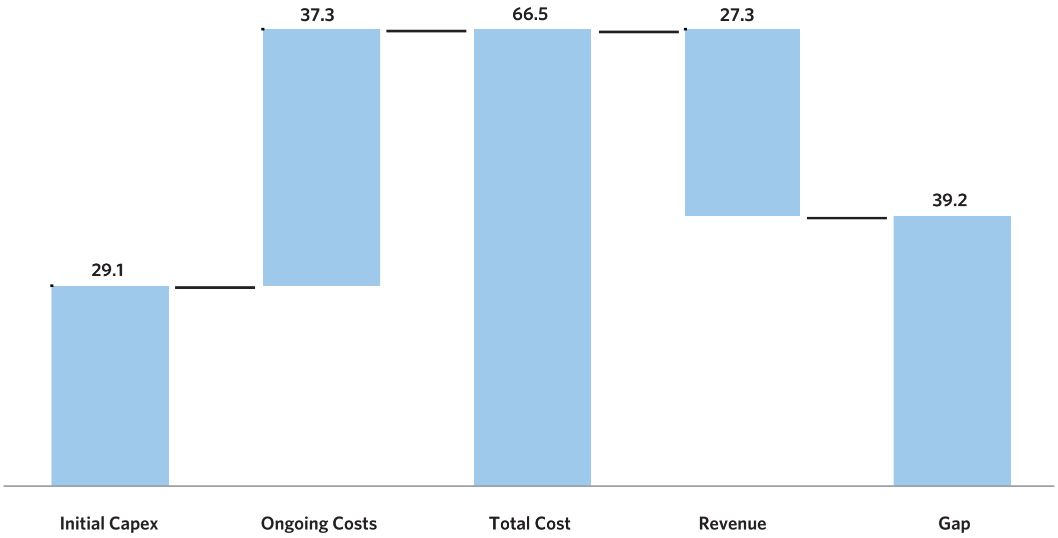
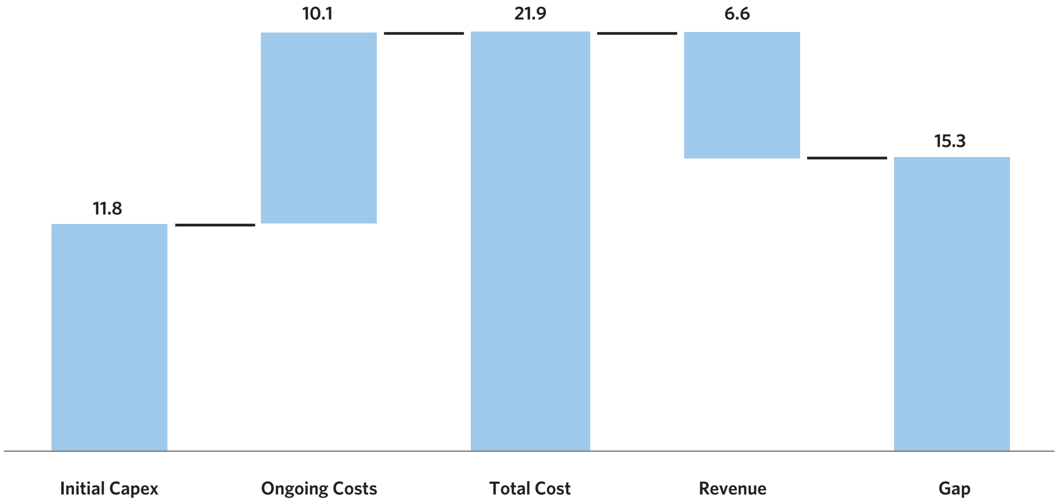


Exhibit 4-BG:
Breakout of 15,000-Foot DSL Gap



definition, homes within the HFC footprint are considered served. However, the investment gap to deploy HFC networks in unserved areas is larger than that of DSL or fixed wireless as noted above.

The near-ubiquity of HFC networks that can provide high-speed broadband access is a tremendous asset that puts the United States in a unique position among other countries. HFC networks were initially designed to deliver one-way video, but have evolved over time to allow two-way transmission of data and voice in addition to video. Today, cable systems pass roughly 90% of U.S. households with high-speed data services; in addition, more than 90% of homes are passed by cable plant, with 50% of those homes taking at least basic cable video service, thereby amounting to 63 million subscribers.[126] Some 52% of broadband subscribers in the United States subscribe to cable-based service, the second highest rate among OECD countries.[127]

History

When cable systems were initially constructed, the industry was highly fragmented, with many small firms operating networks in local markets. Today, there is very little overlap in cable networks because, in most markets, cable operators received exclusive rights to operate in their geography in the form of a franchise agreement granted by local franchising authorities. It is important to note that cable companies have not been subjected to the same network-sharing or carrier-of-last-resort obligations as the telephone companies; however, cable companies do not receive Universal Service Fund (USF) monies to offset the costs of constructing and maintaining their networks. Maintaining one network per geographic area greatly reduced the network cost-per- subscriber, which, along with having monopoly or near-monopoly control over the video market, has allowed these networks to be successful in the face of large up-front capex requirements.

Due to the complementary nature of footprints and scale advantages in content acquisition, the cable industry has experienced significant consolidation over the years. Today, there are almost 1,200 cable system operators but, as shown in Exhibit 4-BH, the top five companies pass 82% of homes passed by cable video service.[128]

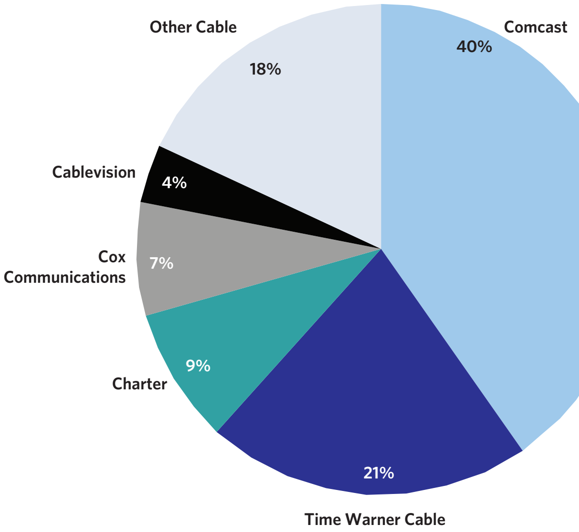
Cable MSOs have spent $161 billon from 1996-2009 on capital expenditures; in part, this was used to enable broadband capabilities.[129] Cable systems were originally constructed to provide one-way video signals, so customers initially could not send information back through the network. In the early deployment of cable (1950s-1970s), the networks were known as CATV (Community Antenna Television) and were built to provide TV and radio services. The network was designed to support all-analog, one-way transmissions from the community satellite antennas (cable headends) to end-user televisions over coaxial cable.

In the 1990s with the advent of the Internet and passage of the 1996 Telecommunications Act, cable companies began upgrading their networks to provide the two-way transmission capabilities required for Internet data traffic and telephony in addition to TV/radio signals. The network needed to be reengineered to handle two-way transmissions of digital communication signals and upgraded to handle higher capacity demands. The original "tree and branch" architecture of cable systems was ideal for transmitting TV signals from the head-end to the home television. However, video transmission over coaxial cable was still susceptible to noise and interference and required amplifiers, line extenders and other active electronics to ensure that the signal would reach end-user TV sets with acceptable quality. Unfortunately, these active electronics a) were not capable of passing signals in the upstream direction and b) were often not spaced properly within the cable plant for upstream transmission. As a result cable companies invested in HFC upgrades throughout the 1990s to overcome these problems. Such upgrades were seen as attractive since millions of homes were already "wired" with high capacity coaxial cable and the revenue potential of triple play services created a compelling business case. Exhibit 4-BI illustrates some examples of the infrastructure upgrades required for HFC networks.

Steps to upgrade cable networks for broadband:

- Invest in fiber optic cable and optic/electronics to replace and upgrade coaxial cable for capacity purposes

Exhibit 4-BH:
Breakout of Cable Coverage— Share of Homes Passed by Cable Companies



Numbers do not sum to 100% due to rounding.

- Replace and redesign headend equipment, line transmission equipment, set top boxes to allow for two-way data transmission, and add DOCSIS modems
- Deploy telephone switching equipment and interconnection facilities to provide VoIP services
- Develop the technology and equipment necessary for more sophisticated network management and control systems
- Implement the back-office, billing and customer service platforms necessary to provide the standard triple play services common among cable operators today

Capabilities

Cable companies coupled their investments in two-way upgrades with a standardization effort. Cable-based broadband relies on Data Over Cable Service Interface Specification (DOSCIS). The first release of DOCSIS was in 1997, with DOCSIS 2.0 released in 2001 and the third-generation standard (DOCSIS 3.0) now being deployed widely. DOCSIS 2.0, currently the most widely deployed, provides up to 36 Mbps of downstream bandwidth and up to 20 Mbps upstream, while DOCSIS 3.0 provides up to 152 Mbps of downstream bandwidth and up to 108 Mbps of upstream (with four bonded channels).[130]

As noted above, cable systems provide shared bandwidth in the last mile, with multiple homes sharing a fixed amount of bandwidth at a single node. Ultimately, bandwidth-per-customer is driven both by the number of customers (and their usage) per node and the total bandwidth available per node. Given typical busy-hour usage rates (see Network Dimensioning section), users on a DOCSIS 2.0 system can receive up to 10 Mbps;[131] under DOCSIS 3.0, that number will increase substantially, to 50 Mbps.[132] Actual figures, however, depend on a large number of variables, including not only the DOCSIS specification, but also spectrum allocation and use and the number of homes per node.

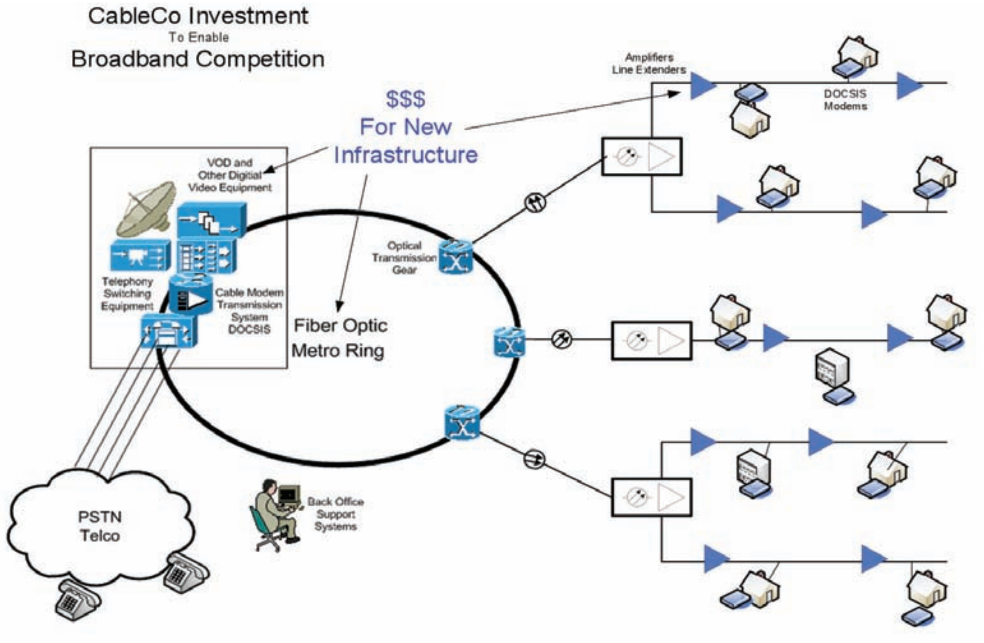
Impact of cable-system spectrum

Spectrum in cable plants, as in over-the-air broadcasting, is a measure of how much "real estate" is devoted to transmitting signals. Most two-way cable plants use 450 MHz or more of spectrum, with many having been upgraded to provide 750 MHz or more. Each analog television channel requires 6 MHz of spectrum. Exhibit 4-BJ shows the spectrum allocation for a typical 750 MHz, DOCSIS 2.0 deployment.

Note that all upstream communications take place in low-frequency spectrum, below 52 MHz. FCC rules requiring that broadcast Channel 2 be carried on Channel 2 of the analog spectrum (54 – 60 MHz) established the low end of downstream spectrum.[133] Cable companies' outside plant equipment is tuned for this: band-pass filters allow upstream traffic only below 52 MHz. In addition, band-pass filters in consumer electronics are tuned to block potentially large amplitude upstream signals only below 52 MHz.

The 52-MHz upper bound on upstream spectrum places limits on upstream bandwidth. First, because it would require

Exhibit 4-BI:
Upgrades to Enable Broadband Services



changes to cable plant and consumer electronics, adding spectrum for upstream use above the 52 MHz would be difficult and costly. In addition, interference at low frequencies (e.g., from motor noise, ham and CB radio, walkie-talkies) could reduce usable upstream spectrum significantly.[134] While DOCSIS 3.0 allows for the bonding of multiple channels to increase upstream capacity, these other spectrum issues will likely provide real-world limits to upstream capacity.

Downstream bandwidth faces fewer constraints; cable companies can devote higher-frequency 6 MHz channels to downstream capacity. In addition, DOCSIS 3.0 allows carriers to devote four or even eight channels to downstream data communications.

Cable companies use Quadrature Amplitude Modulation ("QAM") to increase the bandwidth transmitted over a given amount of spectrum (the Mbps-per-MHz), with typical deployments featuring 16, 64 or 256 QAM. In typical DOCSIS 2.0 deployments, the downstream direction is 64 or 256 QAM and the upstream is 16 QAM. As an example, consider a typical DOCSIS 2.0 deployment with one 6 MHz downstream channel at 64 QAM which delivers approximately 36 Mbps.

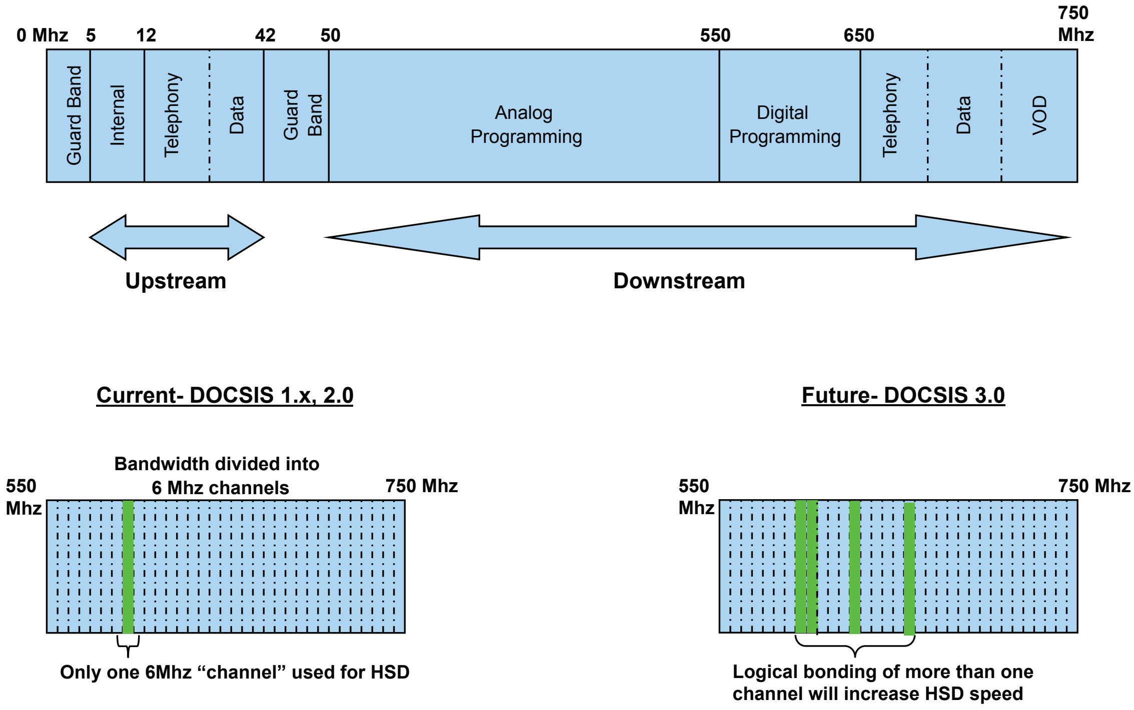
Cable companies can create additional capacity for downstream bandwidth (or for additional broadcast video channels, or other services like video-on-demand) through a number of means. The most obvious may be to increase the frequency of the cable plant, but this requires extensive upgrades in outside plant and is often very expensive.

There are a number of less expensive options available. As discussed above, going from DOCSIS 2.0 to DOCSIS 3.0 allows the cable system to devote more frequency, assuming it can be made available, to data while keeping the plant total unchanged. Cablevision estimated the cost of its DOCSIS 3.0 rollout at about $70 per home passed (there may be additional success-based expense, e.g., CPE). Scale economies may bring that number 10-20% lower for larger MSOs.[135]

Another option is Switched Digital Video (SDV). In the current HFC architecture, all video channels are sent to all subscribers with filtering of channels for different subscription services made by the set-top box. SDV transmits only those channels to a given node when those channels are in use by a subscriber. This means that the majority of channels are not transmitted most of the time, thereby using fewer channels in aggregate. SDV is therefore a relatively inexpensive technique to reclaim on the HFC network bandwidth to be used for other purposes. Cisco Systems estimates the cost of SDV at $12-$16 per home passed.[136] A number of MSOs are moving forward with SDV,[137] although concerns exist for third party providers of DVRs like TiVo.[138]

Another approach is analog reclamation. In analog reclamation, often termed "going all digital," cable companies move away from transmitting analog signals entirely. A single analog channel takes up 6 MHz (the equivalent of more than 30 Mbps as noted above); the same spectrum (or bandwidth) can carry 10 digital standard-definition channels or three high-definition channels. Analog reclamation can therefore "add" a substantial number of channels to a typical system. For example, by

Exhibit 4-BJ:
Spectrum Allocation in Cable Plant



moving a fairly typical 85 analog channels to digital, a cable company can free up over 500 MHz of spectrum, providing enough capacity to carry well over 200 digital HD channels. The cost of analog reclamation is estimated at approximately $30 per home passed.[139]

Finally, cable companies could go all-IP, moving away from the current spectrum allocation entirely. A 750-MHz system could provide 4.5 Gbps[140] of all-IP bandwidth, to be shared among all users and all applications. This would require a significant change not only in network architecture for cable companies, but also significant business-process redesign to figure out how to capture revenue from an all-IP network.

Impact of homes per shared node

As noted above, cable capacity is shared among all users on a given node. Where there are more users, bandwidth is shared more widely and individual users will, on average, have less capacity. By splitting nodes, cable companies can reduce the user-load per node and increase the capacity per user. Some cable companies have been splitting nodes aggressively, moving from 1,000 homes per node to 100 homes per node or fewer.[141] Cisco estimates the cost of splitting a node at approximately $1,500.[142] Assuming 300-400 homes per node puts the cost at approximately $50 per home passed.

As node-splitting continues, HFC networks will reach the point where the run of coaxial cable is quite short—short enough that there is no need for active electronics in the coaxial part of the network. These so-called passive nodes often have roughly 60 homes per node,[143] but the driver is the linear distance covered by the coaxial cable, not the number of homes. Removing active electronics from the field, however, will yield a network that is more robust and that requires less maintenance.

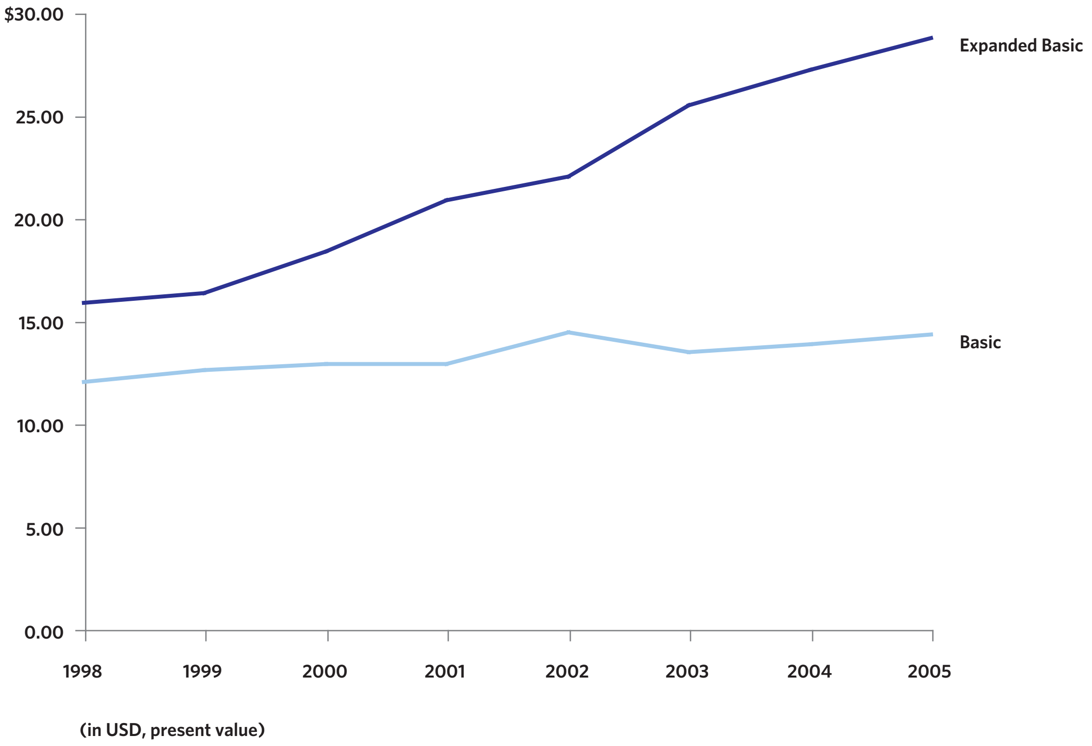
Economics

The economics of providing broadband service over cable plant are driven largely by the presence of existing network. Where networks exist, and costs are sunk, broadband economics are very attractive. In other areas, where one examines greenfield builds, the economics can be far more challenging. Since the network capabilities of an HFC network far exceed the target speed set forth in the plan, the unserved are all in greenfield areas where the investment gap of HFC is much larger than that of DSL or fixed wireless.

Existing cable deployments were funded by video

As noted earlier, cable networks were originally designed to offer video service. And, in many markets, cable companies were granted exclusive franchise agreements. As a result, the video business over

Exhibit 4-BK: Cable Video ARPU Over Time[144]—Cable Pricing



time has accounted for a large portion of cable-company revenue, providing a network on which to build the incremental broadband business. The video business, in fact, has enjoyed increasing ARPU over a long period of time (see Exhibit 4-BK), providing much of the capital for HFC investment in infrastructure. Of all subscribers who have access to these services, 88% subscribe to expanded basic and 55% subscribe to digital programming.[145]

Incremental broadband upgrades

As noted above, large investments have been made in cable systems already, principally funded by the video business. Further, as shown in Exhibit 4-BL, the incremental expense for upgrades—each aspect of which has been discussed previously—is low given the significant sunk investment already in the cable plant. As a consequence, cable systems are relatively well positioned to meet

Exhibit 4-BL:
Upgrade Costs for Cable Plant

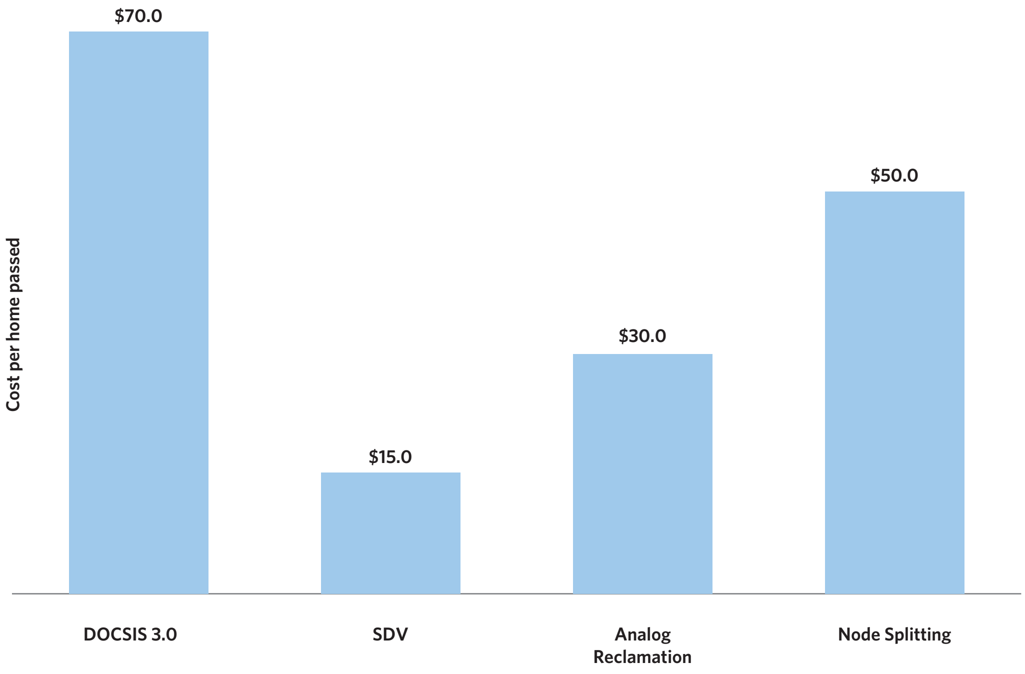
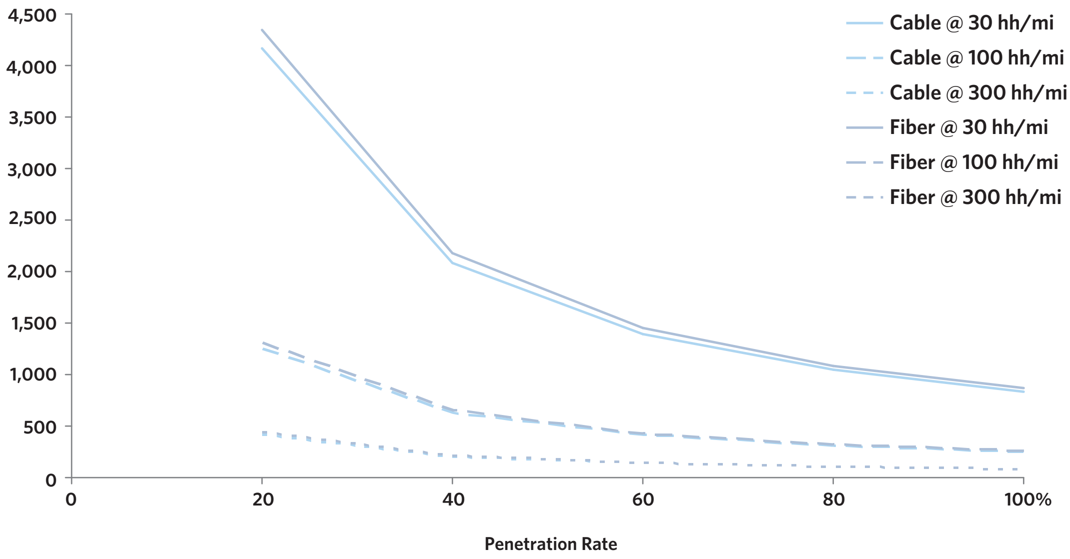


Exhibit 4-BM:
Outside Plant Cost, FTTP or RFoG vs. HFC—Relative Capex Costs of Cable and Fiber, Excluding Headend Equipment[146][147]



Dollars of capex/sub/mile; penetration rate future growth in bandwidth demand.

In summary, where existing two-way cable plant exists, upgrade costs to provide high-speed service of up to 50 Mbps are low: roughly $165 per home passed.

Greenfield deployments

Building a new cable plant requires deploying a new outside plant and some form of headend to aggregate and distribute video and data content. The choice of technology for the outside plant is not an obvious one: providers can deploy a network that is a traditional hybrid fiber-coax plant, or one that is all fiber, a so-called RF over Glass (RFoG) plant.

When connecting a home for the first time—effectively adding a completely new last-mile connection—providers are likely to use the most future-proof technology possible. It would make little sense to deploy, for example, a brand-new long-loop twisted-pair network. The choice is less clear when comparing HFC and RFoG (or any other FTTP deployment). As Exhibit 4-BM shows, HFC and fiber networks have similar outside plant costs, which are mostly a function of labor costs. However, RFoG and FTTP deployments, by removing all active electronics from the outside plant, have lower ongoing expenses.

Estimates suggest these opex savings are approximately $20 per home passed per year.[148] While this may not sound large at

Exhibit 4-BN:
HFC Plant Diagram—CableCo HFC Architecture

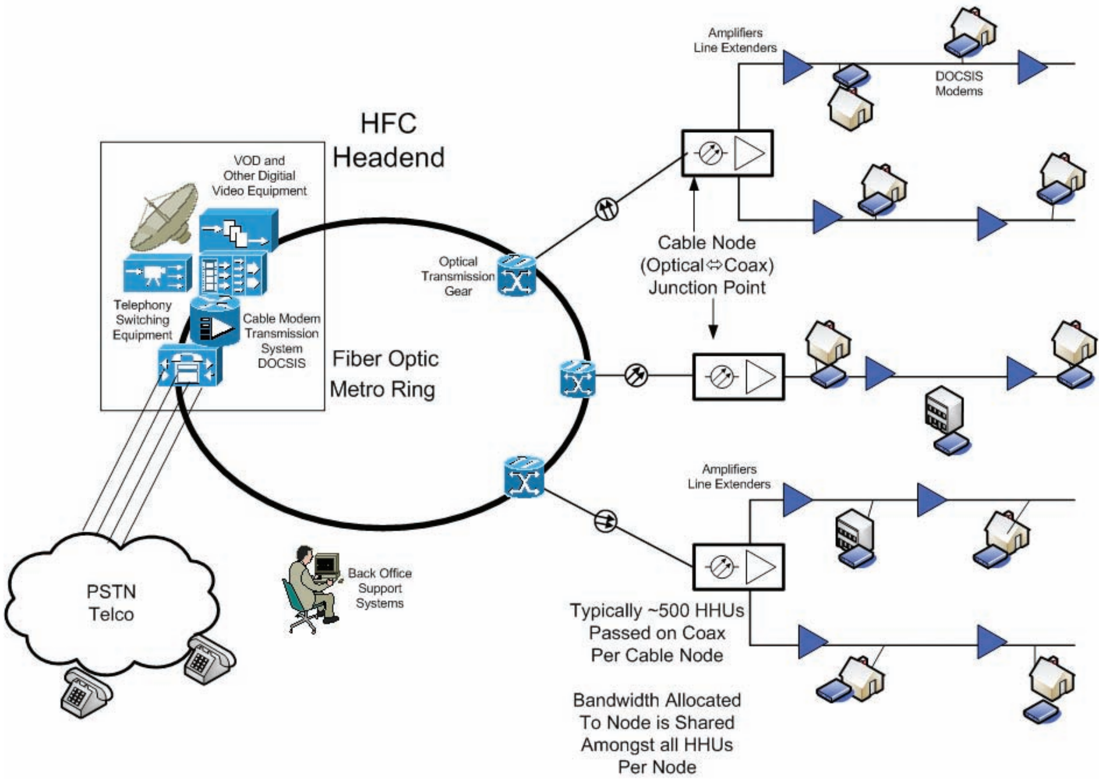


Exhibit 4-BO:
Data Sources for HFC Modeling

Material Costs	Source
Splitter	Cable ONE (filed under protective order)
Fiber Node	Cable ONE (filed under protective order)
CMTS	Hiawatha (filed under protective order)
Up Stream Reciever	Hiawatha (filed under protective order)
Cable Modem	Hiawatha (filed under protective order)
Drop	Hiawatha (filed under protective order)
Tap	Cable ONE (filed under protective order)
Coaxial Cable	Cable ONE (filed under protective order)

the outset, it adds up over the life of the network. A majority of these savings come from power required for active components, system balancing and sweeping, and reverse maintenance.

The other major expense for a new network, whether HFC or RFoG, is the cost of a drop per subscriber. RFoG drops are approximately $175 more expensive than HFC drops.[149] As a consequence, the initial cost of connecting a subscriber is higher for RFoG relative to HFC.

However, the aggregate cost of a typical HFC customer will exceed, in less than 10 years, the aggregate cost of serving the same customer using RFoG. In other words, the operational savings from having an all-passive plant outstrip the initial cost savings from deploying an HFC system. It is reasonable to expect RFoG and FTTP drop costs will decline over time as deployments become increasingly mainstream and the industry attains greater scale. Accordingly, it is likely that as RFoG and FTTP deployments become cheaper, this break-even period will become even shorter. As a consequence, a greenfield developer of wireline infrastructure is more likely to choose RFoG or FTTP over HFC going forward, given both lifecycle cost and future-proofing benefits of an all-fiber network.

Modeled cost assumptions

We modeled the incremental costs of extending HFC networks into unserved areas with a high degree of granularity. Exhibit 4-BN shows the basic network elements of an HFC network and Exhibit 4-BO lists the sources for assumptions used in the model.

NETWORK DIMENSIONING

In order to ensure that the investment gap is reflective of the full costs of deployment, it is important to dimension the network to be able to deliver target broadband speeds during times of peak network demand. In particular, we need to determine that we properly model the capacity of every shared link or aggregation point in order to ensure that the network is capable of delivering required broadband speeds.

However, data flows are far more complex to characterize than voice traffic, making relatively straightforward analytical solutions of aggregated data traffic demand very challenging; this will be discussed ahead in **Complexities of data-network dimensioning**. Our approach is to describe typical usage patterns during times of peak demand, which we then use to estimate the network capacity needed to ensure a high probability of meeting end-user demand; this is discussed at the end of this chapter in **Capacity considerations in a backhaul network**.

Complexities of data-network dimensioning

Network dimensioning will not guarantee that users will always experience the advertised data rates. Note that even traditional voice networks are designed for a certain probability of being able to originate a phone call (e.g. 99% of the time in the busy hour for wireline, 95% for cellular) and a certain average sound quality. For dimensioning IP data networks, it may be useful to point out the difficulty of applying traditional voice traffic engineering principles to IP data-traffic flow. Dimensioning IP data networks is intrinsically more complex than dimensioning voice networks.

To properly dimension a traditional circuit switched voice network, it is typical to use the Erlang B formula that allows an operator to provision the number of circuits or lines needed to carry a given quantity of voice traffic. This is a fairly straightforward process mainly because the bandwidth consumed for each call is effectively static for a given voice codec in the busy hour. In fact, technology has enabled carriers to encode speech more efficiently so a voice conversation today may actually consume much less bandwidth than a voice conversation did 20 years ago. Nonetheless, the three basic variables involved are:

- Busy Hour Traffic, which specifies the number of hours of call traffic there are during the busiest hour[150]
- Blocking, or the failure of calls due to an insufficient number of lines being available and
- The number of lines or call-bearing TDM circuits needed in a trunk group

As long as the average call hold time is known and the operator specifies the percentage of call blocks it is willing to accept in the busy hour, the number of trunks is easily calculated using the Erlang B formula.

For broadband Internet access, however, there is much more uncertainty. Unlike voice telephony, Internet traffic is quite complex, multi-dimensional, and dynamic in the minute-to-minute and even millisecond-to-millisecond changes in its characteristics. Network planning and engineering for broadband Internet are more difficult with higher degrees of uncertainty because of the following principal factors:

- Each application used during an Internet access session, such as video streaming, interactive applications, voice, Web browsing, etc., has very different traffic characteristics and bandwidth requirements.
- End-user devices and applications are evolving continuously at the rate of silicon electronics, as opposed to voice (we continue to speak at the same rate of speech).
- Broadband Internet access supports many different user applications and devices, from streaming high definition video (unidirectional, very high bandwidth), to short messaging (bidirectional, very low bandwidth).
- The scientific community has not yet developed and agreed upon the best mathematical representations for modeling Internet traffic.

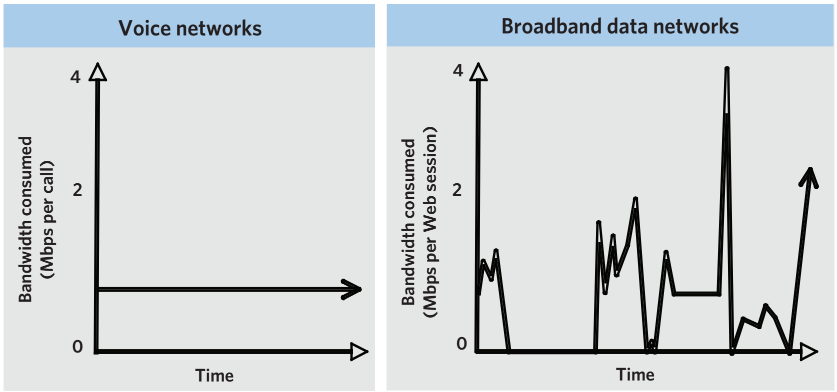
Exhibit 4-BP illustrates the additional complexities of multi-dimensional data traffic verses traditional circuit switched voice traffic. These differences introduce chaotic variables not present in the Erlang traffic model used to dimension voice networks.

Many individual Internet applications are "bursty" in nature. Consider a typical Web-surfing session, in which a user will "click" on an object, which results in a burst of information painting the computer screen followed by a lengthy period of minimal data transmission, followed by another burst of information. The instantaneous burst may occur at several Mbps to paint the screen, followed by many seconds or even many minutes with essentially no traffic, so the average transmission rate during a session may only be a small percentage of the peak rate. This type of traffic does not lend itself to modeling by the traditional mathematical models such as the Erlang formulas used for voice traffic; it can be considered fractal and chaotic in nature, as shown in Exhibit 4-BP. By contrast, the viewing of a high-definition video involves streaming content in one direction steadily at several Mbps. And a typical Skype video conference may involve a two-way continuous streaming of information but at only at around 384 kbps in each direction.[151]

Computer processing keeps improving at the rate set forth by "Moore's Law," as does the price/performance of storage. This doubling every two years enables much better performance of existing applications (e.g., very refined graphics instead of simple pictures, high definition and now even 3D-HD instead of NTSC video or standard-definition TV), as well as new applications that could not have existed several years earlier. So as long as silicon chips and electronics continue to improve, network providers may see more and more demands placed on the network by individual user applications. Moreover, behind an individual network interface, the subscriber is likely to have a local area network with several users running various applications for which traffic characteristics vary widely and with variable timescales such that the cumulative effect is a highly variable and unpredictable traffic flow into the network.

To conclude this discussion, we note that traffic engineering is based on mathematical models involving probabilities and statistics. As noted earlier, modeling voice traffic makes use of the simple inputs of average duration of call, bits-per-second used by the voice encoding scheme and number of call originations per hour. This has enabled scientists and engineers over the years to develop reliable mathematical models that correlate well with real-world experience. However, for Internet traffic, the number of variables, the magnitude of variation of these variables and the statistical nature of the variables have made it difficult for the scientific community to develop

Exhibit 4-BP:
Differences Between Voice and Data Networks



Factor	Relevance to voice network dimensioning	Relevance to data network dimensioning
Number calls/data sessions	Number of calls generated in the busy hour	Number of sessions invoked by user or users during busy hour
Average call/session duration	Average duration of each call (usually in minutes)	Duration of application session (range from hours to milliseconds)
Variation in call/session duration	**Almost all calls measured in minutes with little deviation**	**Variable session duration between applications ranging from minutes to seconds to milliseconds**
Bandwidth intensity (amplitude)	**N/A- bandwidth consumed for each call is static at 64 kbps**	**Bandwidth consumed per application session (Variable based upon active application)**
Variation in bandwidth intensity	**N/A (see previous)**	**Wide variation of bandwidth consumption for different applications**
Calls Blocked / Congestion threshold during busy hour	"blocked" calls tolerated in the busy hour (typically one call block per 100 call attempts)	Minimum bandwidth at which packets are lost

a well-accepted mathematical model that can predict network traffic based on end-user demand. In fact, the underlying behavior of the traffic is still the subject of research and debate.

Consequently, it is very difficult to statistically characterize the traffic per subscriber or the aggregated traffic at each node in the network. And without such a characterization, we cannot dimension the network, *ex ante*, with the level of precision necessary to ensure subscribers will always experience the advertised data rates.

Generally speaking, Internet traffic engineers do not drive the expansion of network capacity from end-user demand models. Rather, they measure traffic on network nodes and set thresholds to increase capacity and preempt exhaust for each critical network element. Adtran remarks in its filing: "While sustainable speed can be measured in existing networks, it is nearly impossible to predict in the planning stages due to its sensitivity to traffic demand parameters."[152]

Still, we need to engineer our network model to deliver a robust broadband experience, capable of delivering burst rates of 4 Mbps in the download and 1 Mbps in the upload even without being able to measure traffic on actual network elements. The approach to do this is to provide sufficient capacity to provide a high probability of a robust user experience (as discussed in the next section). For this, we need a metric that characterizes traffic demand. One such metric that measures traffic demand is the Busy Hour Offered Load (BHOL) per subscriber.[153]

Capacity per user: busy hour offered load (BHOL)

The data received/transmitted by a subscriber during an hour represent the network capacity demanded by the subscriber during that hour. This can be expressed as a data rate when the volume of data received/transmitted is divided by the time duration. BHOL per subscriber is the network capacity demand or offered load, averaged across all subscribers on the network, during the peak utilization hours of the network.

In general, the total BHOL at each aggregation point or node of the network must be smaller than the capacity of that node in order to prevent network congestion. Alternately, the number of subscribers per aggregation node of the network must be smaller than the ratio of the capacity of the node to the average BHOL. This is the general principle we use to dimension the maximum number of subscribers at each aggregation point of the network model.

The BHOL-per-subscriber depends on a subscriber's Internet usage pattern and, as such, is a complicated overlay of the mix of Internet applications in use, the bandwidth intensity of each application and the duration of usage. But, for practical engineering purposes, the average BHOL-per-subscriber can be derived from monthly subscriber usage. Typically, 12.5% to 15% of daily usage happens during the busy hour.[154] We recognize that very high monthly usage on the same connection speeds usually results from increased hours spent online, outside of the busy hours, rather than an increased intensity of usage during the busy hours. As such, very heavy usage may not quite lead to the same proportionate increase in BHOL. However, for the purposes of our network dimensioning, we shall make the simplifying (and conservative) assumption that the effect is proportionate.

Current usage levels and corresponding BHOLs for different speed tiers are shown in Exhibit 4-BQ. Observe that the mean usage is more than five times that of the usage by the median or typical user. In fact, a small percentage of users generate an overwhelming fraction of the network traffic as shown in Exhibit 4-BR. This phenomenon is well known and is discussed in more detail in Omnibus Broadband Initiative, Broadband Performance.[155] For example, the heaviest 10% of the users generate 65% of the network traffic. So, if we were to exclude the capacity demand of these heaviest users, the BHOL of the remaining users would be far lower. For example, by excluding the heaviest 10% of the users, the BHOL by the remaining 90% is only 36-43 kbps. In Exhibit 4-BS, we show the impact on the BHOL by excluding different fractions of the heaviest users. For comparison, we also show the BHOL for the median or typical user.

Suppose we want to dimension a network that will continue to deliver 4 Mbps to all users even after the next several years of BHOL growth. In order to estimate the future BHOL, we first note that average monthly usage is doubling roughly every three years as discussed in Omnibus Broadband Initiative, Broadband Performance.[156] Next, given the significant difference between mean usage and the typical or median user's usage, it is likely that the service provider will seek to limit the BHOL on the network using reasonable network management techniques to mitigate the impact of the heaviest users on the network. For example, an Internet service provider might limit the bandwidth available to an individual consumer who is using a substantially disproportionate share of bandwidth and causing network congestion. Exhibit 4-BS shows the BHOL for possible scenarios, ranging from dimensioning for the typical user to mean usage. For our network dimensioning purposes, we shall use a BHOL of 160 kbps to represent usage in the future. Thus, this network will not only support the traffic of the typical user, but it will also support the traffic of the overwhelming majority of all user types, including the effect of demand growth over time. It is also worth noting that the additional cost of adding capacity on shared links, as described throughout this paper, is low.

Capacity considerations in a backhaul network

Operators of IP broadband networks must provide a consistent, reliable broadband experience to consumers in the most cost-effective way that meets the consumer broadband requirements set forth in the Broadband Plan: 4 Mbps downstream and 1 Mbps upstream of actual speed.

An important consideration for an economical deployment of affordable broadband networks is proper sizing and dimensioning of the middle- and second-mile links. A fundamental element in the design of all modern packet-switched networks is "sharing" or "multiplexing" of traffic in some portions of the network to spread costs over as many users as possible.[157] In other words, network operators can take advantage of the network capacity unutilized by inactive applications and/or users by dynamically interleaving packets from active users and applications thus leading to a better shared utilization of the network. This is commonly known as statistical multiplexing.

This ability to dynamically multiplex data packets from multiple sources contributes to packet-switched networks being more

Exhibit 4-BQ:
Monthly Usage and BHOLs by Speed Tier

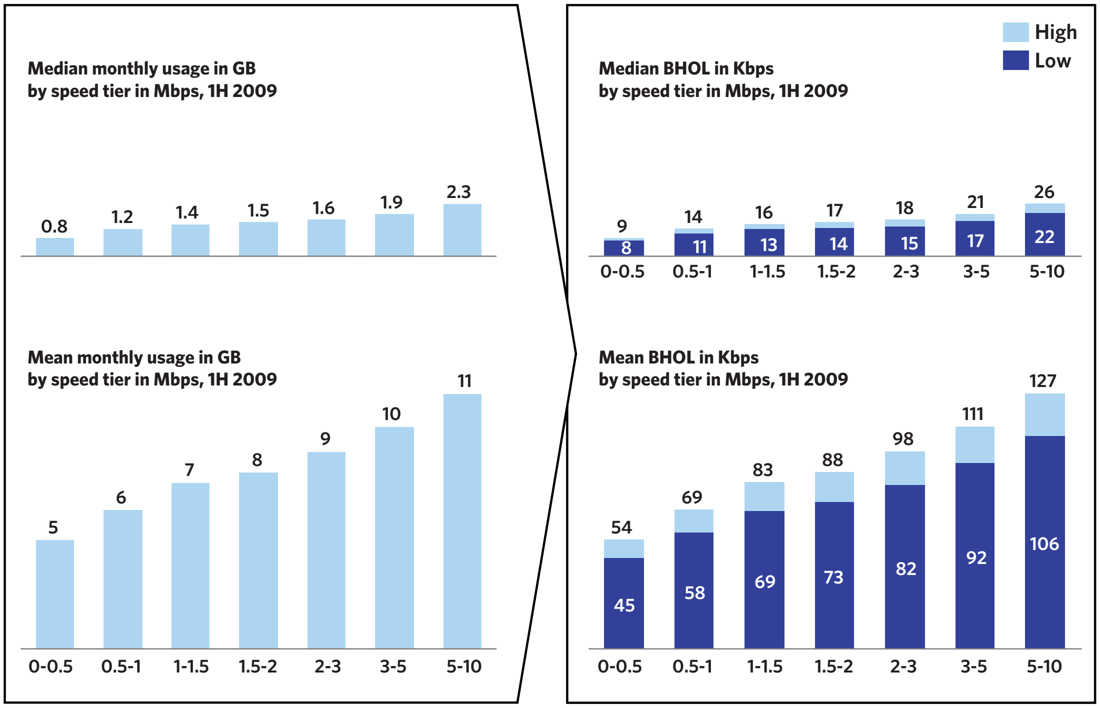
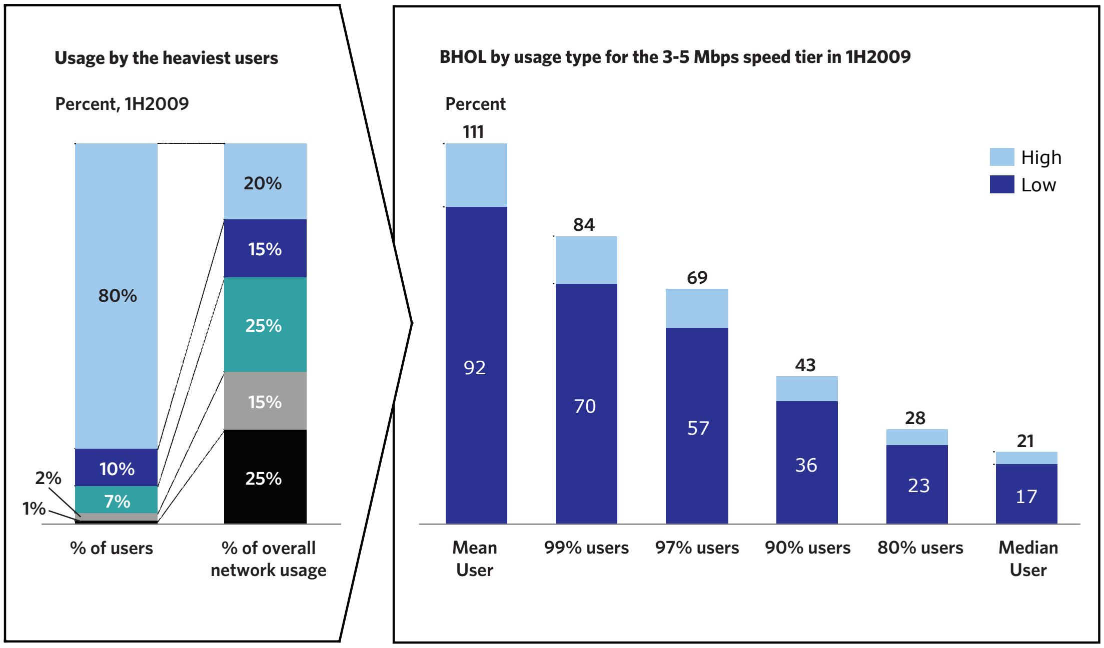


Exhibit 4-BR:
Usage by Tier and BHOL



efficient and economical than circuit-switched networks. Shared network resources are the principle of network "convergence" in practice. Voice, video and data applications like Web browsing and other applications noted above are now all packetized and transmitted using the same network transmission facilities.

Of course there is a downside to shared networks, which are typically oversubscribed in order to exploit the benefits of statistical multiplexing. Oversubscription refers to the fact that the maximum aggregate demand for capacity at a shared link or node in the network can exceed the link or node capacity. Thus, there is a risk, however small, that the total traffic presented at a given time might exceed transport resources in a way that will, in turn, result in congestion, delay and packet loss.

Even though it is challenging, *a priori*, to accurately characterize the user experience on a network because of the complexity of characterizing the traffic per subscriber, we used some available analytical tools to validate the network dimensioning assumptions in our model. Specifically, in Exhibit 4-BT,

Exhibit 4-BS:
Expected Future BHOL in Broadband Network Dimensioned to Deliver 4 Mbps—Expected BHOL in kbps for Different Usage Types in 2015

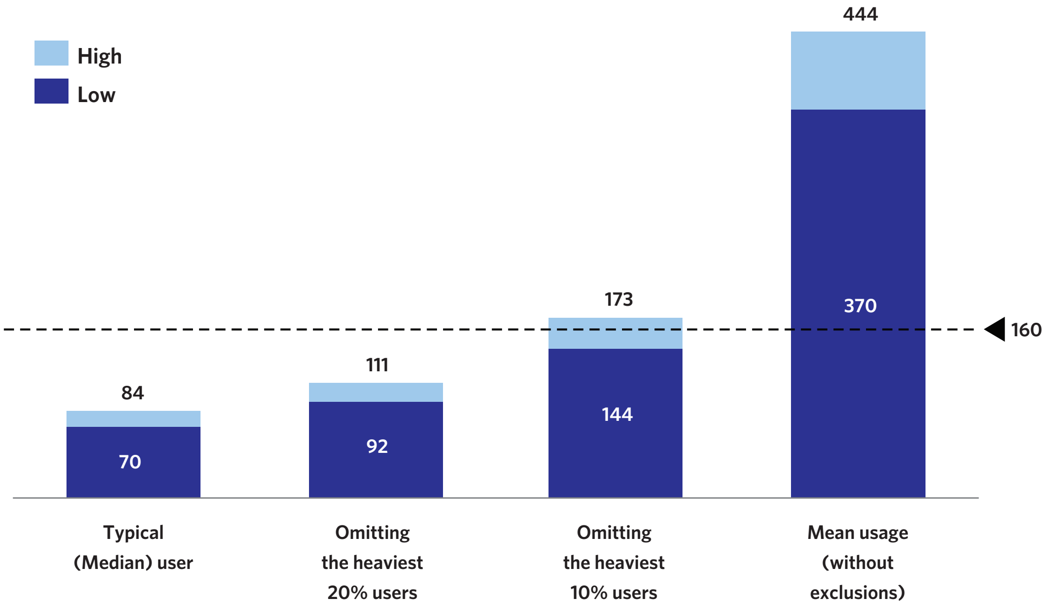
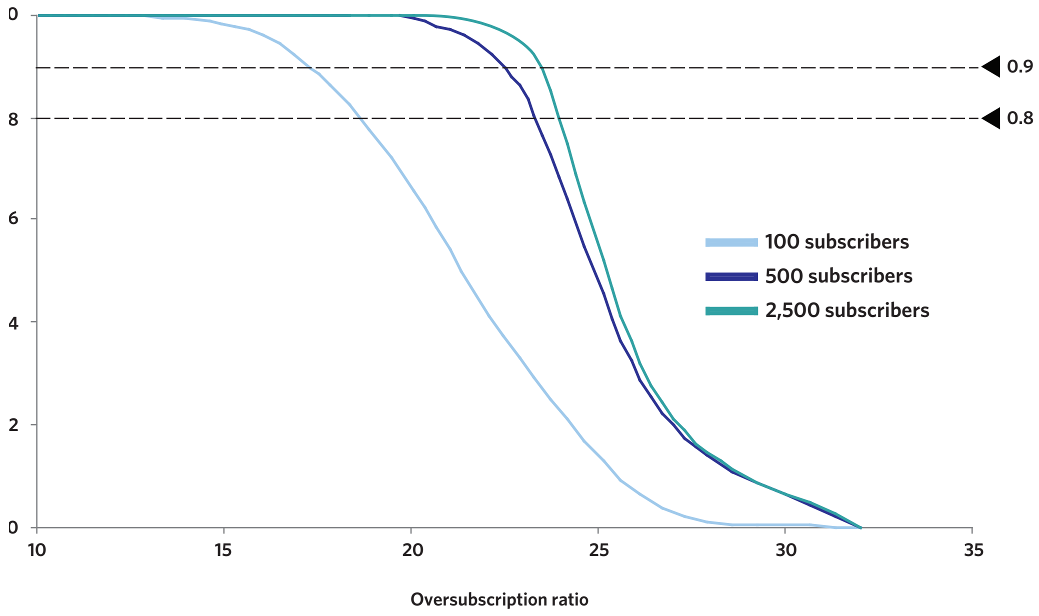


Exhibit 4-BT
Likelihood of Achieving a Burst Rate Greater Than 4 Mbps at Different Oversubscription Ratios with a Varying Number of Subscribers[158]



we show the likelihood of being able to burst at rates greater than 4 Mbps on a shared *wired* or *satellite* link at different oversubscription ratios. For convenience, we shall refer to this likelihood as simply "burst likelihood."

In Exhibit 4-BT, the case with 100 subscribers is meant to represent a typical HFC node with ~100 subscribers; the 500 and 2,500 subscriber curves, on the other hand, represent a DSLAM with ~500[159] and a satellite beam with ~2,500 subscribers, respectively.

We use this chart to validate the network dimensioning assumptions in our model. For example, the chart shows that for a burst likelihood of 90%, the maximum oversubscription ratio on a link with 100 subscribers is approximately 17. Recall that oversubscription ratio of a link of capacity *C* Mbps with *N* subscribers who have an actual data rate of *R* Mbps is:

$$\text{Oversubscription ratio} = \frac{\text{(Number of subscribers) x (Actual Speed)}}{\text{(Link Capacity)}} = \frac{N \times R}{C}$$

That implies that the link capacity must be greater than approximately 23.5 Mbps. Since the capacity of a DOCSIS 2.0 HFC node is about 36 Mbps, we conclude that a single DOCSIS 2.0 node, which serves about 100 subscribers can deliver our target broadband speeds with high likelihood. We can use the same approach to validate the dimensioning of shared links and aggregation points in other networks like DSL, Satellite and FTTP.[160]

We recognize that the results shown in the chart are based on certain traffic demand assumptions,[161] and that these assumptions may not hold in practice. Still, given our conservative choice of parameters in our network models, these results indicate that the network will support the required broadband speeds with very high probability. In reality, network operators may monitor traffic levels at different links within their networks and engineer their respective oversubscription ratios to ensure that capacity in the shared portions of the network is available to support offered service levels; in this case, 4 Mbps download and 1 Mbps upload in the busiest hours of the network.

One very interesting implication of the traffic simulation represented in Exhibit 4-BT is that higher oversubscription rates for the larger number of subscribers mean that capacity can grow more slowly than the number of subscribers. This is due to improved statistical multiplexing with increased number of users. For example, adding five times more subscribers, moving from 100 to 500 or from 500 to 2,500 subscribers, requires adding only roughly four times as much capacity to provide the same probability of end-user service. Thus, adding capacity linearly with the number of subscribers, as we assume in our analysis, is a conservative approach that does not account for the full benefits of statistical multiplexing.

MIDDLE-MILE ANALYSIS

Middle-mile facilities are shared assets for all types of last-mile access. As such, the cost analysis is very similar regardless of last-mile infrastructure. The local aggregation point can vary based on technology (e.g., a cable headend, LEC central office or a wireless mobile switching center (MSC)) while the Internet gateway is a common asset. Middle-mile facilities are widely deployed but can be expensive in rural areas because of the difficulties of achieving local scale, thereby increasing the investment gap. On a per-unit basis, middle-mile costs are high in rural areas due to long distances and low aggregate demand when compared to middle-mile cost economics in urban areas.

While there may be a significant affordability problem with regard to middle-mile access, it is not clear that there is a middle-mile fiber *deployment* gap. The majority of telecom central offices (approximately 95%)[162] [163] and nearly all cable nodes (by definition, in a true HFC network) are fed by fiber.

Please note: terms like "backhaul," "transport," "special access" and "middle-mile" are sometimes used interchangeably, but each is distinct. To avoid confusion, "middle-mile transport" refers generally to the transport and transmission of data communications from the central office, cable headend or wireless switching station to an Internet point of presence or Internet gateway as shown in Exhibit 4-BU.

Middle-Mile Costs

The middle-mile cost analysis concludes that the initial capex contribution to serve the unserved is 4.9% of the total initial capex for the base case. That is, the modeled cost for the incumbent or lowest cost provider to build these facilities incrementally is estimated at approximately $747 million.

In order to accurately model the costs of middle-mile transport, particularly in rural, unserved areas, we examined all available data about the presence of reasonably priced and efficiently provided, middle-mile transport services. However, we recognize that broadband operators who rely on leased facilities for middle-mile transport may pay more for middle-mile than broadband providers who self-provision. This is discussed further within the subsection titled **Sensitivity: Lease vs. Build**. Thus, in a hypothetical case in which leasing facilities turns out to be four times the modeled incumbent build cost, the resulting middle-mile contribution could be estimated as high as 9.8% of the total initial capex for the base case, or approximately $1.6 billion. The following discusses the analysis done to ensure our model accurately captures the appropriate costs.

Broadband networks require high-capacity backhaul, a need that will only grow as end-user speed and effective load grow. Given the total amount of data to be transmitted, optical fiber backhaul is the required middle-mile technology in most instances. Once the transport requirement reaches 155 Mbps and above, the only effective transport mode is at optical wavelengths on a fiber optic-based transmission backbone. Plus, while the initial capital requirements of fiber optic systems are substantial, the resulting infrastructure provides long-term economies relative to other options and is easily scalable.[164] Microwave and other terrestrial wireless technologies are well suited in only some situations such as relatively short middle-mile runs of 5-25 miles. However, microwave backhaul may be a critical transport component in the second mile, primarily for wireless backhaul as discussed in detail in the wireless section.

Approach to Modeling Middle-Mile

The costs associated with providing middle-mile services are heavily dependent on the physical distances between network locations. Therefore, the approach to modeling middle-mile costs revolves around calculating realistic distance-dependent costs.

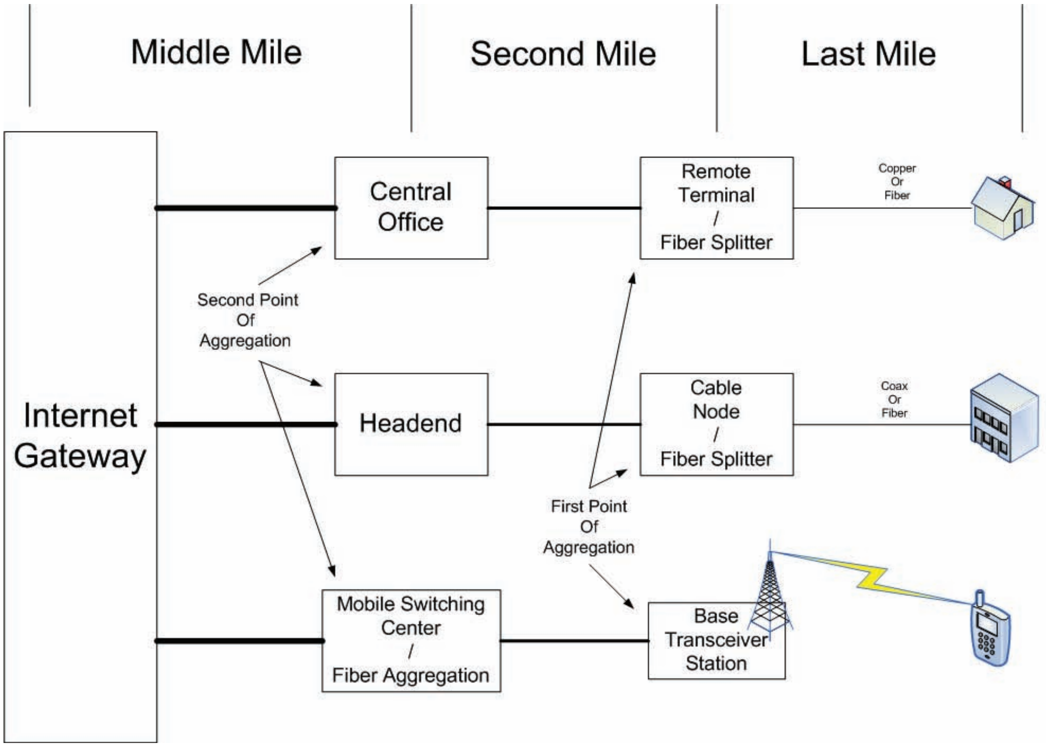
Our focus is on ILEC central offices given the availability of information on their locations. Starting with the location of ILEC central offices and the network homing topology, we estimated the distances and costs associated with providing middle-mile service. Since the cost estimate is distance-dependent, calculating the cost requires making an assumption about the routing used to connect LEC offices as will be discussed below. This same approach—mapping known fiber locations and their logical hierarchy to calculate the distances and costs for providing middle-mile service—could apply equally well to cable headends, or CAP, or IXC POPs given thorough information on their locations. However, publically available information on exact locations of cable headends, private IXC fiber POPs and other entity fiber node locations is limited; thus, the focus exclusively on ILEC fiber suggests that this analysis will significantly underestimate the presence of fiber around the country.

The following sections describe the process of collecting and processing data, along with the cost inputs and assumptions used in the model. The gap calculation assumes internal transfer pricing: i.e., the incremental cost the owner of a fiber facility would assign to the use of the fiber in order to fully cover both the cash cost and opportunity cost of capital. Importantly, as discussed below, this cost may be substantially lower than the price a competitor or other new entrant, like a wireless provider, may be charged for the same facility.

Middle-Mile Data Collection

- Identify all ILEC Central Offices (CO) and obtain each Vertical and Horizontal coordinates (analogous to latitude and longitude)

Exhibit 4-BU:
Breakout of Middle, Second & Last Mile



- Identify all Regional Tandems (RT) within their respective LATA locations and determine which Central Office subtends which RT

After the middle-mile anchor node locations and hierarchical relationships between the nodes are captured, the distances between these nodes must be calculated so that the distance-dependent cost elements can be applied appropriately.

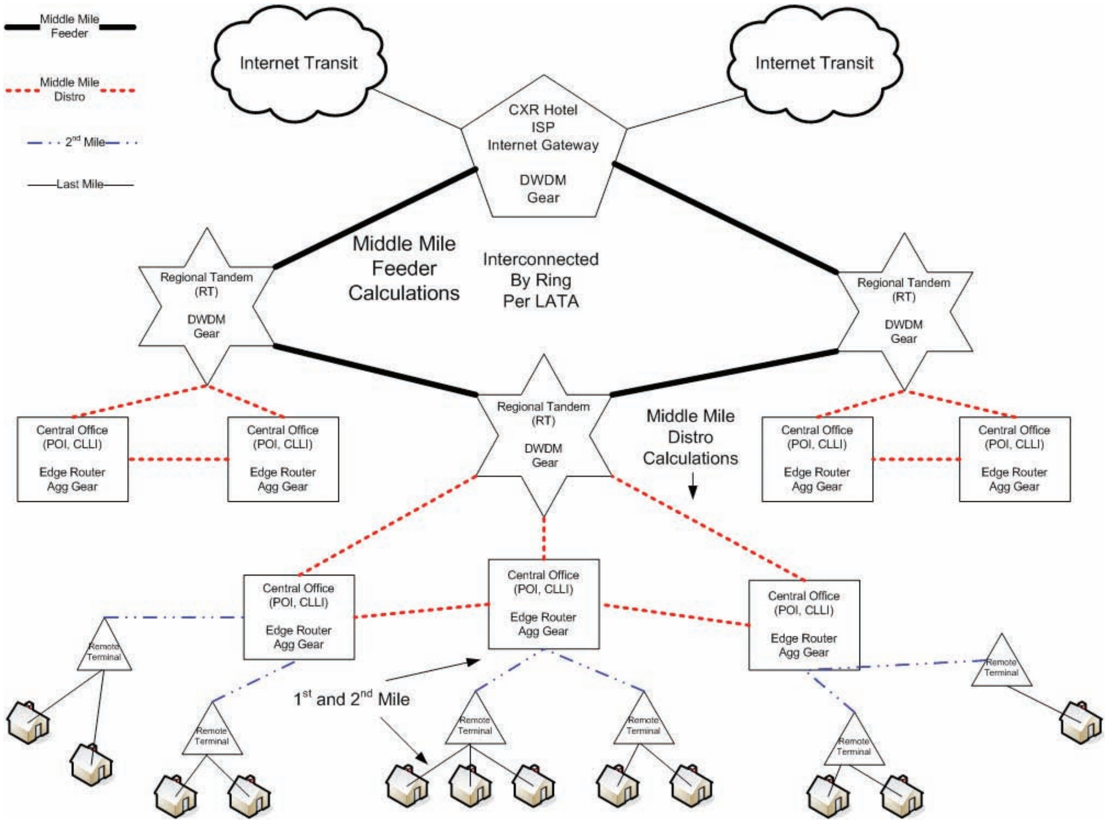
Middle-Mile Processing Steps

- Each subtending CO is assigned to its nearest RT to create the initial relation of COs to RTs.
- COs are then routed to other COs that subtend the same RT using shortest distance routing back to their respective RTs (i.e., we calculate a shortest-distance route to connect the COs to their respective RTs). To achieve this route, the process starts at the CO coordinate farthest from the appropriate RT and selects the shortest CO-to-tandem distance based on airline mileage. The CO starting point is prohibited from routing back to itself and must route toward the tandem. This approach minimizes the amount of fiber needed.
- The RTs within a given LATA are routed together in a ring.
  - The shortest ring is chosen by comparing the distances between RTs and selecting the shortest ring distance within each LATA; this distance is then used for the middle-mile feeder calculations.
  - It is assumed that the Internet gateway peering point is located on the RT ring. In this manner, all COs that are connected to the RT ring have access to the Internet.
  - Internet gateway sites are assumed to be located in regional carrier collocation facilities (known commonly as "carrier hotels"). We estimate there are some 200 of these located regionally throughout the United States.
- The middle-mile calculation is run state-by-state and stored in one central distribution and feeder table.

Tree vs. Ring architecture

- The design depicted in Exhibit 4-BV represents a hub-and-spoke hierarchy interconnected via closed rings. The model contemplates that a typical ILEC would likely interconnect end office, tandems and regional tandems in redundant-path "ring architecture."

Exhibit 4-BV:
Topology Used for Middle-Mile Cost Modeling



- ➤ By assumption, the fiber link and distance calculations between COs and RTs are increased by a factor of 1.8 to account for the redundant, geographically diverse, fiber spans that would be required in ring architecture as opposed to a hub-and-spoke architecture. Note that this assumption could be fairly conservative (i.e., assuming higher than necessary costs) given degree of interconnection among the COs.

Cost Allocations on Facility

These middle-mile facilities by nature and design are engineered as shared infrastructure facilities that aggregate end-user traffic and transport traffic to regional Internet gateways. The cost of a particular middle-mile facility cannot be allocated solely to the consumer broadband users of that facility. Since that facility is shared with other provider services such as residential and enterprise voice, wholesale carrier services, enterprise data services and other management services utilized by the provider, the cost needs to be allocated appropriately.

- ➤ The model assumes that the total cost of the facility is allocated thus: 1/3 for service provider voice service, 1/3 wholesale and enterprise carrier services and 1/3 consumer broadband services. This is an estimation of the allocation of traffic within a typical ILEC transport environment, but the allocation of cost to any single product or customer group is speculative at this point.
- ➤ The model only calculates the consumer broadband services portion of the facility and assumes that BHOL doubles roughly every three years.

Nationwide Middle-Mile Fiber Estimation

Data sources about fiber routes or even the presence of fiber in a given LEC office are extremely limited. Consequently, we created our best approximation of fiber facilities available for middle-mile service; detail on that process is provided below. The overwhelming majority of telecom central offices (approximately 95%)[165] [166] and nearly all cable nodes (by HFC definition) are fed by fiber.

The map shown in Exhibit 4-BW is an illustration of the paths of fiber used in our calculation to connect ILEC offices (and only ILEC offices). While it is based on as much real and calculated data as are available, we had to make a number of assumptions about the specific routes. Therefore, while we believe this map represents an accurate, if conservative, estimate of middle-mile fiber, it is not appropriate for network-planning purposes.

The diagram in Exhibit 4-BW is an estimation based on:

- ➤ Known locations of ILEC CO
- ➤ Topology based on a Gabriel Network[167] topology was considered but likely overestimated the number of links of fiber distribution. Thus, a Relative Network Neighborhood[168] distribution was chosen given the set of points representing the CO locations.
- ➤ Approximately 90% ILEC Fiber CO deployment, which is significantly lower (i.e., more conservative) than most estimates. Exhibit 4-BX, which shows the distribution of fiber-fed CO based on known services available per CO.

Exhibit 4-BW contemplates ILEC fiber only. Estimating the presence of middle-mile fiber based only on the fiber that connects LEC central offices, while excluding the fiber networks of cable companies, CAPs, CLECs and other facilities-based providers, systematically underestimates the presence of fiber. If one imagines overlaying the fiber optic facilities that have been deployed by other entities—such as Tier One IXCs/ISPs (ATT, Sprint, GX, Verizon Business, Level 3, XO, TWTC, etc.); Nationwide and regional Cable Operators (Comcast, Cox, Time Warner, Charter etc); Competitive Fiber Providers (Abovenet, Zayo, Deltacom, 360 Networks, Fiberlight, Alpheus etc.); private fiber deployments (hospitals and institutional); municipal fiber; and utility fiber—it becomes clear that the United States is generally well connected coast-to-coast.

In the limited instances where LEC fiber is not available, Windstream[169] has found that the exchanges typically have the following reasons for lack of deployment:

- ➤ The exchange is an island exchange (i.e., isolated from other exchanges in the LECs footprint) or part of a small, isolated grouping of exchanges;
- ➤ Fewer than 1,000 access lines fall within the exchange; and
- ➤ The closest point of traffic aggregation is more than 50 miles away from the CO.

The combination of a small customer base and long transport distances can make it impossible to build an economic case for fiber deployment.

However, recognizing that fiber-based middle-mile services are physically deployed does not necessarily mean that they are always economically viable in every rural area. The challenge is that access to such fiber may not be available at prices that result in affordable broadband for businesses, residents and anchor institutions, as discussed in the following section.

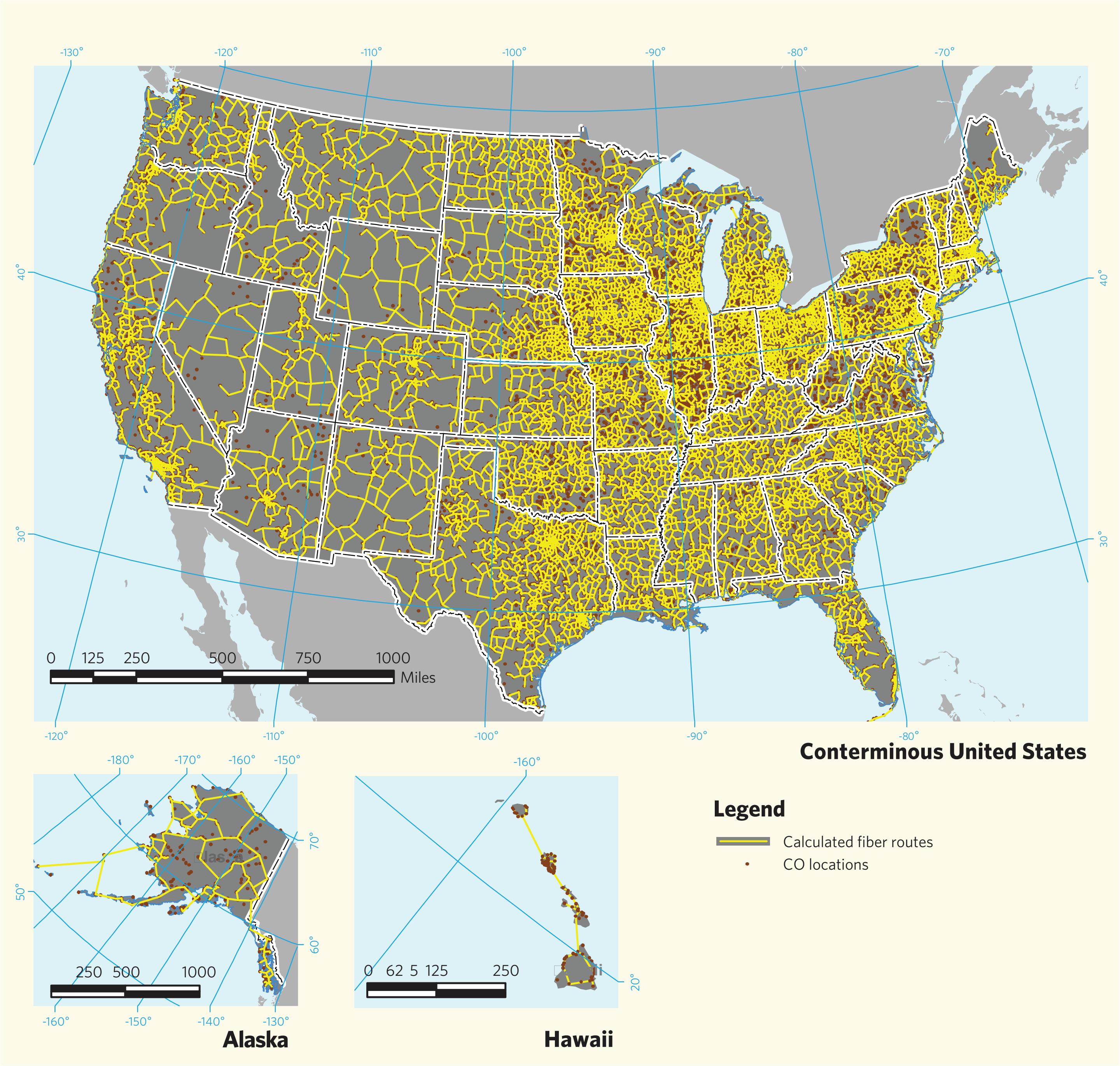
Costs Drivers for Middle-Mile Transport

Transporting data 50 miles or more from a local CO or other access point to the nearest Internet point of presence is a costly endeavor.

The costs of these facilities are proportional to their lengths. In urban or suburban areas, the cost of new fiber network construction varies widely, roughly from $4 to $35 per foot where the largest cost component is installation. The cost range depends on whether the fiber is suspended from utility poles or buried, the number of fiber strands in the cable, right-of-way costs, terrain, soil density and many other factors.[170] In the model, we assume that in rural settings, even for inter-CO transport facilities, 75% would be aerial construction. Of the 25% buried construction, the model calculates fiber burial costs that take into account local terrain, including soil composition.

Providing fiber-based service to low-density areas carries with it higher per-user costs. These costs are driven by larger distances which, even when offset by lower per-foot costs, lead

Exhibit 4-BW:
Calculated Telco Fiber Routes



to higher total cost per link. In addition, there are simply fewer users per link. Given that middle-mile links have very high fixed costs yet low costs associated with adding capacity, larger connections are more cost-effective per bit than smaller links. This is reflected in the prices shown in Exhibit 4-BY.

The low density and demand in rural areas, coupled with the volume-dependent middle-mile cost structure, mean that rural broadband operators do not benefit from the same economies of scale common among providers in denser areas. The distances at issue in unserved areas are much longer than typical

Exhibit 4-BX:
Classification of Central Offices for Creating Fiber Map

special access connections. Moreover, low population density prevents the aggregation of demand that would allow rural carriers to use lower-cost, high-capacity links.[171]

Pricing data are difficult to obtain. Tariffs are widely available but "street prices," including all contract savings and contract-term penalties, are not as readily available. Different discount structures, terms and agreements can cause great variability in middle-mile rates. As part of its COMMENTS ON NBP NOTICE #11, the NTCA provided Exhibit 4-BY that shows that while prices of middle-mile connections are indeed dependent on volume, they also vary widely across providers and geographies.[172] The highest and lowest prices vary by more than an order of magnitude for services below about 100 Mbps.

Exhibit 4-BY illustrates that on a per-unit basis, higher capacity middle-mile facilities are more economical than low-capacity facilities. According to NTCA and NECA filings, the average middle-mile cost contribution per subscriber per month is approximately $2.00 in study areas using middle-mile Ethernet connections of higher than 1,000 Mbps.[173] This can be compared to areas using middle-mile Ethernet connections of less than 10 Mbps, that resulted in monthly middle-mile costs per user of approximately $5.00 or more.[174] Again, these data are consistent with the premise that larger pipes carry lower costs per bit, suggesting the benefit for communities in smaller and less-dense areas to aggregate demand for homes and businesses as much as possible and that long-term commitments to utilize these facilities be in place.

Sensitivity: Lease vs. Build

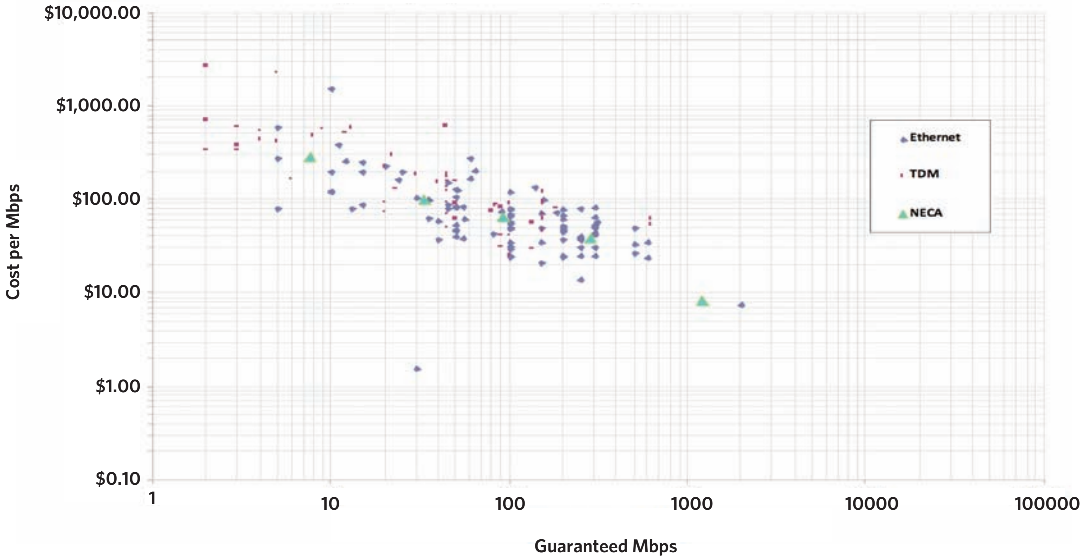
The base case assumes that operators in unserved areas have access to middle-mile transport at economic pricing—cost plus a rate of return. To the extent that middle-mile transport prices exceed this cost-plus pricing model, middle-mile costs can be higher for carriers leasing capacity. The broadband team models the cost to incrementally build middle-mile fiber facilities from scratch to a) understand the overall middle-mile cost contribution for the unserved and b) to establish a baseline middle-mile cost with which to compare to leased middle-mile costs.

The analysis in Exhibit 4-BZ compares middle-mile facility connections of different distances, connection sizes and methods to highlight the lease vs. build decision. Leasing facilities from an incumbent carrier, when properly sized for capacity demand, carries higher costs than the modeled cost for the incumbent provider to build these facilities incrementally. Thus broadband operators who rely on leased facilities for middle-mile may pay more for middle-mile costs than incumbent broadband providers.

To arrive at these estimates, we examine randomly chosen regional routes as shown in Exhibit 4-BZ. Separate "city-pair" routes were selected specifically in rural areas that are homed back to regional carrier collocation facilities (CCF) or "carrier hotels." These particular towns and CCF pairs were selected based upon known locations of CCFs to avoid Tier One MSA access points to best represent rural middle-mile connections. For each route, we calculate the applied tariff rate for the appropriate connection, applying a 30% discount rate for each connection. We recognize, however, that discount levels can range from 10-70% from "rack rates" and that a particular provider in an area may pay more or less than modeled.

NECA Tariff #5 was used as these tariffs are published, and we believe NECA carriers are likely to provide these rural

Exhibit 4-BY:
Middle-Mile Cost Dependency on Capacity



Cost per Mbps by Guaranteed Mbps per Connection middle-mile connections. The towns were selected such that they are likely to be in the high-cost study group in accordance with NECA rate band blends.[175] In its comments, NECA suggests that on average, 1 Mbps is required in the shared portions of the network for every 14.5 users for a typical consumer best-effort DSL service.[176] We use this ratio in the analysis and size middle-mile capacity to provide 1 Mbps for every 14.5 users. For example, in the Exhibit 4-BZ for Flasher, ND, the middle-mile capacity required to support 351 HUs is 24 Mbps. In order to provide middle-mile support in Flasher ND, the lowest-cost facility likely available for lease large enough to carry the required 24 Mbps is a DS-3, which has a capacity of 45 Mbps. This need to "overbuy" capacity is repeated as demand requires the lease of larger facility tiers from DS3 to OC3 to OC12, etc. This illustrates the importance of demand aggregation and capacity utilization in the middle mile.

We also estimate the incremental cost that the owner of existing fiber facilities would assign to the use of these facilities in order to fully cover both the cash cost and opportunity cost of capital along these routes. The cost of the build includes the fiber deployment costs (labor, plowing, trenching, pole attachments, ROW, etc.) and the fiber optic electronics (DWDM transport nodes, regenerators, aggregation electronics, etc.). The capacity of the middle-mile network was modeled as 40 Gbps between interoffice nodes. While we believe that the modeled electronics are very high capacity and represent future scalability, it should be understood that included in this cost model is the fiber itself, which is virtually unlimited in capacity as electronics are upgraded. While we make assumptions about the allocation of cost to the modeled services as discussed in the previous section entitled "Approach to Middle-Mile Model," we also estimate the full cost of providing service along these routes as a price ceiling. The results of the analysis are summarized in Exhibit 4-BZ.

Exhibit 4-BZ suggests that on a per-unit basis, it is cheaper to build than to lease. However, that does not necessarily imply that for a given (small) user base and limited capacity demand that the lowest cost option is to build. Cost-per-unit for fiber builds is highly sensitive to scale and utilization. Consequently, it is possible that cost-per-unit for a build is actually higher than lease when demand and utilization are subscale. There is still a question regarding the extent to which leased facility pricing in rural areas is reflective of high deployment costs—long distances driving high-cost deployments that can be amortized over only a small base of end users—or of rent-seeking by facilities owners. The Federal Communications Commission is currently undertaking a proceeding to address special access pricing generally, not only with regard to interoffice transport in rural areas.[177] That proceeding will delve in greater depth into the question of costs and pricing.

In order to connect some rural areas, providers must deploy

Exhibit 4-BZ:
Middle-Mile Build vs. Lease Comparison

From City	To City	# of unserved HU	Airline miles between	Circuit size	Build cost per HU per month	Lease cost per HU per month	Lease Premium
Nenana, Alaska	Juneau, Alaska	315	648.96	DS3	$26.99	$302.44	1020%
Bagdad, Ariz.	Phoenix, Ariz.	206	100.32	DS3	$36.49	$93.34	156%
Irwinton, Ga.	Macon, Ga.	934	26.95	OC3	$3.46	$10.10	192%
Libby, Mont.	Missoula, Mont.	2,372	127.95	OC12	$10.89	$12.93	19%
Fort Sumner, N.M.	Ruidoso, N.M.	701	113.87	OC3	$28.22	$31.86	13%
Flasher, N.D.	Bismark, N.D.	351	32.66	DS3	$16.73	$28.06	68%
Lindsay, Okla.	New Castle, Okla.	834	29.46	OC3	$4.87	$11.76	141%
Glide, Ore.	Eugene, Ore.	759	51.76	OC3	$11.19	$17.28	54%
Denver City, Texas	Brownfield, Texas	455	35.24	DS3	$17.98	$22.44	25%
Eureka, Utah	Provo, Utah	578	31.02	DS3	$3.61	$16.65	361%
Rock River, Wyo.	Cheyenne, Wyo.	30	73.32	DS3	$155.63	$516.23	232%
Sheffield, Ala.	Huntsville, Ala.	3,570	58.88	OC12	$1.93	$5.00	159%
Hope, Ark.	Fouke, Ark.	3,465	32.65	OC12	$2.40	$3.75	56%
Buena Vista, Colo.	Colorado Springs, Colo.	2,592	70.96	OC12	$5.29	$7.75	47%
Ketchum, Idaho	Boise, Idaho	1,532	92.00	OC3	$2.92	$12.46	326%
Monticello, Miss.	Hattiesburg, Miss.	2,746	50.59	OC12	$2.09	$5.94	184%
Winchester, Tenn.	Chattanooga, Tenn.	5,145	46.77	OC12	$1.46	$3.03	107%
Pomeroy, Wash.	Walla Walla, Wash.	893	45.15	OC3	$9.99	$13.59	36%
Fayetteville, W. Va.	Beckley, W. Va.	2,780	24.30	OC12	$0.86	$4.11	381%

middle-mile facilities over considerable distances at significant cost. These challenges are further compounded by the fact that these areas often do not have the population density necessary to generate the type of demand that justifies the large investment needed to construct these facilities.[178] The list below summarizes the basic conclusions based upon the middle-mile analysis:

- The distances at issue in unserved areas are much longer than typical special access connections and the low housing-unit or population density results in demand that is insufficient for lower cost high-capacity links.[179]
- As Internet demand increases, the total middle-mile cost for all providers will rise.
- Rural broadband operators do not benefit from the economies of scale on middle-mile facility cost in comparison to urban providers.

CHAPTER 4 ENDNOTES

[1] *See* Section 5, Wireless Technology, for a discussion of wireless second mile backhaul.

[2] While we realize that a typical fully configured DSLAM would likely support no more than ~350 subscribers, we used 550 to show maximum subscribers that can be achieved at a DSLAM aggregation point (RT or CO) using Fast Ethernet backhaul.

[3] Note that the number of simultaneous video streams is driven by capacity of the cell site, not the coverage which is limited by upstream signal strength as discussed below.

[4] Simultaneous streams assume non-real-time streams/videos with sufficient buffers at the receiver. Capacity with real-time traffic requirements, such as is required with video-conferencing applications, will be lower. The 480Kbps and 700Kbps video streams here are typical Hulu video streams. *See* Hulu typical video streaming requirements, http://www.hulu.com/support/technical_faq, February 2010. The 1Mbps video stream corresponds to a high-def Skype video conference.

[5] UBS Investment Research, "US Wireless 411," August 14, 2009.

[6] A paired 2x20MHz of spectrum refers to a spectrum allocation where downlink and uplink transmissions occur on two separate 20MHz bands.

[7] Enhanced technologies, such as multiple antenna technologies (aka MIMO), can also help. *See* Wireless Technology section below for more detail.

[8] In the bands below 3.7GHz, 547MHz is currently licensed as flexible use spectrum that can be used for mobile broadband. The NBP recommends an additional 300MHz be made available within the next five years.

[9] Yankee Group, "North America Mobile Carrier Monitor," December, 2009.

[10] Theoretical peak rate inside a cell, does not take into account many real world deployment issues or cell-edge average rate.

[11] The CDMA family of standards has its own 4G evolution called UMB. However, UMB is no longer in development and most worldwide CDMA operators have already announced plans to adopt either WiMAX or LTE for when they upgrade to 4G. In the United States, for example, Verizon has chosen LTE while Sprint is planning to deploy WiMAX.

[12] Includes total cost of network plus success based capital for subscribers.

[13] Based on American Roamer mobile coverage data, August 2009.

[14] In 2G systems, by contrast, the signals were transmitted over 200kHz and 1.25MHz.

[15] For a more detailed exposition on these multiple access techniques, *see*, for example, "Fundamentals of Wireless Communication," David Tse and Pramod Viswanath, as well as references therein.

[16] Letter from Dean R. Brenner, Vice Pres., Gov't Aff., Qualcomm Inc., to Marlene H. Dortch, Secretary, FCC, GN Docket No. 09-51 (Dec. 9, 2009) Attach. A at 2. Figure shows downlink capacities calculated for 2x10MHz spectrum availability. Estimates of spectral efficiency calculated for each technology with the following antenna configuration: WCDMA, 1x1 and 1x2; HSPDA, Rel.5, 1x1; HSPA Rel. 6, 1x2; HSPA, Rel. 7, 1x1 and 1x2; LTE, 1x1 and 1x2.

[17] *See*, for example, "Fundamentals of Wireless Communications," David Tse and Pramod Viswanath, for details on Shannon theory as well as multi-user scheduling.

[18] Our estimate of the limit is based on a simplified evaluation of the "single-user" Shannon capacity of a cell site using the signal quality distribution for a cell site provided in Alcatel Lucent's Ex Parte Presentation, GN Docket 09-51, February 23, 2010, and then adjusting for multi-user scheduling gains. Our analysis also assumes 43% loss in capacity due to overhead; *see*, for example, "*LTE for UMTS - OFDMA and SC-FDMA Based Radio Access*," Harri Holma and Antti Toskala (Eds). *See*, for example, "*Fundamentals of Wireless Communications*." *See*, for example, Section 7.7 in "*The Mobile Broadband Evolution: 3G Release 8 and Beyond, HSPA+, SAE/LTE and LTE-Advanced*," 3G Americas.

[19] *See*, for example, Section 7.7 in "The Mobile Broadband Evolution: 3G Release 8 and Beyond, HSPA+, SAE/LTE and LTE-Advanced," 3G Americas.

[20] *See*, for example, "LTE for UMTS - OFDMA and SC-FDMA Based Radio Access," Harri Holma and Antti Toskala (Eds).

[21] *See*, for example, "The performance of TCP/IP for networks with high bandwidth-delay products and random loss," T. V. Lakshman and U. Madhow, IEEE/ACM Transactions on Networking, June 1997.

[22] CDMA operators can choose either LTE or WiMAX for their 4G evolution. LTE currently supports handoffs from CDMA systems.

[23] Spectral efficiencies calculated for a (paired) 2x10MHz spectrum allocation for all technologies. Downlink spectral efficiency for WCDMA performance based on 1x1 and 1x2 antenna configurations; HSDPA Rel 5 and HSPA Rel 6 results based on 1x1 and 1x2 configurations, respectively; HSPA Rel 7 performance assumes 1x2 and 2x2 configurations while LTE result assumes 2x2. Uplink spectral efficiencies for WCDMA, HSPA and LTE capacities evaluated for 1x2 antenna configurations. Performance of (3G) EV-DO, which is not shown in the chart, is comparable to (3G) HSPA.

[24] CITI BROADBAND REPORT AT 25-28.

[25] CITI BROADBAND REPORT AT 8.

[26] "HSPA to LTE-Advanced: 3GPP Broadband Evolution to IMT-Advanced (4G)," Rysavy Research/3G Americas, September 2009.

[27] Round-trip latencies do not include public Internet latencies. Illustrative latencies for 2G/3G/4G networks; latencies for two networks using the same technology can vary depending on network configuration, infrastructure vendor optimizations, etc.

[28] CITI BROADBAND REPORT AT 8.

[29] *See*, for example, Figure 9.12 in "LTE for UMTS - OFDMA and SC-FDMA Based Radio Access," Harri Holma and Antti Toskala (Eds); and "LS on LTE performance verification work" at http://www.3gpp.org/FTP/tsg_ran/WG1_RL1/TSGR1_49/Docs/ R1-072580.zip.

[30] In terms of cell radius, this gain translates to nearly a three-fold improvement in coverage.

[31] *See* also Clearwire Ex-Parte filing, "Mobile broadband link budget example – for FCC", GN Docket No. 09-51 (Nov. 13, 2009) and link budget templates in http://www.3gpp.org/ftp/tsg_ran/TSG_RAN/TSGR_45/Documents/RP-090740.zip. Both documents perform downlink and uplink link budget analyses for a number of data rates and show that the limiting link budget in each scenario is the uplink.

[32] Okumura-Hata is a RF propagation model. *See*, for example, "*Introduction to RF propagation*," by John Seybold.

[33] Using the Okumura-Hata model, we obtain the maximum cell-size at 700MHz to be 12 miles or higher.

[34] We chose to classify CTs instead of counties or Census Block Groups (CBG) because counties can be very large and CBGs too small—especially when compared with a typical cell size. Studying the variation over too large an area can lead to picking up terrain effects that are well outside of the cell-coverage area. On the other hand, looking at variations over an area that is too small compared with the desired cell size can lead us to overlooking significant terrain variations that are within the cell coverage area.

[35] Based on data provided in Qualcomm Ex-Parte filing, "Mobile broadband Coverage by Technology," GN Docket No. 09-51 (Feb. 22, 2010); Clearwire Ex-Parte filing, "Mobile broadband link budget example – for FCC," GN Docket No. 09-51 (Nov. 13, 2009); "LTE for UMTS - OFDMA and SC-FDMA Based Radio Access," Harri Holma and Antti Toskala (Eds); and link budget templates in http://www.3gpp.org/ftp/tsg_ran/TSG_RAN/TSGR_45/Documents/RP-090740.zip.

[36] Maximum transmit power: fixed CPEs can have higher transmit powers and higher antenna gains through the use of directional antennas and can avoid body losses. Receiver noise figure assumes the use of low-noise amplifiers. Effective noise power is calculated as: Total noise density + 10log10 (Occupied bandwidth), where total noise density = thermal noise density +receiver noise figure = -172dBm/Hz. Required SINR assumes the use of two receive antennas at the base station. Penetration losses can be reduced by fixed CPEs by placing the antennas in ideal locations within the house or outside. MAPL without shadow fading margin is appropriate when using RF planning tools because these tools enable shadowing and diffraction losses due to terrain. Shadow fading margin is required for 90% coverage reliability. MAPL with shadow fading margin is appropriate when using propagation loss models, such as the Okumura-Hata model.

[37] RF planning tools by EDX Wireless; see http://www.edx.com/index.html.

[38] Propagation loss analysis using RF planning tools takes into account shadowing and diffraction effects due to terrain. So, it is not necessary to include a shadowing margin in the MAPL.

[39] Propagation losses due to foliage are ~2-7dB at 700MHz.

[40] "PL" denotes propagation loss.

[41] Signal quality is the ratio of the received signal strength to the sum of the aggregated interference from other cell sites and thermal noise. This ratio is often called SINR or Signal to Interference and Noise Ratio.

CHAPTER 4 ENDNOTES

[42] A *serving* cell site is the cell site that is transmitting the desired data to the end-user. All other cell sites are, then, interfering cell sites.

[43] Based on data and analysis provided in: Alcatel Lucent in Ex Parte Presentation, GN Docket 09-51, February 23, 2010; Ericsson in Ex Parte filing, GN Docket 09-51, February 17, 2010; "*The LTE Radio Interface - Key Characteristics and Performance*," Anders Furuskar, Tomas Jonsson, and Magnus Lundevall, Ericsson Research; "LTE-Advanced – Evolving LTE towards IMT-Advanced," Stefan Parkvall, et al, Ericsson Research; "LTE and HSPA+: Revolutionary and Evolutionary Solutions for Global Mobile Broadband," Anil Rao, et al, in Bell Labs Technical Journal 13(4), (2009); "LS on LTE performance verification work," at http://www.3gpp.org/FTP/tsg_ran/WG1_RL1/TSGR1_49/Docs/ R1-072580.zip; 3GPP RAN-1 submission by QUALCOMM Europe, Ericsson, Nokia and Nokia Siemens Networks in 3GPP TSG-RAN WG1 in "Text proposal for TR on system simulation results," http://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_53/Docs/R1-082141.zip.

[44] *See*, for example: Ericsson in Ex Parte filing, GN Docket 09-51, February 17, 2010; 3GPP RAN-1 submission by QUALCOMM Europe, Ericsson, Nokia and Nokia Siemens Networks in 3GPP TSG-RAN WG1 in "Text proposal for TR on system simulation results," http://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_53/Docs/R1-082141.zip; "The LTE Radio Interface - Key Characteristics and Performance," Anders Furuskar, Tomas Jonsson, and Magnus Lundevall, Ericsson Research; "LTE-Advanced – Evolving LTE towards IMT-Advanced," Stefan Parkvall, et al, Ericsson Research; "LS on LTE performance verification work," at http://www.3gpp.org/FTP/tsg_ran/WG1_RL1/TSGR1_49/Docs/ R1-072580.zip.

[45] Based on signal quality distribution data provided by Alcatel Lucent in Ex Parte Presentation, GN Docket 09-51, February 23, 2010. We then determine spectral efficiency for mobile and FWA networks by mapping signal quality to data rates using the method and results published in "LTE Capacity compared to the Shannon Bound," by *Morgensen, et al*, in IEEE 65th Vehicular Technology Conference, 2007.

[46] A paired 2x20MHz of spectrum refers to a spectrum allocation where downlink and uplink transmissions occur on two separate 20MHz bands. This is also referred to as Frequency Division Duplex, or FDD, allocation. Note that the total spectrum allocation in this example is 40MHz. Similarly, the total allocation in a paired 2x10MHz of spectrum is 20MHz.

[47] When SINR is 0 dB, the power of the signal is equal to the sum of the powers of the interfering signals and noise.

[48] MIMO techniques use multiple antennas at the transmitter and receiver to improve spectral efficiency of communication. *See*, for example, "Fundamentals of Wireless Communications," David Tse and Pramod Viswanath, for a detailed exposition.

[49] In a system with 2x2 MIMO downlink, both the transmitter (base station) and the receiver (CPE) are equipped with two antennas.

[50] For the rest of this section, we shall refer to a "paired 2x10MHz" carrier as simply a 2x10MHz carrier. Thus, for example, a 2x20MHz carrier will imply a "paired 2x20MHz" carrier.

[51] Based on results published by QUALCOMM Europe, Ericsson, Nokia and Nokia Siemens Networks in 3GPP TSG-RAN WG1 in "*Text proposal for TR on system simulation results*," http://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_53/Docs/R1-082141.zip.

[52] *See* "WCDMA 6-sector Deployment - Case Study of a Real Installed UMTS-FDD Network," by Ericsson Research and Vodafone Group R&D, in IEEE Vehicular Technology Conference, Spring 2006; "LTE for UMTS - OFDMA and SC-FDMA Based Radio Access," Harri Holma and Antti Toskala (Eds); "Higher Capacity through Multiple Beams using Asymmetric Azimuth Array," by TenXc wireless, April 2006. The last two references show that 6-sector cells result in an 80% to 90% capacity improvement per cell site.

[53] Based on signal quality distribution data provided by Alcatel Lucent in Ex Parte Presentation, GN Docket 09-51, February 23, 2010, and "LTE Capacity compared to the Shannon Bound," by *Morgensen, et al*, in IEEE 65th Vehicular Technology Conference, 2007.

[54] "Downlink user data rate" refers to burst rate in a fully utilized network.

[55] *See* American Roamer Advanced Services database (accessed Aug. 2009) (aggregating service coverage boundaries provided by mobile network operators) (on file with the FCC) (American Roamer database); see also Geolytics Block Estimates and Block Estimates Professional databases (2009) (accessed Nov. 2009) (projecting census populations by year to 2014 by census block) (on file with the FCC) (Geolytics databases).

[56] "Mobile Backhaul: Will the Levees Hold?", Yankee Group, June 2009.

[57] Sprint Nextel in Ex Parte Presentation, GN Docket 09-51, January 13, 2010.

[58] Level(3) Communications, Notice of Ex Parte Presentation, GN Docket 09-51, November 19, 2009; the filing notes that gigabit links are also available, albeit with limited range; see also "Microwave, Leased Lines, and Fiber Backhaul Deployments: Business Case Analysis."

[59] Dragonwave, "Achieving the Lowest Total Cost of Ownership for 4G Backhaul," and "Microwave, Leased Lines, and Fiber Backhaul Deployments: Business Case Analysis."

[60] Fiber-to-the-Home Council (FTTH Council), Notice of Ex Parte Presentation, GN Docket 09-51,October 14, 2009, Response to September 22, 2009, FCC Inquiry regarding Broadband Deployment Costs.

[61] Dragonwave, "Achieving the Lowest Total Cost of Ownership for 4G Backhaul."

[62] Clearwire Ex Parte Presentation, GN Docket 09-51, November 12, 2009 at 12.

[63] Ancillary equipment here refers to communication cables, antennas, etc.

[64] Average HU density in mountainous and hilly areas is 3 POPs/square mile and 7.4 POPs/square mile, respectively, while in flat areas it is 308 POPs/square mile.

[65] Cost and gap shown for counties that have a negative NPV. Recall that the rural cell radius in the 700MHz band can be as much as 57% greater than that at 1900MHz. We chose the cell radius in mountainous areas to be 2 miles as well. In these areas, terrain rather than propagation losses dominate the determination of cell radius; so, it is unlikely that cell sizes will get much smaller than 2 miles.

[66] This exhibit supports information and conclusions found in Exhibit 4-Z: Sensitivity of Buildout Cost and Investment Gap to Terrain Classifications.

[67] *See* Tower Maps database (Accessed August, 2009) (on file with the Commission).

[68] Mobile Satellite Ventures Subsidiary, LLC, Comments, in PS Docket 06-229 at 50 (June 20, 2008). They show that 30% of the sites required to cover 95th percentile of the population in the rural United States are "greenfield;" that number grows to 75% for the 99th percentile. We assume in our model that the number of greenfield sites required is 52.5%, which is the average of those two numbers.

[69] Other network costs include those incurred in the Core (Node-0) network as well as on CPE (Node-4) subsidies

[70] IDC, United States Consumer Communications Services QView Update, 3Q09, pg. 5, December 2009.

[71] United States Telecom Association, Telecom statistics, http://www.ustelecom.org/Learn/TelecomStatistics.html (last visited Feb. 3, 2010). It should be noted that these 1,311 operating companies comprise fewer than 850 holding companies.

[72] IDC, United States Consumer Communications Services QView Update, 3Q09, pg. 5, December 2009.

[73] *See* Network Dimensioning section below.

[74] Adtran -"Defining Broadband Speeds: Estimating Capacity in Access Network Architectures." Submissions for the Record -- GN Docket No. 09-51, (January 4, 2010) at 8.

[75] Adtran -"Defining Broadband Speeds: Estimating Capacity in Access Network Architectures." Submissions for the Record -- GN Docket No. 09-51, (January 4, 2010) at 8.

[76] Zhone Applications, http://www.zhone.com/solutions/ethernet/, (last visited Nov. 17, 2009).

[77] Level 2 Dynamic Spectrum Management (DSM-2) is currently available and aids in the management of power and begins to cancel some crosstalk. Level 3 Dynamic Spectrum Management (DSM-3), also known as vectoring, is currently being tested in the laboratory and in field trials. Vectoring is discussed in greater detail in the 3-5 kft section of the appendix because, although possible on ADSL2+, the technique is most beneficial on line lengths below 4,000 feet; Broadband Forum Jan. 19, 2010 Notice of *Ex Parte* Communication – Addendum at 5.

[78] Letter from Robin Mersh, Chief Operating Officer, Broadband Forum, to Marlene H. Dortch, Secretary, FCC (Jan. 19, 2010) ("Broadband Forum Jan. 19, 2010 Notice of *Ex Parte* Communication – Addendum") at 4.

[79] Adtran -"Defining Broadband Speeds: Estimating Capacity in Access Network Architectures." Submissions for the Record -- GN Docket No. 09-51 (January 4, 2010).

CHAPTER 4 ENDNOTES

[80] Broadband Forum Jan. 19, 2010 Notice of *Ex Parte* Communication – Addendum at 10.

[81] Comments of National Exchange Carrier Association (NECA) at Table 1, Impact of Middle and Second Mile Access on Broadband Availability and Deployment, GN Docket #s 09-47,09-51,09-137 (filed November 4, 2009).

[82] "Current backhaul dimensioning" is based on comments from NECA that on average ~1Mbps is required in the shared portions of the network for every 14.5 users.

[83] Comments of National Exchange Carrier Association (NECA) at Table 1, Impact of Middle and Second Mile Access on Broadband Availability and Deployment, GN Docket #s 09-47,09-51,09-137 (filed November 4, 2009).

[84] Load coils, which are in-line inductors used as low-pass filters to balance response for voice frequency transmission, effectively block xDSL signals. Load coils generally exist on loops exceeding 18,000 feet.

[85] Bridged taps, lengths of unterminated wire typically formed when changes are made to the loop and unneeded cable is left attached to the loop, can cause some service degradation, especially for data services.

[86] TCP acceleration is the consolidation of requests for and acknowledgement of data to minimize the number of serial transmissions over communications links. TCP fast-start is the disabling of slow-start, which entails error checking before the link is brought to full speed, in order to provide full link bandwidth from the outset of the session. TCP pre-fetch is the use of the predictive caching of Web content and DNS look-ups.

[87] Letter from John P. Janka on behalf of ViaSat, Inc. to Marlene H. Dortch, Secretary, FCC (Jun. 24, 2009) ("ViaSat Jun 24, 2009 *Ex Parte*") at 6.

[88] Max Engel, Satellite Today, http://www.satellitetoday.com/via/satellitegetspersonal/Why-ViaSat-Acquired-WildBlue-and-Why-WildBlue-Needed-It_32911.html (last visited Jan. 12, 2010).

[89] Peter B. de Selding, Space News, http://www.spacenews.com/satellite_telecom/with-wildblue-acquisition-viasat-doubles-bet-satellite-broadband.html (last visited Jan.12, 2010).

[90] CITI BROADBAND REPORT AT 57.

[91] ViaSat Comments at 3.

[92] BHOL is the average demand for network capacity across all subscribers on the network during the busiest hours of the network. BHOL is discussed later in the Network Dimensioning section.

[93] *See* OBI, Broadband Performance.

[94] ViaSat Jan. 5, 2010 *Ex Parte* at 2.

[95] Hughes Oct. 26, 2009 *Ex Parte* at 6.

[96] See OBI, Broadband Performance.

[97] ViaSat Comments in re A National Broadband Plan for Our Future, GN Docket No. 09-51, Notice of Inquiry, 24 FCC Rcd 4342, (2009) at 13.

[98] ViaSat Comments in re National Broadband Plan NOI, at 13.

[99] ViaSat Comments in re National Broadband Plan NOI, at 3.

[100] We assume a growth rate that doubles exactly every three years, i.e. 26.5%, for this analysis.

[101] It is unclear what the effect of the Plan will be for satellite broadband providers' subscriber churn due to the buildouts in areas that are currently served only by satellite.

[102] ViaSat 2009 Annual Report at 17.

[103] ViaSat 2009 Annual Report at 4.

[104] Note that the investment gap calculation does *not* exclude NPV-positive counties as the base case does, which explains why the revenue number differs from the $8.9 billion in the base case.

[105] Hughes, High-speed Internet Service Plans and Pricing, http://consumer.hughesnet.com/plans.cfm (last visited Mar. 8, 2010).

[106] Operational savings are offered by the Point to Point (P2P) and Passive Optical Network (PON) varieties of FTTP, not by the Active Ethernet variety.

[107] RVA LLC, FIBER TO THE HOME: NORTH AMERICAN HISTORY (2001-2008) AND FIVE YEAR FORECAST (2009-2013), 7 (2009), *available* at http://www.rvallc.com/FTTP_subpage7.aspx.

[108] CISCO SYSTEMS, FIBER TO THE HOME ARCHITECTURES, 4 (2007), *available* at http://www.ist-bread.org/pdf/FTTP%20Architectures.pdf.

[109] Dave Russell, Solutions Marketing Director, CALIX, Remarks at FCC Future Fiber Architectures and Local Deployment Choices Workshop 31 (Nov. 19, 2009).

[110] National Exchange Carrier Association Comments in re PN#11 filed (Nov. 4, 2009) at 10.

[111] See OBI, Broadband Performance.

[112] Dave Russell, Solutions Marketing Director, CALIX, Remarks at FCC Future Fiber Architectures and Local Deployment Choices Workshop 31 (Nov. 19, 2009).

[113] Letter from Thomas Cohen, Counsel for Hiawatha Broadband Communications, to Marlene H. Dortch, Secretary, FCC (November 10, 2009) ("Hiawatha Broadband November 10, 2009 *Ex Parte*") at 7.

[114] Letter from Thomas Cohen, Counsel for the Fiber to the Home Council, to Marlene H. Dortch, Secretary, FCC (October 14, 2009) ("Fiber to the Home Council October 14, 2009 *Ex Parte*") at 9-10.

[115] This equation was derived from fitting a curve to the data, and as such averages over the type of outside plant (aerial or buried). This curve fit may underestimate costs in very high-density areas or other areas with a greater mix of buried infrastructure. The r2 for the curve fit is 0.992 and the R2 adjusted is 0.990.

[116] JOHN A. BROUSE, JR., FIBER ACCESS NETWORK A CABLE OPERATOR'S PERSPECTIVE, 3 (2006), http://www.itu.int/ITU-T/worksem/asna/presentations/Session_2/asna_0604_whitepaper_brouse.doc.

[117] DOREEN TOBEN, FIBER ECONOMICS AND DELIVERING VALUE, 34 (2006) *available* at http://investor.verizon.com/news/20060927/20060927.pdf.

[118] Letter from Thomas J. Navin, Counsel for Corning, to Marlene H. Dortch, Secretary, FCC (October 13, 2009) ("Corning October 13, 2009 *Ex Parte*") at 17.

[119] RVA LLC, FIBER TO THE HOME: NORTH AMERICAN HISTORY (2001-2008) AND FIVE YEAR FORECAST (2009-2013), 7 (2009), http://www.rvallc.com/FTTP_subpage7.aspx.

[120] Data obtained from Comcast SEC Form 10Q dated 11/4/09, Verizon SEC Form 10Q dated 10/29/09, and Verizon Communications, FIOS Briefing Session, 37-41, 2006.

[121] Broadband Forum Jan. 19, 2010 Notice of *Ex Parte* Communication – Addendum") at 7.

[122] Broadband Forum Jan. 19, 2010 Notice of *Ex Parte* Communication – Addendum") at 8.

[123] Qwest, Wireline Network News, http://news.qwest.com/VDSL2 (last visited Jan. 20, 2010).

[124] Broadband Forum Jan. 19, 2010 Notice of *Ex Parte* Communication – Addendum") at 7.

[125] Broadband Forum Jan. 19, 2010 Notice of *Ex Parte* Communication – Addendum") at 8.

[126] NCTA, Industry Data, http://www.ncta.com/Statistics.aspx, (last visited Jan. 13, 2010).

[127] OECD, OECD Broadband subscribers per 100 inhabitants, by technology, June 2009, http://www.oecd.org/sti/ict/broadband; (last visited Feb. 10, 2010).

[128] National Cable & Telecommunications Association, Industry Data, http://www.ncta.com/StatsGroup/Availability.aspx (last visited Feb. 3, 2009) and ROBERT C. ATKINSON & IVY E. SCHULTZ, COLUMBIA INSTITUTE FOR TELE-INFORMATION, BROADBAND IN AMERICA: WHERE IT IS AND WHERE IT IS GOING (ACCORDING TO BROADBAND SERVICE PROVIDERS) at 20 (2009) ("CITI BROADBAND REPORT"), *available* at http://www4.gsb.columbia.edu/citi/.

[129] National Cable & Telecommunications Association, Industry Data, http://www.ncta.com/StatsGroup/Investments.aspx (last visited Feb. 3, 2009).

[130] David Reed, Chief Strategy Officer, CableLabs, Remarks at FCC Future Fiber Architectures and Local Deployment Choices Workshop 31 (Nov. 19, 2009).

[131] Adtran, Defining Broadband Speeds: Deriving Required Capacity in Access Networks, at 24, GN Docket No. 09-51, January 4, 2010. Assumes 40% penetration of 350 person node so that capacity = 36 Mbps/(40% x 350) = 250 kbps of capacity per subscriber, well in excess of the 160 kbps average usage forecast.

[132] This does not mean that every cable operator will offer packages at these speeds, nor that every subscriber will have service at these speeds; instead this is a comment on the capability of the access network for typical user loads. Localized heavy use, e.g., from heavy use of peer-to-peer programs could load the network more than is typical and lead to lower realized speeds.

[133] FCC, US spectrum allocation (http://www.fcc.gov/mb/engineering/usallochrt.pdf), (last visited Feb. 19, 2010).

[134] ADRIANA COLMENARES et al., DETERMINATION OF THE CAPACITY OF THE UPSTREAM CHANNEL IN CABLE NETWORKS, 3-4, https://drachma.colorado.edu/dspace/bitstream/123456789/74/1/NCS_Spec_031299.pdf, (last visited Feb. 9, 2010).

[135] Stacey Higginbotham, DOCSIS 3.0: Coming Soon to a Cableco Near You, http://gigaom.com/2009/04/30/docsis-30-coming-soon-to-an-isp-near-you/, (last visited Feb. 9, 2010).

[136] Cisco Systems, The Economics of Switched Digital Video, http://www.lanpbx.net/en/US/solutions/collateral/ns341/ns522/ns457/ns797/white_paper_G1701A.pdf, (last visited Feb. 9, 2010).

[137] Zacks Equity Research, Switched Digital Video Thriving, http://www.zacks.com/stock/news/30346/Switched+Digital+Video+Thriving+-+Analyst+Blog,

CHAPTER 4 ENDNOTES

(last visited Feb. 25, 2010).

[138] TiVo Comments in re NBP PN#27 (Video Device Innovation – NBP PN#27, GN Docket Nos. 09-47, 09-51, 09-137; CS Docket No. 97-80, Public Notice, DA 09-2519, rel. Dec. 3, 2009), filed Feb. 17, 2010, at 1.

[139] Lightreading, Comcast's 30-to-1 Odds, http://www.lightreading.com/document.asp?doc_id=152873, (last visited Feb. 9, 2010).

[140] Assumes 50% of the spectrum operates at 256-QAM and the other 50% at 64-QAM.

[141] Cisco Systems, Understanding Data Throughput in a DOCSIS World, https://www.cisco.com/en/US/tech/tk86/tk168/technologies_tech_note09186a0080094545.shtml, (last visited Feb. 9, 2010).

[142] Cisco Systems, Unicast Video Without Breaking the Bank: Economics, Strategies, and Architecture, https://www.cisco.com/en/US/solutions/collateral/ns341/ns522/ns457/unicast_video_white_paper.pdf, (last visited Feb. 9, 2010).

[143] Cisco Systems, Understanding Data Throughput in a DOCSIS World, https://www.cisco.com/en/US/tech/tk86/tk168/technologies_tech_note09186a0080094545.shtml, (last visited Feb. 9, 2010).

[144] Report on Cable Industry Prices, MM Docket No. 92-266, ATTACHMENT 4 (2009).

[145] Report on Cable Industry Prices, MM Docket No. 92-266, ATTACHMENT 3-b (2009).

[146] Charter Communications, Fiber Access Network: A Cable Operators Perspective, http://www.itu.int/ITU-T/worksem/asna/presentations/Session_2/asna_0604_s2_p4_jb.ppt, (last visited Feb. 19, 2010).

[147] Penetration rate denotes attach rate of homes passed for digital TV, high-speed data and voice; cost does not include CPE cost.

[148] Charter Communications, Fiber Access Network: A Cable Operators Perspective, http://www.itu.int/ITU-T/worksem/asna/presentations/Session_2/asna_0604_s2_p4_jb.ppt, (last visited Feb. 19, 2010). Assumes 50% penetration of homes passed.

[149] Letter from Thomas Cohen, Kelley Drye & Warren LLP, to Marlene H. Dortch, Secretary, FCC (Nov. 10, 2009) at 1.

[150] Westbay Engineers - http://www.erlang.com/whatis.htm; February 2010.

[151] *See* https://support.skype.com/faq/FA1417/How-do-I-know-if-I-have-sufficient-bandwidth?: For Skype-to-Skype video (both normal and high quality) we recommend: 384 kbps.

[152] Adtran, *Defining Broadband Speeds: Deriving Required Capacity in Access Networks*, at 22, GN Docket No. 09-51, January 4, 2010.

[153] IEEE: Similarities between voice and high speed Internet traffic provisioning, IEEE CNSR'04, 25 October 2004.

[154] "LTE for UMTS - OFDMA and SC-FDMA Based Radio Access", *Harri Holma and Antti Toskala* (Eds).

[155] *See* OBI, Broadband Performance.

[156] *See* OBI, Broadband Performance.

[157] Consumer-oriented broadband today is provided as a best-effort service whereby the transport network elements are shared among many users. However, business-oriented broadband networks often are sold with service level guarantees that provide performance assurances. As such, last mile as well as the backhaul network elements must be engineered with higher capacity to assure that bandwidth is always available to the subscribers at all times, regardless of network conditions. This adds cost to the transport portions of the networks, which are reflected in much higher prices to the end-users. Business class "dedicated" Internet services have a pricing structure that can be many times more expensive on a cost-per-bit basis.

[158] Adtran Ex-Parte Filing; *A National Broadband Plan for Our Future*, GN Docket No. 09-51, (FCC filed 23 February, 2010).

[159] While we realize that a typical fully configured DSLAM would likely support no more than ~350 subscribers, we used 500 per the availability of the simulation tool. Assuming that fast Ethernet backhaul is still used for a ~350 subscriber DSLAM would result in an even better oversubscription ratio and even greater probability performance.

[160] The results of this analysis do not easily apply to wireless networks. Unlike in other networks, the signal quality or data rate in a wireless network is strongly dependent on the location of the user relative to the cell site. We need to account for this non-uniformity in signal quality to dimension the wireless network [See Wireless Section above.] Still, we note that the spectral efficiency of a Fixed Wireless Access (FWA) network is ~2.35—2.7 b/s/Hz. So, the oversubscription ratio of a 3-sector cell site with 2x20 MHz spectrum allocation and 650 subscribers is ~16—18.5. Therefore, at first blush, this figure indicates that a FWA network should be able to deliver 4 Mbps in the download with high likelihood. And, as we show in more detail in the Wireless Section above, the FWA network can indeed support this subscriber capacity.

[161] The analysis is based on a simulation of N subscribers on a link with capacity C. Specifically, the simulation determines the burst likelihood for the Nth subscriber on the link when the remaining subscribers generate traffic according to a Pareto distribution of mean 160 kbps. Note that the mean of this distribution corresponds to our BHOL assumption of 160 kbps. For more details, *see* Adtran, *Defining Broadband Speeds: Deriving Required Capacity in Access Networks*, at 22, GN Docket No. 09-51, January 4, 2010.

[162] Centurylink Ex-Parte filing; *A National Broadband Plan for Our Future*, GN Docket No. 09-51; *International Comparison and Consumer Survey Requirements in the Broadband Data Improvement Act*, GN Docket No. 09-47; *Inquiry Concerning the Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion, and Possible Steps to Accelerate Such Deployment Pursuant to Section 706 of the Telecommunications Act of 1996, as Amended by the Broadband Data Improvement Act*, GN Docket No. 09-137(FCC filed January 22, 2010).

[163] Windstream Ex-Parte Filing; *A National Broadband Plan for Our Future*, GN Docket No. 09-51; *International Comparison and Consumer Survey Requirements in the Broadband Data Improvement Act*, GN Docket No. 09-47; *Inquiry Concerning the Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion, and Possible Steps to Accelerate Such Deployment Pursuant to Section 706 of the Telecommunications Act of 1996, as Amended by the Broadband Data Improvement Act*, GN Docket No. 09-137 (FCC filed January 13, 2010).

[164] Comments of Kodiak-Kenai Cable Company, LLC. at 5, *A National Broadband Plan for Our Future*, GN Docket # 09-51, PN #11 (FCC filed November 4, 2009).

[165] Centurylink Ex-Parte filing; *A National Broadband Plan for Our Future*, GN Docket No. 09-51; *International Comparison and Consumer Survey Requirements in the Broadband Data Improvement Act*, GN Docket No. 09-47; *Inquiry Concerning the Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion, and Possible Steps to Accelerate Such Deployment Pursuant to Section 706 of the Telecommunications Act of 1996, as Amended by the Broadband Data Improvement Act*, GN Docket No. 09-137(FCC filed January 22, 2010).

[166] Windstream Ex-Parte Filing; *A National Broadband Plan for Our Future*, GN Docket No. 09-51; *International Comparison and Consumer Survey Requirements in the Broadband Data Improvement Act*, GN Docket No. 09-47; *Inquiry Concerning the Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion, and Possible Steps to Accelerate Such Deployment Pursuant to Section 706 of the Telecommunications Act of 1996, as Amended by the Broadband Data Improvement Act*, GN Docket No. 09-137 (FCC filed January 13, 2010).

[167] The Gabriel network for a point set is created by adding edges between pairs of points in the source set if there are no other points from the set contained within a circle whose diameter passes through the two points, introduced as one means of uniquely defining contiguity for a point set such that no other point could be regarded as lying 'between' connected pairs; *available* at: http://www.spatialanalysisonline.com/output/html/Gabrielnetwork.html.

[168] A subset of the Gabriel network in which the additional constraint is applied that no other points may lie within the area of intersection defined by circles placed at each Gabriel network node with radius equal to the inter-node separation: *available* at: http:*//www.spatialanalysisonline.com/output/html/Gabrielnetwork.html.*

[169] Comments of Windstream at16 1, *A National Broadband Plan for Our Future*, GN Docket # 09-51, PN #11 (FCC filed November 4, 2009).

[170] Comments of XO Communications at 10, *A National Broadband Plan for Our Future*, GN Docket # 09-51, PN #11 (FCC filed November 4, 2009).

[171] Comments of Verizon at 3, *A National Broadband Plan for Our Future*, GN Docket # 09-51, PN #11 (FCC filed November 4, 2009).

[172] Comments of National Telecommunications Cooperative Association (NTCA) at 10, *Comment Sought on Impact of Middle and Second Mile Access on Broadband Availability and Deployment*, GN Docket #s 09-47,09-

CHAPTER 4 ENDNOTES

51,09-137 (filed November 19, 2009).

[173] Comments of National Telecommunications Cooperative Association (NTCA) at 8, *Comment Sought on Impact of Middle and Second Mile Access on Broadband Availability and Deployment*, GN Docket #s 09-47,09-51,09-137 (filed November 19, 2009).

[174] Comments of National Exchange Carrier Association (NECA) at 3, *Impact of Middle and Second Mile Access on Broadband Availability and Deployment*, GN Docket #s 09-47,09-51,09-137 (filed November 4, 2009).

[175] High Cost group is the average of special access rate bands 8, 9, 10; Middle Cost group is the average of special access rate bands 4, 5, 6 and 7; Low Cost group is the average of special access rate bands 3 or lower Comments of National Exchange Carrier Association (NECA) at Table 3, *Impact of Middle and Second Mile Access on Broadband Availability and Deployment*, GN Docket #s 09-47,09-51,09-137 (filed November 4, 2009).

[176] Comments of National Exchange Carrier Association (NECA) at Table 1, Impact of Middle and Second Mile Access on Broadband Availability and Deployment, GN Docket #s 09-47,09-51,09-137 (filed November 4, 2009).

[177] See Parties Asked to Comment on Analytical Framework Necessary to Resolve Issues in the Special Access NPRM, WC Docket No. 05-25, Public Notice, 24 FCC Rcd 13638 (WCB 2009).

[178] Comments of Verizon at 1, *A National Broadband Plan for Our Future*, GN Docket # 09-51, PN #11 (FCC filed November 4, 2009).

[179] Comments of Verizon at 1, *A National Broadband Plan for Our Future*, GN Docket # 09-51, PN #11 (FCC filed November 4, 2009).