An ADTRAN White Paper

Defining Broadband Speeds: Estimating Capacity in Access Network Architectures

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Executive Summary

This white paper assesses the extent to which various wireless and wireline facilities will be needed to support network capacity required for consumer broadband access through 2015. To perform this analysis, the paper first identifies the maximum area that theoretically could be served by various technologies' access nodes, i.e., a DSLAM for DSL access, Optical Node for cable access, Optical Line Terminal for fiber to the home access, and cell site (typically including a tower, base station, and antenna system in rural areas) for wireless access. The paper then considers whether the size of the coverage area will need to be reduced to ensure sufficient capacity is available to support multiple subscribers on the same access node. Given policymakers' interest in rural deployment, this analysis focuses on the impact of subscriber densities expected in rural areas, and does not explore the constraints posed by subscribership in more densely populated towns and urban areas.

This data-driven analysis indicates that for fixed broadband access, the maximum area covered by wireless technologies will almost never be realized in even very rural areas. The capacity provided by a wireless cell site will be sufficient for only a small number of fixed broadband subscribers. Indeed, wireless coverage can be significantly constrained even when the population density of an area served is less than 2 fixed broadband subscribers per square mile.

Wireline technologies may offer the most effective means for fixed broadband access in many rural areas, especially where outside plant cables are is already in place. ADSL2+ and cable access nodes and supporting infrastructure often may be less expensive to deploy than wireless access nodes and supporting infrastructure, and fewer access nodes typically will be needed to support wireline deployments as compared to wireless deployments. In a region populated by 19 subscribers per square mile (an area served by "very low density carriers"), a single ADSL2+ DSLAM or cable Optical Node can cover a territory that is several times greater than the area served by an LTE or WiMAX cell site. Or considered in another way, 10 ADSL2+ DSLAMs or 18 cable Optical Nodes can support broadband service over a similarly populated region that encompasses 100 square miles. A total of 66 LTE or 38 WiMAX cell sites would be required to cover the same expanse.

1 Introduction

As part of the Federal Communications Commission's work in developing the National Broadband Plan, the FCC has sought comments on a number of subjects related to broadband access. In NBP Public Notice # 1 [1], the FCC sought comments regarding the definition of broadband. More recently in NBP Public Notice # 11 [2], the FCC sought comments regarding middle and second mile access, including the amount of second-mile and middle-mile capacity required to provide adequate broadband Internet access to the end users of the network.

ADTRAN has responded to both Public Notices, most recently with a white paper [3] that addresses the relationship between capacity and the sustainable speed experienced by users in access networks. The white paper shows that sufficient capacity, relative to the traffic demand placed on the network, is necessary to support the sustainable speeds required by widely used application classes such as streaming video. It also uses data from Cisco's Visual Networking Index [4] and other sources to derive the capacity required for consumer broadband on a per-subscriber basis. Required capacities are projected out to year 2015.

This paper applies the required capacity projections derived in the previous ADTRAN white paper to a number of different access network architectures and technologies. Each architecture is described and illustrated with an example showing how capacity is calculated. The architectures include:

- Digital Subscriber Line (DSL). Two technologies – Asymmetric DSL (ADSL2+) and Very High Speed DSL (VDSL2) – are discussed.
- Hybrid Fiber Coax (HFC). The technology for data transmission over this architecture is Data over Cable Service Interface Specification (DOCSIS).
- Fiber To The Home (FTTH). Gigabit Passive Optical Network (GPON) is the specific technology analyzed.
- Broadband Wireless Access (BWA). Both Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX) are discussed.

Finally, a number of use cases are presented. The use cases show what is required for each architecture to provide the required capacity for year 2015 in deployments spanning population densities from one to 100 subscribers per square mile. The examples and use cases illustrate where capacity is limited in each network architecture, and provide some insight into the resources required (in terms of remote terminals, wireless base stations, etc.) to provide sufficient capacity across different population densities.

2 Capacity

ADTRAN's white paper on deriving required capacity [3] provides a detailed discussion of speed, capacity, and how they relate to each other in broadband access networks. This section describes how the capacity of an access network is determined, and provides projected capacity requirements that will be used throughout this paper to compare access network architectures.

2.1.1 Determining Capacity

The capacity of an access network is expressed quantitatively as the bandwidth available between the core network (the Internet) and the subscribers served by the access network. The available bandwidth is defined by the "weakest link," or the segment of the access network between the core network and the subscribers with the least amount of bandwidth. As an example, Figure 1 shows a network where the available bandwidth between points A and B is 2 Gbps, defined by the bandwidth between Nodes 3 and 4.

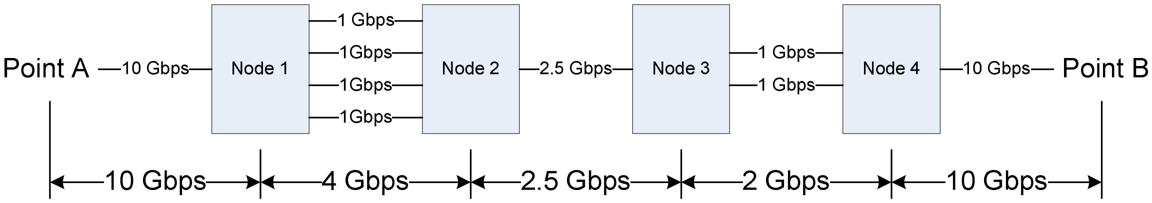

Figure 1 – Available bandwidth

Since an access network (or a portion thereof) can serve anywhere from tens to thousands of subscribers, we will express capacity on a per-subscriber basis. The capacity for a given subscriber is the prorated share of the bandwidth available between the core network and the subscriber. The capacity per subscriber can be different in different portions of a network. For example, the network in Figure 2 has three nodes, each of which serves 100 subscribers over a dedicated 20 Mbps link. The capacities for the subscribers served by each node are summarized in Table 1.

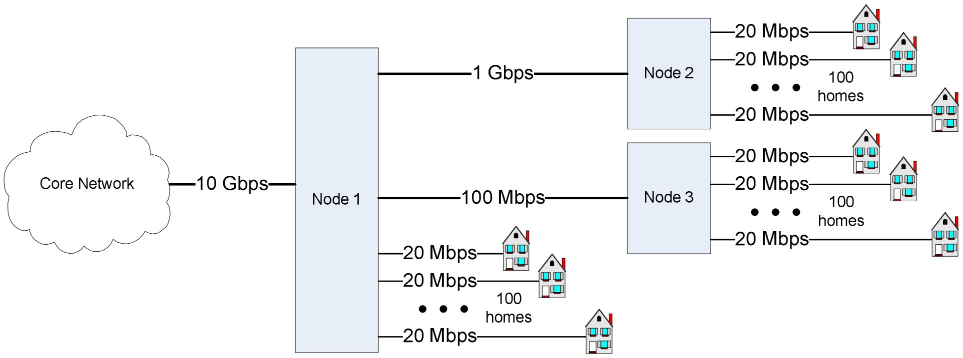

Figure 2 – Network capacity example

Table 1 – Capacities in Figure 2 example

Subscriber Segment	Capacity per Subscriber
Subscribers Served Directly from Node 1	20 Mbps
Subscribers Served from Node 2	10 Mbps
Subscribers Served from Node 3	1 Mbps

It is important to note that when capacity is prorated per subscriber, the proration occurs across all subscribers served by the network, not just the active ones. The demands used in [3] to generate projected capacity requirements are averaged over all subscribers, regardless of whether they are active or not at any given instant.

Consider the specific case of the subscribers served from Node 3. From left to right in the figure, there are three links between the core network and each of those subscribers:

1. The 10 Gbps link from the core network to Node 1. This link is shared by 300 subscribers, making the prorated capacity (10 Gbps / 300) = 33 Mbps per subscriber.
2. The 100 Mbps link between Nodes 1 and 3. This link is shared by 100 subscribers, so its prorated capacity is 1 Mbps per subscriber.
3. The dedicated 20 Mbps link from Node 3 to the subscriber. Since the link serves a single subscriber, its prorated capacity equals its rate.

The prorated capacity for the subscribers served from Node 3 is the smallest of the individual link capacities, or 1 Mbps.

2.2 Required Capacity Projections

ADTRAN's previous white paper [3] calculated North American consumer Internet traffic, using the data in Cisco's Visual Networking Index [4] and other sources [5, 6, 7] to generate per-household average traffic volume (as measured during the busiest period of the day)[1] in the upstream and downstream directions. It then applied a 2:1 margin to the average traffic to account for the burstiness of Internet traffic [8, 9] to generate projected capacity requirements on a per household basis for residential access networks. The projected capacity requirements from that paper are reproduced in Table 2. Throughout this paper, we will use the year 2015 capacity projections in the table to determine the resources required by each access network architecture.

Table 2 – Approximate required capacity/household for shared facilities in the access network

Direction	2009	2012	2015
Down (kbps per household)	200	500	1200
Up (kbps per household)	100	150	300

It is important to note that the capacity requirements in Table 2 are derived from average traffic values generated from data representing the entire United States, estimated in [3] to contain 70 million households with broadband access in 2009. In contrast, a typical access node (such as a DSL Access Multiplexer [DSLAM], an Optical Node, or a wireless base station tower) may serve anywhere from a few dozen to a few thousand broadband subscribers. The "average traffic per subscriber" as applied to a single access node is not necessarily the same as the "national average." There can be substantial

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[1] The well documented pattern of diurnal activity for Internet usage shows that average demand for residential access peaks during the evening hours [10].

differences in the average traffic for one access node as compared to another, because the subscriber population served by each access node is different. Most of the traffic on a network is generated by a small percentage of heavy users [10], and small changes in the number of heavy users served by an access node generate disproportionately large changes in the average traffic measured on that node. Indeed, the average traffic per subscriber measured over a single node can easily exceed twice the national average. A node on which the average traffic is higher than the national average will require proportionally higher capacity.

In this paper, we use capacity requirements based on the national average in order to provide a comparative view of the capabilities of different network architectures. However, a broadband access provider using these figures to plan or deploy a network needs to accommodate the node-to-node variation that will be experienced in average traffic and the resulting variation in the required capacity for each node. One way to do this would be to monitor utilization for each node and adjust the capacity per node as necessary (this monitoring may be necessary in any case, just to keep up with the rapid year-over-year growth in per-household traffic).

3 Access Network Architectures

In each section below, the access network architecture is described, and network features that affect capacity are discussed. In all cases, the scope of the capacity analysis is limited to the access network between the subscriber and an Internet Gateway or peering exchange (the interface between the broadband access provider's network and the Internet). Any elements beyond the Internet Gateway, which are outside the control of the access network provider, are excluded.

In general, an access network comprises three stages between the Internet Gateway and the subscriber. While the terminology varies (for instance, the terms "backhaul" and "subtending" see common usage), we will generally adhere to terminology used by the FCC as shown in Figure 3, which is copied from NBP Public Notice # 11 [2]. The three stages are:

1. The "middle mile" network between the Internet Gateway and aggregation nodes, nodes that aggregate traffic from many subscribers onto high bandwidth shared facilities. Aggregation nodes are generally located at a relatively small number of locations, such as telephone companies' Central Offices (COs). The types of aggregation nodes and their interfaces can be specific to the type of access network. The middle mile is generally a high speed network operated at speeds ranging from DS3 (45 Mbps) for smaller existing aggregation nodes to multiple Gigabits per second for newer or larger nodes.
2. The "second mile" network between the aggregation nodes and the access nodes, which are the nodes closest to subscribers and from which subscribers are served. Access nodes are specific to the access technology, and in general they also perform an aggregation function. Such nodes include DSLAMs, Optical Nodes, and wireless base stations. These nodes may be located outside in the form of curbside cabinets, pole mounted enclosures, or cellular towers. Depending on the access technology and the specific network, an access node may also be co-

located with an aggregation node or even implemented in the same piece of equipment. The capacity of the second mile network can range from Megabits to Gigabits per second, depending on the number of subscribers supported and the type of network.

3. The "last mile" network between the access nodes and the subscriber. The nature of this network is specific to the access technology.

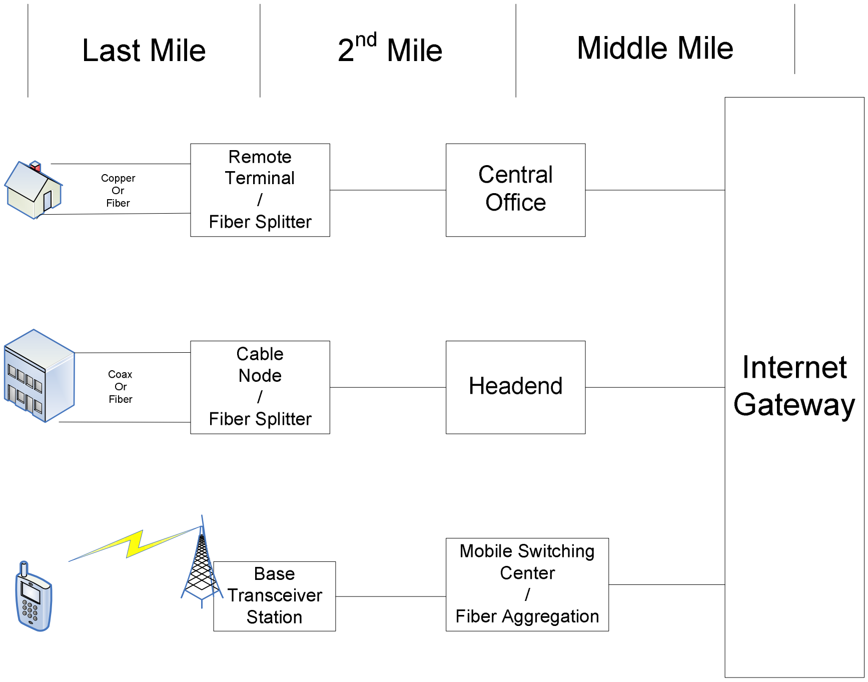

Figure 3 – Access network stages (from [2])

3.1 Digital Subscriber Line (DSL)

In a DSL access network, the last mile (in this case, the subscriber loop) is dedicated to a single subscriber. The DSL access architecture comprises two or three stages between the Internet Gateway and the subscriber, as shown in Figure 4. They are:

1. The middle mile network between the Internet Gateway and the CO. Within the CO, the aggregation nodes are frequently large multi-service, modular DSL Access Multiplexers (DSLAMs) which may be populated with different types of access cards. CO-based DSLAMs can support thousands of DSL subscribers, both directly and through second mile connections to other DSLAMs. Connections between the Internet Gateway and the CO frequently include multiple Gigabit or higher rate links.

2. The second mile network between the CO and remote DSLAMs in the Outside Plant (OSP). These smaller DSLAMs are typically mounted in Remote Terminals (RTs) or other cabinets, the numbers and locations of which depend on the specific DSL technology used. The lengths of the loops between subscribers and the DSLAM are reduced when DSLAMs are placed in the OSP, rather than the COs only – a reduction that enables higher data rates on last mile connections.

Each DSLAM usually serves from 24 to 384 subscribers. Second mile connections may be either copper or fiber, with the trend moving towards high speed fiber for new deployments and network upgrades.

3. The last mile comprises the twisted pair copper digital subscriber loop. The loop provides a dedicated connection to each subscriber from the DSLAM. As shown in Figure 4, the last mile can terminate in the OSP or it can extend back to the CO, if the loop between the CO and subscribers is short enough to sustain sufficient broadband speeds.

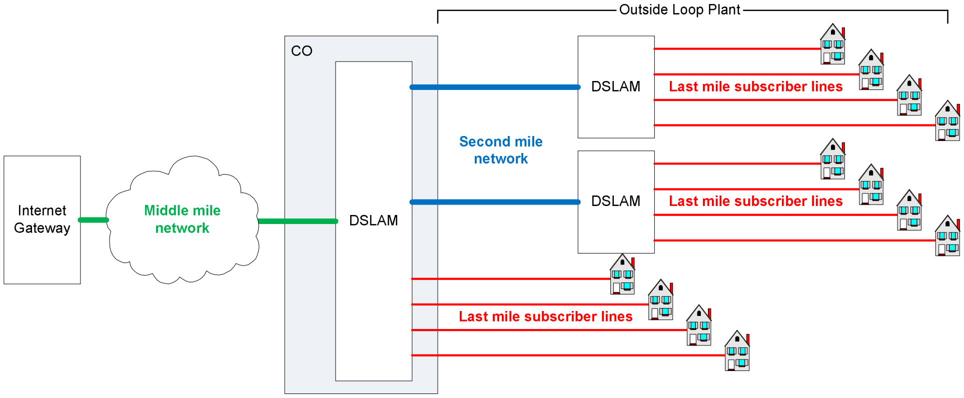

Figure 4 – DSL access network architecture

The middle mile and second mile connections described above are resources over which data from multiple subscribers share bandwidth. Each subscriber line connection is a point-to-point link between the DSLAM and a single subscriber, with all traffic transmitted across that loop dedicated to the subscriber served by the loop. DSL modems are generally capable of transferring data at the full DSL line rate.

3.1.1 ADSL2+

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. When loops are served by a remote DSLAM dedicated to a single distribution area, the maximum loop length is typically less than 6000 feet, supporting downstream data rates of 15 Mbps or higher per subscriber. Loop bonding can be used to multiply the rates by the number of loops, for delivered rates above 30 Mbps.

3.1.2 VDSL2

VDSL2 is defined in ITU-T Recommendation G.993.2 [12]. VDSL2 technology provides 25 Mbps downstream and 4 Mbps upstream over 1.2 km (4 kft) loops at 24 AWG, with rates as high as 80 Mbps on short loops. As with ADSL2+, loop bonding can be used to multiply the delivered rate by the number of loops used. Additionally, vectoring (G.993.5, pre-published) can provide single line rate increases of up to 50% on short loops.

3.2 Hybrid Fiber-Coaxial (HFC)

In an HFC cable access network, the last-mile channel is a shared resource. The current protocol specified for data transmission on an HFC network is DOCSIS 3.0 [13]. An HFC access network typically comprises three sections between the Internet Gateway and the subscriber (Figure 5). They are:

1. The middle mile network between the Internet Gateway and the Cable Modem Termination System (CMTS), which may be located at a head end or a hub site. The data portion of this network is generally a high speed network with data rates at or above the Gigabit per second range.
2. The second mile fiber connection between the CMTS and an Optical Node. The Optical Node performs a conversion between optical and electrical signals for downstream traffic, and the inverse conversion from electrical to optical signals for upstream traffic. Optical Nodes are usually located in small curbside or pole-mounted enclosures.
3. The last mile coaxial network from the Optical Node to the pool of subscribers served by that node. Each coaxial network can serve up to 2000 subscribers in a tree and branch topology. In a modern network which includes data service, the coaxial network is typically sized on the order of 125 to 500 subscribers.

The signal transmission format is the same in the fiber and coaxial portions of the HFC network. In the downstream direction, data is modulated as an RF signal in one or more 6 MHz channel bands and multiplexed with analog and digital video which occupy their own separate channel bands. The downstream spectrum includes 52 MHz to 760 MHz (some systems extend this range to 860 or 1000 MHz) and is divided into 6 MHz channels. The majority of these 6 MHz channels are used for delivery of television signals, while several of the channels are used for data transmission by the CMTS and cable modems (CMs). Multiple subscribers share the same 6 MHz channel for data transmission. Within this channel, the downstream data RF signal is broadcast to all subscriber CMs, each of which decodes only the data intended for it.

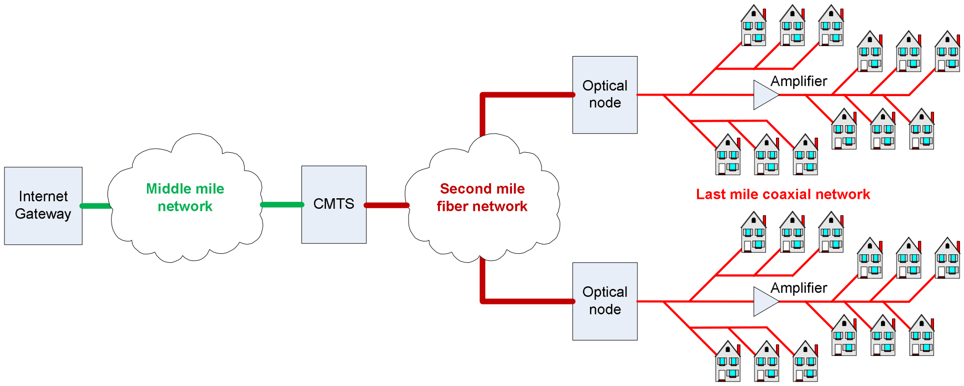

Figure 5 – HFC access network architecture

Upstream data, like downstream, is RF modulated and multiplexed into fixed channels. The upstream spectrum includes 5 MHz to 42 MHz and, depending on the version of the

DOCSIS in use, may be divided into channels of 6 MHz or smaller increments.[2] Unlike the downstream path, the upstream path must merge data from many different sources onto the shared transmission channel. This is generally accomplished using Time Division Multiple Access (TDMA), although some versions of DOCSIS specify Synchronous Code Division Multiple Access (S-CDMA) as an option.

Bidirectional amplifiers are positioned at regular intervals in the coaxial network to amplify and equalize the upstream and downstream signals. Since each amplifier adds some amount of noise and distortion to the amplified signal, the design of the coaxial portion of the network must balance the length and topology of the network, which defines the number of amplifiers required, with the upstream data bandwidth required.

Under DOCSIS 2.0, usable shared data rates are up to 38 Mbps per downstream channel and up to 27 Mbps per 6 MHz upstream channel. A typical residential deployment allocates one or two downstream channels to data [14]. Issues such as noise funneling from amplifiers and RF noise ingress tend to impose practical limits on both upstream channel bandwidth and transmission density, resulting in a total shared upstream capacity in current systems on the order of 35 Mbps for networks serving 250 subscribers [15]. DOCSIS 3.0 adds the capability to bond data from multiple channels together in each direction to increase peak rates, although it does not increase the per-channel rate in either direction.

In addition to the shared channel limits, the rate realized by the subscriber may be limited by the data rate that can be sustained by a single cable modem. This is much more likely to be a limit in the downstream rather than the upstream direction.

3.3 Fiber To The Home (FTTH)

While there are a number of technologies available for FTTH, this paper focuses on Gigabit Passive Optical Network (GPON) technology, which is used in many current deployments. GPON, defined in the ITU-T G.984 series of Recommendations [16], uses passive splitters in the fiber to share the last mile bandwidth between subscribers. A typical GPON network, as shown in Figure 6, comprises the following connections:

1. The middle mile network between the Internet Gateway and the Optical Line Terminal (OLT). As in the previously described networks, this is generally a high speed network with data rates at or above the Gigabit per second range.
2. The last mile[3] Passive Optical Network (PON) between the OLT and the Optical Network Units (ONUs) located at the customer premises. Within the PON, a fiber splitter (which may be located in the OSP) optically splits the downstream

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[2] DOCSIS 3.0 adds an option to increase the high end of the upstream band from 42 to 85 MHz. When this option is used, the low end of the downstream band moves from 52 to 108 MHz. However, this requires a frequency band-plan change for all services, eliminating television channels 2-5.

[3] While the fiber splitter has been referenced by the FCC as a delineation point between the last mile and the second mile networks [2], it is strictly a passive device. Since the signaling from one end of the PON to the other is identical – and since the fiber splitter can be located anywhere between the OLT and ONU without affecting performance, including next to the OLT at the CO – the PON is treated in this paper as a single network section.

signal onto separate fibers and merges upstream signals from separate fibers onto a common connection.

Data in a GPON is provided by separate wavelengths in the downstream and upstream directions. The total downstream capacity is 2.5 Gbps, which is shared between the ONUs. In the upstream direction, the total capacity is 1.25 Gbps. As in HFC networks, the upstream path merges data from different sources onto the shared transmission channel using TDMA. In addition to the downstream and upstream data wavelengths, GPON networks may use a third wavelength to provide video services.

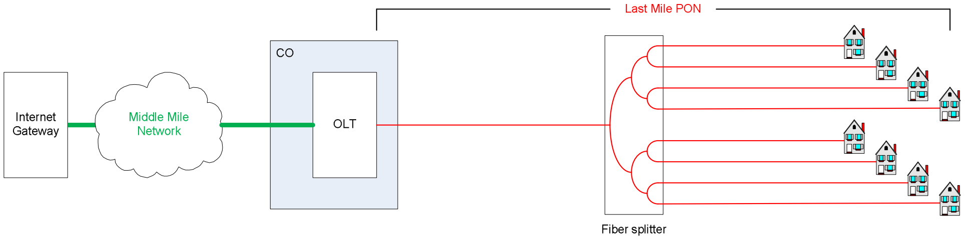

Figure 6 – GPON access network architecture

Each OLT can serve multiple PONs. The split ratio for a PON (the number of ONUs served by a single PON) is typically 1:32, but higher split ratios of 1:64 or even 1:128 are possible. The maximum reach of a 1:32 PON is approximately 20 km, with shorter reaches for higher split ratios.

The rate available to the subscriber may be limited by the design of the ONU. For example, an ONU may have an Ethernet interface to connect to customer equipment that supports only 1 Gbps or even 100 Mbps.

3.4 Broadband Wireless Access

Broadband wireless access (BWA) is another example of shared last-mile access. With broadband wireless access, a number of subscribers share the wireless channel using a multiple access protocol. A BWA network comprises three network sections between the Internet Gateway and the subscriber (Figure 7). They are:

1. The middle mile network between the Internet Gateway and aggregation nodes (which may be Serving Gateways, Radio Network Controllers, or Base Station Controllers, depending on the specific network architecture).
2. The second mile network between the aggregation nodes and the cellular base stations, which include the wireless transmission equipment, amplifiers, and antennas, as well as the physical tower necessary to support them in areas where there is no pre-existing structure. Next generation networks also incorporate direct communications between neighboring base stations in the second mile network. Second mile networks may use a combination of wireless (using point-to-point WiMAX or proprietary technology), fiber, DSL, and other technologies.
3. The last mile wireless networks between the base stations and the subscribers. Each base station terminates the wireless network for the subscribers within its geographic area, known as a “cell.” A regional wireless access network is divided

into many such cells, and subscribers communicate through the base station which provides the best wireless connection. Three cells are shown in Figure 7.

While a number of BWA deployments have made use of either WiFi (IEEE 802.11b/g) or proprietary technologies, most wireless deployments going forward are based on either Long Term Evolution (LTE) or Worldwide Interoperability for Microwave Access (WiMAX). While both of these technologies were developed to support mobile wireless access,[4] they can both also serve fixed broadband subscribers, and most deployments serve a combination of fixed and mobile subscribers on the same network. Each technology is discussed below.

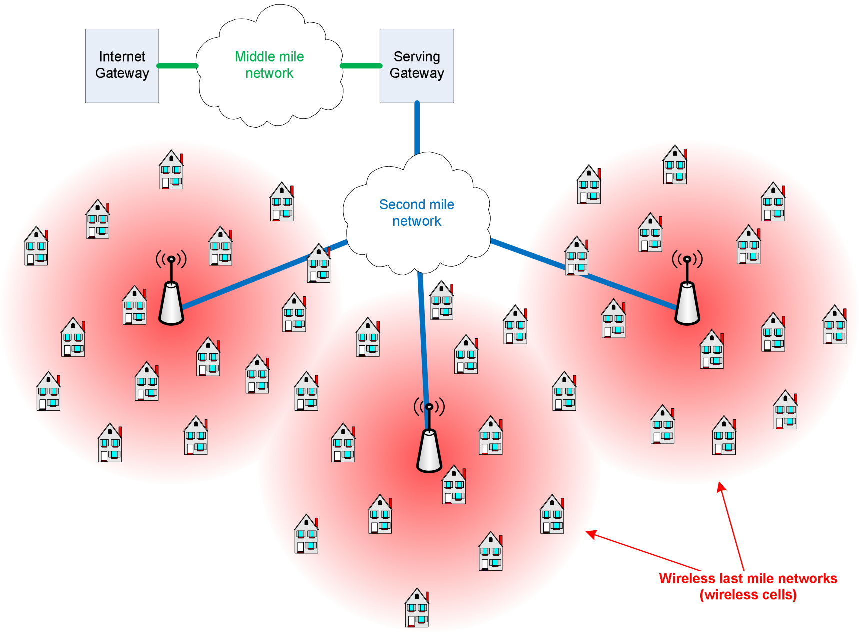

Figure 7 – Wireless access network architecture

3.4.1 LTE

LTE represents a comprehensive set of standards for network architecture and mobile radio access developed by the 3rd Generation Partnership Project (3GPP) and formalized as 3GPP Release 8 [17]. The air interface defines flexible channel bandwidths from 1.4 MHz to 20 MHz, as well as specific frequency bands for Frequency Division Duplex (FDD) operation and other bands for Time Division Duplexing (TDD). In the United States, the primary spectrum expected to be used for LTE deployments is in the 700 MHz band, where paired FDD channels of up to 10 MHz in each direction are permitted. With FDD, one channel in the pair is dedicated to downstream transmission and the other to upstream transmission.

LTE uses Orthogonal Frequency Division Multiple Access (OFDMA) in the downstream direction and Single Carrier Frequency Division Multiple Access (SC-FDMA) in the

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[4] The first version of WiMAX, based on IEEE 802.16-2004 and earlier versions, is designed for fixed broadband access. However, most current and planned deployments use "mobile WiMAX," based on IEEE 802.16e-2005.

upstream direction. Both technologies allow data from different subscribers to be multiplexed in both the time and frequency domains. Transmission is scheduled in 10 ms radio frames which are further divided into 1 ms subframes.

3.4.2 WiMAX

WiMAX specifies a set of profiles for wireless transmission based on IEEE 802.16e-2005 [18] and related standards. While the IEEE standards define a large set of options, the profiles defined by WiMAX specify a subset of features that compliant systems must implement to ensure interoperability.

A notable deployment of WiMAX in the United States is using the Broadband Radio Service (BRS) spectrum at 2.5-2.7 GHz. While multiple channel bandwidths are allowed in the 802.16e standard, the use of 5 MHz or 10 MHz channel bandwidths is common. Current profiles for mobile WiMAX (which can also support fixed subscribers) specify TDD. Since TDD uses the same channel for upstream and downstream transmission and spends part of each time slot transmitting in each direction, the effective shared rate in either direction is reduced by the proportion of the time spent transmitting in the other direction and the guard time required while switching directions. With highly asymmetric traffic, this can result in greater spectral efficiency than FDD (using equal size paired channels) for an equivalent total bandwidth.

WiMAX uses OFDMA in both the downstream and upstream directions, organized in 5 msec radio frames. OFDMA allows upstream and downstream data from different subscribers to be multiplexed in both the time and frequency domains. Resource allocation is defined on a per-frame basis using MAP fields, which have a variable length component that increases with the number of subscribers being scheduled [19].

3.4.3 Wireless Attributes

Both LTE and WiMAX include support for a variety of Multiple Input, Multiple Output (MIMO) techniques that can be used to increase the throughput to specific users, support additional users, or provide diversity to increase coverage, depending on specific operating conditions. These techniques can be combined with other techniques such as dynamically allocated subchannels to enable a frequency reuse factor of 1, meaning that the entire amount of spectrum allocated to the network is shared dynamically in all cells.

While the theoretical maximum shared rate on a 10 MHz channel can approach 50 Mbps, the (non-MIMO) payload rate for both LTE and WiMAX after subtracting PHY and MAC layer overhead is about 38 Mbps. The speed experienced by a subscriber is virtually always lower than that, however, both because the wireless channel is shared between multiple subscribers and because only those closest to the base station are capable of receiving the maximum shared rate, which decreases with distance and obstructions between the transmitter and receiver. An idealized view of this is shown in Figure 8, which also shows an example of the relative areas within a cell that receive varying levels of performance. Since the area covered at a given rate increases with the square of the distance from the base station, the areas getting lower rates tend to be larger than those getting higher rates.

The performance of wireless cells may be limited by different factors. If there are no nearby cells using the same wireless channel, the performance may be limited by the signal loss (or attenuation) between the subscriber and the base station. The attenuation is primarily affected by distance, but also by obstructions, terrain, and signal reflections. In this case the performance is considered to be range limited.

If there are cells nearby using the same wireless channel, then the performance may be limited by interference between cells, known as co-channel interference. While older cellular networks spaced multiple channels such that the same channel was not used in adjacent cells, LTE and WiMAX both use complex frequency domain and signal processing techniques to allow the same channel to be used in every cell, thus increasing the overall spectral efficiency of the network. As a result, the performance in the vast majority of cells is limited by co-channel interference.

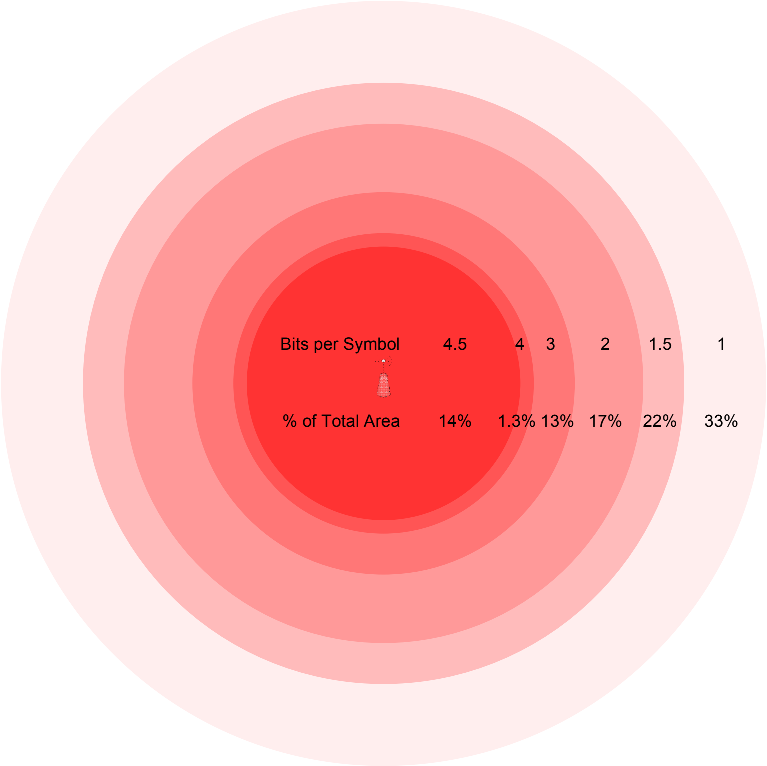

Figure 8 – Wireless performance within range limited cell

A cell's performance is also limited by the number and type of subscribers trying to use it. Since the wireless channel is a shared medium, average performance per user decreases as the number of users in a cell increases. If a cell's area (and hence the expected number of users) is limited by design to allow it to serve those users at a minimum performance level, the cell is said to be capacity limited.

As with other technologies, in addition to the shared channel bandwidth limits, there may be limits to the data rate that a single subscriber terminal (such as a smartphone or a wireless transceiver) can sustain.

4 Access Network Capacity

Per-subscriber capacities for the different types of access network architectures are derived in the sections below.

4.1 DSL Capacity

Three DSL network configurations are analyzed, with all three configurations sharing the basic architecture shown in Figure 9. The first ("ADSL A") represents a typical ADSL2+ network designed to CSA parameters, with DSL loop rates configured to 6 Mbps downstream and 1 Mbps upstream. Five 96-port remote DSLAMs, serving a total of 480 subscribers, are located in the loop plant and fed by DS3 circuits (at 44.7 Mbps) to the CO-based DSLAM. The CO-based DSLAM supplies the second mile to each remote DSLAM and also directly serves an additional 20 subscribers located near the CO, bringing the total number of subscribers served to 500. The middle mile network connection is 1 Gbps.

The second configuration ("ADSL B") represents an upgrade that supports year 2015 capacities. The network topology and ADSL2+ links are the same, but the second mile circuits are upgraded from DS3 to 1 Gbps over fiber.

In the third configuration, the DSLAMs are placed closer to the subscribers, supporting VDSL2.

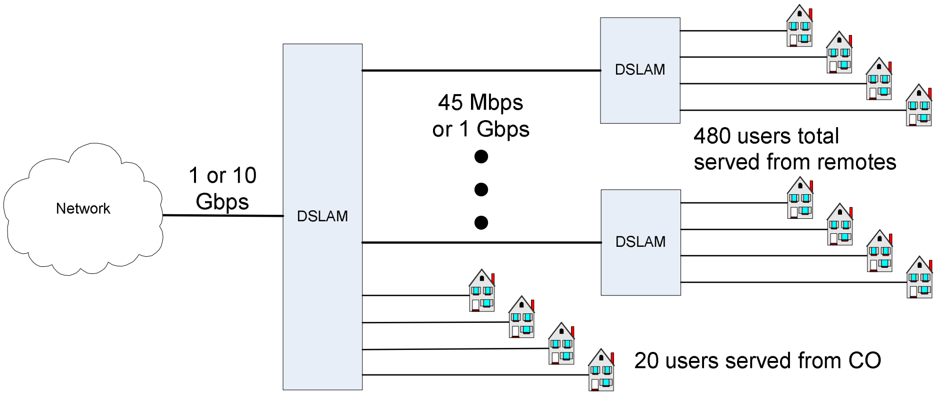

Figure 9 – DSL access network

The relevant parameters and capacity for each network configuration are calculated per the definition in Section 2.1.1 and shown in Table 3. In the first and third cases, downstream capacity is limited by the second mile. Comparing the ADSL A and ADSL B cases shows that the capacity per subscriber can be upgraded by upgrading shared facilities in the network, without necessarily changing out last mile DSL equipment or shortening loops.

Table 3 – DSL parameters

Network	Direction	Connection	Resource type (# subscribers)	Total capacity	Capacity per subscriber
ADSL A (fed by DS3 circuits)	Both	Middle mile	Shared (500)	1 Gbps	2 Mbps
	Both	Second mile	Shared (96)	44.7 Mbps	0.466 Mbps
	Down	Subscriber loop	Dedicated	6 Mbps	6 Mbps
	Up	Subscriber loop	Dedicated	1 Mbps	1 Mbps
	Down	**Capacity per subscriber**			**0.466 Mbps**
	Up	**Capacity per subscriber**			**0.466 Mbps**
ADSL B (fed by 1 Gbps over fiber circuits)	Both	Middle mile	Shared (500)	1 Gbps	2 Mbps
	Both	Second mile	Shared (96)	1 Gbps	10.4 Mbps
	Down	Subscriber loop	Dedicated	6 Mbps	6 Mbps
	Up	Subscriber loop	Dedicated	1 Mbps	1 Mbps
	Down	**Capacity per subscriber**			**2 Mbps**
	Up	**Capacity per subscriber**			**1 Mbps**
VDSL	Both	Middle mile	Shared (500)	10 Gbps	20 Mbps
	Both	Second mile	Shared (96)	1 Gbps	10.4 Mbps
	Down	Subscriber loop	Dedicated	25 Mbps	25 Mbps
	Up	Subscriber loop	Dedicated	4 Mbps	4 Mbps
	Down	**Capacity per subscriber**			**10.4 Mbps**
	Up	**Capacity per subscriber**			**4 Mbps**

4.2 HFC Capacity

Two HFC network configurations are analyzed. The first network ("HFC A," shown in Figure 10) serves 250 customers off each Optical Node, with two RF channels in each direction allocated to data. DOCSIS 3.0 channel bonding is enabled for a shared downstream rate of 76 Mbps and a shared upstream rate of 35 Mbps.

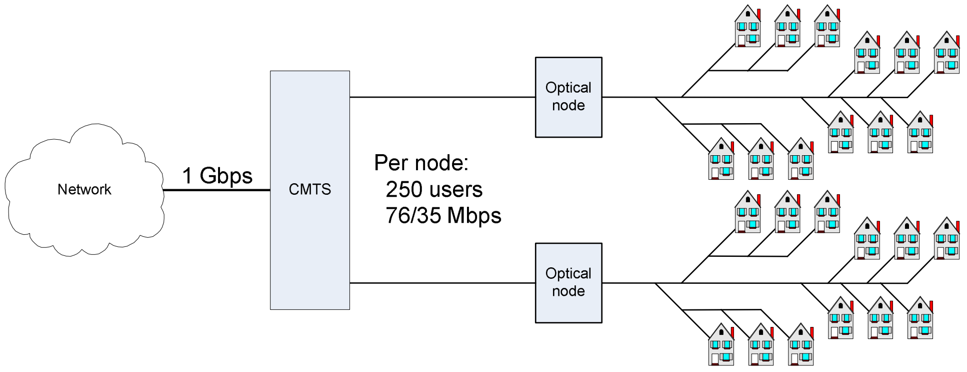

Figure 10 – HFC network A

The second network ("HFC B," shown in Figure 11) adds additional Optical Nodes so that each shared Optical Node now serves only 125 subscribers. Two additional downstream channels are converted from video to data, which brings the total shared rate with channel bonding to 152 Mbps. The smaller split in the cable plant improves the performance of the two upstream channels to 54 Mbps total.

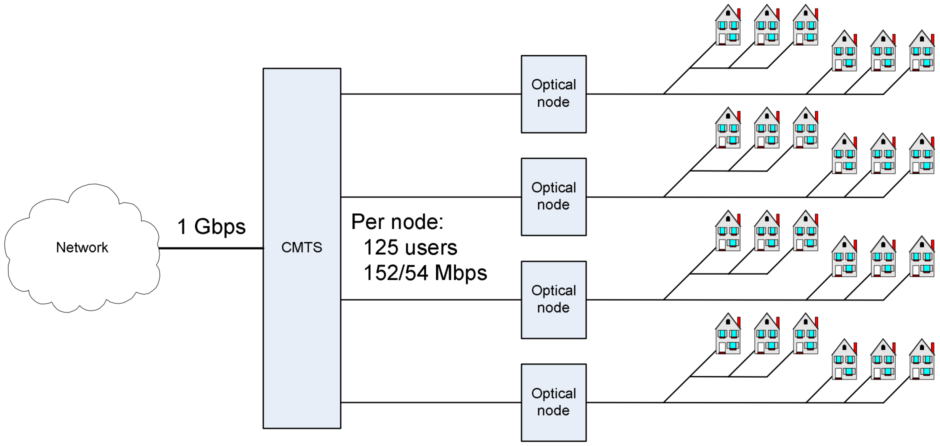

Figure 11 – HFC network B

In both cases, the CMTS serves a total of 500 subscribers. The upstream bandwidth lost to the TDMA multiple access protocol is ignored for the purposes of this analysis, so these numbers may slightly overstate the actual rate available. The relevant parameters and capacities for each configuration are shown in Table 4. The results show that the HFC B configuration meets the projected capacity requirements for year 2015

Table 4 – HFC parameters

Network	Direction	Connection	Resource type (#subscribers)	Total capacity	Capacity per subscriber
HFC A (serves 250 subscribers off each Optical Node)	Both	Middle mile	Shared (500)	1 Gbps	2 Mbps
	Down	Fiber/coax	Shared (250)	76 Mbps	0.304 Mbps
	Up	Fiber/coax	Shared (250)	35 Mbps	0.140 Mbps
	Down	**Capacity per subscriber**			**0.304 Mbps**
	Up	**Capacity per subscriber**			**0.140 Mbps**
HFC B (serves 125 subscribers off each Optical Node)	Both	Middle mile	Shared (500)	1 Gbps	2 Mbps
	Down	Fiber/coax	Shared (125)	152 Mbps	1.22 Mbps
	Up	Fiber/coax	Shared (125)	54 Mbps	0.432 Mbps
	Down	**Capacity per subscriber**			**1.22 Mbps**
	Up	**Capacity per subscriber**			**0.432 Mbps**

4.3 GPON Capacity

Two GPON network configurations are analyzed, based on the general architecture in Figure 12. In the first case (“GPON A”), 512 subscribers are served from an OLT via a total of 16 PONs, each having a 1:32 split ratio. The middle mile from the OLT to the core network is provided by a 1 Gbps link.

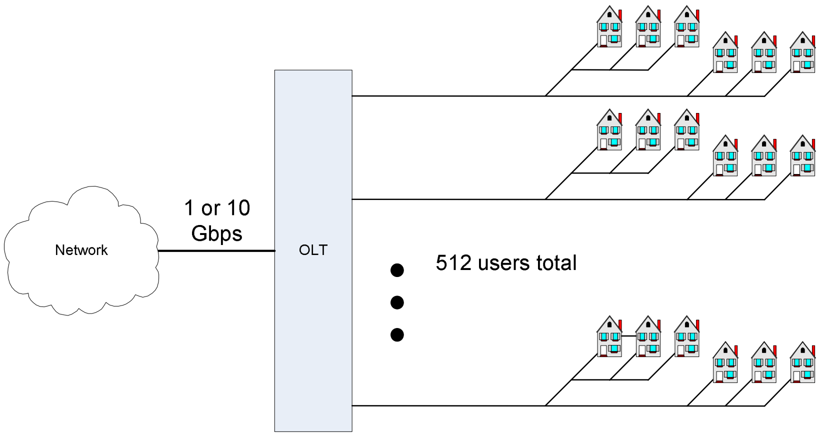

Figure 12 – GPON access network

In the second configuration ("GPON B"), the middle mile is upgraded to 10 Gbps. The relevant parameters and capacities for each configuration are shown in Table 5. The results show that in both cases, the capacity per subscriber is defined by the middle mile network, rather than the GPON. Both cases also meet the projected capacity requirements for year 2015.

Table 5 – GPON parameters

Network	Direction	Connection	Resource type (#subscribers)	Total capacity	Capacity per subscriber
GPON A (1 Gbps middle mile)	Both	Middle mile	Shared (512)	1 Gbps	1.95 Mbps
	Down	GPON	Shared (32)	2.5 Gbps	78.1 Mbps
	Up	GPON	Shared (32)	1.25 Gbps	39 Mbps
	Down	**Capacity per subscriber**			**1.95 Mbps**
	Up	**Capacity per subscriber**			**1.95 Mbps**
GPON B (10 Gbps middle mile)	Both	Middle mile	Shared (512)	10 Gbps	19.5 Mbps
	Down	Fiber/coax	Shared (32)	2.5 Gbps	78.1 Mbps
	Up	Fiber/coax	Shared (32)	1.25 Gbps	39 Mbps
	Down	**Capacity per subscriber**			**19.5 Mbps**
	Up	**Capacity per subscriber**			**19.5 Mbps**

4.4 Wireless Capacity

Capacity estimation for the wired network architectures discussed above is a relatively straightforward matter. Wireless networks, however, do not lend themselves to closed form analysis. A sampling of the many factors that preclude a simple and precise capacity analysis of wireless networks includes the following:

- The multiple antenna techniques supported by both LTE and WiMAX have many permutations, including diversity and beamforming (to combat fading and improve coverage), spatial division multiple stream transmission (to increase the rate to a single user), and spatial division multiple access (to allocate the same time/frequency resource to multiple users). While in general only one method can be used for a specific time/space/frequency/subscriber instance, implementations can dynamically switch between methods in an attempt to balance performance and coverage. For instance, users with high Signal to Interference+Noise Ratio (SINR) may receive multiple streams, while spatial diversity may be used instead to combat fading in areas with lower SINR.

- Both technologies support dynamic assignment of resources to subscribers in both the time and frequency domains, which along with other techniques enables the same wireless channel to be used across all cells in a network, resulting in a frequency reuse factor of 1. While this maximizes spectral efficiency, it requires sophisticated scheduling and processing to handle the resulting severe co-channel interference issues.
- Since the scheduling of resources between competing subscribers is entirely a function of the base station (meaning that there are no interworking issues between base stations and subscriber stations), scheduling algorithms are not standardized in either LTE or WiMAX. Different scheduling algorithms have significantly different impacts on individual subscribers. For instance, Proportional Scheduling, which is widely implemented, provides resources in proportion to the average received rate, a practice that severely penalizes fixed broadband users who happen to be located far from the base station.

Due to the above issues and many others, link and system simulations are required to gain an understanding of wireless system capacity. While such simulations are outside the scope of this paper, simulation results are available [20]. These simulation results provide spectral efficiency factors that we can use for an approximation of sector capacity. The downlink and uplink spectral efficiency values for LTE simulations including full frequency reuse and MIMO are provided in Table 6. Values for both FDD and TDD implementations are included.

Table 6 – LTE spectral efficiency

	FDD	TDD
Downlink	1.73 bps/Hz/sector	1.66 bps/Hz/sector
Uplink	1.05 bps/Hz/sector	0.94 bps/Hz/sector

While the values in Table 6 are specific to LTE, WiMAX is similar in many respects and the spectral efficiencies reported in simulation results are either roughly the same as or slightly lower than LTE, depending on the specific scenario tested [21]. One source [19] reports a spectral efficiency of 1.7 bps/Hz/sector for WiMAX with 2x2 open loop MIMO and frequency reuse factor of 1. We will use the values in Table 6 to approximate the capacity for both technologies.

4.4.1 Sectors

The previous section introduced the term “sector.” A wireless cell is typically divided into a number of sectors as shown in Figure 13, with each sector having its own radio transmitter, receiver, and directional antenna system. By dividing cells into three sectors each, the capacity of the network can be nearly tripled[5] without a corresponding increase in the number of cell towers required. It is common to see three sectors per cell in wireless networks. While higher degrees of sectorization are possible, co-channel interference from adjacent sectors can begin to limit the gains realized from more than three sectors.

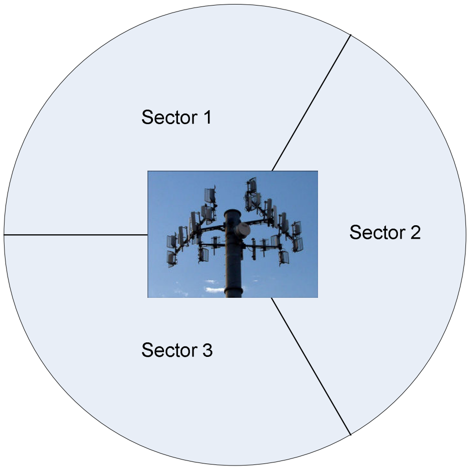

Figure 13 – Example of cell sectorization

4.4.2 Fixed vs. Mobile Subscribers

An additional feature unique to the wireless networks being discussed is that they support mobile users as well as fixed broadband users. We define a fixed broadband user as a user accessing the network via a device with full size display and keyboard. For the purpose of this analysis, we place laptop users in the category of "fixed broadband users," regardless of their location. In contrast, a mobile user accesses the network via a smartphone or other device with a limited keyboard and display. This delineation between "fixed" and "mobile" users aligns the type of user with the volume of data accessed by each type.

Both LTE and WiMAX deployments can be expected to serve many more mobile users than fixed users at any given time. How can we account for the shared traffic, considering that the two sets of users may place very different demands on the network?

While data for mobile traffic is not available at the same granularity as that used to develop the capacity projections for fixed consumer access, there are some comparison points we can use to approximate the split between fixed and mobile traffic. First, Cisco has estimated that while a smartphone generates as much traffic as 30 basic cell phones, a laptop computer generates as much traffic as 450 basic cell phones [22]. Simple division tells us that laptops (and by extension, fixed broadband users in general) generate about 15 times as much traffic as smartphones.

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[5] In wireless networks that have frequency reuse factors of less than 1, sectorization can actually provide capacity gains higher than the number of sectors used, due to reduced interference resulting from the directionality of the sector antennas. Since we are examining LTE and WiMAX networks, however, the maximum spectral efficiency occurs for frequency reuse = 1, even with a corresponding reduction in the sectorization gain.

We also need to determine the down/up division of smartphone traffic. Even if we estimate that the basic down/up ratio for data is the same as for fixed users, smartphones are likely to have more symmetric loads overall than fixed subscribers, in part due to the much higher ratio of signaling traffic that they place on the network. Airvana has measured this load at eight times the signaling load for laptop users [23], and further reports that the ratios between laptop and smartphone usage are 25:1 for data and 3:1 for signaling. If we assume that signaling traffic is approximately symmetric, we can start with the down/up ratio of 4:1 for fixed subscribers (based on the traffic projections derived in [3]), apply some algebra, and find that the corresponding ratio for mobile users is approximately 2:1.

Finally, we need to estimate the number of mobile users on average compared to the number of fixed broadband users. There is little data to guide us here, since neither LTE nor mobile WiMAX networks have been widely deployed yet. As an order-of-magnitude estimate, we assume 90% mobile users and 10% fixed users, given that the primary purpose of the network is enabling mobility. Using that estimate and the ratios arrived at earlier, we apply some more algebra and arrive at the overall traffic mix shown in Table 7.

Table 7 – Fixed and mobile traffic allocations

	Fixed	Mobile
Downlink	67%	33%
Uplink	50%	50%

In the analyses below, we will calculate the total capacity for a cell and then scale that capacity by the percentages allocated to fixed broadband users in Table 7 to determine the numbers of fixed subscribers supported at the required capacities.

4.4.3 LTE Capacity

In the United States, one of the largest spectrum allocations intended for LTE deployment is known as “Block C” in the 700 MHz band. This block of spectrum includes paired channels (one uplink, one downlink) up to 10 MHz wide which are aligned with E-UTRA Operating Band 13 as defined by 3GPP.

If we assume paired channels of 10 MHz each, three sectors per cell, and apply the spectral efficiency values for FDD from Table 6 and the traffic mix from Table 7, we arrive at the following values for the portion of LTE cell capacity allocated to fixed broadband subscribers:

- Downstream: 1.73 bps/Hz/sector * 10 MHz * 3 sectors * 67% fixed = 34.7 Mbps
- Upstream: 1.05 bps/Hz/sector * 10 MHz * 3 sectors * 50% fixed = 15.7 Mbps

Dividing by the required capacities for year 2015, we find that an LTE cell will support about 29 fixed broadband subscribers in the downstream direction, and about 52 fixed broadband subscribers in the upstream direction. The smaller of the two values (29) defines the number of fixed broadband subscribers supported by LTE in a capacity limited cell.

4.4.4 WiMAX Capacity

As noted earlier, a notable deployment of WiMAX in the United States is using spectrum licensed within the 2.5 GHz band. The service provider implementing that deployment has stated their intention to use "a minimum of three contiguous blocks of 10 MHz of spectrum bandwidth" wherever possible [24]. As we examine use cases that concentrate on lower population densities later in this paper, we will use that minimum value as the standard bandwidth for WiMAX cell capacity and assume three 10 MHz channels in each sector with full frequency reuse and TDD in each channel.[6]

Ignoring the TDD allocation of time for downlink and uplink for the moment, we calculate the overall cell capacity in a channel for all traffic (both fixed and mobile), using the spectral efficiency values for TDD from Table 6:

- Downstream: 1.66 bps/Hz/sector * 10 MHz * 3 sectors = 49.8 Mbps
- Upstream: 0.94 bps/Hz/sector * 10 MHz * 3 sectors = 28.2 Mbps

The optimum down/up ratio for TDD is 63% down and 37% up, determined by combining the ratios for fixed and mobile traffic from section 4.4.1 with the overall capacities identified above. Using these values and the traffic mix from Table 7, we find the following values for the portion of mobile WiMAX cell capacity allocated to fixed broadband subscribers:

- Downstream: 49.8 Mbps * 63% downlink time * 67% fixed = 20.9 Mbps
- Upstream: 28.2 Mbps * 37% uplink time * 50% fixed = 5.2 Mbps

Dividing by the required capacities for year 2015, we find that capacity limited mobile WiMAX cells support about 17 fixed broadband subscribers per channel per cell in each direction. With three 10 MHz channels deployed in each cell, the capacity per cell is 3 * 17 = 51 fixed broadband subscribers.

5 Comparing Architecture Coverage

In this section we provide some comparisons of the areas that can be covered by last mile networks using the different technologies discussed above. For each use case, we define a benchmark based on the maximum geographic area that can be covered by a single access node with service at the capacity per user defined for year 2015 in Table 2. An "access node," as defined in Section 3, is the demarcation point between the second mile and the last mile in an access network. The typical locations and equipment requirements for each type of access node are specific to the network architecture and technology, and are discussed in the sections below.

The FCC has defined a population density of "less than 19 End User Common Line charge lines per square mile served" as a benchmark to identify "very low density" or "primarily rural" access providers [25, 26]. We will center our comparison on this benchmark and define three use cases:

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[6] Note that these are three independent channels of 10 MHz each, and not a shared channel of 30 MHz.

1. Extremely rural: One-tenth the density of the “very low density” benchmark, or 1.9 subscribers per square mile. There are 337 acres for each subscriber in this extremely remote use case.
2. “Very low density” benchmark: 19 subscribers per square mile, the threshold the Federal Communications Commission uses to identify “very low density carriers.” There area 34 acres per subscriber for this very low density use case.
3. Moderately rural: Ten times the density delineating very low density carriers, or 190 subscribers per square mile. There are 3.4 acres per subscriber in this rural use case.

5.1 Access Node Types

The types of access nodes applicable to each technology are described below. In addition, we discuss the maximum area that can be covered by the last mile for each technology, and provide some insight into how that area is defined. Note that depending on the technology, the maximum area may not be applicable to each use case, since factors such as the number of subscribers served and required capacity may limit the area served to a smaller value.

5.1.1 ADSL2+

An ADSL2+ access node is a DSLAM which serves subscriber loops up to a designated reach, based on network deployment guidelines. For the use cases, we define the maximum reach as that corresponding to an ADSL Carrier Serving Area, or 3.7 km (12 kft) of loop at 24 AWG.[7,8] The absolute maximum area corresponding to this reach is a circle with a radius of 12 kft, but that would require straight line routing from the node to each subscriber at the maximum reach. Instead, we define the maximum area as a square with the maximum reach extending from the center to one corner. This allows a loop at the maximum length to reach anywhere on the perimeter with orthogonal (horizontal/vertical, or north-south/east-west) routing, as would align with the roads and easements that would be likely in a rural area (see Figure 14). When defined this way, the CSA supported by ADSL2+ covers approximately 10.3 square miles.

ADSL2+ DSLAMs are typically located in outdoor curbside cabinets or mounted on posts, depending on the number of subscriber loops being served. On the low end, DSLAMs designed for deployment in the outside plant may have as few as 24 loop interfaces. High density DSLAMs installed within cabinets can serve over a thousand loops, and multiple DSLAMs can be placed at a single location, so the maximum area served by an ADSL2+ access node is independent of population density.

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[7] We use 24 AWG rather than 26 AWG as heavier gauges are most likely in the rural use cases examined.

[8] While ADSL can operate at longer loop reaches, we will limit discussion to CSA, which supports rates of 6 Mbps downstream and 1 Mbps upstream.

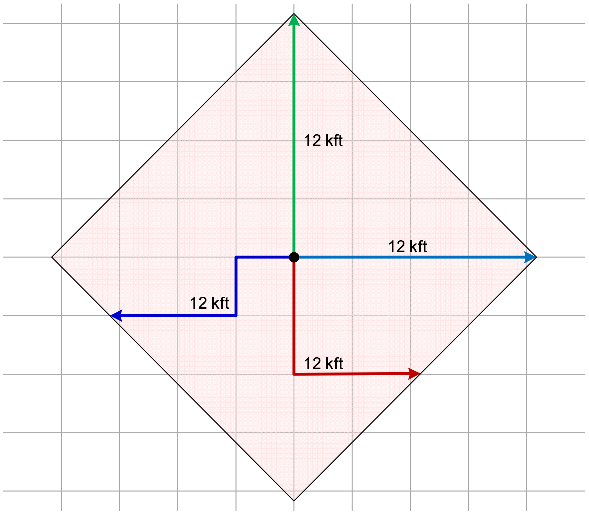

Figure 14 – CSA with orthogonal loop routing

5.1.2 VDSL2

A VDSL2 access node is identical to an ADSL2+ access node in most respects. VDSL2 DSLAMs can be mounted in cabinets or on posts within the outside loop plant and they can serve similar numbers of loops, making the area served independent of the population density. We define the Carrier Serving Area for VDSL2 using a shorter loop length, which allows the technology to support higher downstream and upstream rates. For the use cases, we define the maximum reach for VDSL2 as 1.2 km (4 kft) at 24 AWG. The maximum area of 1.1 square miles is defined using the same method as for ADSL2+.

5.1.3 HFC (DOCSIS)

The access node in an HFC network (using DOCSIS technology) is the Optical Node, which converts between the fiber-based second mile network and the coaxial last mile network. Optical Nodes are typically located in outdoor curbside enclosures or on posts. A single Optical Node can serve multiple coax networks, and multiple Optical Nodes can be co-located, so area coverage is independent of population density.

In order to meet the capacity requirements projected for year 2015, HFC networks will probably serve no more than 125 subscribers from a single coax network. The maximum reach for the coaxial portion of an HFC network varies based on the RF bandwidth of the network, the network topology (*e.g.*, how many branches are split off), and the number and spacing of amplifiers. While this varies from network to network, we will estimate the reach at 2.7 km (9 kft), based on a cascade of five amplifiers located at 1500 foot intervals. We use that maximum reach to derive the maximum area of 5.8 square miles using the same method as for the DSL technologies.

5.1.4 FTTH (GPON)

The access node in a GPON network is the OLT, which is typically located in the CO although it may also be placed in the outside plant. OLTs are frequently implemented as modules within a large chassis which supports over a thousand subscribers. As many

GPONs as necessary can be served out of a single CO, so area coverage is independent of population density.

We will limit the split ratio to 1:32 for the use cases studied. The maximum reach at that split ratio is 20 km, which supports a maximum area (defined as per the above technologies) of 309 square miles.

5.1.5 Wireless Access Technologies

The access node for wireless access technologies is the base station. The base station includes the transmitter, receiver, amplifiers and antennas for each sector supported by the cell served by the base station, as well as the second mile communications equipment. It also includes the physical support structure for the antenna arrays. In urban and suburban areas, base station antennas are increasingly mounted on top of existing structures (such as buildings, steeples or billboards) when possible. In rural areas, base stations usually require towers that may be up to 400 feet tall.

Instead of the square areas defined for coverage of wireline technologies, we define the area covered by a wireless cell as a hexagon. Since a wireless cell is not constrained by routing along easements, the ideal shape for a single cell is a circle – however, when multiple cells must adjoin one another in a network without leaving gaps in coverage, the most efficient shape becomes a hexagon as shown in Figure 15.

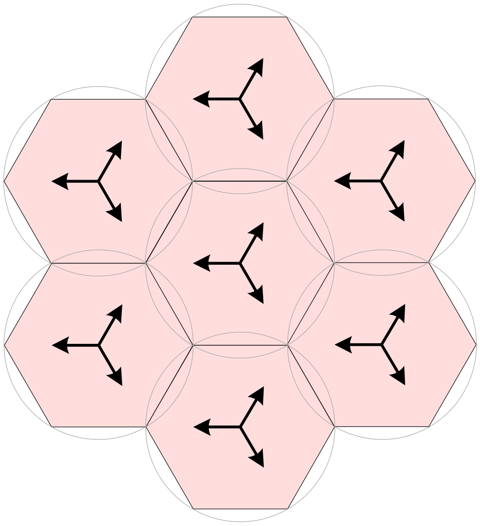

Figure 15 – Hexagonal wireless cells

The maximum ranges for range limited cells in the absence of co-channel interference using the technologies below are modeled using link budget parameters from [19] and using the enhanced Erceg C propagation model, which is most appropriate for rural areas with few hills or trees. The maximum range in each case is defined by mobile performance, since a fixed broadband station with a roof mounted, directional antenna can reach further than a mobile station with an omnidirectional antenna located near the ground.

5.1.5.1 LTE

At a maximum range of 16.3 km, the area covered by an LTE cell in the 700 MHz band is 269 square miles. However, an LTE cell with two 10 MHz channels and the parameters discussed in Section 4.4.3 is limited to serving about 29 fixed broadband subscribers at year 2015 required capacity projections. This means that the maximum size cell will not be reached in deployments serving fixed broadband subscribers unless the population density is at or below about 0.107 subscribers per square mile.

5.1.5.2 WiMAX

At 5.9 km, the maximum range in the 2.5 GHz band is significantly smaller than that in the 700 MHz band. At the range available in the 2.5 GHz band, the maximum area covered by a WiMAX cell is 35 square miles. Since a WiMAX cell with three 10 MHz channels and the parameters discussed in Section 4.4.4 can serve about 51 fixed broadband subscribers per cell, a single base station can offer broadband to the maximum distance of 5.9 km only if the population density of the area covered does not exceed 1.5 subscribers per square mile.

5.2 Use Cases

Figure 16 shows the comparative area that can be covered by the last mile for each technology in each of the use cases. We discuss the effect of the different population density use cases on each technology below.

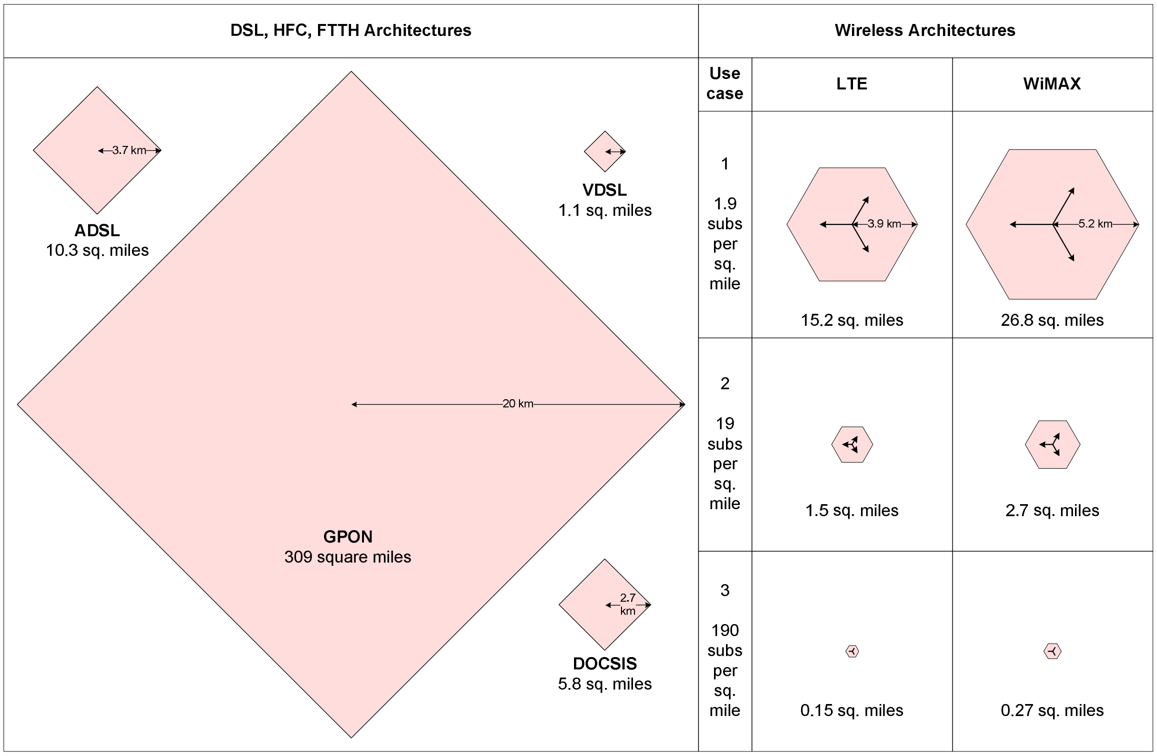

Figure 16 – Comparative last mile coverage areas

5.2.1 DSL (ADSL2+)

The CSA for ADSL2+ is approximately 10.3 square miles. For the use cases under consideration, a single CSA serves approximately 20 to 1960 subscribers. This range is consistent with the number of ports that can be served from a single curbside cabinet.[9]

The total required capacity for the second mile ranges from 24 Mbps (at 1.9 subscribers per square mile) to 2.4 Gbps (at 190 subscribers per square mile). For Use Cases 1 and 2, multiple CSA nodes could be connected in a common 1 Gbps second mile network while meeting the required capacity. In all use cases, the capacity per subscriber is dependent on the second mile and middle mile networks. This capacity per subscriber ranges from 1.2 Mbps to 6 Mbps per subscriber downstream, and from 0.3 Mbps to 1 Mbps per subscriber upstream.

5.2.2 DSL (VDSL2)

The CSA for VDSL2 is approximately 1.1 square miles. For the use cases under consideration, a single CSA serves approximately 2 to 220 subscribers. As with ADSL2+, this range is consistent with the number of ports that can be served from a single curbside cabinet.[10]

The total required capacity for the second mile ranges from 2.6 Mbps (at 1.9 subscribers per square mile) to 262 Mbps (at 190 subscribers per square mile). For all use cases, multiple nodes could be connected in a common 1 Gbps second mile network while meeting the required capacity. In all use cases, the capacity per subscriber is dependent on the second mile and middle mile networks and ranges from 1.2 Mbps to 25 Mbps per subscriber downstream, and from 0.3 Mbps to 4 Mbps per subscriber upstream.

5.2.3 HFC (DOCSIS)

With a serving area of 5.8 square miles, an Optical Node can serve from approximately 11 to 1100 subscribers. This requires one coaxial network for Use Cases 1[11] and 2, and nine coaxial networks (at a maximum of 125 subscribers per network) for Use Case 3.[12]

For each use case, Table 8 provides the total capacity required by the subscribers served by each coaxial network, the number of channels required to provide that capacity, and the resulting capacity per subscriber. As long as the middle mile network supports the total capacity provided in each case, the capacities per subscriber are defined by the last mile values in the table.

---

[9] In areas exhibiting the population density in Use Case 3, a service provider might opt to use several smaller nodes instead of a single large node. Engineers would consider routing of existing copper loops and availability of easements when deciding how to design the network.

[10] Depending on loop routing and the availability of easements, a service provider might opt to employ several smaller nodes, rather than a single larger node, at the population density in Use Case 3.

[11] In Use Case 1 where the number of subscribers in the coax network (and the corresponding noise funneling) is small, it may be possible to extend coax runs further than the 9 kft and five cascaded amplifiers assumed as a maximum for the use cases.

[12] For Use Case 3, the optimal number of Optical Nodes could vary, based on coax routing and easements.

Table 8 – Capacity requirements for HFC use cases

Use case	# subscribers	Dir.	Total required capacity	# chls	Total capacity provided	Capacity provided per subscriber
1	11	Down	13.2 Mbps	1	38 Mbps	3.45 Mbps
		Up	3.3 Mbps	1	27 Mbps	2.45 Mbps
2	110	Down	132 Mbps	4	152 Mbps	1.38 Mbps
		Up	33 Mbps	2	54 Mbps	0.49 Mbps
3	125	Down	150 Mbps	4	152 Mbps	1.22 Mbps
		Up	37.5 Mbps	2	54 Mbps	0.43 Mbps

5.2.4 FTTH (GPON)

Since the reach of a GPON last mile network is 20 km, the maximum serving area for this technology dwarfs the other areas at 309 square miles. At this range, an OLT can serve from about 587 to about 58,700 subscribers. At a 1:32 split ratio, this requires from 19 to 1834 PON networks.[13]

At a 1:32 split ratio, each PON supports a capacity of up to approximately 78 Mbps per subscriber downstream and approximately 39 Mbps per subscriber upstream. The overall capacity per subscriber is dependent on the middle mile network and can range anywhere from the minimum required values to the above values. Up to 12 PONs can be connected in a common middle mile network at 1 Gbps while meeting the required capacity.

5.2.5 Wireless (LTE)

LTE cells are capacity limited to 29 fixed broadband subscribers in all three of the use cases shown. This capacity limit results in a serving area that varies inversely with the population density, ranging from 15.2 square miles per cell for Use Case 1 to 0.15 square miles per cell for Use Case 3.

The capacity per fixed broadband subscriber is defined by the wireless last mile and is 1.2 Mbps downstream and 0.54 Mbps upstream. The total capacity per cell, including both fixed and mobile subscribers, is approximately 51.9 Mbps downstream and 31.5 Mbps upstream. At these values, up to 19 cells can be connected in a common second mile network at 1 Gbps.

5.2.6 Wireless (WiMAX)

WiMAX cells are capacity limited to 51 fixed broadband subscribers in all three of the use cases shown. This capacity limit results in a serving area that varies inversely with the population density, ranging from 26.8 square miles per cell for Use Case 1 to 0.27 square miles per cell for Use Case 3.

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[13] For all three use cases, a service provider would determine the optimum number of OLT locations for a specific area based on fiber routing and easements.

The capacity per fixed broadband subscriber is defined by the wireless last mile and is 1.23 Mbps downstream and 0.31 Mbps upstream. The total capacity per cell, including both fixed and mobile subscribers, is approximately 93.8 Mbps downstream and 31.5 Mbps upstream. At these values, up to 10 cells can be connected in a common second mile network at 1 Gbps.

5.2.7 Use Case Summary and Trends

Table 9 provides a summary of the use cases. For each technology and each use case, the maximum area that can be served by the last mile network is shown, along with the downstream capacity per subscriber supported by the last mile.

The first six rows of Table 9 summarize the use cases as they are discussed above, with network deployments designed for each use case to meet the capacity requirements shown in Table 2 for year 2015. Two additional rows, showing the maximum areas that could be covered by range limited wireless cells and the capacities per fixed broadband subscriber that would result, are also provided at the bottom of the table. These rows are provided for comparison only, as it becomes clear from inspection that range limited wireless cells cannot meet the required capacities even for the lowest population density use case.

Table 9 – Use case summary

Technology	1.9 subscribers / sq. mi.		19 subscribers / sq. mi.		190 subscribers / sq. mi.	
	Max area (sq. miles)	Cap/sub (Mbps)	Max area (sq. miles)	Cap/sub (Mbps)	Max area (sq. miles)	Cap/sub (Mbps)
ADSL2+	10.3	6	10.3	6	10.3	6
VDSL2	1.1	25	1.1	25	1.1	25
DOCSIS	5.8	3.45	5.8	1.38	5.8	1.22
GPON	309	78	309	78	309	78
LTE	15.2	1.2	1.5	1.2	0.15	1.2
WiMAX	26.8	1.23	2.7	1.23	0.27	1.23
LTE (max range)	269	0.068	269	0.007	269	0.0007
WiMAX (max range)	35	0.94	35	0.094	35	0.009

The capacity values provided in Table 9 are the values supported by the last mile networks for each technology. As noted in the detailed discussions above, the actual capacity per subscriber can be further limited by the second mile and/or middle mile networks. This may occur for ADSL2+, VDSL2, and GPON networks (and also DOCSIS at the lowest subscriber density), because the last mile capacity provided by those networks can be significantly higher than the required value. For the wireless technologies and for DOCSIS at higher subscriber densities, the last mile capacity is just above the required value, so the last mile is likely to define the limit on performance.

As noted above, only the capacity limited wireless cells meet projected requirements for fixed broadband access in any of the wireless use cases. In order to meet those requirements, the area coverage for capacity limited cells shrinks rapidly as the population density rises. Even for Use Case 2, which is based on the FCC's definition of "very low density carriers", the coverage for wireless cells using 20 MHz (as in the LTE deployment) or even 30 MHz of spectrum (as in the WiMAX deployment) is significantly lower than that provided by ADSL2+. At the relatively low population density of 190 subscribers per square mile defined in Use Case 3, both the LTE and WiMAX cell sizes are dwarfed by the VDSL2 serving area. An LTE network meeting projected capacity requirements for Use Case 3 would need to space base stations only 675 meters apart. These capacity constraints will probably force wireless networks to use one or more techniques to increase the population served by each cell:

- Additional sectors. The above analyses assume three sectors per cell. Cell capacity can be improved by adding sectors, but with full frequency reuse the improvement will be limited as interference due to overlap from adjacent sectors increases.
- Additional spectrum. Capacity is directly proportional to spectrum – however, spectrum is a finite resource and the recent 700 MHz band auction was thought to be the last clear block of spectrum available. Allocation of additional spectrum for wireless broadband access may take years.
- Traffic engineering. By closely monitoring demand and applying advanced traffic engineering, it may be possible to provide adequate service at lower capacity values in some cells. However, as noted in Section 2.2, the required capacity values provided in Table 2 are based on national averages, and the user populations in some cells will place significantly higher than average demands on the system. This variation in demand may be very significant given that the user populations supported by the cells are small, and the traffic from a very small (but variable) number of heavy users will dominate the overall volume. As a result, many cells may actually need to be smaller than the values shown in these use cases.

The challenge that wireless networks face in providing enough capacity for fixed broadband access is daunting. Even if the number of sectors is doubled to six per cell – and assuming, optimistically, that doubling the sectors results in a doubling in capacity – the relatively low density in Use Case 3 would still require spacing between LTE base stations of only 950 meters.

An alternative way of expressing coverage is to consider how many access node locations are required to cover a fixed area. This is shown (using a fixed area of 100 square miles) for the different technologies and use cases in Table 10.

Table 10 – Access nodes required per 100 square miles

Technology	1.9 subscribers / sq. mi.	19 subscribers / sq. mi.	190 subscribers / sq. mi.
ADSL2+	10 at all population densities		
VDSL2	88 at all population densities		
DOCSIS	18 at all population densities		
GPON	1 at all population densities		
LTE	7	66	658
WiMAX	4	38	373

The maximum area that can be covered by the last mile in an access network – or alternately, as shown above, the minimum number of access node locations required to cover a given area – provides one metric for comparing technologies, but it is far from complete. Some of the other factors for comparison include:

- The type of node and the associated equipment required. DSLAMS, Optical Nodes, and OLTs designed for installation in the outside plant are all relatively compact devices which can be installed in a curbside cabinet or a smaller enclosure. A base station, especially if it requires a tower for the antennas, is much more costly and requires significantly more real estate than any of the other access node types.

  The cost of new cell towers in rural areas may be one of the most significant factors for new wireless data deployments. Deployments designed to provide fixed broadband service at the required capacities will require many towers in addition to existing locations, which were designed to support voice and earlier generation mobile data services.

- Buildout of new lines to the access nodes and, if necessary, to the subscriber premises. The second mile capacities and the technology required for different technologies vary as shown below.
  - DSL networks may require fiber or may be able to use copper in the second mile, depending on the total required capacity and the availability of multiple copper loops. Point-to-point wireless circuits may also be an option on some second mile connections. The last mile for all networks except new construction will already be in place due to the near ubiquity of the existing copper loop plant.
  - HFC networks require fiber by definition over the second mile, and deliver video as well as data services over it. Availability of pre-existing coax in the last mile is much less common in rural areas than the copper loops used for DSL, so HFC will frequently require of the last mile.
  - FTTH requires fiber by definition to the subscriber premises. It may deliver video as well as data services, either using a different wavelength or via IPTV.

- Wireless networks require enough capacity to meet the demands associated with both fixed and mobile subscribers, which together are estimated (in Section 0) at about 1.5 times the fixed-only requirement in the downstream direction. Second mile connections may be fiber, copper, or point-to-point wireless depending on the individual requirements of the base station. By definition, wireless networks do not require wired facilities in the last mile.

6 Conclusion

The analyses presented in this paper show that the network capacity of wireline architectures can be scaled to meet capacity requirements independent of subscriber density, while the fixed capacity of wireless networks limits their size for fixed broadband use even in very rural areas. This distinction has a significant impact on network design and deployment costs for fixed broadband access in rural areas. Based on 2015 estimates of required capacity, more wireless access nodes will frequently be required to cover the same rural territory as wireline access nodes. At the benchmark subscriber density used to identify "very low density carriers," the area covered by an LTE cell site will be less than one-sixth of that covered by an ADSL2+ DSLAM and about one-forth of that covered by a cable Optical Node. Differences in coverage areas have a significant impact on network design and deployment costs for fixed broadband access in rural areas, and they should be accounted for in any assessment of the costs to deploy broadband in rural areas.

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