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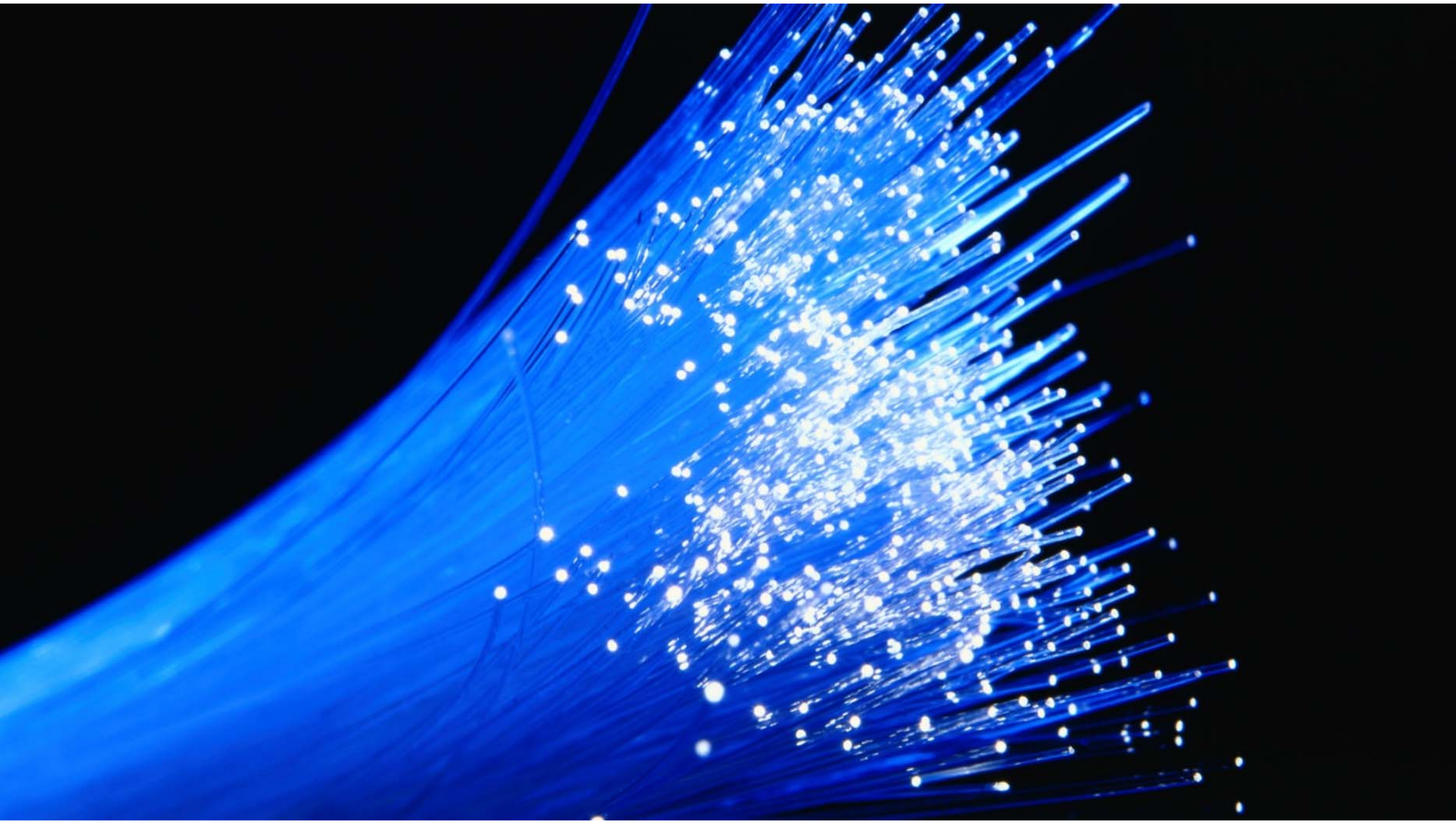

Mobile Broadband Service Is Not an Adequate Substitute for Wireline

A report prepared by the engineers and analysts of CTC Technology & Energy with financial support from the Communications Workers of America. The content is entirely independent and reflects CTC's analysis and conclusions.

October 2017

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1 Executive summary

This report[1] analyzes the current and emerging generation of mobile wireless technologies and compares those technologies to wireline technologies such as fiber-to-the-premises (FTTP), cable broadband, and copper DSL across a range of technical parameters, including reliability, resilience, scalability, capacity, and latency. The report also evaluates wireless carriers' mobile pricing and usage structures—including so-called "unlimited" data plans—because those policies play a significant role in whether consumers can substitute mobile for wireline service.

The report concludes that, for both technical and business reasons, wireless technologies are not now, and will not be in the near to medium future, adequate alternatives or substitutes for wireline broadband.

Technology limitations: Modern wireline broadband services are superior to wireless services in terms of capacity, reliability, and scalability. Figure 1 illustrates a range of wireline and wireless technologies, both existing and under development, and provides the speed range in which the technologies operate.

While cutting-edge wireless technologies may surpass the theoretical bandwidth capabilities of some wireline products, FTTP networks easily surpass even the best of all planned or deployed wireless technologies and cable modem networks can, with existing technologies, deliver faster speeds than existing or emerging wireless products. Even DSL networks can deliver a higher bandwidth, more reliable experience to consumers than can mobile so long as the DSL network is well-maintained and includes adequate investment in electronics.

It is also important that existing mobile technologies be understood based on their actual, current and relatively near-term performance, rather than on the hypothetical speeds posited for "5G" technologies that the industry suggests will emerge in the coming decade or so. "5G" has not been defined and standards have not been finalized for this new technology. Rather, the term "5G" has effectively served as marketing tool—suggesting that new technologies that will deliver far faster mobile speeds are somewhere on the horizon. That horizon, from an engineering standpoint, is quite distant—and the path to it is undetermined.

Suggesting that "5G" can currently or in the near to medium term serve as a substitute for adequate wireline service is suggesting that a non-existent, non-deployed technology should

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serve as an alternative. The hypothetical “5G” future should not serve as part of the current discussion about the relative merits of existing wireline and mobile networks.

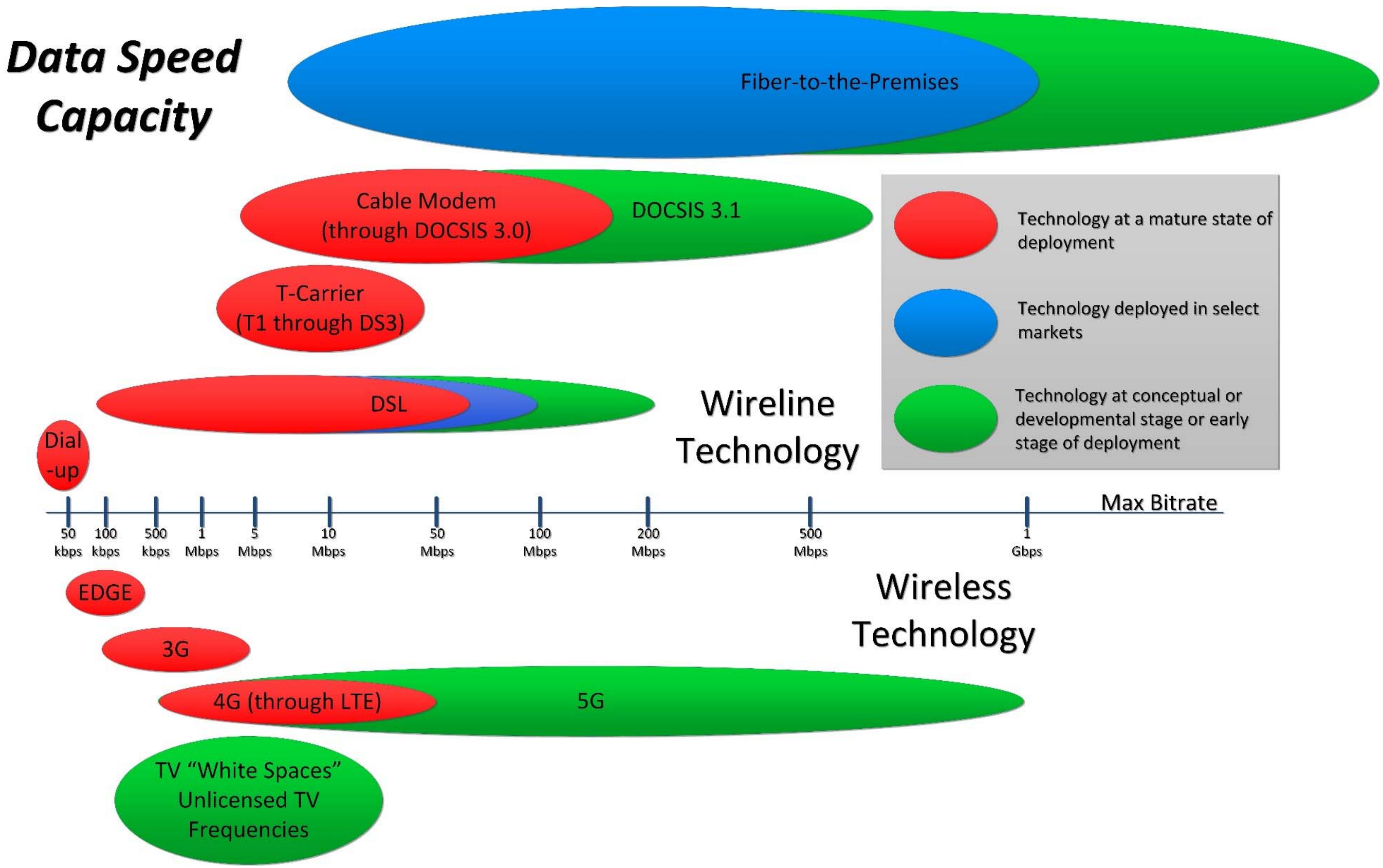
Further, the highest capacity wireless networks still require a large amount of fiber infrastructure for backhaul—meaning that rural communities and other areas where fiber infrastructure is scarce will likely have substandard, inadequate mobile service unless fiber is improved or expanded.

Business and usage policy limitations: The business policies imposed by mobile companies further impact the usability of mobile service as a primary or sole source of broadband. Mobile pricing and usage limits make mobile service a poor substitute for wireline broadband services.

The recent shift in mobile pricing models from data caps to so-called “unlimited” plans has not changed this outcome because, even though the product is not capped, users experience significant degradation of speeds via throttling after certain levels of use. Mobile providers dramatically limit customer usage and exert significant control over how applications run on their networks; these policies may have good technical or business justification but *they have the impact of making the mobile service far inferior and less usable for consumers than wireline broadband service*.

In summary, in light of the technical and business restrictions inherent in existing mobile networks, mobile service cannot be considered an adequate alternative to robust wireline broadband. Rather, mobile and wireline have been—and will continue to be—essential, complementary services. Those Americans who have access to only one of them will face significant disadvantages relative to their peers.

Figure 1: Wireline and Wireless Capacity



2 State-of-the-art wired and wireless technologies have widely different capacities and limitations

The sections below describe the state of the art in wired and mobile wireless technologies. They present an analysis of the technologies' current capabilities and limitations, then describe their potential future states. (For details on fixed wireless technologies, see Appendix A.)

2.1 Fiber-to-the-premises offers the highest speeds and other technical advantages

Fiber is the most advanced form of wireline communications infrastructure. It has been incorporated into middle-mile and backhaul connections—the lines that are used to aggregate data traffic and provide high-capacity transport between cities and across continents—since the 1980s. Almost all commercial broadband providers use fiber in portions of their networks, then connect their end users over wireless, coaxial, or copper lines.

Fiber cables contain many thin strands of glass (or in some cases plastic), with the number depending on the specific application. A backbone fiber cable could have hundreds of strands, while a fiber cable serving a neighborhood or a few buildings would have a few dozen strands and a cable to an individual house might have one or two strands.

Fiber has become the medium of choice for wireline broadband communications for several reasons:

- Fiber optic cables have enormous bandwidth, which enables operators to offer symmetrical download and upload speeds
- Optical light signals can travel great distances (up to 50 miles between electronics) with minimal signal deterioration[2]
- Optical fibers do not conduct electricity and are immune to electromagnetic interference; fiber can be deployed where conductive materials would be dangerous, such as near power lines
- Fiber offers essential, flexible, high-speed backbone/backhaul for wireless services
- Fiber networks are highly reliable and require less maintenance than any other communications infrastructure; once a location is connected to fiber, there is no need for significant outside plant infrastructure investment for decades.

[2] Maximum distances depend on specific electronics—six to 25 miles is typical for fiber optic access networks.

These technical advantages are why the vast majority of the internet backbone, as well as the interconnection system for wireless networks, comprise bundles of fiber cable strands.

The main limitation on the speeds fiber networks can achieve is not based on the properties of the fiber optic cables themselves but instead on the processing power of the network electronics connected to the fibers. Off-the-shelf FTTP equipment can deliver 1 Gbps ("Gig") symmetrical services to each customer over a single fiber. Meanwhile, 10 Gbps equipment is widely available and falling in cost.

Figure 2 (below) illustrates a sample FTTP network, demonstrating how high levels of capacity and reliability are brought directly to the premises.

Figure 2: Sample FTTP Network

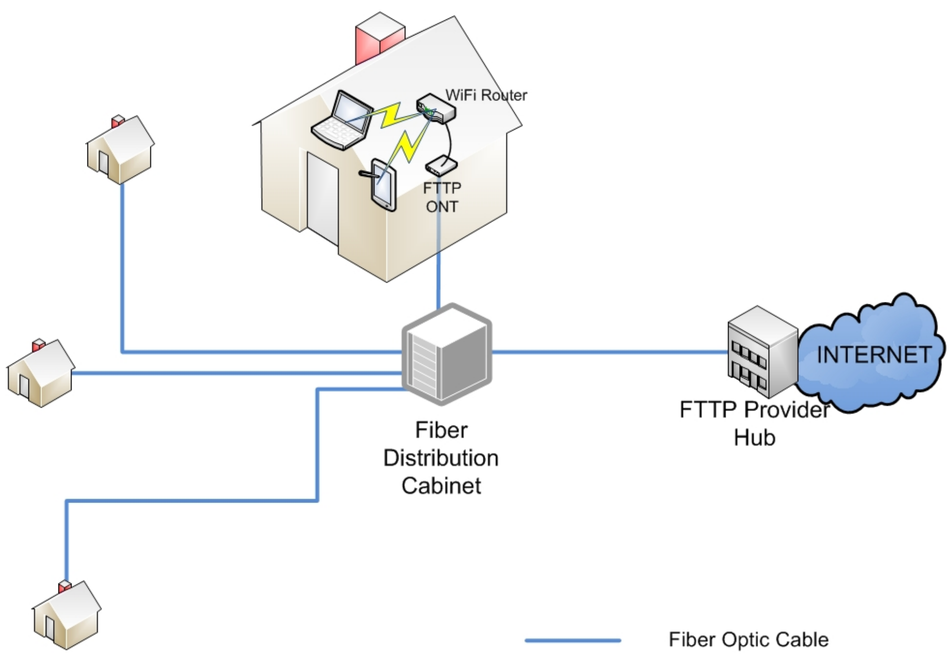
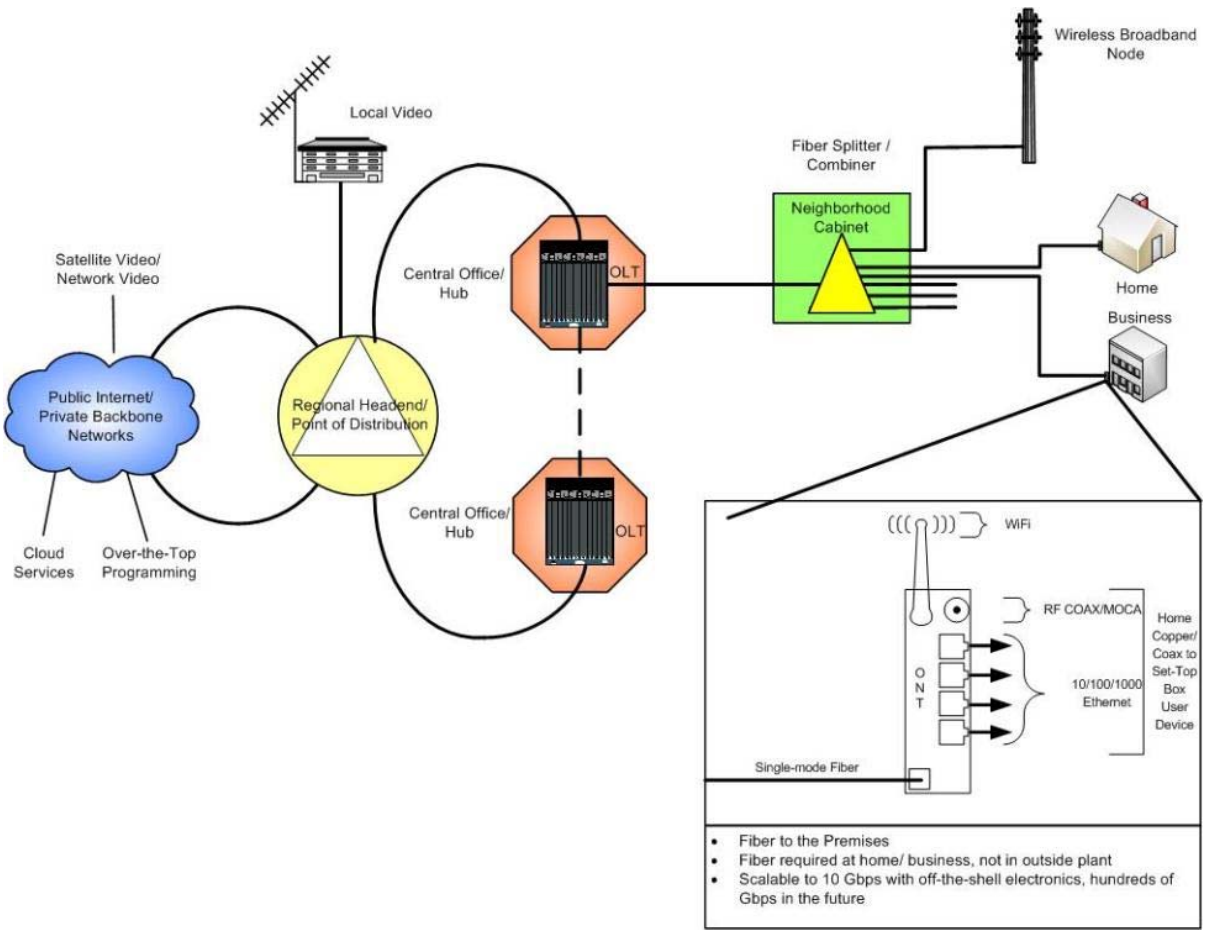


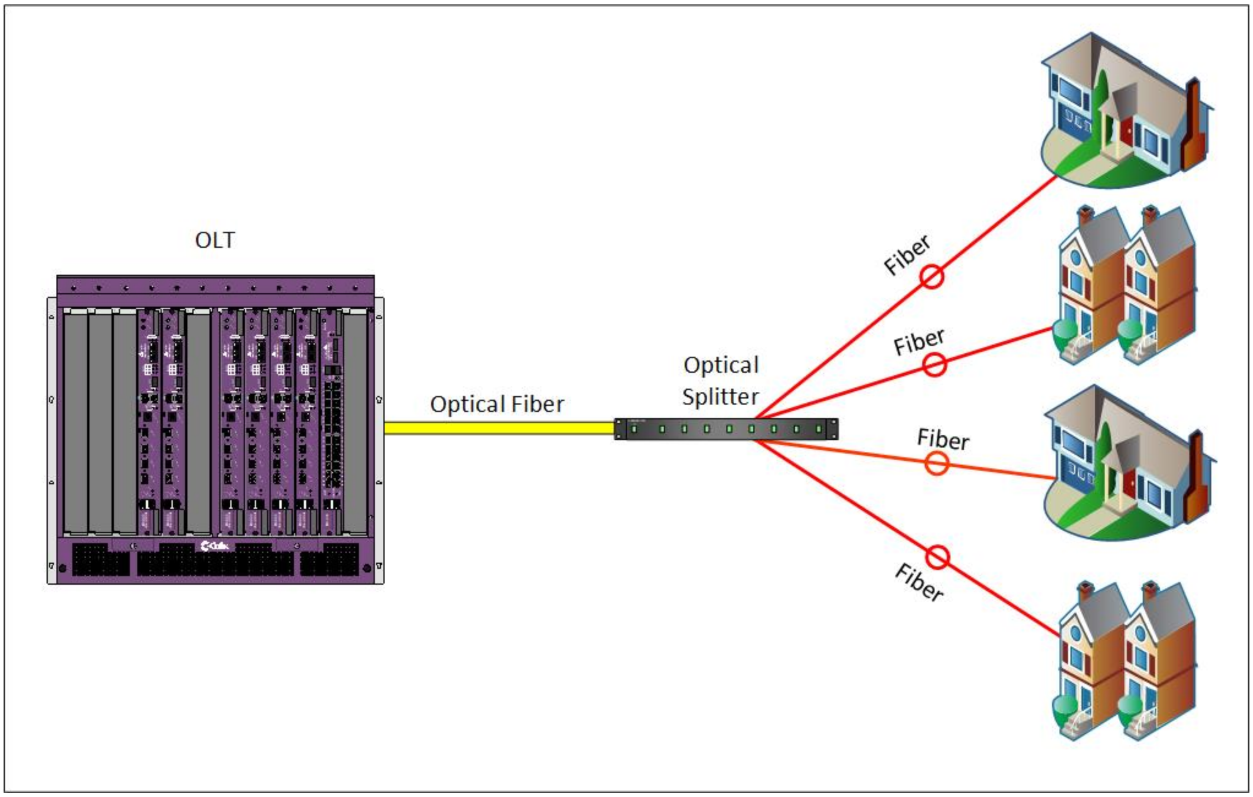
Figure 3 illustrates in more detail how an FTTP network provides connectivity without a technical bottleneck to the internet or other service providers, and can also provide a flexible, high-speed backbone for wireless services.

Figure 3: Sample FTTP Network (Detailed)



Most FTTP operators, such as Verizon, AT&T, and Google Fiber, use passive optical network (PON) technology, typically splitting the fiber capacity in a neighborhood cabinet to connect 16 to 32 customers (Figure 4).

Figure 4: FTTP-PON Network Architecture



A PON architecture provides less dedicated capacity than a network where each customer is connected to their own dedicated Ethernet connection (also known as active Ethernet or point-to-point), but direct connection is rarely done in residential and small business settings. PON technology is generally able to sustain a constant speed in excess of 100 Mbps to all users in the downstream direction; indeed, because most customers' broadband consumption is highly variable, most PON networks can support symmetrical Gig connections.

2.2 Broadband cable service is a robust wireline broadband technology, though not as capable as FTTP

Cable broadband technology is currently the primary means of providing broadband services to homes and small and medium-sized businesses in urban, suburban, and small-town areas in the United States. Because of its relative ubiquity in non-rural areas and its inherently greater capacity than commercial wireless service and copper telephone lines (the medium underlying digital subscriber line, or DSL, service), broadband cable networks will continue as a major broadband communications technology for most homes and businesses for the foreseeable future.

Coaxial cables were originally designed to provide video services. One legacy of this design is the highly asymmetrical capacity of coaxial systems, with 95 percent of the physical capacity originally designed for the downstream direction. In order to provide sufficient capacity for data services and reduce the noise in long runs of coaxial cable, cable operators built fiber to each neighborhood they serve (to within a mile or so of each customer), typically lashing the fiber to the coaxial cables. Thus, coaxial cable networks have transformed into hybrid fiber-coaxial (HFC) networks.

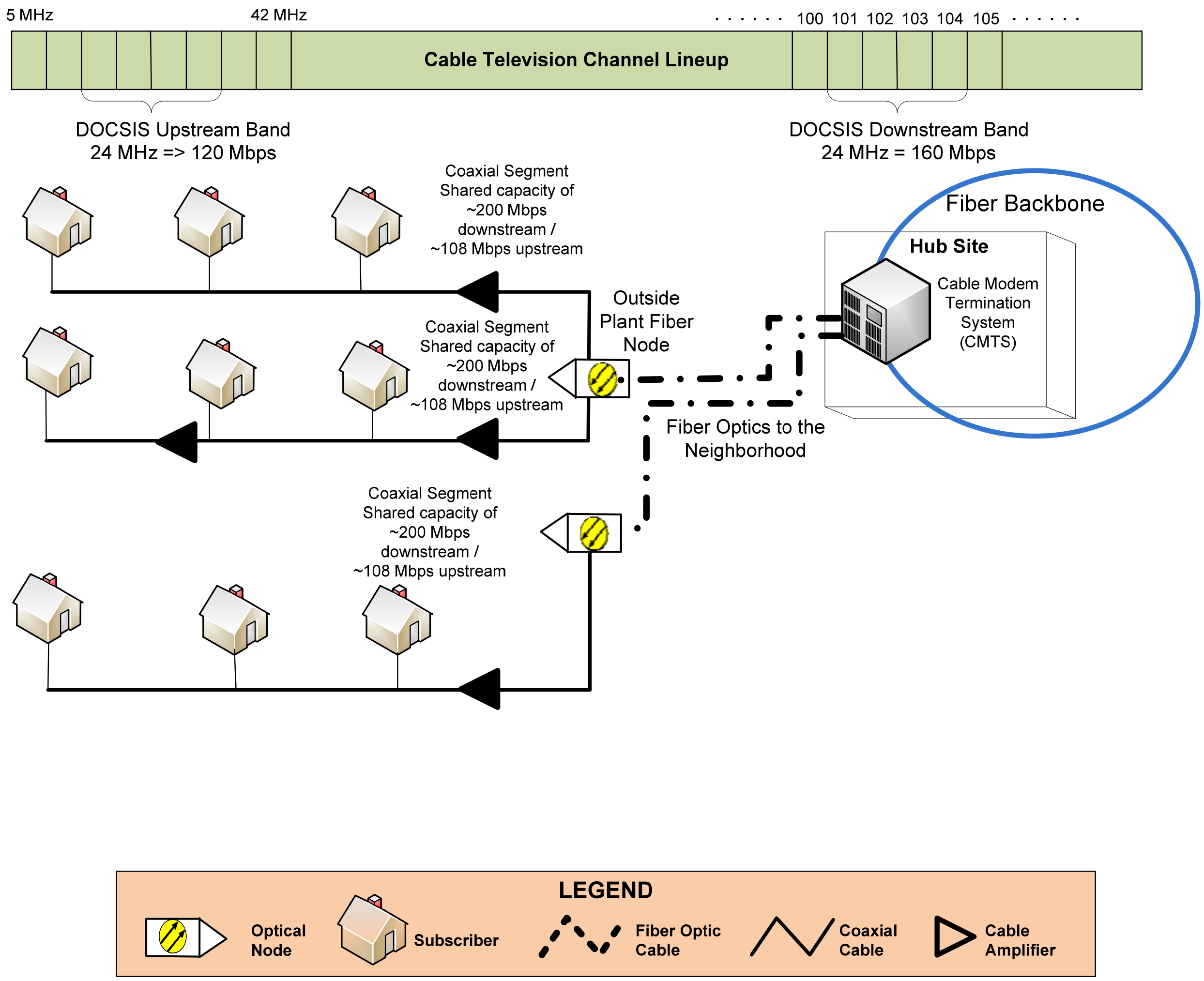
Although there are a number of significant limitations inherent in cable systems relative to fully fiber optic networks, cable system capabilities will increase over the next few years with the deployment of new technologies and the extension of fiber closer to customers.

In an HFC network, headend or hub locations house the core transmission equipment. Fiber connections extend from these hubs to multiple nodes, each of which serves a given geographical area (e.g., a neighborhood). These optical nodes are electronic devices located outdoors, attached to aerial utility lines or placed in pedestals. The equipment in the node converts the optical signals carried on fiber into electronic signals carried over coaxial cables. Coaxial cable then carries the video, data, and telephony services to individual customer locations. Figure 6 illustrates an HFC network.

Cable operators have extended fiber optics progressively closer to their subscribers but, for cost reasons, have generally stopped at nodes about one mile from the premises. Comcast, for example, typically only constructs fiber to the premises of customers that subscribe to Metro Ethernet and other advanced services.

The current leading cable technology for broadband data, known as data over cable service interface specifications version 3.0 or DOCSIS 3.0 (Figure 2), makes it possible for cable operators to increase capacity by bonding multiple channels together. The DOCSIS 3.0 standard requires that cable modems bond at least four channels, for connection speeds of up to 200 Mbps downstream and 108 Mbps upstream (assuming use of four channels in each direction). A cable operator can carry more capacity by bonding more channels.

Figure 5: DOCSIS 3.0 Network Architecture



Both Comcast and Spectrum are in the process of upgrading their systems to the faster DOCSIS 3.1 technology. The cable industry claims that DOCSIS 3.1 will eventually provide up to 10 Gbps downstream capacity and up to 1 Gbps upstream.

2.3 Digital subscriber line, if well maintained and supported, can provide reliable, consistent service

During the last century, phone companies connected nearly every home and business in the United States to a copper telephone wire. Copper has a fraction of the bandwidth capacity of coaxial cable, and suffers from greater signal loss and interference. But because of copper's ubiquity, digital subscriber line (DSL) technology over copper continues to be a critical way for people to connect to the internet. Moreover, DSL lines provide a more consistent physical path than wireless connections, which depend strongly on distance and line of sight and vary sharply based on utilization.

The main determinant of maximum DSL speed for a given copper telephone line is the length of the copper line from the telephone company central office. In systems operated by large telecommunications companies, the average length is 10,000 feet, corresponding to DSL speeds between 1.5 Mbps and 6 Mbps. In systems operated by small companies in rural areas, the average length is 20,000 feet, corresponding to maximum speeds below 1.5 Mbps. The technologies can attain the FCC's standard for broadband (25 Mbps downstream and 3 Mbps upstream) if the length is kept sufficiently short and the copper lines are very well maintained.

The fastest copper telephone line technologies widely deployed in outside infrastructure in the United States are VDSL and VDSL-2, the technologies underlying AT&T's U-verse and comparable services. Because these technologies use high frequencies, they are limited to 3,000 feet over typical copper lines and require fiber to the node (FTTN)—much closer to the customer than in most HFC systems. Therefore, in order to operate VDSL and VDSL-2, telecommunications companies must invest in large-scale fiber optic construction and install remote cabinets in each neighborhood.

In practice, telephone companies using VDSL-2 over highly upgraded copper lines have been able to provide 25 Mbps over a single copper pair and 45 Mbps over two pairs to the home or business. Providing even greater speeds will require some combination of even deeper fiber construction, a breakthrough in transmission technology over copper lines, and conditioning and upgrading of the existing copper lines.

The Nokia (Alcatel-Lucent) G.Fast DSL product reportedly reaches speeds of 500 to 800 Mbps in various environments—but it only delivers such speeds for a few hundred feet, which essentially requires the construction of fiber to the curb in front of each home or business—an investment that would be comparable to building a full fiber network.[3] As a result, G.Fast has so far mostly been focused on deployments using telephone wires already installed inside older office or apartment buildings.

2.4 Mobile broadband speeds are increasing, but face technical limitations

Cellular wireless carriers have consistently increased data speeds with the rollout of faster and higher capacity technologies, such as Long-Term Evolution (LTE).[4] Over the past few years, the

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[3] See, for example: "Nokia and Frontier Communications deploy G.fast technology to expand gigabit ultra-broadband access across Connecticut," News Release, Nokia, May 25, 2017, https://www.nokia.com/en_int/news/releases/2017/05/25/nokia-and-frontier-communications-deploy-gfast-technology-to-expand-gigabit-ultra-broadband-access-across-connecticut

[4] LTE is a 4G cellular wireless technology offering data speeds typically up to 30 Mbps, depending on the signal quality, local configuration, and level of use of the connection.

carriers have introduced services with speeds comparable to many residential wireline services. Indeed, AT&T offers cellular wireless technology as a replacement for copper telephone service.[5]

Wireless carriers operate a mixture of third-generation (3G) and fourth-generation (4G) technologies.

The main 4G technology is Long Term Evolution (LTE). LTE provides a speed increase over 3G technologies as well as a difference of architecture—more like a data cloud than a cellular telephone network overlaid with data services.

These speeds vary by carrier and region. However, the fastest wireless speeds require an ideal connection and low congestion on the wireless network. Mobile broadband may not consistently be available, however—even in areas where cell service exists. Furthermore, there are some areas, particularly indoors, where the cell service is relatively weak, and the broadband service is nonexistent or limited to slower service with speeds comparable to telephone dial-up.

[5] See, for example: "AT&T Wireless Home Phone Service," AT&T, https://www.att.com/shop/wireless/devices/wirelesshomephone.html (accessed September 2017). See also: Harold Feld, "Will The Landlines Come Back On After Harvey? Only If The FCC Does Its Job," *HuffPost*, September 1, 2017, http://www.huffingtonpost.com/entry/will-the-landlines-come-back-on-after-harvey-only_us_59a97151e4b0c50640cd5ed2 (accessed September 2017).

3 Wireless technologies have shortcomings compared to wireline services

For several technical reasons, wireless technologies provide lower performance than state-of-the-art wireline broadband services. In the sections below, we describe mobile broadband's shortcomings as compared to those wireline technologies.

3.1 Mobile broadband provides only about one-tenth the speed available from wireline

Despite advances in recent years, wireless broadband technologies cannot achieve the speeds that modern, wired networks can deliver. Mobile broadband speeds are constantly increasing as technology improves, but average, real-world speeds stay below what is available through fiber and cable broadband services by about a factor of 10.

In coming years, LTE Advanced may be capable of offering speeds of hundreds of Mbps and potentially Gig speeds—assuming the availability of optimum spectrum and a dense build-out of antennas. But that capacity will be shared with the users in a particular geographic area and can be surpassed by more advanced versions of wireline technologies.

To contrast mobile broadband with other technologies, it is useful to compare the available spectrum in the medium and the number of users that are sharing the medium. The spectrum available to a mobile broadband operator varies based on the design of the network in any given area, but the largest operators have 150 MHz of spectrum at most, and this capacity is shared among the few hundred customers connected to the cell site.

In contrast, a strand of standard single-mode fiber optic cable has a theoretical physical capacity in excess of 10,000 GHz (or 10 million MHz),[6] far greater than the entire usable wireless spectrum combined, and thousands of times the capacity of any other type of wired or wireless medium.

This capacity is shared among the 16 or 32 customers in the PON—providing a theoretical capacity advantage of a factor of one million relative to mobile broadband—indicating that fiber optics will easily maintain a strong capacity lead over mobile broadband far into the future.

A typical cable broadband network has a capacity of about 800 MHz shared among approximately 100 customers[7]—substantially lower than fiber but still several times the capacity of any mobile broadband network. And though a copper-line DSL line has a few MHz of capacity, it still can

[6] Conservative estimate derived from the channel widths of the 1285 to 1330 nm and 1525 to 1575 nm bands in G.652 industry-standard single-mode fiber optics.

[7] This number is constantly decreasing as cable operators incrementally add fiber to increase data speeds.

provide capacity greater than mobile broadband—because all the capacity in the copper line is fully dedicated to the single customer, instead of shared among multiple customers.

Some 4G services may offer maximum service speeds that meet the FCC's current speed requirements for fixed broadband, but consumers cannot expect to achieve those speeds everywhere within the provider's coverage area, nor can they expect to receive the same speed in the same area at all times (as explained in the next section).

3.2 Mobile broadband delivers asymmetrical capacity and higher latency

Most businesses and residents find that wireless broadband has technical limitations relative to wireline. These include:

1) *More asymmetrical capacity, with uploads limited in speed.* Asymmetrical speeds make it more difficult to share large files (e.g., video, data backup) over a wireless service, because these will take too long to transfer; it is also less feasible to use video conferencing or any other two-way, real-time application that requires high bandwidth and low, predictable latency.

2) *Greater latency:* LTE ping times (round-trip, end-to-end latency) range from 30 to 70 milliseconds—compared to 10 or 15 milliseconds on typical wireline internet connections—which, again, will have an impact on sensitive interactive applications such as voice and video.

3.3 Mobile broadband cannot deliver performance as consistent as wireline services

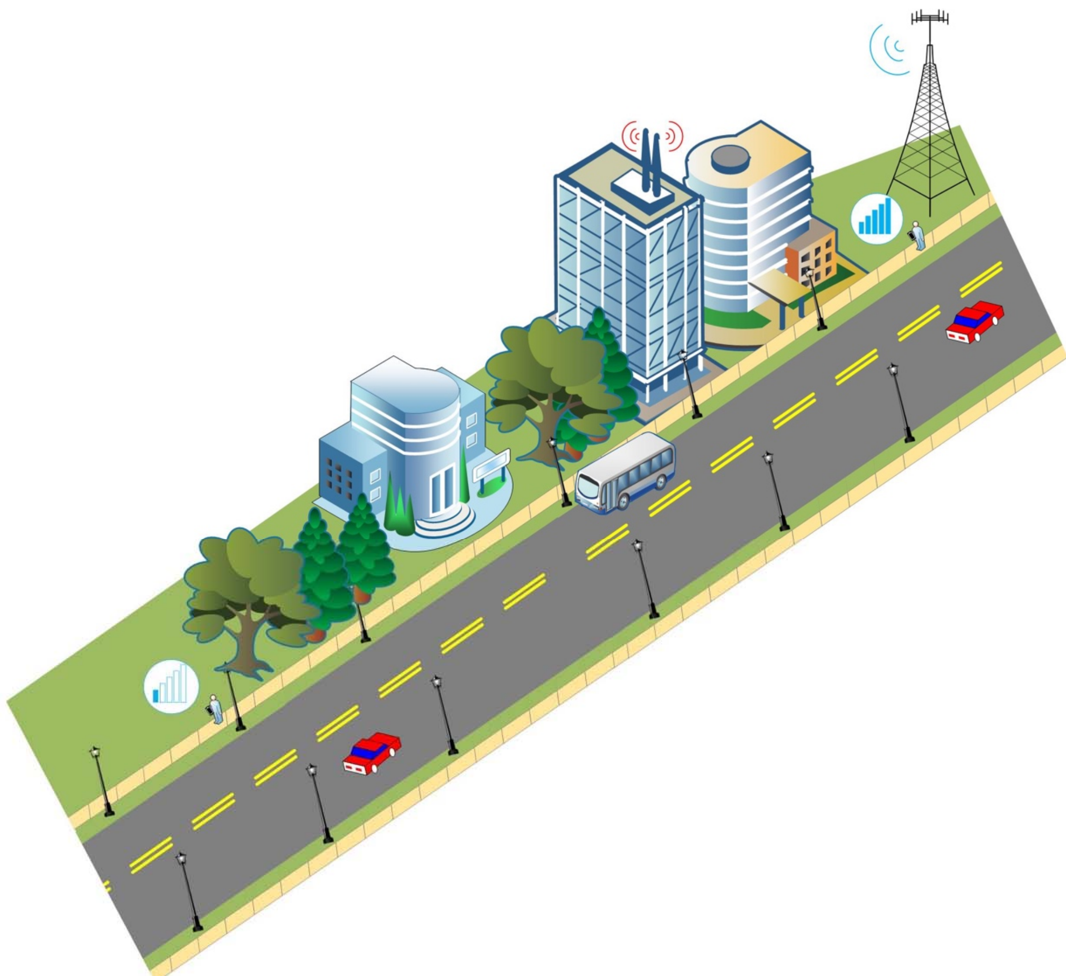
For many consumers, the minimum speed they can reliably get from a broadband service may be more important than the maximum available speed. While faster network speeds allow certain online tasks to be completed more quickly—and enable customers to connect a greater number of devices to their networks without experiencing congestion issues—many tasks can be completed in an acceptable fashion on a relatively slow connection so long as that connection is consistent.

It is important to note that wireline services are sufficiently consistent to allow service providers to offer service-level agreements to premium customers—guaranteeing both minimum and maximum speeds, maximum outage time, and minimum technical performance parameters for latency and jitter. If the parameters are not met, the service provider pays a penalty to the customer. Mobile broadband providers do not provide these guarantees, because the technology does not lend itself to that level of quality.

Even a well-engineered mobile broadband network cannot provide entirely consistent service within a service area. One contributor to reduced mobile service speed consistency is the distance between the antenna and the device. Mobile broadband wireless signals can reach anywhere from a few hundred feet to a few miles depending on the antenna's frequency and power, and environmental factors, but users closer to a wireless antenna will receive better signals and, therefore, better speed and quality of service.

As distance increases, or more obstructions block the signals between the antenna and the user, signal strength (and service quality) are diminished (see Figure 6).

Figure 6: Wireless Signals Diminish with Distance and Obstructions



Even taking distance into account, wireless coverage is not consistent within a service area. Wireless signals are degraded by natural features such as mountains, valleys, trees, and weather; buildings and other structures; and interference from other radio frequency (RF) signals in the area.

Another consideration is the enormous variety and complexity of possible obstructions—and their variability as vehicles and customers move, and as utilization of the network increases and decreases. By comparison, a wireline path remains the same.

Fiber optics can provide extremely low losses within a wide range of frequencies, or wavelengths, of transmitted optical signals, enabling long-range transmissions. As discussed in Section 2.1 fiber optic cable can carry a signal of equivalent capacity over dozens of miles, without amplification, with minimal signal loss. Broadband cable and copper DSL networks leverage fiber optics over most of their transmission paths, and then transition to the coaxial or copper medium—which has lower range and capacity but is still consistent—for the last mile.

Obstructions and environmental factors will have an even greater impact on service quality as the industry introduces millimeter-wave frequencies in the coming years. That's because millimeter-wave frequencies, as discussed further in Section 3.4, may be entirely blocked by building walls or foliage, potentially requiring a separate wireless system for propagating signals indoors. These frequencies may require that a user's device be within a few hundred feet of the antenna and have a relatively unobstructed line of sight. (Lower-frequency wireless signals will generally propagate further and better penetrate obstacles—but those signals offer less bandwidth per MHz of spectrum.)

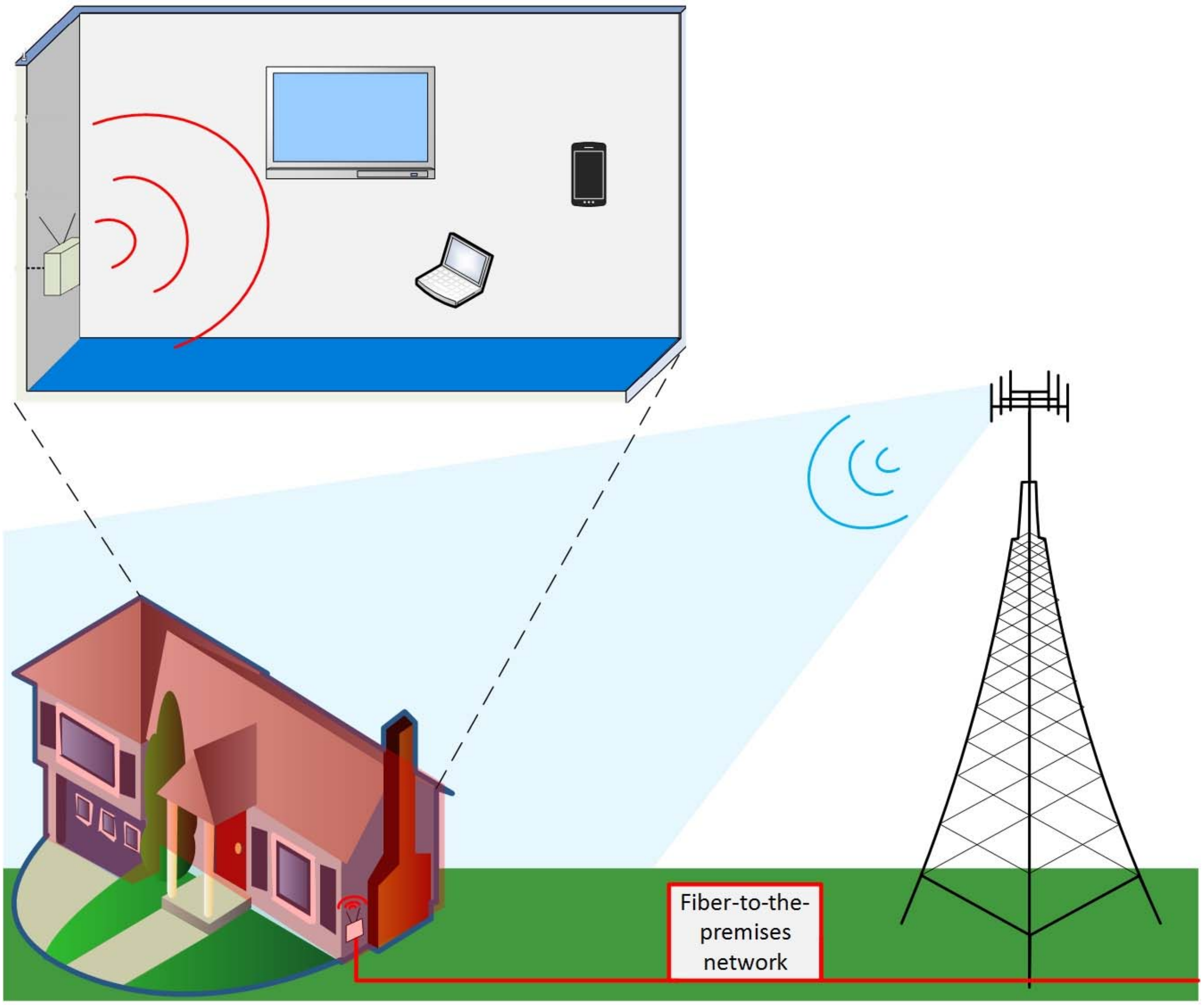
3.4 Mobile broadband may require a separate wireless network for indoor coverage

Mobile broadband service is often inconsistent for users indoors, in part because the materials used to construct buildings attenuate wireless signals. Even if fast wireless service is available outside a structure, service inside—especially in basements and elevators—can be degraded or completely blocked in some areas of the building. And because indoor signal strength can be affected by a number of factors (e.g., building materials, the design of the structure, and the location of the device within the building), it can be difficult to predict or mitigate indoor wireless signal disruptions.

In some cases, wireless carriers make available "microcell" devices (also called picocells or network extenders), which are placed within a customer's home or office and connected to the user's network (see Figure 7).[8] These devices broadcast a 3G or LTE wireless signal inside the building—but they send mobile data back to the wireless carrier over the customer's wireline broadband service, so they depend on, rather than replace, a wireline broadband connection.

[8] "4G LTE CellSpot overview," T-Mobile, https://support.t-mobile.com/docs/DOC-24269 (accessed September 2017); "AT&T Microcell," AT&T, https://www.att.com/att/microcell (accessed September 2017); "Network Extender (SCS-2U01)," Verizon Wireless, https://www.verizonwireless.com/accessories/samsung-network-extender-scs-2u01 (accessed September 2017).

Figure 7: Wireless Signals May Not Be Able to Penetrate Some Buildings



For indoor spaces requiring broader coverage, such as large buildings on a university campus or an airport, wireless carriers may work with the organization that owns the space to deploy a distributed antenna system (DAS) to deliver consistent indoor wireless signals. A DAS may be "carrier neutral" if the wireless carriers operating in the area reach an agreement to share the DAS infrastructure; otherwise, multiple DAS may need to be installed.

3.5 Mobile broadband access points have limited capacity

Mobile broadband is relatively restricted in the number of devices that can connect to a single access point. A wireless signal is a shared medium; using LTE technology, a cell site (also known as an eNodeB) actually only communicates with one or a few devices in a single instant. LTE technology addresses the challenge of simultaneously serving multiple devices by holding a finite number of devices in either a "connected" or "idle" state and by "time slicing," in which the eNodeB rapidly switches between as many as a few hundred user devices so that no single device is left waiting for long. Wireless providers further mitigate this issue with technologies such as MIMO, beam-forming, and directional access points, but limits in the capabilities of the parts of the mobile broadband network still fundamentally limit the number of devices connected to a single antenna before congestion begins to degrade service.

The limitation on simultaneous users is especially critical during emergencies, when a larger than usual number of users attempt to use a mobile network.[9] Even in non-emergency situations, a large number of people gathered in one area, such as a football stadium during a game, can overwhelm mobile broadband networks.[10]

On an LTE network, capacity and coverage are closely related in a way that can compound connectivity issues. A device experiencing poor LTE connectivity will automatically be moved to a different modulation scheme. This may provide the device with a more stable connection to manage distance and interference, but switching that user to a new modulation scheme makes less efficient use of the wireless spectrum, providing lower speeds and using more bandwidth per device. In a situation where many devices are experiencing poor connectivity, more devices will be moved to different modulation schemes, resulting in poor service for these users despite the mitigation measures.

3.6 Mobile broadband is not suited to some applications

The variability of mobile broadband quality can make wireless technologies unsuitable for certain network applications. Many tasks that consumers perform on mobile devices, such as browsing the internet, messaging, and checking email, do not require a constant and consistent network connection. In addition, many applications can manage the variable performance of a wireless network by using push notifications or downloading content in the background, and creating a buffer of content, which is how video or audio streams can continue to work even if the underlying network is inconsistent.

However, when pushed beyond a critical point, slowdowns or breaks in mobile network service cause applications such as streaming video to experience severe delays or reductions in quality.

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[9] Michael B. Farrell, "Cellphone networks overwhelmed after blasts in Boston," *Boston Globe*, April 17, 2013, https://www.bostonglobe.com/business/2013/04/16/cellphone-networks-overwhelmed-blast-aftermath/wq7AX6AvnEemM35XTH152K/story.html (accessed September 2017). see also: Marguerite Reardon, "How the wireless carriers fared during Hurricane Harvey," *CNET*, September 3, 2017, https://www.cnet.com/news/hurricane-harvey-phone-service (accessed September 2017).

[10] Andy Vuong, "AT&T upgrades network at Broncos stadium with largest cell site," *Denver Post*, November 14, 2013, http://www.denverpost.com/2013/11/14/att-upgrades-network-at-broncos-stadium-with-largest-cell-site (accessed September 2017).

This might merely be an annoyance for a Netflix subscriber trying to watch a movie, but can mean a loss of revenue for a business or a loss of productivity for a student.

Even where wireless service is generally good, the rapid and frequent variations in connectivity on a shared wireless network will cause teleworkers to periodically experience garbled audio and video on conference calls or have difficulty sending large files.

Employees who need to operate over a virtual private network (VPN) may find that they are unable to reliably maintain the connection throughout the day. A VPN acts as a virtual wire between an employee's computer and the employer's network, keeping the employee's traffic separate from other local and internet traffic. Congestion and instability in the employee's wireless network connection can cause the virtual network to stall or disconnect. The effect is similar to losing wireless reception and may cause instability and lost work in applications operating over the VPN.

Students attempting to download video lectures or media-rich assignments and textbooks may find they can sometimes access their materials in a manner of minutes, while at other times, downloads may take hours or may time out and need to be restarted.

Health professionals may have a difficult time providing consistent care to their patients if they cannot reliably predict how long it will take to transfer patient records or test results among remote labs and clinics. Similarly, businesses that rely on real-time network communications, such as for credit card transactions or inventory lookups, may experience delays or lose sales if the systems they rely on to serve customers do not work quickly and reliably.

Even formerly lower-tech businesses are operating more data-intensive applications and require connections beyond what is typically available wirelessly. For example, auto parts stores and mechanics need to download software updates and data to calibrate and update test equipment; these tasks can take hours over a wireless connection compared to minutes over a wireline service.

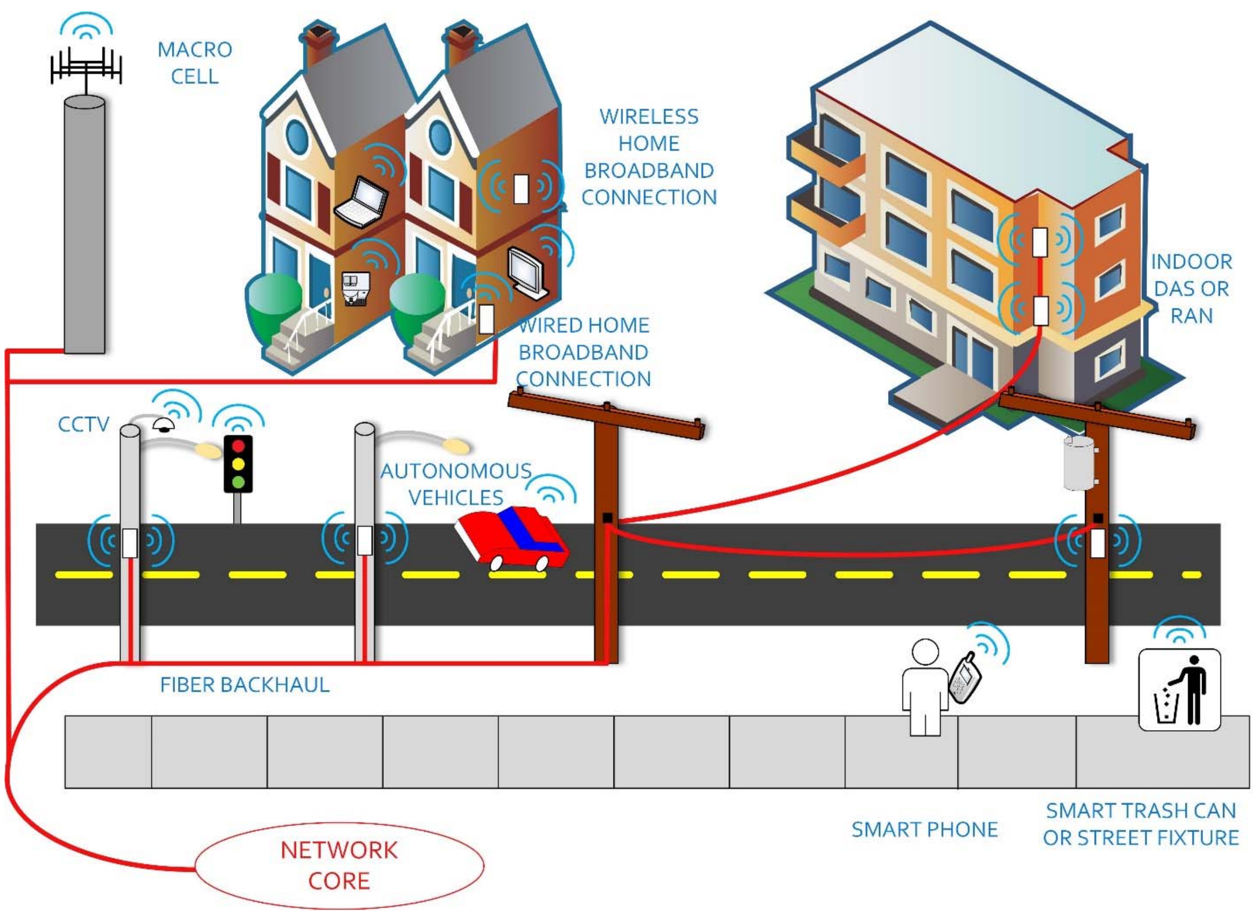
At the same time, higher-tech businesses are saving money on infrastructure and staff by moving local applications to the cloud—which places significant demands on the businesses' internet connections. Some cloud-based applications, such as computer-aided design (CAD) and geographic information systems (GIS), continuously transfer large data files as employees work. Without a consistently fast network connection, these applications may be slow or unusable. Nightly tasks, such as computer backups or software updates, may not be completed before employees return to the office, affecting productivity the next day.

3.7 Mobile broadband requires fiber infrastructure

The ongoing call for wireless broadband capacity is driving the deployment of a new generation of wireless infrastructure, which in turn is driving the deployment of even more fiber infrastructure to connect it.

While mobile broadband does not require fiber to each home and business, any high-capacity mobile broadband infrastructure requires a substantial amount of fiber. Fiber is standard at almost all cell sites owing to the greatly increased need for capacity there.[11] (See Figure 8.)

Figure 8: Mobile Broadband Ecosystem Includes Extensive Fiber



Wireless carriers are currently undergoing a process of "network densification." This involves deploying additional, smaller antenna sites to enhance wireless performance within an existing service area or to reach new services areas. Called "small cells" because of their reduced service

[11] Prior to widespread demand for connectivity to smartphones and tablet computers, many cell sites could be effectively connected using copper telephone lines or microwave connections.

area (not because of the size of equipment), these sites use 4G LTE technology and are being placed in high-density areas such as near busy intersections and roads, shopping centers, and dense neighborhoods.

In new markets, some carriers are also considering a strategy of deploying several small cell sites instead of a single macro site to meet coverage needs. The result is that, rather than the cell site being a mile or two away as in the past, your cell site is now more likely to be less than a mile away. Taken together, these deployments are requiring a considerable amount of fiber infrastructure, even creating fiber shortages.[12]

Small cell deployment and densification are also expected to be a major part of the industry's transition to "5G"—a marketing catchphrase encompassing efforts by the research and development community, hardware and software manufacturers, wireless service providers, and standards committees.[13]

The use of high-capacity, high-frequency, millimeter-wave spectrum will make these wireless signals even more susceptible to attenuation problems caused by foliage and buildings than current wireless technologies; "5G" may even require wireline service indoors to connect separate indoor "5G" wireless antennas.

Rural areas, which typically face a lack of both wireless and wired infrastructure, may continue to lag behind the rest of the country in future "5G" deployment because of the need for even more fiber infrastructure.

For more details on "5G," see Appendix B.

[12] Gina Narcisi, "Verizon Inks $1.05B Fiber Deal With Corning To Build Out Fiber Footprint, Speed 5G Deployment Plans," CRN, April 18, 2017, http://www.crn.com/news/networking/300084601/verizon-inks-1-05b-fiber-deal-with-corning-to-build-out-fiber-footprint-speed-5g-deployment-plans.htm (accessed September 2017).

[13] No formal "5G" standard yet exists; elements of it are being developed in the ITU, and by 3GPP (which developed GSM and LTE). See: Andreas Maeder et. al, "A Scalable and Flexible Radio Access Network Architecture for Fifth Generation Mobile Networks," IEEE Communications Magazine, Volume: 54, Issue: 11, November 15, 2016, p. 16, http://ieeexplore.ieee.org/document/7744804/?reload=true (accessed September 2017).

4 Mobile business policies—including pricing and usage restrictions—further challenge the potential to substitute wireline broadband with mobile service

The technical limitations of wireless networks are not the only significant constraint on mobile as a substitute for reliable wireline service. Rather, the business policies imposed by mobile companies further impact the usability of mobile service as a primary or sole source of broadband.

Indeed, mobile pricing and usage limits by the mobile companies, even without the technical limitations of mobile, make mobile service a poor substitute for fixed broadband services. Even though the two technologies can be used to access the same digital content, the differences in pricing structures and terms of service makes wireless broadband an inadequate substitute for wireline broadband.

4.1 Consumer behavior demonstrates that Americans do not view fixed and mobile products as substitutes for each other, but rather as complements

Consumer behavior clearly indicates that wireless and wireline subscriptions are complementary products. Most Americans who can afford to subscribe to both services often do so. While the number of Americans that rely on mobile subscriptions for home internet access has grown over the past few years, these households tend to be lower-income.

The authoritative Pew Research Center found in a 2016 survey that 20 percent of adults living in households earning less than $30,000 a year were smartphone-only internet users, compared with 4 percent of those living in households earning $100,000 or more.[14] Many mobile-dependent households are forced to decide between mobile and wireline services because of budget constraints. Others may be forced to rely on mobile plans due to the lack of availability of wireline broadband services in their area. Regardless of the reason, the fact that some households make do with mobile subscriptions does not indicate that such services adequately meet these households' needs.

If mobile and wireline services were replacements for one another, we would expect to see consumers eliminating their wired broadband subscriptions, just as many consumers have cut

[14] Monica Anderson, "Digital divide persists even as lower income Americans make gains in tech adoption," Pew Research Center, March 22, 2017, http://www.pewresearch.org/fact-tank/2017/03/22/digital-divide-persists-even-as-lower-income-americans-make-gains-in-tech-adoption/ (accessed September 2017).

their cable television subscriptions in recent years because over-the-top (OTT)[15] video serves as an alternative.[16] And yet wired-broadband cord-cutting is not taking place.

As analyst Craig Moffett recently explained in a report to investors, "cellular-for-wired broadband substitution isn't likely to reach anywhere near the heights that cellular-for-wired voice has achieved." Moffett points out that a subscription to a wireline network not only tends to offer faster speeds and a more reliable connection, but does so without setting strict data threshold limits that force customers to restrict their usage:

> "Perhaps the largest impediment to switching from wired to wireless broadband, however, is throughput volume. Beyond threshold volumes, wireless data connections are intentionally de-prioritized or degraded. Those thresholds are well below average usage levels for wired broadband. (And remember, those usage levels for wireless are often measured on a per user basis, while for wired broadband they are measured at the household level.)"[17]

Moffett's skepticism about consumers choosing to substitute mobile data for wireline data illustrates a key point: ***these products are not substitutes for each other if Americans, given a choice, do not treat them that way***.

Indeed, even if many Americans rely only on a smartphone for internet access at home[18] and the number of Americans who own smartphones is increasing, this does not necessarily indicate that users are relying on mobile broadband networks for the majority of the data they transfer. Rather, those who have the option of wireline broadband in addition to mobile are likely relying heavily on Wi-Fi that is fed from a wireline broadband connection at home, school, and work, and in public places.

Consumers who do not have wireline broadband service at home because of financial restrictions are unlikely to purchase expensive data plans and may need to be heavy users of free Wi-Fi connections at libraries and restaurants. Pew Research Center calls this a "workaround

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[15] "Over-the-top" (OTT) content is delivered over the Internet by a third-party application or service. The ISP does not provide the content (typically video and voice) but provides the internet connection over which the content is delivered.

[16] John Patrick Pullen, "Cable Television Needs You More Than You Need Cable Television," *Time*, August 15, 2017, http://time.com/4875549/cable-cord-cutting-streaming-television/ (accessed September 2017).

[17] Tiernan Ray, "Comcast Versus AT&T: Wireless Won't Replace Cable, For Now, Says Moffett-Nathanson," *Barron's*, April 12, 2017, http://www.barrons.com/articles/comcast-versus-at-t-wireless-wont-replace-cable-for-now-says-moffett-nathanson-1492004588 (accessed September 2017).

"Internet/Broadband Fact Sheet," Pew Research Center, January 12, 2017, http://www.pewinternet.org/fact-sheet/internet-broadband (accessed September 2017).

system"[19]—and it comes at a cost to smartphone-only users, who often have more trouble accessing and sending content than their counterparts who have wireline broadband service at home.

Smartphone-only consumers who are not financially constrained are also likely relying heavily on Wi-Fi access points fed by wireline broadband connections—not only for cost savings but also for performance reasons, because in stable environments, wireline-fed Wi-Fi can support communications at hundreds of Mbps, allowing video, file sharing, and software upgrades to move more quickly.

4.2 Mobile carriers and cloud service providers treat wireline and mobile products as complements, not substitutes for each other

The fact that mobile and wireline broadband complement rather than replace each other is demonstrated by the business decisions and policies made by mobile carriers, developers of the Android and iOS operating systems, cloud service providers, and other internet-based service providers.

Consider the following policies and trends, all of which illustrate how companies endeavor to supplement mobile data with Wi-Fi (and by extension, the robust wireline network behind the Wi-Fi) as a critical part of delivering a high-quality and cost-effective experience:

- Professional and college stadiums deploy massive Wi-Fi and DAS infrastructures to enable fans to use their devices during games[20] without having to rely on traditional mobile networks.

- Many applications with bandwidth-intensive features, such as video conferencing and photo uploading, offer the ability to block those features unless the mobile device is connected to a Wi-Fi network. Microsoft's Skype for Business, for example, restricts certain conference call features to Wi-Fi networks. (See Figure 9.)

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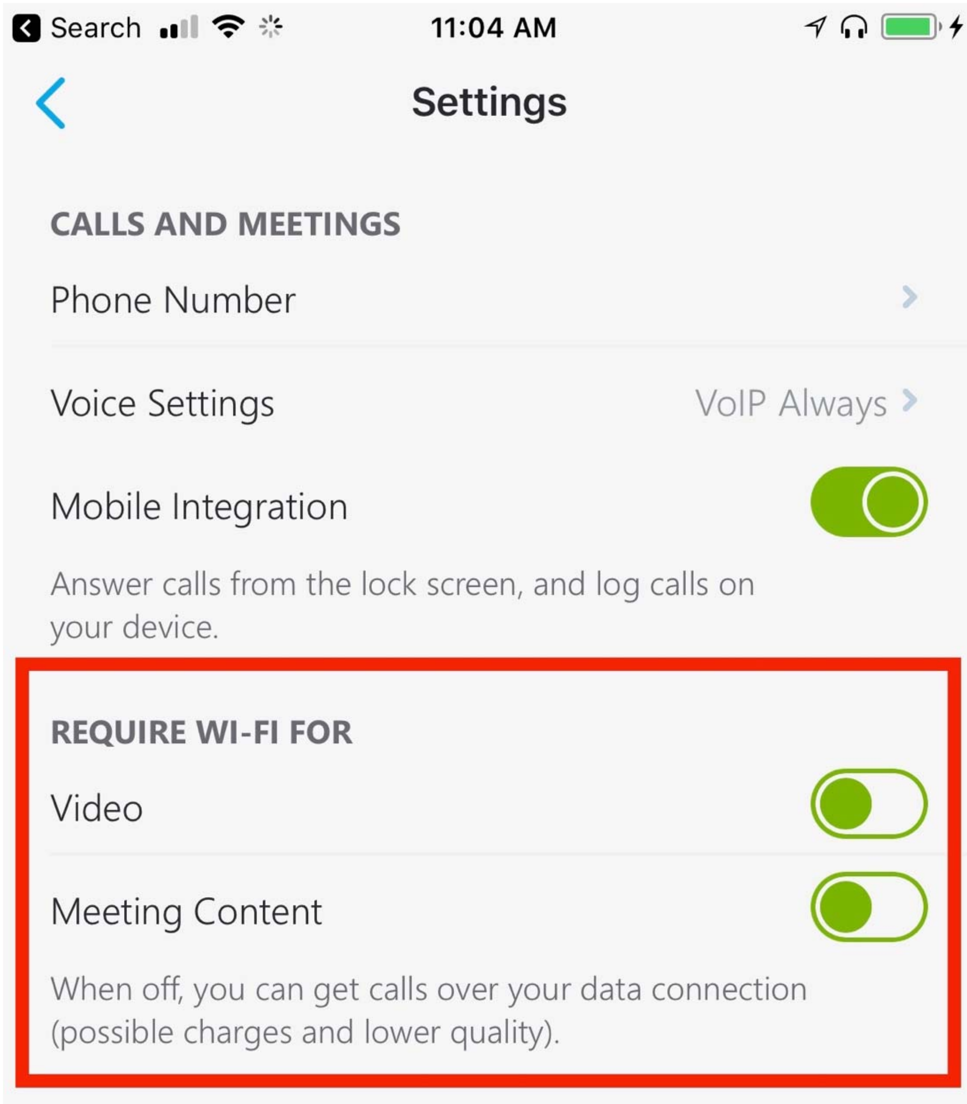
[19] Monica Anderson and John B. Horrigan, "Smartphones help those without broadband get online, but don't necessarily bridge the digital divide," Pew Research Center, October 3, 2016, http://www.pewresearch.org/fact-tank/2016/10/03/smartphones-help-those-without-broadband-get-online-but-dont-necessarily-bridge-the-digital-divide (accessed September 2017).

[20] "University of Houston Partners with Boingo for Football Stadium Wireless," Boingo, News Release, April 29, 2014, http://www.boingo.com/press-releases/university-houston-partners-boingo-football-stadium-wireless (accessed September 2017). See also: "Connected Sports Case Study: Denver Broncos," Cisco, Case Study, https://www.cisco.com/c/en/us/solutions/industries/sports-entertainment/denver-broncos.html (accessed September 2017). See also: "University Of Oregon: Wireless Performance as Potent as the Ducks' Offense on Game Day," SOLiD, Case Study, http://www.solid.com/docs/resources/OREGON_CASE_STUDY_2pg.pdf (accessed September 2017).

Figure 9: Settings in Microsoft's Skype For Business iPhone Application



- Mobile operating systems include controls that allow users to block individual applications from using the cellular network or to turn off cellular data entirely and allow only phone calls and texts over cellular service. They may also restrict users from certain bandwidth-intensive activities such as backing up their devices or downloading large applications while on mobile networks.

- Google's Chrome web browser offers a service called Data Saver that compresses data before it is sent to or from the mobile device; several VPN services perform similar functions at a device level.

- Mobile carriers themselves have invested in technologies designed to reduce the amount of data that flows over their networks. These include Wi-Fi offloading of both data and calls, and services that send lower-resolution video to devices attempting to stream over the mobile network. In the past, carriers have even entirely blocked services from their mobile network, such as when AT&T prevented iPhone users from using FaceTime, Apple's video calling application, over AT&T's 3G network unless users paid for certain data plans.[21]

4.3 Mobile broadband services are not actually "unlimited"

Despite the claims of wireless carriers' marketing campaigns, there is currently no way to receive unlimited mobile broadband in the United States. While all four major wireless carriers now tout unlimited plans, all of these plans have usage restrictions that limit how customers can use their connections, and that allow the carriers to throttle customers to sub-broadband speeds after they exceed certain usage thresholds.

Even the most generous "unlimited" mobile data plan throttles users and deprioritizes their hotspot traffic after they have consumed 32 GB of data in a month.[22] To put that number in context, a 2016 study found that the average American household uses 190 gigabytes of data each month.[23]

Table 1 summarizes the unlimited plans of the major wireless carriers.[24]

[21] Esther Sheins, "AT&T Blocks FaceTime, Net Neutrality Complaint Filed," *InformationWeek*, September 21, 2012, https://www.informationweek.com/consumer/atandt-blocks-facetime-net-neutrality-complaint-filed/d/d-id/1106448 (accessed September 2017).
[22] "T-Mobile One," T-Mobile, https://support.t-mobile.com/docs/DOC-31900 (accessed September 2017).
[23] John Engebretson, "iGR: Average Monthly Broadband Usage is 190 Gigabytes Monthly Per Household," *Telecompetitor*, September 26, 2016, http://www.telecompetitor.com/igr-average-monthly-broadband-usage-is-190-gigabytes-monthly-per-household/ (accessed September 2017).
[24] "Verizon's Unlimited Data Plan Has Changed. Here How It Compares to Other Carriers," *Wired*, August 22, 2017, https://www.wired.com/2017/08/verizons-unlimited-data-plan-back-heres-compares-carriers/ (accessed September 2017).

Table 1: Summary of Unlimited Wireless Plans

Plan name	Connection speed	Cost per month* (1 user/ 4 users)	Throttling threshold	Hotspot allowance	Video quality limits
Verizon Go Unlimited[25]	4G LTE, but may be throttled at any time	$75/$160	0 GB	Unlimited, but speed limited to 600 Kbps	480p on phones, 720p on tablets
Verizon Beyond Unlimited[26]	4G LTE	$85/$200	22 GB	15 GB, then throttled to 3G	720p on phones, 1080p on tablets
AT&T Unlimited Choice[27]	3 Mbps	$60/$155	22 GB	Not allowed	480p
AT&T Unlimited Plus[28]	4G LTE	$90/$185	22 GB	10 GB, then throttled to 128 Kbps	720p
T-Mobile One[29]	4G LTE	$70/$160	32 GB	Unlimited at 3G	480p
T-Mobile ONE Plus[30]	4G LTE	$80/$200	32 GB	10 GB, then throttled to 3G	'Typically' in HD
Sprint[31]	4G	$50/$90	23 GB	10 GB, then throttled to 2G	1080p

*Customers who do not opt-in to paperless billing are charged an additional fee each month

25 "Unlimited for All," Verizon Wireless, https://www.verizonwireless.com/plans/verizon-plan/ (accessed September 2017).
26 "Unlimited for All," Verizon Wireless, https://www.verizonwireless.com/plans/verizon-plan/ (accessed September 2017).
27 "Don't want TV? Get unlimited data only," AT&T, https://www.att.com/plans/unlimited-data-plans.html (accessed September 2017).
28 "Don't want TV? Get unlimited data only," AT&T, https://www.att.com/plans/unlimited-data-plans.html (accessed September 2017).
29 "Unlimited everything. Now with Netflix on us," T-Mobile, https://www.t-mobile.com/cell-phone-plans (accessed September 2017).
30 "Unlimited everything. Now with Netflix on us," T-Mobile, https://www.t-mobile.com/cell-phone-plans (accessed September 2017).
31 "Sprint Unlimited data, talk & text cell phone plans," Sprint, https://www.sprint.com/en/shop/plans/unlimited-cell-phone-plan.html?INTNAV=TopNav:Shop:UnlimitedPlans (accessed September 2017). Promotional pricing ends October 31, 2018; after promotional period, one line is $60, four lines is $160.

These plans theoretically allow customers to use as much data as they want, but not at speeds that meet the FCC's proposed mobile broadband benchmark of 10 Mbps download/1 Mbps upload. ***Customers are only entitled to speeds that meet the definition of broadband until they hit a threshold that is a fraction of the average U.S. household data usage each month***.

Although some wired providers also cap usage, caps on wired services tend to be far higher. Comcast, Cox, and AT&T (wired) all have a 1 TB data cap, more than 30 times the throttling threshold of the most generous wireless plan.[32]

Customers who rely on their mobile service as their primary home connection either must restrict their usage, or face the possibility of an extremely slow connection for the latter part of the billing cycle. For most residential users, streaming video on smartphones, TVs, and tablets through applications like YouTube, Netflix, Hulu, HBO Go, and other OTT services is the largest use of data—and continues to increase. Throttling and data caps will thus continue to be a major limitation for the average wireless customer.

The restrictions on hotspot usage also make mobile plans less than ideal as a substitute for wireline service. While some wireline providers force customers to use a company-provided router, there is generally no limit to what devices the customer can connect. In contrast, wireless customers who want to turn their wireless device into a hotspot to which other devices can connect often need to pay more for that ability—and may also be restricted to sub-broadband hotspot speeds. Once customers exceed the stricter usage threshold that providers set for hotspots, they are forced to either accept throttled speeds or turn off their hotspot function.

As is illustrated below, the possibility of throttling makes it difficult for customers to rely on mobile connections for critically important tasks like telecommuting and telehealth applications.

4.4 Pricing and usage policies have the potential to further increase the gap between wireline and mobile services

Mobile providers dramatically limit customer usage and exert significant control over how applications run on their networks; these policies may have good technical or business justification but *they have the impact of making the mobile service far inferior and less reliable for consumers than wireline service*.

Just a few months after Verizon announced an "unlimited" plan, the company tweaked the plan to further restrict usage and announced that it would begin limiting the quality of video its customers could stream. Speed tests have shown that Verizon's average network speeds have dropped since the rollout of the unlimited plan, and many commentators suspect that Verizon

[32] Jacob Kastrenakes, "Cox is the latest ISP to expand data caps," *The Verge*, July 5, 2017, https://www.theverge.com/2017/7/5/15924658/cox-data-caps-expand-four-more-states (accessed September 2017).

tweaked the plan to decrease network congestion.[33] Regardless of the reasons, Verizon's mobile customers have no choice in the matter—and if they have no wireline option, their choice is to stick with Verizon or switch wireless carriers.

Some mobile providers are partnering with video and audio content producers like Netflix and Spotify—allowing customers to access those services without that usage counting toward a customer's data limits. In AT&T's case, the company uses its mobile service to promote its own paid video content brand, DirecTV.

If the trend of promoting the services of a partner or subsidiary company continues, mobile users may face a far less competitive marketplace for applications and connected appliances in the future. While fixed broadband subscribers will likely be able to connect any home appliance to their Wi-Fi routers, mobile-dependent customers could be forced to rely on their mobile provider's partner and subsidiary companies. As more and more household devices try to connect to the internet each year, the gap between user experience on a wireline network versus a mobile network could widen dramatically.

4.5 Real-world scenarios illustrate the ways in which mobile broadband fails to act as a substitute for wireline broadband

These mobile restrictions have consequences for American consumers who are forced to rely only on mobile services—and they create significant barriers to how these consumers can use the internet for positive economic, educational, and health outcomes. Consider these three hypotheticals:

4.5.1 Hypothetical 1: Throttling telework

Casey works as a customer service representative for a small software company in Lawrence, Kansas. He spends his workdays in front of his computer, talking to customers, often taking over their screens to help them troubleshoot problems with his company's software. When his mother falls ill, he asks his boss whether he can return to his hometown of St. Paul, Kansas, and work remotely for an extended period of time while he cares for his mother. His boss agrees, provided that Casey can continue to deliver the same level of customer support that he did from the office.

Casey moves back home and is disappointed to find that the local phone company still offers the same dial-up service that it had available when he was in high school. Fortunately, he discovers that his smartphone connects to a 4G LTE network, so he signs up for Verizon's Beyond Unlimited plan and starts working from home. He is careful to restrict his tethered usage to make sure that he can access the 4G speeds he needs for screen-sharing with his customers.

[33] Chris Mills, "Why did Verizon kill the Unlimited data plan that everyone loved?" *BGR*, August 22, 2017, http://bgr.com/2017/08/22/verizon-unlimited-data-throttle-vs-t-mobile-2017/ (accessed September 2017).

The Beyond Unlimited plan provides a satisfactory connection for the first few months, but streaming music on his laptop causes him to exceed his 15 GB of tethered data. For the next few days, his connection speed is throttled, causing him to drop his connection to customers on numerous occasions. One of his customers complains to Casey's boss—who then informs Casey that he must either return to the office or face termination.

The bandwidth limitations on Casey's mobile service make that product insufficient to support Casey teleworking from a remote area—a disadvantage that is not faced by Americans with wireline broadband options.

4.5.2 Hypothetical 2: Capping inquiry-driven learning

Tanya is a ninth grader in Tupelo, Mississippi. The only internet connection she has at home comes from the Sprint "unlimited" plan her mother's employer provides for use at home. Her family cannot afford wireline broadband or the extra fee to enable mobile tethering, so Tanya either has to complete homework assignments at school or a library, or try to get them done on her mother's phone when she returns home from work.

One night, Tanya follows up on a fascinating lesson she received on black holes. She watches a Kahn Academy video on black holes, which then leads her down a cosmic rabbit hole. She gets so excited about learning the make-up of the universe that she watches multiple videos on the life and death of stars. In just a few hours of streaming educational video, Tanya exceeds the 23 GB usage threshold of the product that her mother needs to rely on for her work. The throttled speeds could put Tanya's mother's job in jeopardy.

Tanya loses home internet privileges, and is forced to restrain her curiosity and learning. While her peers with wired broadband can feed their passions at home, Tanya has to wait until she gets to a place with unfettered internet access.

The mobile internet connections available to Tanya are insufficient to allow her to learn to her potential, unlike her peers with wireline broadband options.

4.5.3 Hypothetical 3: Restricting telehealth options

Bill lives in a small, remote town in North Dakota, and has been struggling with depression. With winter on the way, he is worried about his ability to cope on his own. He searches for a therapist nearby, but cannot find one willing to take on new clients.

He goes to see his doctor, who asks whether Bill would be interested in using a tele-psychiatry service. Bill decides to give it a try. He only has dial-up internet available at home, but signs up for a T-Mobile One plan, which generally provides fast enough speeds to enable video chatting.

Bill is able to use his mobile connection to have some productive private sessions with a therapist based in New Jersey. The therapist invites him to participate in a depression support group, and

Bill enthusiastically accepts. Members of the support group share a number of strategies they use to manage their depression. Unfortunately, the multi-party video chats eat through Bill's data allowance, leading him to reach the throttling threshold early in the monthly billing cycle—meaning that he cannot join the group again until the next billing cycle begins.

The mobile internet connections available to Bill are insufficient to allow him to access telehealth services that are available to Americans with wireline broadband options.

For Casey, Tanya, and Bill—and millions of Americans like them—mobile broadband is a useful and essential service, but not a substitute for robust wireline broadband. Rather, mobile and wireline have been—and will continue to be—essential, complementary services. Those Americans who have access to only of them will face significant disadvantages relative to their peers. In light of the technical and business restrictions inherent in existing mobile networks, mobile service cannot be considered an adequate alternative to wireline broadband.

Appendix A: Fixed wireless cannot deliver the speeds or coverage that wireline offers

Many rural areas lack an adequate wired broadband option. Wireless internet service providers (WISP) are potentially able to fill these coverage gaps, sending signals from base stations to antennas on or near customer premises. But WISPs are not able to offer connection speeds on a market-wide basis comparable to wireline networks built to each premises.

Even as fixed wireless technologies continue to advance, they will still lag the performance available from fiber optics, broadband cable, or high-quality DSL, for two reasons: First, because of the challenge of delivering high-capacity wireless connections over the wide range of terrain, foliage, distances, and weather conditions that exists in any WISP service area, and second, because the spectrum capacity has to be shared among all the customers in the user area. The upstream speed is especially low relative to a wireline provider, owing both to the need to segment the capacity and to have complex technical mechanisms for providing fair access to the users, all of whom are in different directions and at different distances from the antenna.

In addition, fixed wireless equipment generally requires replacement every five to 10 years, both because exposure to the elements causes deterioration and because the technology continues to advance at a rapid pace, making equipment from a decade ago mostly obsolete. So while the cost of deploying a wireless network is generally much lower than deploying a wireline network, the wireless network will require more regular investment.

Line of sight is a significant requirement for fixed wireless service

WISPs like San Francisco's Webpass and Monkeybrains, and the New York capital region's Hudson Valley Wireless, use the same unlicensed spectrum bands as Wi-Fi or emerging millimeter-wave technologies. None of these technologies has strong long-distance transmission qualities.[34] (This is in contrast to the large mobile carriers like AT&T, Sprint, T-Mobile, and Verizon Wireless, which offer 4G service using licensed spectrum and are authorized to use higher power.) WISPs may also use other unlicensed or semi-licensed bands like 3.5 GHz or 900 MHz, but these have low data speed capabilities as well.

Most wireless networking solutions require the antenna at the customer premises to be in or near the line of sight of the base station antenna. This can be especially challenging in mountainous regions. It is also a problem in areas with dense vegetation or tall buildings. WISPs often need to lease space on rooftops or radio towers; even then, some customers may be unreachable without the use of additional repeaters. And because the signal is being sent through the air, climate conditions like rain and fog can impact the quality of service.

[34] Webpass and Monkeybrains are also using higher-speed millimeter-wave proto-5G equipment.

Because WISPs use higher frequencies than, for example, broadcasters and mobile broadband operators, the signal is very susceptible to any obstruction. The general design rule with WISP technology is that the customer needs to be able to see the WISP antenna; if there are trees, buildings, or terrain in the way, the customer gets no service or extremely slow service.

The typical WISP service model is to obtain space on a handful of towers or buildings where the provider can obtain affordable access, then connect antennas to fiber backbone and serve customers that can "see" the antennas. Because there is no requirement for ubiquitous service, customers are connected on a best-effort basis; customers who cannot connect simply are not served.

The WISP can scale its network opportunistically by adding antennas at new locations or relaying through the buildings of cooperating customers, but unlike a wireline service provider, the service area grows in an ad hoc way and often never develops the well-defined footprint that is characteristic of a wireline provider.

Some wireless providers in rural areas have begun to use vacant television frequencies called TV white spaces to deliver broadband service. These TV bands have much better non-line-of-sight transmission qualities than the unlicensed bands and thus can fill in some coverage gaps; however, because white space technology is still in an early phase of development, compatible equipment is far more expensive than other off-the-shelf wireless equipment.

Also, because white space technologies typically have less spectrum available and use smaller channels, white space customers get slower service than other WISP customers. There is a tradeoff, then, between a wireless service's ability to reach through difficult terrain and foliage, and the speed it is able to deliver.

Wireless equipment vendors offer a variety of point-to-multipoint and point-to-point solutions. Point-to-multipoint solutions are more affordable to implement and are typically used in a WISP environment. However, they limit the capacity of the network, particularly in the upstream direction, making the service inadequate for applications that require high-bandwidth connections.

Fixed wireless systems built with off-the-shelf Wi-Fi-band equipment tend to have an aggregate capacity between 100 and 250 Mbps.[35] With innovations like higher-order multiple input, multiple output (MIMO) antennas and the use of spatial multiplexing, these capacities will likely increase across vendors; some providers are now offering speeds in excess of 1 Gbps.[36]

[35] As noted above, the speed delivered by white spaces broadband technology is substantially lower.
[36] See, for example: "GB+," Everywhere Wireless, https://ewfiber.com/#explore (accessed September 2017).

It is important to note, however, that this is aggregate capacity; in a point-to-multipoint architecture, bandwidth is shared among dozens or hundreds of users served by a single base station. As a result, typical services offered to customers over fixed wireless range from 5 to 20 Mbps. Millimeter-wave technologies provide the potential for significantly higher bandwidth, yet these technologies are mostly used in point-to-point architectures, or in very short range, point-to-multipoint deployments.

Backhaul connections affect the quality and speed of fixed wireless service

Although the most severe bottleneck is often in the last-mile connection, a WISP also connects its antennas to the internet with a high speed, reliable connection. This is known as the backhaul portion of the network. In order for an antenna to consistently deliver hundreds of Mbps of aggregate capacity as described above, it is necessary to use either fiber optics or a high-speed point-to-point wireless technology in the backhaul network.

Appendix B: "5G" wireless is promising but does not represent a replacement for FTTP

Though no formal standard yet exists, next-generation wireless technologies are often referred to as "5G" in marketing and other contexts. At the moment, "5G" is currently a catchphrase encompassing efforts by research and development community, hardware and software manufacturers, wireless service providers, and standards committees. It is not a single standard, but elements of it are being developed by the International Telecommunication Union (ITU) and the 3rd Generation Partnership Project (3GPP, which developed GSM and LTE).[37]

Suggesting that "5G" can currently or in the near to medium term serve as a substitute for adequate wireline service is suggesting that a non-existent, non-deployed technology should serve as an alternative. The hypothetical "5G" future should not serve as part of the current discussion about the relative merits of existing wireline and mobile networks.

It is also important to realize that "5G," as envisioned, would not render wired connections obsolete. Quite to the contrary, it would require further deployment of fiber optic cable to provide backhaul to dense deployments of relatively short-range but high-capacity transmitters. As conceived, it may also link to the development path of unlicensed Wi-Fi and WiGig technologies, so that in some ways there may be more synergies and connections between the wireless networks built by service providers and the wireline networks feeding unlicensed networks deployed by individuals and institutions. It may also provide an alternative broadband medium for homes and businesses, though it is important to note that a wired service will always be able to provide a higher speed and more reliable service than will a wireless connection.

Two ISPs in San Francisco are already giving the city a sense of what "5G" might look like. Monkeybrains and Webpass (the latter having been acquired by Google last year) are providing services using proprietary equipment that might be considered an early version of "5G" technology. These providers interconnect their fiber networks with high-speed wireless networks. In these examples, very high-frequency (microwave and millimeter wave, respectively) link rooftops of tall buildings, and serve apartments and businesses in the buildings via the internal wiring of the buildings.[38]

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[37] Andreas Maeder et. al, A Scalable and Flexible Radio Access Network Architecture for Fifth Generation Mobile Networks, IEEE Communications Magazine > Volume: 54 Issue: 11, 15 November 2016, p. 16, http://ieeexplore.ieee.org/document/7744804/?reload=true (accessed September 2017).

[38] Boris Maysel, When and How to Use Multi-Gig mmWave, https://www.siklu.com/wp-content/uploads/2016/09/mmWave-for-Consultants-webinar.pdf, p. 8 (accessed September 2017).

Required functionality of "5G" and driving forces

The "5G" community envisions "5G" bringing six major improvements relative to existing wireless technologies:[39]

1) Higher capacity
2) Higher data rate
3) Lower latency
4) Massive device connectivity
5) Reduced cost
6) Consistent quality of experience

Higher capacity is the ability to simultaneously connect many more users and devices than the current network. As currently envisioned, a "5G" served area needs to be able to serve 20 Gbps of aggregate capacity, which is the amount expected in some environments in the early 2020s.[40] Therefore, the access device—whether a macro cell, small cell, or indoor device—needs to have sufficient spectrum, and, using a variety of advanced technologies, potentially needs to serve 100 times more devices than do current cell sites. The network also needs fiber to most if not all access devices in order to accommodate users' demand for capacity.

Higher data rate is the ability of an individual user or device to send and receive high speed transmissions. The "5G" standard is being developed with data rate potentially in the 1 Gbps or more range per user/device[41]—with "power users" being able to access even higher speed in some situations. This compares to 30 Mbps in current 4G wireless networks. Since the wireless environment is expected to support more interactive applications, the data rate also needs to be much more symmetrical than the current environment, which typically has ten to a hundred more times as much capacity in the network-to-user direction as in the user-to-network direction.

Lower latency is a reduction in the time it takes for a signal or message to go from one end to another end of the network. The objective is less than 10 milliseconds (ms) and potentially less than 5 ms[42] to support critical machine to machine communications—notably including cars and other vehicles, for which low latency is critical for collision avoidance and other safety-related applications. This compares to latency up to about 50 ms in current 4G wireless networks. The reduction is to be accomplished by reducing the number of intermediate components and the

[39] Akhil Gupta, R.K. Jha, A Survey of 5G Network: Architecture and Emerging Technologies, IEEE Access, Volume 3, p. 1208, http://ieeexplore.ieee.org/document/7169508/ (accessed September 2017).
[40] Maeder, p. 17.
[41] Maeder, p. 17.
[42] Gupta, p. 1209.

delay from each network "hop." It will also be accomplished by providing the ability to directly connect devices to each other independent of base station in a relay mesh mode.

Massive device connectivity is the ability to seamlessly connect large numbers of critical devices in a dense configuration. As it is being developed, "5G" needs to be able to simultaneously connect more than 100 mission critical devices per square kilometer (in addition to a complement of standard devices and users).

5G needs to optimize and **reduce costs** in all network components. Unlike in previous deployments, where the service providers built to connect more people and businesses to wireless networks and thus increase the total size of the revenue "pie," the industry now understands that almost all people and businesses are already connected. If the many new components and systems of "5G" are to be deployed and operated using a similar level of revenue as the industry receives today, the network buildout needs to be cost-effective. Because of the large number of components, the components must each be lower cost, lower complexity devices. They need to be small, minimizing the "real estate" they occupy and be highly energy-efficient and low maintenance. And "5G" networks must have ability to operate even if individual devices fail, and not require each site being costly and resilient, with full backup power. Service providers may consider business models in which one or more infrastructure companies provide access to shared radios and fiber backhaul to multiple providers at once.

Finally, there needs to be **consistent quality of experience provisioning**. "5G" will support an extremely diverse set of users, devices and applications. The network needs to provide a quality of service or quality of experience that suits each one.[43] Current 4G networks can prioritize applications and users, and provide packet delivery and service guarantees. "5G" will need to do all of that but also support user groups that currently are served by wireline services, and user groups and devices that do not yet exist. This calls for a wider range of customized services, including high-criticality, low bandwidth uses (such as electric utility control components); moderate-bandwidth, high-criticality uses (automated vehicles); moderate-bandwidth, moderate-criticality uses (email, texting); and high bandwidth; and moderate criticality (video, CCTV, gaming). The network must be able to tune to the appropriate use and work with a business model that efficiently accommodates all the uses.

Proposed architecture

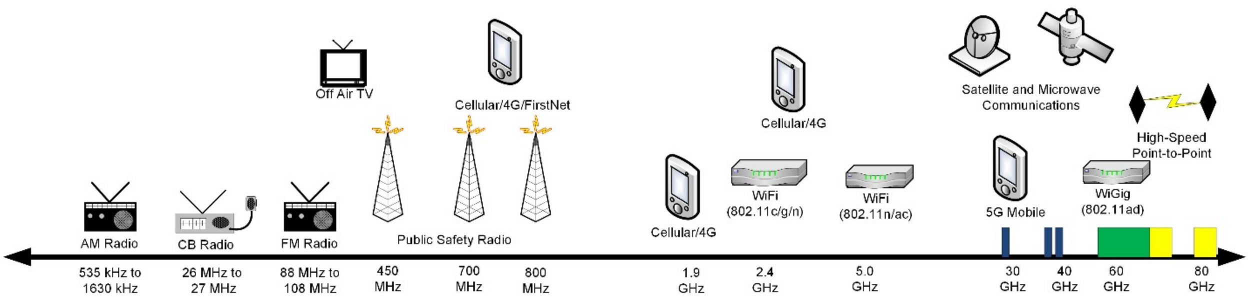
5G is planned to use a range of network layouts, including some that resemble current point-to-multipoint cellular deployments, and some that add multitiered service delivery, mesh, and separate indoor and outdoor networks. Given the increased number of sites and the short transmission distances of the equipment, all of the envisioned layouts require significant

[43] Maeder, p. 21.

expansion of fiber backhaul networks. "5G" is expected to use spectrum currently assigned for licensed wireless use, along with new higher-frequency bands and unlicensed bands.[44] Emerging and future generations of Wi-Fi may also be included under "5G," potentially leading to greater integration between private unlicensed networks and commercial carrier networks.[45]

5G can be expected to use any of the existing commercial bands—including the 700 and 800 MHz cellular, and the higher-frequency 1.9, 2.1 and 2.5 GHz bands (Figure 10). In addition, high-frequency spectrum bands at 28 GHz and 39 GHz (blue bands) are becoming available for mobile use, as well as an unlicensed band at 60 GHz (green bands).

Figure 10: New Spectrum Is Likely to Be Central to "5G" Deployment



The high-frequency bands have several advantages, including wide channels, and small wave forms that enable the use of smaller antenna elements on microchips. However, high frequencies have the disadvantage that they are more susceptible to being blocked or scattered by obstructions including buildings, walls, foliage, and even raindrops. As a result, high frequency signals need a direct line of sight or near light of sight. Long distance links are not advisable.

Near 60 GHz there is high absorption from oxygen, further limiting the range. Still, the bands near 60 GHz are envisioned for unlicensed use—potentially for connectivity indoors, or short range connections from utility poles to houses.

At frequencies above 70 GHz (yellow bands), spectrum is set up in a lightly-licensed arrangement, for point-to-point communications. In the future, technological innovations may also make mobile communications feasible in these bands.[46]

Deployment path

It is envisioned that "5G" deployment will begin as an enhancement of existing 4G networks, filling especially high demand areas.[47] For example, in a busy city street or in a transit center,

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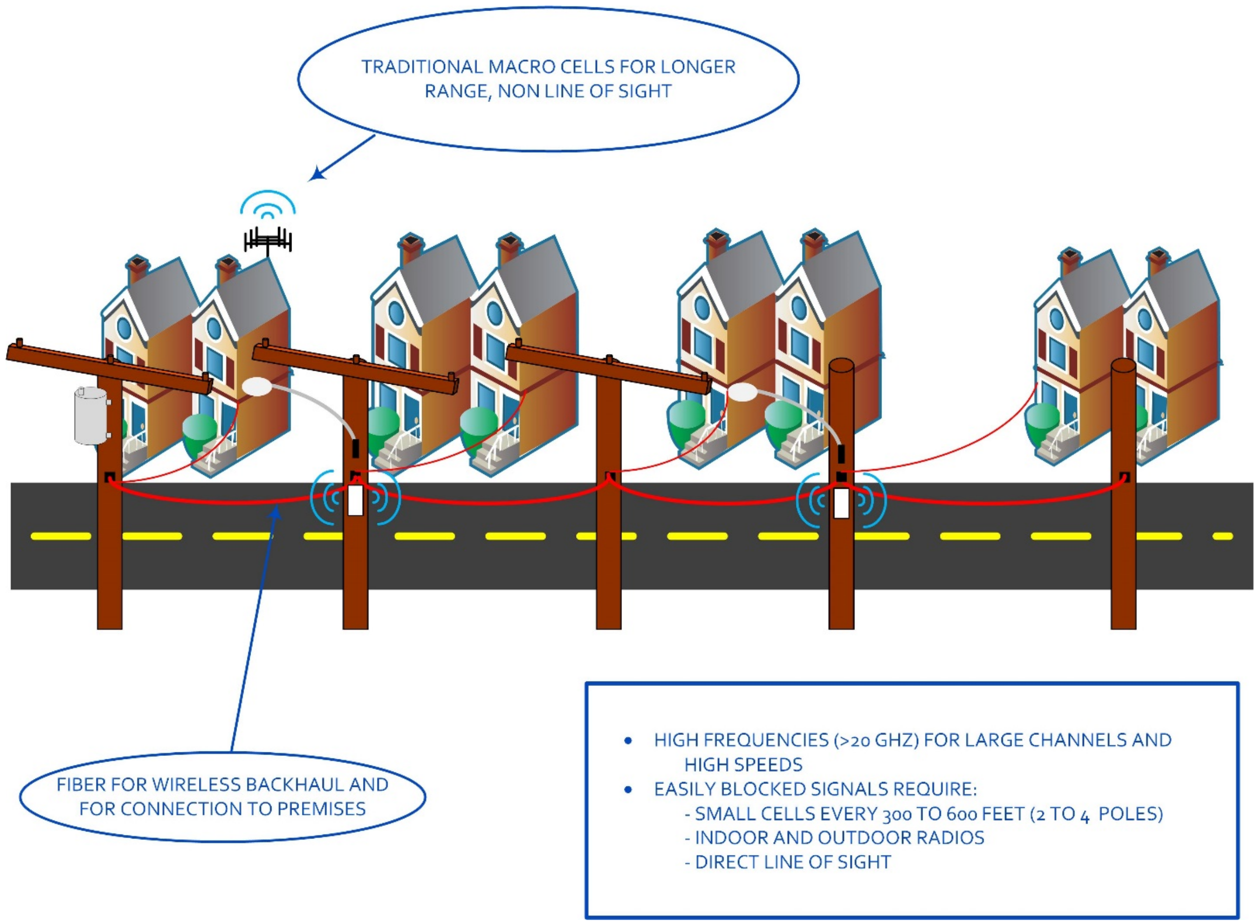
[44] Maeder, p. 17.
[45] Maeder, p. 16.
[46] FCC NPRM, https://apps.fcc.gov/edocs_public/attachmatch/FCC-15-138A1.pdf, p. 145 to 154, adopted October 22, 2015 (accessed September 2017).
[47] Maeder, p. 22.

"5G" access points connected to fiber can provide boosted data capacity to "5G"-ready phones and devices within a few hundred feet, offloading capacity from the 4G network while those devices and users are in proximity to the "5G" access points (Figure 11).

Figure 11: "5G" Devices Installed on Poles Augment Capacity Nearby



As demands of automated vehicles grow, corridors can be activated with fiber-connected "5G" access points on light poles, utility poles, or building facades. As access points become widespread, they can provide alternative broadband service to residences and businesses near the devices. Since the high-frequency signals have difficulty passing through walls and windows, service to buildings with "5G" networking may require wireline service into the building or outdoor antennas to pick up the signals.

It is estimated that 80 percent of "5G" use will be indoors;[48] because of the attenuation from the walls, "5G" networking indoors will require both outdoor and indoor antennas. These can be provided through different approaches. In a single-family residence, one approach would be to

[48] Gupta, p. 1208.

set up an indoor, customer-owned IEEE 801.11ac/ad WiGig/Wi-Fi hotspot, connected through the home wireline broadband connection to the public network. A variation of that approach would be to use a service-provider-supplied indoor hotspot that uses licensed "5G" spectrum. The home broadband connection could be a wired connection or a wireless connection through an outdoor-mounted "5G" antenna. In multi-dwelling or industrial buildings, service providers could deliver "5G" service through "5G" versions of distributed antenna systems (DAS) or indoor small cells.

The future environment will likely be a continuation of 4G and "5G" communications over currently used wireless bands complemented by the "5G" high frequency antennas. The lower-frequency spectrum bands and macro cells will be needed to fill in the gaps with non-line of sight coverage where "5G" antennas are not built, or coverage gaps in between, or for service to areas where it is not cost effective to place antennas or backhaul links to the antennas.

Flexible approach to radio access network (RAN) infrastructure

4G and "5G" networks are evolving to enable service providers to flexibly apportion "slices" of network connectivity on demand in the network core and wireless infrastructure. This evolution results from developments in processing speed, aggregation of spectrum bands, and software designed radios.[49] Slicing would enable new ways of doing business, including 1) enabling a wireless user to connect through a wider pool of spectrum and capacity, 2) facilitating a smoother handoff of services between carrier networks and home/business/institutional wireless networks, and 3) potentially facilitating the separation of the wireless service provider and the operation of the RAN infrastructure—enabling service providers to connect their core networks to RAN providers and enabling the RAN providers to manage the RAN.

This trend is already visible with the increasing role of infrastructure companies in building towers, DAS networks, small cells, and wireline backhaul. The technology potentially enables the infrastructure companies to manage the spectrum and the RAN, if they can obtain the rights to the spectrum. The technology also potentially reduces overall deployment costs, if a smaller pool of RAN providers can serve multiple service providers over a consolidated RAN or RANs. From the point of view of the City, the result may be fewer placements of antennas on poles.

The ability to have a more fluid network that can operate over a range of separate physical networks also creates a greater role for providers without their own licensed spectrum (cities, institutions, cable operators) that can provide "5G" service through unlicensed spectrum, particularly on campuses and indoors, or use the licensed spectrum of an infrastructure company that operates antennas and spectrum and makes it available on a wholesale basis.

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[49] Maeder, p. 21.

Status of development and deployment

Cities are experiencing a substantial increase in applications for placing wireless infrastructure in the right of way and on public and private property. At this point, the focus is on deployment of 4G small cell technologies that provide "densification" in busy areas. This equipment may also become a placeholder for higher-frequency "5G" equipment, which will need to be more closely spaced. In addition, the policies and practices that are adopted in the 4G densification will set the stage for practices in the "5G" buildout in the coming years.

The current research includes development of Massive MIMO—essentially placement of multiple antennas within access points and devices. MIMO is already in use in 4G and Wi-Fi using dual or four antennas, but Massive MIMO may use dozens or hundreds of antennas, and increase capacity by enabling devices to connect simultaneously through many separate physical paths.[50] Because of the small waveform, high frequency bands are well suited to the development of devices with multiple miniaturized antennas.

Wireless service providers are in the process of beginning trials and acquiring spectrum for "5G." Several companies hold 28 GHz and 39 GHz spectrum but little deployment has taken place. Verizon and AT&T are acquiring spectrum in those bands and firms that hold the spectrum.[51]

Need for fiber to enable and complement "5G"

The increasing call for broadband capacity, especially mobile and in support of new applications, is driving the deployment of a new generation of wireless infrastructure, which in turn is driving the deployment of fiber and other infrastructure to connect it. Fiber is unique in its ability to deliver hundreds of Gbps in single strand. Once constructed, fiber does not require large-footprint cabinets or intermediate power. Powered components are only required in the central office hub facilities or at the endpoint—and the endpoint equipment can be very compact.

Considering that "5G" infrastructure requires access points every 300 to 600 feet (every two to four utility poles or streetlights),[52] and that each of the access points requires upwards of 20 Gbps, then one mile of street needs hundreds of Gbps of capacity, and an entire city needs hundreds of Tbps (or hundreds of thousands of Gbps).

[50] Gupta, p. 1213.
[51] Thomas Gryta and Ryan Knutson, Verizon, AT&T in Billion-Dollar Bidding War for 5G Spectrum, April 25, 2015, https://www.wsj.com/articles/verizon-at-t-in-billion-dollar-bidding-war-for-5g-spectrum-1493146927?mg=id-wsj (accessed September 2017).
[52] Tianyang Bai, Ahmad Alkhateeb, and Robert W. Heath, "Coverage and capacity of millimeter-wave cellular networks," *IEEE Communications Magazine*, Volume 52, Issue 9, p. 76, http://ieeexplore.ieee.org/document/6894455/ (accessed September 2017).