ACCESS NETWORK BUILD COMPARISONS:
FTTH, HFC FIBER DEEP, AND LTE

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Abstract

The service characteristics and technology evolution of fiber-to-the-home (FTTH), HFC fiber deep, and 4th Generation Wireless (LTE) will define the next generation of access network and broadband competition. We argue that it is from these developing technologies and delivery platforms that broadband customers will choose the manner in which they receive their future broadband services.

In comparing the alternatives we consider several questions. What will the broadband competition for each alternative look like from a consumer perspective? What factors or trends might influence the outcome? Which access technology can best be optimized for future broadband service? Can the alternatives co-exist? What level of capital would justify the expected services?

The purpose of this paper is to provide a competitive, technology and economic framework for comparing next generation broadband access alternatives from both a greenfield and upgrade basis.

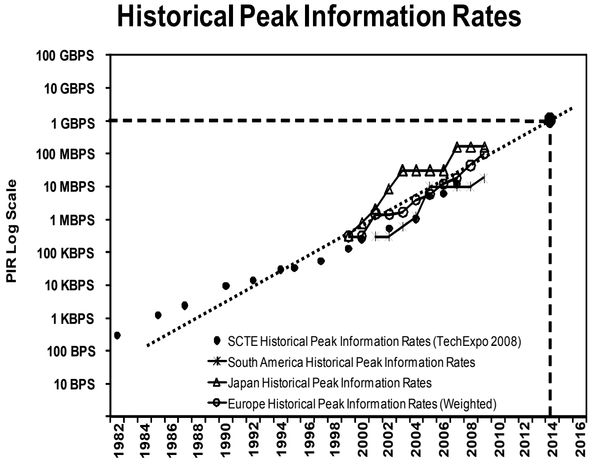
BROADBAND COMPETITION

Broadband competition may be examined along several attributes including: Speed, Price, and Service Types; with all broadband competitors facing what could be called a “capital threshold”.

Faster Broadband Speeds

Broadband competition between access technologies is also highlighted by pressure to offer faster peak advertised speeds or Peak Information Rates (PIR). Considering 28 years of historical trends, and subject to regional variations in competition, it is not inconceivable that Peak Information Rates of 1Gbps could be required by 2014!

Figure 1: Peak Information Rates Continue To Grow [1]

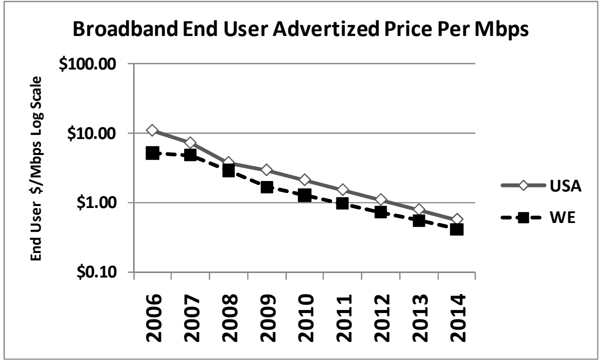


If we assume that, based on historical trends, end users will continue to decide between competing offerings based on advertised speed or peak information rates, this has an impact on the access network technology choices an operator needs to consider in order to remain competitive.

Price and Competition

Broadband prices per Mbps continue to decline over time for fixed line broadband. The declining price per Mbps is a function of increasing information rates and competition. For example, in markets where broadband access competition is particularly intense, or there are irrational competitors, price per Mbps per month declines can be more dramatic. We illustrate with an example of U.S. broadband prices per Mbps below in Figure 2.

Figure 2: Broadband Price Per Mbps [2]



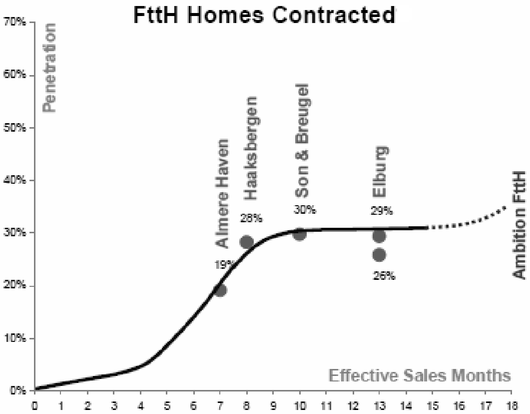
Similar Service Types
With Telco's addressing the need for Video and very high speed data services by moving from Digital Subscriber Line (DSL) to Gigabit Passive Optical Network (GPON), we contend that for fixed line broadband the core "service types" that are offered will be similar to Cable.

Mobile Broadband or Long Term Evolution (LTE), on the other hand can support Voice and Data "service types" that are also offered by fixed line operators, with the unique attribute of mobility, but will struggle with mainstream Video services[3].

The Customer Base Potential
In a highly competitive environment, we believe it is unlikely that a service provider could achieve more than 50% penetration of addressable homes on average (i.e. the "customer base potential[4]"). Looking at industry examples we see that a typical penetration of addressable homes would be around 30%. For example, noting a 3 year horizon, Verizon stated in Q1 2007 that, "By 2010, Verizon expects to have a 35-40% penetration rate of FiOS Internet customers, and a 20 to 25% penetration rate of FiOS TV customers"[5]. In July 2009, it was reported that Verizon had achieved sales penetration of 28.1 percent for FiOS Internet and 24.6 percent for FiOS TV[6].

Similarly, worldwide other Telcos have stated in that their FTTH pilot results, offering triple play packages of Broadband, TV and Telephony, have met expectations with up to 30% of FTTH homes

Figure 3: Example of FTTH Sales Curve [7]

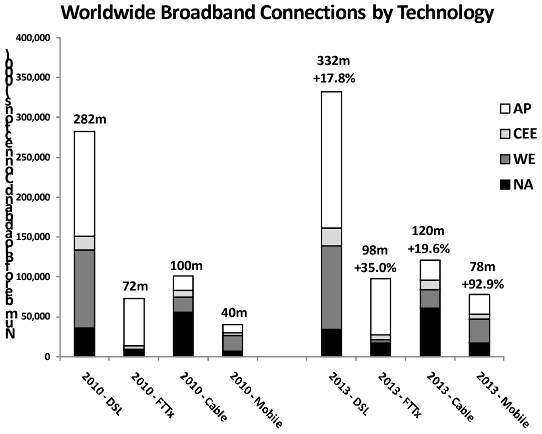


Today, Telcos recognize the effect competition has on penetration potential. In some countries Telcos have stated targets to have one third or 33% of the population connected by FTTH by 2015[8].

Operators that own both Fixed and Mobile Broadband operations, such as AT&T, are also looking at a hybrid model where the alternative access technologies are complimentary rather than competitive by splitting the service types by technology. For example DSL/FTTH could be used for Video and Fixed Data, while LTE is used for Mobile Data and Voice[9]. Using a service bundle, this enables the Telco to maximize the penetration of both technologies by minimizing service type competition between the access alternatives.

Future Competition
Today, Cable and DSL are the most widely deployed broadband technologies worldwide, with Mobile Broadband emerging as a rapidly growing segment. Regional variations are evident, with Cable broadband dominating in North America, and DSL dominating in Asia-Pacific and Europe.

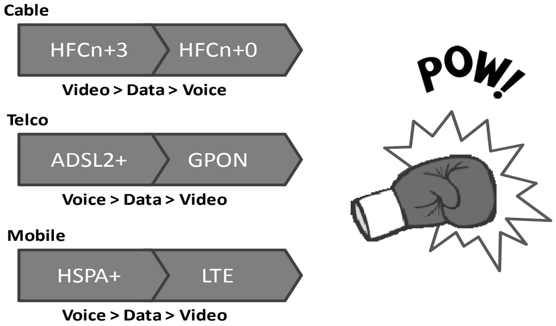
Figure 4: Worldwide Broadband Connections by Technology 2010 vs. 2013 [10]



The points for future competition in the broadband market place are clear: (a) Between future fixed line technologies there are unlikely to be any major "service type" advantages to attract subscribers away from their existing access provider, (b) Without a service type advantage, FTTH/GPON adoption will be driven by Greenfield or future Telco upsell of the existing DSL subscriber base in order to counter higher Peak Information Rates from competing alternatives, and; (c) Mobile broadband offers two of the three service types in the market, which could be expected to place additional pressure on fixed line penetration potential.

If we assume that tomorrow's Fiber access deployments are primarily a Telco competitive response to the limitations of existing DSL technology with its comparatively low data rates[11], rather than a new category of broadband service provider; then three categories of next generation access technology emerge: Cable's HFC Fiber Deep, Telco's Gigabit Passive Optical Networks (GPON), and Mobile Broadband (LTE), as show in Figure 5 below.

Figure 5: Future Broadband Access Competition



TECHNOLOGY

The Telcos and Cablecos use land or terrestrial based technologies via the medium of fiber, coaxial cable or copper cable. Mobile operators utilize the spectrum or airwaves they own or lease to provide these same broadband services. As the offered speeds for broadband access continually increase from 1Mb/s to 100 Mb/s and beyond, the technologies deployed by fixed line and mobile companies must evolve.

The terrestrial based companies will continue to bring the highest capacity and most efficient medium, fiber optics, closer and closer to the customer. Cablecos do this via Hybrid Fiber Coax (HFC) deployments that bring fiber deeper into the network (beyond current Fiber Node locations) so that no regenerators are required beyond the FN. Telcos deploy fiber to Remote Terminals (RTs) or cabinets that contain DSL electronics, called DSLAMS, located in neighborhoods. Because Telcos have much stricter bandwidth (and capacity) limits inherent in the copper plant versus the Cablecos coax, many Telcos have even begun to pull fiber all the way to the home.

Likewise, the wireless operators will need to add more spectrum, make more efficient use of their radio technology and move cell sites closer in, towards their customers' homes.

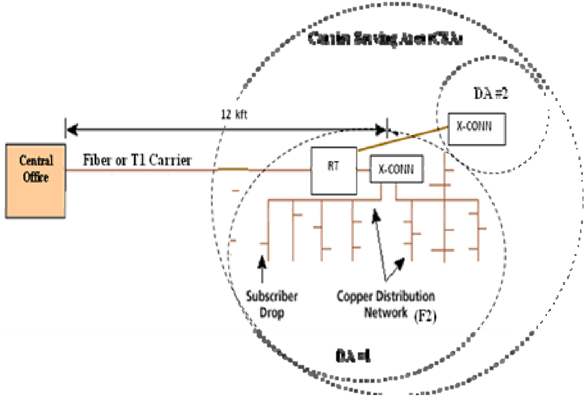
The incremental economics associated with these evolutionary moves are the key to how quickly technology change-outs will occur. The economic challenge for fixed operators has always been the cost/benefit of reusing the existing medium (copper pairs or coax) in the last mile (or ½ mile) to the customer premises versus undergoing the substantial costs and time to rewire the local loop with fiber optics. Similarly, mobile operators need to spend additional capital to build more towers closer to customer locations in order for mobile devices to receive the sufficient signal strength required for high speed services inside homes.

Finally, it makes economic sense to share network elements across as large a group of customers as possible. Contrary to this economic need, network resources are being shared across smaller and smaller groups of customers as the average speed offered to the end users increases and customer penetration levels rise.

Telephone Company Networks

In the U.S. the Telco architecture is quite varied as the number of homes served by a Central Office (C.O.) can range from less than 1,000 to over 50,000 households. Likewise, the distances from the C.O. to the edge of the C.O. area (called wire center) vary from 10,000 to 20,000 feet. Figure 6 provides a visual representation of the Telcos outside plant architecture.

Figure 6: Telco Outside Plant Architecture



As Figure 6 shows, the wire center district can be broken up into many smaller CSAs (Carrier Serving Areas) that pass from 600 to 2,000 homes, where the furthest home can be easily 12,000 feet from the CO. CSAs are made up of smaller geographic neighborhoods called DAs (Distribution Areas) serving 250 to 300 homes. DAs contain cross-connect points called Feeder Distribution Interfaces (FDI) or Serving Area Interfaces (SAI) where the furthest home is usually between 3,000 to 5,000 feet from the FDI. These cross-connect cabinets terminate the twisted copper pairs that originate in each home and are called distribution pairs. FDI cabinets typically terminate 2 to 3 lines per home, so large cross connects may be required. Historically, these cross connect cabinets were fed by copper coming all the way from the CO where half as many feeder pairs from the CO matched up against the distribution pairs going to the homes. Over time, digital T1s and fiber optics replaced the copper feeder and fiber optic electronics were placed in Remote Terminal cabinets (RTs) right next to the cross-connects

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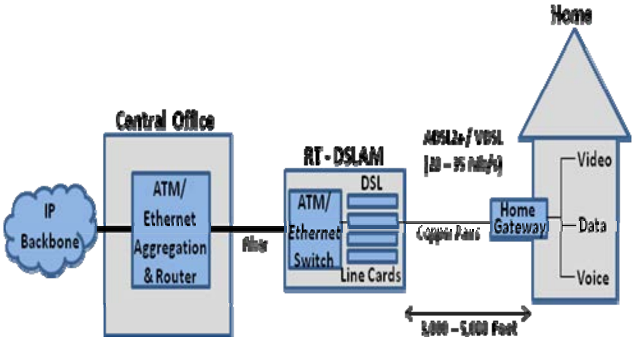
Fiber to the Node using DSL Technology

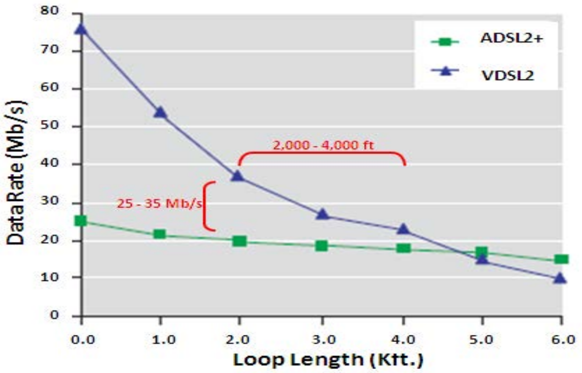
As ADSL and VDSL technology was deployed, remote DSLAMS that contain the DSL line cards, ethernet or ATM switches and fiber optic transmission equipment were placed in these RTs. Figure 7 shows the current ADSL2+ or VDSL architecture used by AT&T (uVerse) and other Telcos.

Figure 7: DSL Network Architecture



The main variants of DSL technology all take advantage of using an increasing amount of the usable spectrum available on twisted pairs of copper wires. VDSL enhancements increased the spectral band plan to 12 MHz from the 2.2 MHz limit of ADSL2+. Consequently, the obtainable speeds increased as long as the quality of the copper plant was very good and the distances from the line cards in the remote DSLAM to the home were less than 4,000 feet. It is important to note that twisted pair copper wires contain a number of impairments such as crosstalk, noise and bridge taps that severely reduce data speeds, even when the distances are short. Because ADSL2+ and VDSL technologies are so sensitive to distances, charts showing data rates versus loop lengths of the copper plant are useful. Figure 9 is a good example of a rate versus reach graph for ADSL and VDSL technologies. Given the Telcos' Distribution Area (DA) architecture, the key range is 2,000 to 4,000 feet which corresponds to maximum speeds of 25 to 35 Mb/s.

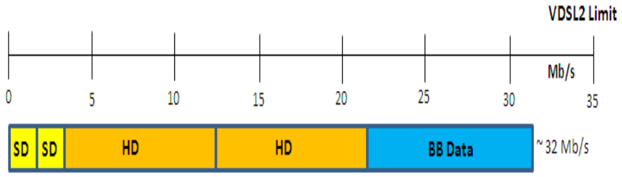
Figure 9: ADSL VDSL Rate vs Reach[12]



When one looks at an overlay of the bandwidths required for triple play services, it becomes apparent that VDSL technologies quickly become obsolete as end user demands increase. Because of the shorter loop lengths in many European countries VDSL speeds are higher and technology lifetimes will be extended.

For instance, Figure 10 shows a household requiring two High Definition (HD) and two Standard Definition (SD) video streams along with 10 Mb/s of broadband data that max's the VDSL bandwidth limits even when MPEG4 SD and HD compression technology are assumed (2 Mb/s and 9 Mb/s).

Figure 10: Triple Play Customer Requirements and VDSL2 Capacity Limits



Fiber to the Home (FTTH)
In the near future most TelCo's will realize they have to deploy fiber directly to the customer premises to meet the growing customer broadband demands as the capacities of twisted pair copper are limited with DSL technology. Additionally, the operational expense of managing many individual copper strands and cross-connect points in the outside plant will continue to be an economic burden.

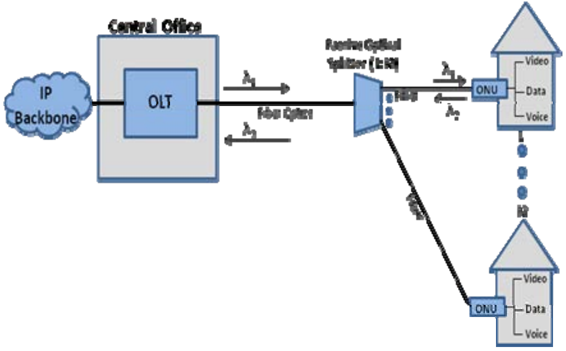
As video demands are added into the broadband end user speed requirements the Telco decision to extend the fiber to the home will become even more urgent. Some Telcos with a longer financial payback view, such as Verizon, have already reached this conclusion and made FTTH (branded FiOS) a cornerstone of their broadband and video services. Telcos without the financial strength and longer term view have opted to avoid the large FTTH investment by making the copper last longer using ADSL2+, VDSL, satellite and digital terrestrial (DTT) access means for video and broadband services. This is the strategy of AT&T in the U.S. and many European Telcos.

Passive Optical Networks (PONs)
The highest capacity and most economical way of providing FTTH is to deploy PON technology. Although PON architecture requires a complete change-out of the current

Telco architecture, at a huge capital expense, it does solve the capacity and economic constraints inherent with upgrading and re-using the Telco copper plant.

A Passive Optical Network is an end-to-end optical network using a point-to-multipoint architecture containing no active elements at any location in the outside plant. It is an extremely efficient way of providing high capacity broadband services, as the only active (or powered) components are in the CO and at the customer premises. Additionally, the economic benefit of sharing resources is possible as a single fiber optic strand is shared across multiple homes (32 or 64) via the utilization of a fiber optic splitter. It is also possible to configure two tiers of splitters in the network where a 1:4 splitter is followed by a 1:8 splitter closer to the served homes. Figure 11 gives us an illustration of the typical PON architecture.

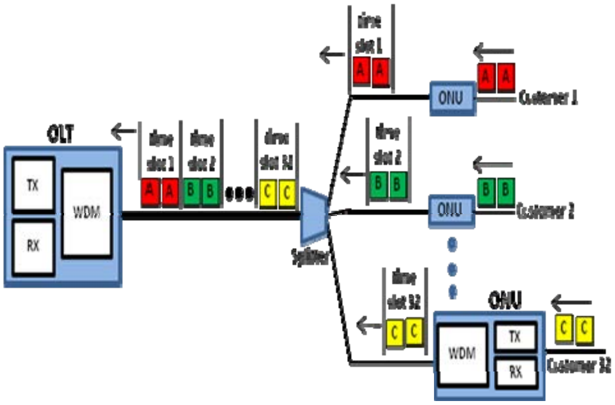
Figure 11: PON Architecture



A key network element shown in Figure 11 is the Optical Line Terminal (OLT) located in the Central Office. Since PON architecture is point-to-multipoint (or multicast) in the downstream direction, the OLT transmits the entire PON bandwidth (2.5 Gb/s for GPON technology) to the PON splitter and all 32 homes receive the packets broadcast by the OLT. The Optical Network Units (ONU) shown in Figure 11 selectively extract the packets from the entire line rate that pertain to the address of the particular customer's ONU. The proper encryption and security mechanisms are implemented in the downstream direction to eliminate eavesdropping and theft of services. Typically, a single optical fiber is used to serve each group of customers connected to a PON splitter, where different wavelengths are associated with the downstream and upstream data flows. Figure 11 designates the different optical wavelengths as λ_1 and λ_2.

The upstream transmission in PON architectures is much more complicated than the downstream. There must be a separation of the information coming from each of the 32 customer ONU's going back to the OLT, as they are all sharing the total upstream bandwidth (1.25 Gb/s for GPON technology). PONs use TDMA (Time Division Multiple Access) schemes that allocate each customer's ONU in the group of 32 to a separate timeslot. The upstream PON technology is quite sophisticated, as it is important for the ONU to have burst mode transmitters/lasers that turn on and off very quickly yet operate at the full upstream line rate. Additionally, the OLT contains advanced receiver technology and performs complex centralized controller functions, as it must be highly synchronized with the ONT's so that upstream timeslots are accurately assigned. Figure 12 provides a visual representation of the upstream TDMA transmission process just described.

Figure 12: PON TDMA Upstream Transmission[13]

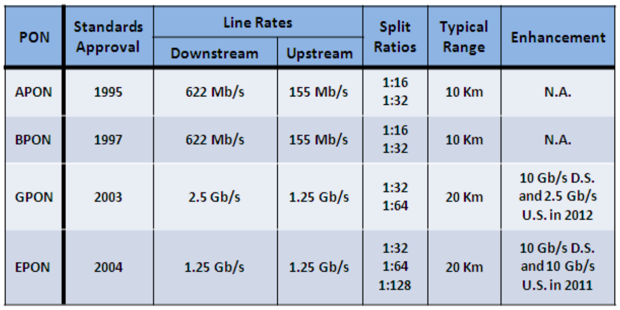


PON Standards

In the mid 1990s a group of Telcos formed an association called the Full Service Network (FSAN) to create a PON standard. The outcome of that collaborative effort was the APON specification. APON is based on the ATM transmission protocol and is the reason for the APON abbreviation. Very quickly, the FSAN association upgraded the specification to BPON (Broadband PON) to accommodate higher line rates and interfaces with ethernet protocols while retaining its ATM transmission format. BPON became an ITU standard and was the original technology deployed in Verizon's FTTH FiOS initiative. BPON utilizes a 622 Mb/s downstream line rate and 155 Mb/s upstream speed shared across 32 customers using a single 1:32 splitter.

In the early 2000s, Verizon and other Telcos realized that higher line rates and the ability to more easily accommodate Ethernet data traffic was required. As a result of those efforts the GPON (Gigabit PON) standard was born in 2003. GPON was able to accomplish the goals of higher line speeds, more efficient carrying of Ethernet packets and backwards compatibility to ATM and circuit based TDM applications (e.g. - circuit switched voice). Unfortunately, GPON required the creation of a new framing and encapsulation specification within its standard and some very stringent OLT to ONU timing requirements. The result has been greater overall complexity and costs of the network elements. GPON provides 2.5 Gb/s downstream and 1.25 Gb/s upstream line rates and can accommodate either 1 to 32 or 64 split ratios. The typical range from OLT to ONU is 20 Km. and the upstream usually operates at 1310 nm wavelength while the downstream is set in the 1550 nm region. Figure 13 compares the PON standards.

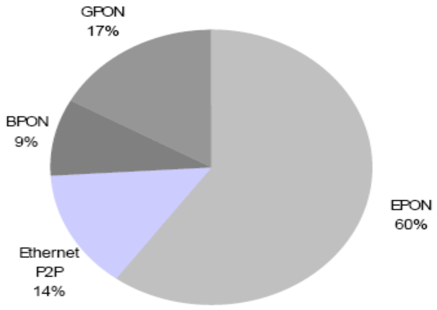
Figure 13: Comparison of PON Standards



PON	Standards Approval	Line Rates		Split Ratios	Typical Range	Enhancement
		Downstream	Upstream			
APON	1995	622 Mb/s	155 Mb/s	1:16 1:32	10 Km	N.A.
BPON	1997	622 Mb/s	155 Mb/s	1:16 1:32	10 Km	N.A.
GPON	2003	2.5 Gb/s	1.25 Gb/s	1:32 1:64	20 Km	10 Gb/s D.S. and 2.5 Gb/s U.S. in 2012
EPON	2004	1.25 Gb/s	1.25 Gb/s	1:32 1:64 1:128	20 Km	10 Gb/s D.S. and 10 Gb/s U.S. in 2011

In parallel to the creation of the GPON standard, an association of equipment manufacturers and Asian Telco operators decided to put together a "pure" Ethernet PON specification that did not make concessions for legacy ATM and circuit based technologies. The resulting specification was ratified by the IEEE in 2003 and became the EPON standard. The key goals of the EPON developers were to combine the simplicity and worldwide economies of Ethernet with the high capacity capabilities of FTTH PONs. As a result of this effort and the worldwide deployments of EPON it has become the most popular PON standard and looks to have increasing market potential going forward. Foremost to its greater potential over GPON is the lower cost of ONUs and higher worldwide volumes primarily driven by Asia deployments. Figure 14 gives us a glimpse of the current PON technology market shares.

Figure 14: FTTH Technology Market Share[14]



The key developmental paths for both GPON and EPON are the increasing line rates. The enhanced EPON standard approved in 2009 will provide 10 Gb/s symmetrical or 10 Gb/s downstream and 2.5 Gb/s upstream speeds.

Commercial chipsets and products will be available in 2011. Additionally, split ratios of 1:128 will be feasible.

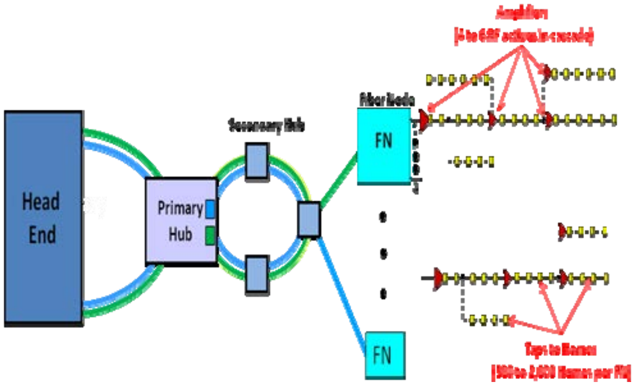
Not to be outdone, GPON will have standards enhancements in 2010 that also provide 10 Gb/s downstream and 2.5 Gb/s upstream line rates. It is expected that commercial products will be available in 2012. At issue for GPON is having sufficient worldwide volumes for chip makers to justify large commercial production levels as North American GPON deployments (e.g. - Verizon) are slowing.

For Cablecos there is an inherent compatibility of ethernet and the IP nature of DOCSIS protocols that makes EPON a stronger future technology choice of MSOs. Because business and commercial customer requirements are typically symmetrical in nature and Ethernet based it is expected that EPON technology for business applications will materialize first for MSOs[16].

Cable TV Company Networks

The other terrestrial based broadband network provider is the Cable TV Company or Multiple Systems Operator (MSO). The MSOs network has evolved in a very advantageous way over the years from both a technology and economic point of view. Figure 15 illustrates the typical two-way Hybrid Fiber Coax (HFC) plant in service today in over 90% of an MSO's footprint.

Figure 15: Modern HFC Network



The Head End (HE) location shown in Figure 15 serves a single or sometimes multiple metropolitan areas covering millions of homes. It contains the video equipment and feeds (satellite and terrestrial) as well as the IP data routers, voice switches, internet and voice network interconnects. Redundantly routed fiber optic transmission equipment is used to transport video, data and voice services from the HE to primary and secondary hub locations. These hubs also serve very large geographic areas of 20,000 to 40,000 homes. In most cases, these hub locations are relatively small unmanned buildings, as they are primarily comprised of optical transmission equipment and Cable Modem Termination Systems (CMTSs).

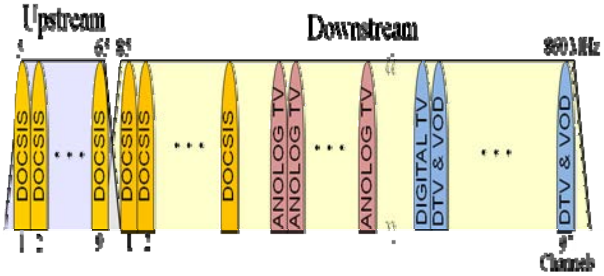
Over the last ten to fifteen years most MSOs have upgraded their outside plant so that fiber optic strands and equipment is deployed out into the residential neighborhoods. The fibers terminate in small, hardened Fiber Node (FN) cases located either in ducts or on the aerial plant. The FN converts the optical signal to an electrical signal that is transmitted over coax to the household in the FN's neighborhood. As shown in Figure 15, most fiber nodes are designed with four coax distribution segments directed towards the homes in the node. This capability allows for an economical way of adding specific capacity for the various services via service groups. Additionally, this architecture allows MSOs to cleanly segment the fiber node into smaller groups of homes passed without adding new fiber, if demand warrants. A node split or segmentation effectively doubles the available bandwidth per customer by halfing the number of customers served by a fiber node. Typically an FN serves between 500 and 2,000 homes passed (HP) where each coax distribution segment contains between four and six amplifiers (or RF actives) in cascade. Such a configuration is commonly referred to as an N+4 (Node plus 4 amplifiers) or N+6 arrangement. The final network elements to the home are in what is called the drop portion of the plant and are made up of passive components called taps, splitters and drop cable.

There are inherent advantages to this architecture that lends itself to a graceful and economical evolution: (a) The coaxial cable to the customer premises has a very large capacity that does not limit services or bandwidth in the final mile, (b) The architecture was designed from the beginning with a tree and branch or shared topology that mimics an efficient current day corporate LAN, (c) The plant was designed with a common architectural uniformity so that no matter where you go within an MSOs footprint the structure is similar, (d) A minimal amount of active components are resident in the outside plant as the more intelligent and expensive electronics are either in the hubs or at the customer premises and, (e) Incremental new services (e.g. - video, data and voice) and increasing levels of capacity can be easily added across the existing network elements, so the business scales efficiently.

HFC Customer Bandwidth and Capacity

The capacity of the coax cable portion of the plant has no sharp cutoff.[15] Capacity is limited by the distance from the fiber node to the furthest customer's home and more importantly by the number of amplifiers in series along that particular branch.[16] Additionally, bandwidth is constrained by how much spectrum can pass through the taps and splitter components in the drop segment of the network. Assuming a typical 860 MHz HFC plant common in Europe, Figure 16 pictorially describes the upstream and downstream bandwidth capacities. European HFC networks utilize 8 MHz wide channels (versus 6 MHz in the US) and have 10 more MHz of upstream bandwidth than the U.S.

Figure 16: European 860 MHz Bandwidth



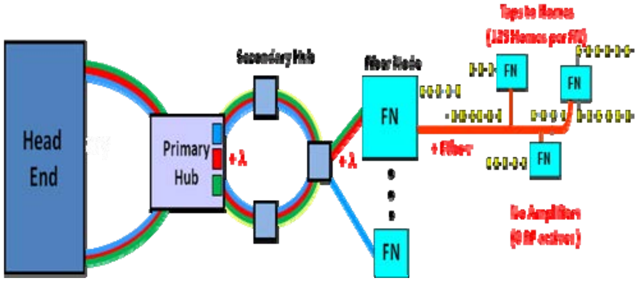
In the upstream direction, a European MSO has a theoretical broadband (DOCSIS) capacity of approximately 270 Mb/s shared across all the homes in the fiber node. This calculation assumes nine usable 6.4 MHz upstream DOCSIS channels operating at a 64QAM modulation (30 Mb/s throughput per channel). Obviously, a clean upstream plant that may have to operate in an SCDMA mode will be required for this capacity scenario. Additionally, substantial capacity gains are possible if operating in a DOCSIS 3.0 mode as the upstream channels are bonded together. Combining 270 Mb/s into one large "pipe" adds a statistical multiplexing gain that is very efficient in the shared LAN type environment of the HFC architecture.

Likewise, downstream bandwidth delivers plenty of capacity in an "all digital" world. Assuming 782 MHz available for downstream traffic in the European scenario of Figure 16, 4.85 Gb/s of capacity is possible. This total assumes 8 MHz channels operating at 256 QAM modulation which provides 50 Mb/s of throughput per DOCSIS channel. Certainly this capacity provides a very future proof capability to support multiple HDTV, VOD, high speed data and voice services. As Figure 16 notes, there need to be allocations for Analog TV requirements and the simulcasting of these signals, so an evolution to the all digital, all IP (including IPTV) world described in the above paragraphs is required.

Hybrid Fiber Coax-Fiber Deep (HFC-FD)

At some point in the life of the HFC architecture, end user demands are so great, that even in an all digital environment 4.85 Gb/s capacities across 500 homes may not be sufficient. At that point, a further reduction in the proportion of customers vying for the available bandwidth is undertaken by driving fiber optics deeper into the distribution portion of the coax network. This architectural enhancement is illustrated in Figure 17.

Figure 17: HFC Fiber Deep Architecture



Additional optics capacity is added to the hubs and the original serving FN by adding wavelengths to existing fiber pairs (shown as λ in Figure 17). New fiber optic cable is placed in the distribution portion of the plant where formerly the coax and remaining amplifiers were located. In performing this work, the node size is reduced from 500 to 125 HP per FN. The fiber deep scenario provides an added benefit of eliminating the amplifiers and leads to the N+0 terminology, which refers to a node plus zero RF actives. Additionally, having no amplifiers in the HFC plant improves network reliability and operational expenses, as less maintenance support and powering is required.

A critical component to enhancing the HFC plant to a fiber deep architecture is the ability to leverage existing fibers by adding wavelengths to in place fiber. Wave Division Multiplexing is the fiber optic technology that enables multiple wavelengths, each operating at very high line rates, to simultaneously use the same fiber strand. Unique to MSOs, they have deployed the more economical version of WDM, called Coarse WDM. In CWDM systems, the spacing between wavelengths using the same fiber strand is wider (20 nm apart) than other WDM technologies. The large channel spacing was designed to establish a cost effective framework able to accommodate less sophisticated lasers with high spectral width and less stringent temperature and power requirements[17]. This has enabled MSOs to build HFC plants with hardier, smaller, lower power, and consequently more economical, Fiber Nodes.

The higher capacity version of WDM technology is called Dense WDM (DWDM) and allows for very tightly spaced wavelengths (.2 nm apart). Consequently, DWDM systems have extremely high capacity and are usually found in Telcos and long haul transmission systems. MSOs are beginning to deploy DWDM systems where needed in HFC-FD deployments.

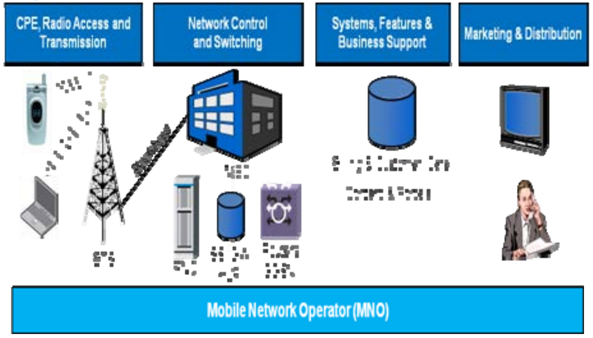
As mentioned previously coaxial cable does not have an upper bound at 860 MHz of spectrum. Therefore, when the remaining amplifiers are removed the ability to operate in the GHz frequencies is possible. Fortunately, in many MSOs, passive taps and splitters capable of 1 GHz performance were deployed when the 860 MHz plant upgrades were built. Hence, additional bandwidth can be created from 860 MHz to 1 GHz to be used in either the upstream or downstream direction. The additional 140 MHz of spectrum will create an additional 850 Mb/s of downstream capacity. Therefore, the new capacity allows for 5.7 Gb/s of downstream bandwidth available to the 125 homes in the fiber deep node.

Mobile Network Operators (MNO's)
With the increasing success of MNOs providing mobile based "DSL like" speeds in their broadband offerings, it makes sense for operators to own a mix of wireless and terrestrial based access. Therefore, the existence of standalone wireless or fixed operators, will probably over time, become more and more the exception rather than the rule. Fourth generation (4G) wireless technologies will become the enabler of the

dramatic increase in these end user speeds and mobile network capacities.

Even though the core wireless technologies have evolved over the last twenty years, the overall MNO architecture has remained relatively constant. Figure 18 provides us with a generic layout of a mobile operator's major network elements.

Figure 18: Network Architecture of an MNO

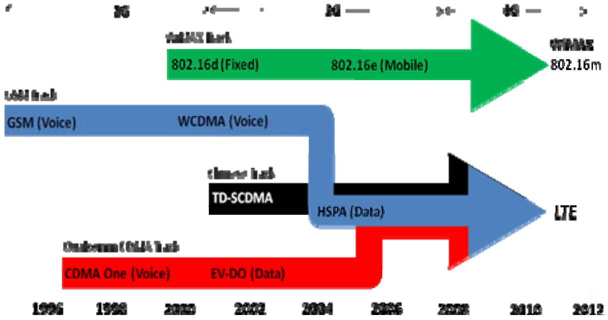


Mobiles provide the end user with wireless connectivity and include traditional voice phones, smart phones and laptops devices. Cell sites are the main infrastructure component and are primarily located on towers and rooftops. The network electronics located at these sites are referred to as Base Transceiver Stations (BTS) and contain antennas, radios and baseband electronics. These elements are both the most expensive and critical portion of the network. As higher speed broadband services are offered, the network component that is gaining an increasingly important role is cell site backhaul. Both microwave and fiber are being used to transport broadband Ethernet back to the main hub location, called the Mobile Switching Center (MSC). The main component in the MSC is the Base Station Controller (BSC) or Radio Network Controller (RNC) that manages the BTSs and the mobility and handover aspects of the network. In 3rd generation systems (UMTS and HSPA), there are various network elements that control and transport the voice and data streams (SGSN & GGSN). Additionally, the voice switch (soft switch and gateways) controls the mobile voice services in a very similar manner as the fixed voice network, the main exception being the role of the Home Location Register (HLR) used to manage subscriber information and roaming mobiles. Fourth generation networks (e.g. - LTE) have simplified the number and complexity of the network elements in the core as they evolve to a flatter, all IP network.

The back office systems shown in Figure 18 have gained increasing importance, as companies, called Mobile Virtual Network Operators (MVNOs), emerge that only own mobile IT systems and marketing functions.

The unrelenting technological progress in wireless has been quite amazing over the last twenty years. Figure 19 provides an illustration of the evolution of wireless standards and technologies since the mid-90s. The progression shows 2nd, 3rd and 4th generation digital wireless standards. First generation mobile technology called Advanced Mobile Phone Service (AMPS) was created in the mid-80s, preceded the standards shown in Figure 19 and was analog based.

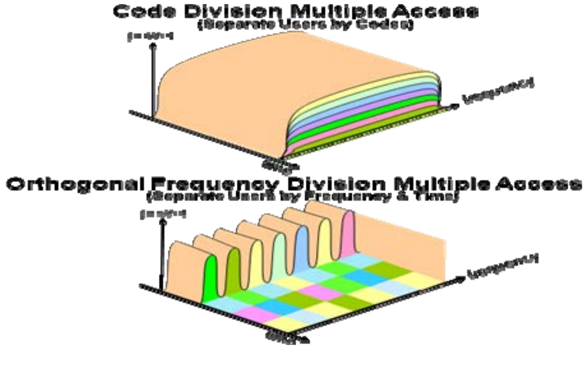
Figure 19: Evolution of Wireless Standards



The dominant worldwide standards tract, called GSM, is based on the original digital standard that evolved in Europe. Enhancements have been made to this Time Division Multiple Access (TDMA) based specification to provide increasing levels of capacity and capability. For instance, data service capability was created while continuing to use the TDMA format with GPRS and EDGE technology. A major upgrade occurred in the early 2000s with the changeover to 3rd generation Code Division Multiple Access (CDMA) based technology called Wideband CDMA (or UMTS). Likewise, the evolution to a 4th Generation technology based on Orthogonal Frequency Division Multiple Access (OFDMA) formats is occurring now with the deployments of LTE. Of particular importance to the evolutionary path is the aspect of backwards compatibility. This means that every new standard keeps the prior standard in place even when major change-outs, such as changing modulation formats, (TDMA to CDMA to OFDMA) occur. For instance, an LTE handset device will have the capability to also operate in the HSPA and GSM mode. Although there have been offshoot technologies over the last fifteen years, such as CDMA One, TD-SCDMA and WiMAX, it appears that the great majority of mobile technology deployments and subscribers are converging to the single LTE standard. Figure 19 shows the other standards as separate evolutionary paths.

The key goal of mobile services is to choose a core technology that uses spectrum efficiently and is also able to effectively separate users (and conversations) within the total spectrum available. First and 2nd generation mobile standards separated voice conversations using frequencies only (AMPS) and both time & frequency (GSM). Figure 20 is a visual representation of 3rd and 4th generation standards (CDMA and OFDMA).

Figure 20: CDMA & OFDMA

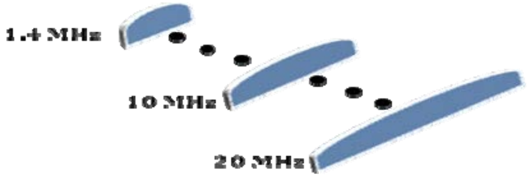


CDMA is quite unique in that it is a spread spectrum technique where every user operates in the same frequencies but conversations are kept separated by the use of unique codes. CDMA operation is best described using the "cocktail party" analogy. Imagine a party held in a small room filled with many couples where each couple speaks only one language which is different from the next pair. Although everyone is speaking at the same time, across the same frequencies, conversations are understandable between a particular couple only. In the same way, unique CDMA codes are like the different languages used by couples in the cocktail party. As in the case of the cocktail party, a key for understandable conversations is the ability to keep the volume in the room low as more and more couples speaking different languages enter the small space. Likewise, CDMA operation requires controlling the power (volume) in the network so noise (adjacent conversations) does not impact the usability and separation of codes.

Although CDMA technology has performed very well over the last 10 years, capacities have begun to reach limits especially for broadband type data services. As a result, the development of 4G technology based on OFDMA technology ensued. Figure 20 illustrates OFDMA's separation of users using the combination of frequencies and time. It differs from 2nd generation TDMA technology in that the frequencies used in OFDMA (shown as peaks in Figure 20) are very tightly spaced and called sub-carriers. The notion of orthogonality is a mathematical way of keeping these close frequencies separate or unique. A conversation between two users would utilize packets appearing across constantly changing frequencies and time slots (shown as the same colors in Figure 20).

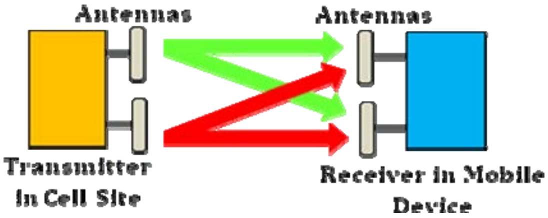
Because the number of subcarriers in LTE is variable, LTE allows for a variety of channel bandwidth sizes. This concept is extremely powerful as 3G technologies are restricted to operating at only a 5 MHz channel bandwidth. Figure 21 shows how the LTE specification can operate at various channel bandwidth settings from 1.4 MHz to 20 MHz. A larger channel bandwidth provides the benefit of statistical multiplexing gain.

Figure 21: LTE Channel Bandwidth Options



Another key enabling technology associated with LTE is the concept of Multiple Input Multiple Output (MIMO) antennas. Figure 22 illustrates this concept. MIMO technology provides for the simultaneous transmission of multiple bit streams across the same frequencies at the same time. The result is the doubling of the transmission speed. Figure 22 shows a typical LTE 2 x 2 MIMO downlink scenario. The base station has two antennas and transmitters simultaneously transmitting down to the mobile. Likewise, the mobile device has two receive antennas and receivers that are also simultaneously receiving the data transmission.

Figure 22: 2 x2 MIMO Antennas



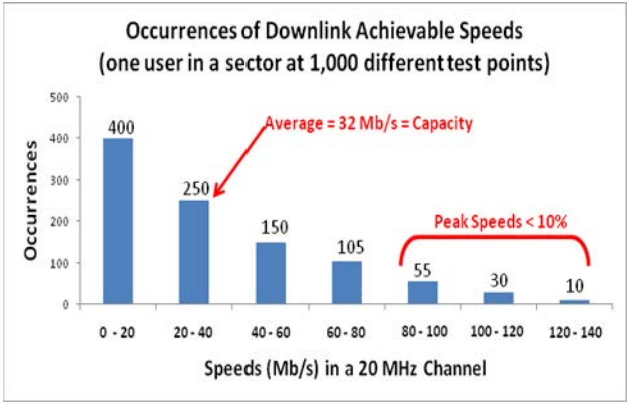
Unfortunately the uplink direction (mobile to the base station) does not employ 2 x 2 MIMO. Because of the high cost and difficult implementation issues associated with multiple transmitters in a small, low power mobile device, only 1 x 2 MIMO is used in the uplink direction. Therefore a single transmitter is used in the mobile and multiple receivers and antennas are used in the base station. This limitation is a contributor to the lower speeds associated with the uplink versus the downlink in an LTE network.

Wireless Peak Speeds

There is a myth that seems to be continually perpetuated in the wireless industry regarding how often peak speeds can be obtained by end users. Peak speeds in 3G and 4G wireless technologies are obtainable only when the maximum modulation mode is used. Unfortunately, these maximum modulation formats (e.g. - 64 QAM) are possible only when perfect RF (Radio Frequency) conditions exist. Wireless technologies differ from terrestrial in that they use variable modulation and error correction formats. Only if the mobile receives the strongest signal from the base station will the highest modulation and most forgiving error correction formats be used, resulting in the peak speeds.

Figure 23 illustrates the 3GPP (Third Generation Partnership Project) mobile standards body simulation results of an LTE device in a 4G data network. In the simulation, 1,000 different test points were assumed in a single sector. Each point assumed differing losses and interference levels and the device having full access to the capacity of the sector without competing for capacity with other users.

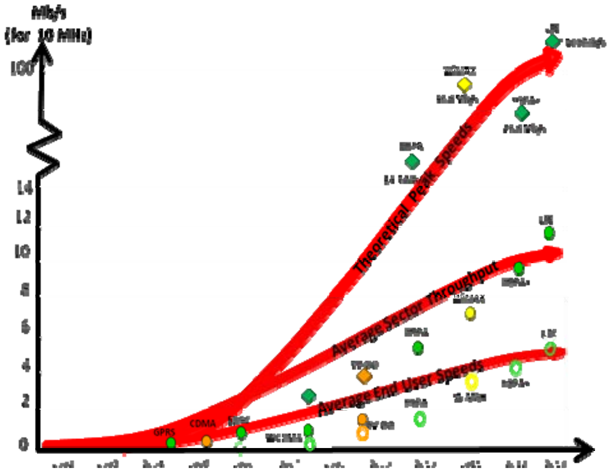
Figure 23: Peak Speeds in an LTE Network [18]



A main conclusion resulting from the data in Figure 23 is that peak speeds are possible in an LTE wireless network less than 10% of the time. Actual testing performed in operational HSPA networks also validates this result in 3G networks.[19]

Another important conclusion of Figure 23 is the determination of the true capacity of an LTE channel. The average speed of the 1,000 test points is 32 Mb/s. This average is called the average sector throughput and is used by 3GPP and LTE vendors to determine the spectral efficiency of the technology. Since the data assumed a 20 MHz channel, the spectral efficiency is 1.6 bps/Hz (32 Mb/s ÷ 20 MHz). Figure 24 provides us with a side by side comparison of peak speeds, the true capacity of a wireless network (called average sector throughput) and the average end user speeds. These speeds are plotted over time as the various technologies (2G, 3G & 4G) have advanced the speeds and capacities possible in wireless networks.

Figure 24: Wireless Peak and Average Speeds

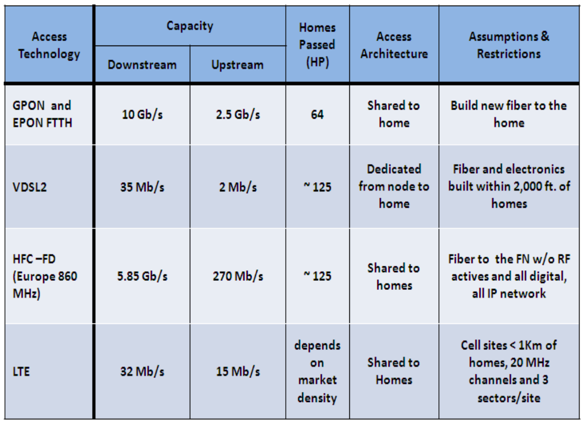


The uppermost curve represents the peak speeds achievable only 5 % to 10% of the time. The middle curve illustrates the "true" capacity of a wireless technology. It is equivalent to the capacity of a DOCSIS channel (50 Mb/s for a 8 MHz channel operating at 256 QAM) or a VDSL2 line (35 Mb/s at 2,000 feet). The average sector throughput number is calculated using probability or statistical means (e.g. - the Figure 23 methodology). Finally, the bottom curve is the average end user speed that a customer will truly receive. These numbers are determined after the typical oversubscription (or concurrency) calculations are applied to the average sector throughput values.

Technology Comparison

Figure 25 shows a comparison chart of the four main technologies discussed in the technology section of this paper. It is clear that the upcoming enhancements to the fiber to the home GPON and EPON technologies offer the highest capacities on both the upstream (2.5 Gb/s) and downstream (10 Gb/s) directions. The combination of high line rates and a low number of shared users (64) in the PON examples makes it a difficult technology to exceed. HFC-Fiber Deep comes very close to matching FTTH PON and offers quite attractive speeds in an 860 MHz plant (4.85 Gb/s) and could exceed 5.7 Gb/s if a 1 GHz plant is assumed. The biggest issue on the HFC-FD comparison chart is the allocation of this bandwidth across a larger amount of customers (125 versus 64) and the much lower upstream capacity.

Figure 25: Access Technology Comparison



Access Technology	Capacity		Homes Passed (HP)	Access Architecture	Assumptions & Restrictions
	Downstream	Upstream			
GPON and EPON FTTH	10 Gb/s	2.5 Gb/s	64	Shared to home	Build new fiber to the home
VDSL2	35 Mb/s	2 Mb/s	~125	Dedicated from node to home	Fiber and electronics built within 2,000 ft. of homes
HFC –FD (Europe 860 MHz)	5.85 Gb/s	270 Mb/s	~125	Shared to homes	Fiber to the FN w/o RF actives and all digital, all IP network
LTE	32 Mb/s	15 Mb/s	depends on market density	Shared to Homes	Cell sites < 1Km of homes, 20 MHz channels and 3 sectors/site

Both DSL and LTE offer much lower capacities where the dedicated nature of capacity to a single user makes DSL have higher speeds. If dedicated video delivery is assumed for VDSL, then little capacity (say 10 Mb/s as shown in Figure 10) is left for broadband services and makes it quite comparable to LTE shared capacities. In fact, both the Frigo and Shankaranaryanan technical papers from AT&T show how a shared 30 Mb/s channel is equivalent to a dedicated 10 Mb/s DSL channel.[20, 21]

DEMAND AND CAPACITY

What levels of demand can each technology support?

We utilized a typical high density city network architecture (HFC n+0 and N+3), unicast service demand profile and cost structure as a specific high density, underground scenario for modeling. We defined two demand profiles, Moderate and Heavy, with the unicast service types including Internet, Voice, and Video on Demand, projected out to 2014 as described in Tables 1 and 2, below. For the purposes of a unicast only analysis, we assume a conservative flat "broadcast floor" of 62 channels (30 analog, 29 digital multiplexes, 3 not usable) across all years.

Table 1: Unicast Service Profile, Moderate *(Digital Max 26% Pen., No 3D-VoD, Internet Kbps Growth 1.6x Per Year)*

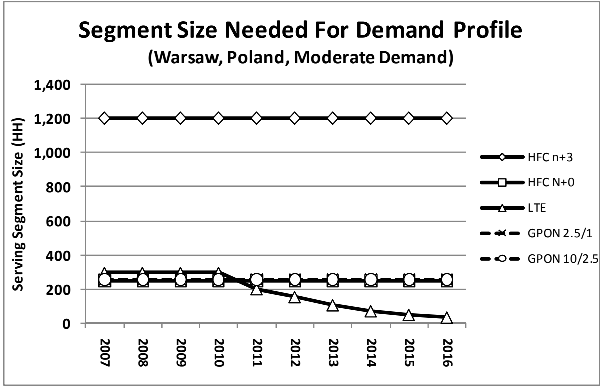
	2009	2014
HSD Pen.	23%	26%
Voice Pen.	12%	19%
DTV Pen.	14%	**32%**
HSD,Peak /Sub	30 Mbps	**1,024 Mbps**
HSD Wtd /Sub	9 Mbps	**70 Mbps**
HSD,Avg /Sub	100 Kbps	**1,050 Kbps**
SD VoD	Yes	Yes
HD VoD	No	Yes
3D VoD	No	**No**
Traffic Per HH	69 Kbps	448 Kbps
Traffic Per Sub	179 Kbps	1,597Kbps

Table 2: Unicast Service Profile, Heavy *(Digital Max 36% Pen., 3D-VoD, Internet Kbps Growth 2.0x Per Year)*

	2009	2014
HSD Pen.	23%	26%
Voice Pen.	12%	19%
DTV Pen.	14%	**39%**
HSD,Peak /Sub	30 Mbps	**1,024 Mbps**
HSD Wtd. /Sub	9 Mbps	**290 Mbps**
HSD,Avg /Sub	100 Kbps	**3,200 Kbps**
SD VoD	Yes	Yes
HD VoD	No	Yes
3D VoD	No	**Yes**
Total Per HH	69 Kbps	1,163 Kbps
Traffic Per Sub	179 Kbps	4,062 Kbps

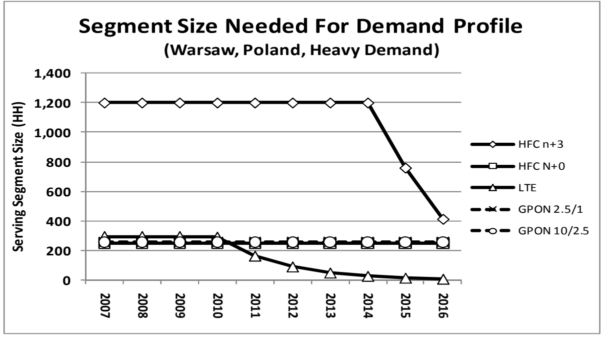
We can see that by 2014, under the moderate scenario each home will demand 448 Kbps of unicast bandwidth, and with the heavy scenario each home will demand 1,163 Kbps of unicast bandwidth. This has a varying impact on the serving size needed by 2014 as noted in Figure 26 and Figure 27 below.

Figure 26: Serving Segment Size by Technology, Moderate Demand



In the moderate demand scenario, by 2014, the 1200 homes passed HPC n+3, HFC n+0, GPON2.5/1 and GPON10/2.5 are able to support the demand profile; while the LTE 296 homes covered per sector reduces significantly to 70 homes per sector. Even with the capacity constraints of LTE, comparable HFC and PON speeds are unavailable.

Figure 27: Serving Segment Size by Technology, Heavy Demand



In the heavy demand scenario, by 2014, the 1200 home passed HPC n+3,HFC n+0, GPON2.5/1 and GPON10/2.5 are able to support the demand profile; the LTE 296 homes covered per sector reduces to a very small 28 homes per sector … that's almost a "base station in every home[22]" !

How many broadband subscribers can each access technology support?

If we assume that the peak Internet speeds required to remain competitive in 2014 are 1 Gbps and that the peak advertized speeds represents historically about 60% of the port capacity, this means we require a port size of about 1.6 Gbps or the equivalent of about 32 channels of HFC capacity would be required. Advances in electronics such as channel bonding can enable an operator, with enabling spectrum, to support higher peak speeds, but as a result also provide segment capacity without the need for dramatically smaller serving group sizes.

Using Shankaranaryanan's 2001 Equivalent Circuit Rate approach[23], We take LTE, HFCn+3/HFCn+0 with 32 bonded channels or 1.6 Gbps, GPON2.5/1, GPON10/2.5, and plot the subscribers supported for differing speeds, including the weighted average product speeds. Since each technology has a different serving group size, we examine at the number of customers supported and consider the penetration level that can be supported, where GPON is assumed to be dimensioned at 4 OLT PONs x 64 ONTs or 256 homes connected. At 30% penetration that translates into 853 homes passed.

We find that where technology advances and spectrum availability allow, HFC n+3 can provide a good fit to the moderate demand profile in 2014, in Table 3 below, with n+0 a good option for supporting heavier demand if needed for additional unicast services, in Table 4 below, while LTE is unable to support 1Gbps speeds; and GPON 10/2.5, far exceeds the demand profile for 2014 in its capacity requirements even for peak speeds.

Table 3: Internet Subs Supported at 70 Mbps Weighted Average Speeds in 2014, Moderate Demand

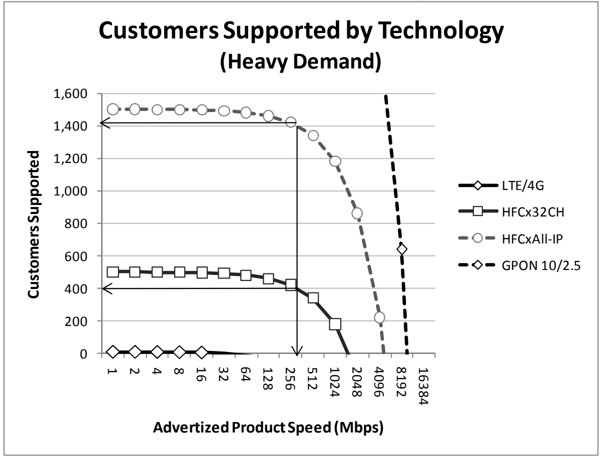
	LTE	HFC n+3	HFC n+0	GPON 10/2.5
70 Mbps Wtd.Avg.	0 Subs	478 Subs	478 Subs	3,178 Subs
Group Size HH	296	1,200	250	853
Max Pen. %	0%	40%	191%	372%

Table 4: Internet Customers Supported at 290 Mbps Weighted Average Speeds in 2014, Heavy Demand

	LTE	HFC n+3	HFC n+0	GPON 1 0/2.5
290Mbps Wtd.Avg.	0 Subs	409 Subs	409 Subs	3,109 Subs
Group Size HH	296	1200	250	853
Max Pen. %	0%	34%	163%	364%

As we can see from Figure 28 below, considering only Internet demand, HFC n+0 would not be required yet, noting the vertical arrow at 290 Mbps weighted average product speed intersecting with 409 customer supported or 34% penetration, with the potential for more where spectrum allows.

Figure 28: Internet Customers Supported relative to Advertized Internet Speeds



With the increased demand profile require to support all unicast traffic, we can see that the increase demand profile results in fewer homes supported, where the 290 Mbps weighted average speed intersects with a reduced 323 homes, or 26% penetration, potentially a candidate for either HFCn+0, or where spectrum allows additional channel bonding.

Moreover, LTE is not able to offer either the peak speeds or capacities of fixed line alternatives. Comparing the fixed line alternatives, Telcos GPON exceeds what is needed by 2014; while HFC has an incremental flexible approach to meet future demand. Advances in electronics are able to leverage spectrum to reach peak speeds, and HFC Fiber Deep is able to be used to reduce serving segments sizes.

COST ECONOMICS

A common factor when considering fiber-to-the-home, HFC fiber deep, and LTE, is that they are all capital-intensive. We compare the fixed upfront cost for each alternative on a 'greenfield' and upgrade basis. Varying assumptions for outside plant environments (e.g. - aerial versus underground) and wireless broadband frequencies and spectrum quantities are analyzed.

Greenfield or New Build Costs

We considered 'greenfield' capital costs associated with each technology, including LTE, HFCn+3, HFCn+0, and GPON/FTTH.

What do we define as 'greenfield' capital costs?

We assume that, with the exception of LTE, each 'greenfield' design will be able to support the heavy demand profile in 2014, noted earlier. We included LTE upgrade costs for comparison purposes, even though it will not be able to support the demand profile or peak end user speeds required.

Included in the 'greenfield' capital costs are the cost to (a) build the distribution network including materials such as optical, coax, splitters, combiners, nodes and amplifiers, in addition to the cost of aggregation electronics such as the BTS, CMTS[24] and OLTs; and labor for ducting or pole mounting; and (b) the materials and labor cost of the drop from the distribution network to the home; We excluded any rights of way costs, NMS, OSS, BSS costs, backhaul costs, headend costs, and Customer Premise Equipment (ONTs are included) costs.

The following cost economics are based on an analysis of actual build costs for high density cities (1,508 HH and 1,754 HH per Km^2)[25,28] Those high density, underground examples were used to baseline labor rates and materials against actual U.S. builds of varying density.

Table 5: Greenfield Cost Per Home Passed/Covered

	LTE	HFCn+3	HFCn+0	GPON
Greenfield High Density Underground	$106	$381	$374	$700
Greenfield High Density Aerial	$106	$124	$140	$231
Greenfield Low Density Aerial	$296	$700	$750	$1,438
Greenfield Low Density Underground	$296	$1,080	$1,229	$1,871

Table 6: Greenfield Cost Per Home Connected

	LTE	HFCn+3	HFCn+0	GPON
Greenfield High Density Underground	$0	$97	$97	$650
Greenfield High Density Aerial	$0	$37	$37	$590
Greenfield Low Density Aerial	$0	$37	$37	$693
Greenfield Low Density Underground	$0	$97	$97	$750

We also considered U.S. public FTTH material in the context of high labor cost economics, including the following cost outline in Table 7 below, where Jaguar & Hiawatha are rural U.S. deployments:

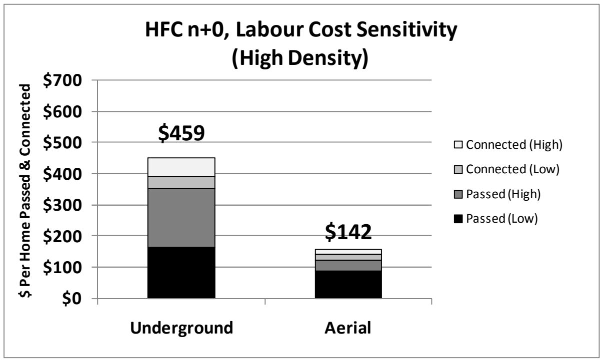
Table 7: Cost To Pass A Home [26]

Service Provider	Cost to Pass	Cost to Connect	Density
Verizon	$700	$650	High
Jaguar	$1,438	$693	Low
Hiawtha	$1,871	$750	Low

Using this analysis we explored several scenarios for new build, considering aerial vs underground plant and high density vs low density conurbations, noted in Table 4 above. Low density aerial scenarios are probably more representative of U.S. topologies.

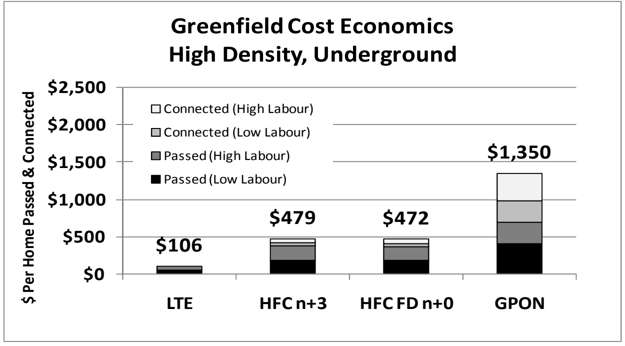
We looked in further detail at the labor sensitivity component for a specific example. In the chart below we show that for HFCn+3, in a high density market, the underground cost per home passed is $105 for markets with low labor costs based on an analysis of HFCn+3 and HFCn+0 vs $361 for markets with high labor rates (i.e. - the U.S). Adding connection costs, this translates into $142 per home connected in low labor cost markets and $459 per home connected in high cost labor markets.

Figure 29: Underground New Build, With Its Substantial Labor Component, Is Sensitive To Individual Market Labor Costs.



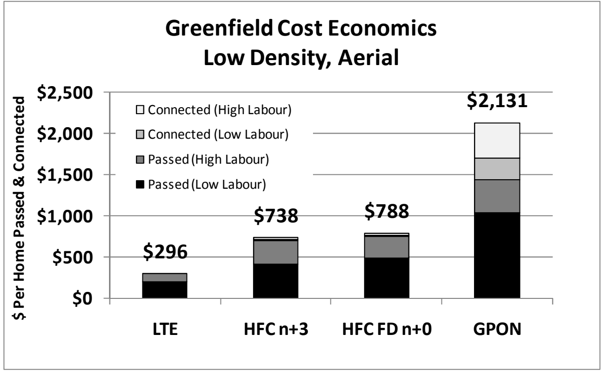
Considering the typical high density, underground scenario across the broadband technology choices, we see in Figure 30 below, keeping in mind LTEs capacity and service type limitations, it is able to achieve cost effective coverage at $106 per home covered, compared to HFC n+3/HFC n+0 at about US$475 per home connected, and GPON at US$1,350 per home connected.

Figure 30: Greenfield/New Build: High Density, Underground



Conversely in a low density, aerial scenario, in Figure 31 below, results, as expected with lower densities, in a higher cost per home connected, at around $750 per home connected for HFCn+3/n+0 and $2,131 per GPON home connected.

Figure 31: Greenfield/New Build: Low Density, Aerial



Upgrade Costs

We also considered upgrade costs from HSPA+ to LTE, HFC n+3/DOCSIS 2.0 to HFC n+0/DOCSIS 3.0 with channel bonding and DSL to GPON. In this way, we believe that the upgrade economic comparison is fair in that all technologies are able to offer end users faster peak speeds after the upgrade.

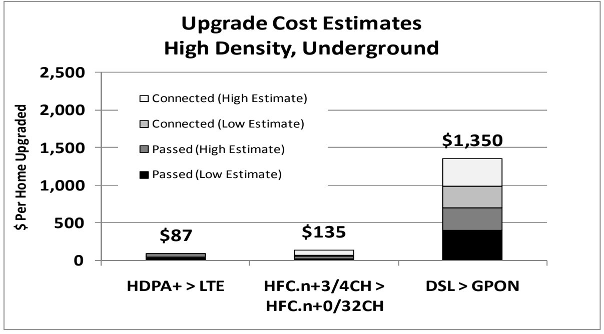
What do we define as an Upgrade cost?

For the purposes of this analysis, we assumed for LTE that a minimum of additional site licenses, cards and radios would be required to upgrade from HSPA+ to LTE, an additional 40MHz of spectrum (2x20MHz) at US$0.03 per MHz per head (low estimate in Figure 32), and in addition, we assume an additional upgrade may be needed from 3 sectors to 6 sectors; and that additional spectrum may cost up to US$0.06 per MHz per head of population[27] (high estimate in Figure 32).

In the case of upgrading from HFCn+3 with 4 bonded channels to HFC n+0 with 32 bonded channels we assumed that CMTS electronics would be required to provide fast speeds and that the technology would be available to support this at US$20 per home passed[28], (low estimate in Figure 32) while segmentation may be required in a high case for the heavy demand scenario. We assumed segmentation "can exceed $10,000 per node split[29]", and we used a range of $5,000 to $25,000 per service group (high estimate in Figure 32).

For an upgrade from DSL to GPON we assumed that, due to the need to replace most of the plant to a completely different architecture, the upgrade cost would be the same as Greenfield, and that low and high estimates are largely a function of the labor cost variations between different markets. We assume $250 for ONT pricing, using HFC's labor drop costs for the low estimate, and using public total drop costs to determine the high estimate.

Figure 32: Upgrade Cost Estimates



It is clear from this comparison that those operators with spectral flexibility (Mobile, Cable) are able to leverage advances in electronics to meet faster peak information rates; where as other operators that lack spectral flexibility (Telco) require a step function in order to move to a new last mile technology (i.e. from Copper to Optical) in order to overcome information rate limitations.

For the purpose of assessing the business model, we assumed that a home passed is a fixed cost, and a home connected is a variable cost that increases as the penetration of homes increases.

BUSINESS MODEL

We provide a sensitivity of the access technology alternatives by market density, broadband penetration and product speeds; and using illustrative unicast service revenues for future broadband services; we look at the Greenfield business model [30].

Table 8: Hypothetical Monthly Unicast Service Revenues Per Subscriber 2014

	Access Network		
	Mobile Broadband	Cable HFC	Telco GPON
Voice	$25	$0	$0
Data	$15	$25	$25
VoD	$0	$15	$15
Total	$40	$40	$40

Investment thresholds

We assume that the hypothetical unicast service revenue for each technology is $40 per month per subscriber, applying the data revenue projection from Figure 2, and assuming that mobile voice has a significant value to the subscriber relative to fixed voice. We also assume that Video on Demand (VoD) revenue for the mobile device will have a low value to the subscriber relative to fixed VoD services that can be viewed on a large screen. What is the upper limit of capital expenditure per subscriber that may be justified by the operator?

Using an approach described by Friggo, Lannone and Reichmann, AT&T Labs Research in an IEEE Optical Communications paper in 2004[31], we looked at a selection of operators in Table 9 below and concluded that the upper limit an operator could tolerate would be about 15% of revenue in interest payments.

Table 9: Interest Expenses as a Proportion of Revenue in 2009[32]

	Revenues (m)	Interest Expenses (m)	% of Revenue
Telco A	$107,808	$4,209	3.7%
Cable A	$35,756	$2,040	5.7%
Cable B	$11,080	$946	8.5%
Cable C	$6,755	$1,088	16.1%

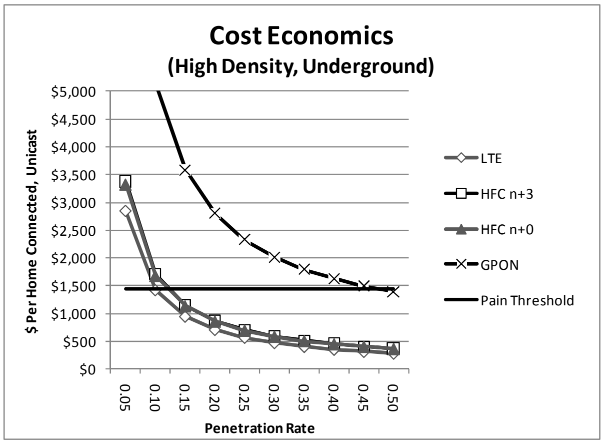
We assumed an upper limit of 15% of revenue for interest payments and an annual interest rate of 5% we deduce that a worst case capital payback time of 3 years or 36 months provides the payback limit. Assuming $40 per month in service revenue we can project that the operator capital expenditure "investment threshold" is $1,440 per home connected.

Under what conditions may the investment related to each access technology be argued to outweigh the economic benefit to be realized by the operator?

Focusing on 'greenfield' cost economics, we considered each technology by penetration rate, applying the fixed home passed associated with unicast traffic and variable home connected associated with uncast traffic for the "high density, underground" and "low density, aerial" scenario's described in the cost economic section above. High labor rates are assumed for both scenarios, and where broadcast services are supported the proportional plant and drop costs are excluded for fixed services so as to consider only the unicast element. We assumed LTE is all unicast, that for HFCn+3/n+0 32 of 91 usable channels related to unicast in 2014, and for GPON we assumed that of 3 wavelengths, 1 is for upstream, 2 are for downstream services of which 1 is for broadcast and the other is for unicast. Upgrade costs are excluded.

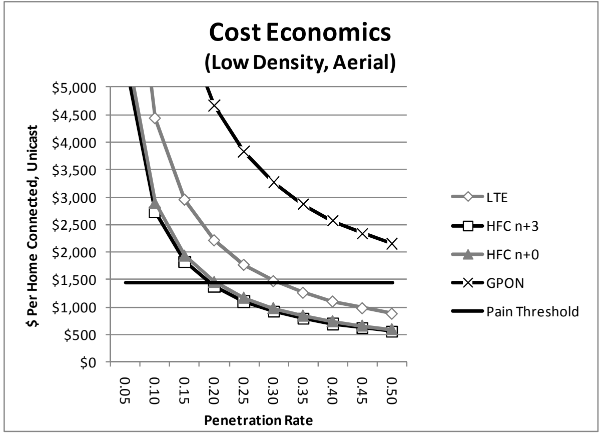
In Figure 33 and Figure 34 below, the investment threshold represents the upper limit of capital expenditure tolerated by the operator. As penetration increases, the cost per home connected falls to an intersection with the investment threshold, identifying the penetration level required to meet the payback period associated with the investment threshold.

Figure 33: Greenfield, High Density, Underground, High Labor vs Investment Threshold



Looking at where each technology crosses the investment threshold (point where technology pays back), we can conclude that LTE, HFCn+3 and HFCn+0 fall below the investment threshold at relatively low penetration levels of 10%, noting that LTE has lower end user speeds, and fewer services. GPON only crosses the investment threshold at a penetration of 50%.

Figure 34: Greenfield, Low Density, Aerial, High Labor vs Capital Investment Threshold



Considering the Low Density, Aerial scenario, we can see that all technologies require a higher penetration to fall below the investment threshold. In this scenario, HFCn+3/HFCn+0 fall below the investment threshold at 20%, LTE falls below the investment threshold at 30%, and GPON falls below the investment threshold at about 80% penetration.

CONCLUSION

The competitive, technical and economic findings are summarized[33].

Competitive: Competition Drives the Need for Faster Peak Information Rates (PIRs), Limits Service Penetration Potential.

Competition is driving the need for faster Peak Information Rates (PIRs) which in turn forces the operator to make technology choices to remain competitive in the market place. However, the corn does not grow all the way to the sun. Operators realize that, in a competitive environment with multiple service providers and similar service types, there may be a constrained "customer base potential" upon which to examine relevant 'investment thresholds". These thresholds may define an upper limit to 'greenfield capital expenditures. Additionally, those operators with compelling upgrade economics that do not require a move to a new last mile technology, are best able to compete.

Technical & Capacity: Because DSL is challenged, HFCn+3/n+0, and GPON will be the key broadband technologies in the future; LTE, on the other hand, cannot provide the same peak speeds, capacity or services types as fixed line alternatives.

Considering the technology alternatives, we note that LTE, while it has a unique attribute of mobility, is not able to support the capacity required, peak speeds (e.g.- 1 Gbps) or all of the service types to the home that will be delivered by fixed line technologies in 2014; and is therefore unable to offer a complete substitute for fixed line services. Fixed line operators face decisions about capacity based demand and competing peak information rates. HFCn+3/n+0 offers great flexibility to meet both varying demand scenarios, and increasing peak information rates.

Economic: In Competitive Markets, There Is No Business Case For Physical Replacement of Plant for Faster PIRs, Low Density New Build.

Cable operators do not have to re-build physical plant in the process of increasing peak information rates, but rather rely on spectral flexibility and/or advances in electronics. This results in an advantage in 'non-greenfield' markets or markets reaching subscriber saturation over operators that require a complete rebuild or plant. Telcos need to totally rebuild their plant to match Cable operators. Mobile operators do not need to rebuild, but they cannot meet the speeds required to compete.

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