COMPARING THE DOCSIS® 3.1 AND HFC EVOLUTION TO THE FTTH REVOLUTION

A TECHNICAL PAPER PREPARED FOR THE SOCIETY OF CABLE TELECOMMUNICATIONS ENGINEERS

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INTRODUCTION

Questions often asked by cable operators worldwide surrounds the understanding of the access network evolution from coax to the home (CTTH) to fiber to the home (FTTH). Though many MSOs have concluded that new build markets, where CTTH does not exist, will likely use FTTH and eventually over 10G Ethernet passive optical network (EPON) technology. The core purpose of this paper is to discuss the least understood technology, which is the long-term best path for the existing HFC access network. Many cable operators are asking, is the continued investment in the existing HFC and DOCSIS® network, moving to smaller nodes and service groups, and possibly increasing spectrum allocation, a better choice than just moving to FTTH and passive optical network (PON) technology? Some MSOs are wondering if an evolutionary approach is best, which may include deploying fiber deeper with HFC and smaller nodes leveraging the coax to the home and then migrating to FTTH on an as needed basis. Alternatively, they are wondering if a revolutionary approach is best, which may include stopping the investment in HFC and DOCSIS 3.1 and directly moving to fiber to the home and PON.

This paper will focus completely on the existing network migration options and not new build or the multiple dwelling unit (MDU) market segments. The paper examines several different migration paths for the existing coax-to-the-home (CTTH) network supporting more IP/data capacity with DOCSIS 3.0/3.1 over HFC. This paper will define several different migration options for FTTH using 10G EPON and hybrid passive optical network (HPON) a radio frequency over glass (RFoG) type of solution that is free from optical beat interference. The paper will examine the technologies to compare the economics of the different migration options. The paper will examine the two-core economic categories enablement capital and success capital for the comparative study.

WIRELINE NETWORK OVERVIEW

This section provides an overview of the access technologies used in the wireline network space. The author encourages the readers to gather additional materials from industry publications and system suppliers regarding the current capabilities of these technologies and systems. The network access layer technologies in this section are deployed or under consideration by service providers worldwide. The figure below illustrates at a high-level the next generation wireline broadband networks.

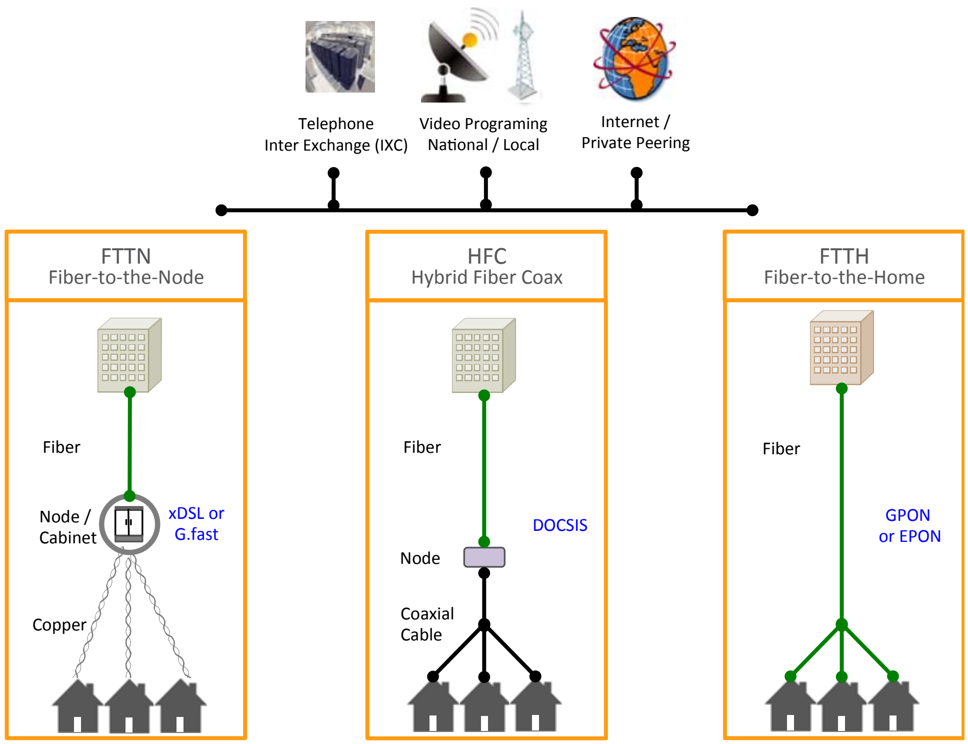

Figure 1 - Next Generation Wireline Broadband Networks

Network Technology Overview

- FTTN (Fiber to the Node/Neighborhood)
    - Fiber is deployed to the neighborhood outdoor telco cabinets housing VDSL2 Terminals
    - Leverages copper telephone twisted pair lines using VDSL2 and in the future G.fast
    - Capacity / speed of VDSL2 varies on distance from the Node/Cabinet and Home
    - FTTN + VDSL2 is a point-to-point (P2P) technology to VDSL2 terminal and then shared traffic
    - VDSL2 and G.fast should have backward compatibility
- HFC (Hybrid Fiber Coax)
    - Data Services Uses Technologies defined by CableLabs®
    - DOCSIS 1.0 (Data Over Cable System Interface Specification) was released in 1997
    - DOCSIS has release five (5) specification enhancements all with backward compatibility
    - DOCSIS 3.1 offers multiple Gbps data rates capacity / speed varies based on spectrum allocation
- FTTH (Fiber to the Home)

- Capacity / speed varies on technology selected
- FTTH use many different technologies (IEEE EPON, ITU-T GPON, IEEE Ethernet, RFoG, HPON)
- Significant upfront capital remains a challenge
- Highest cost metrics: Cost per HHP, Cost to connect homes, and cost per subscriber served
- Lowest Operational costs due to all passive network and lowest cost per bit remain compelling

Fiber to the Node (FTTN) with Twisted Pair Copper xDSL / G.fast

Copper 'twisted pair' is used for data, voice and video services in the access network. It is the most widely deployed delivery mechanism of these services for telephone operators and worldwide market [PTGB]. The use of twisted pair allows telephone operators to leverage existing copper lines to the home. The use of twisted pair has distance limitation of the selected technology. The main driver for the use of twisted pair is the economic value of existing wiring currently installed to most every home. The use of twisted pair has many dependencies in determining the viability for video services and very high bit rate Internet services. Distance or length of the copper pairs to the xDSL terminal is the single biggest determining factor for capacity. To increase the capacity of the existing twisted pair network Telcos extend fiber to the node / cabinet, place the xDSL terminal device within 3,000 feet, and if necessary deploy more fiber to reduce this distance to increase capacity. Reducing the distance between the xDSL terminal and the subscriber will increase the spectrum to be used. For extensive details and history of the data technologies over twisted pair please refer to paper by Thomas Cloonan [CLOO].

VDSL2 Solution

The telecommunications industry has invested resources in the development of many standards utilizing twisted pair over the last two decades. The International Telecommunication Union (ITU), specifically the ITU-T, has defined a recommendation (standard) for Very High Bit Rate Digital Subscriber Line 2 (VDSL2) for the use over the twisted pair phone lines. The VDSL2 protocol is known as ITU-T G.993.2, and was released in February of 2006. The VDSL2 standard builds on previous ITU-T standards in the DSL technology area known as ADSL, ADSL2+, and VDSL. The backwards compatibility of these technologies may be vendor-dependent as some suppliers support what is referred to as 'fall back', whereby a particular port VDSL2 port may support ADSL2+.

The capacity of VDLS2 technology varies widely in published reports and vendor materials. In fact, in one published report, VDSL2 performance was listed at 910 Mbps, 825 Mbps, 700 Mbps, 390 Mbps, and 100 Mbps. In some cases, the published reports of the data throughput rates may omit key factors that may determine the applicability in real-world environment and applications. The distance of copper wires between the DSLAM and CPE impacts the variation in the published performance data of VDSL2, like all DSL technologies. Additionally, the use of channel bonded copper pairs will also increase the throughput numbers stated in published reports. Channel bonding is referred to in many network technology areas, such as VDSL, T1, and DOCSIS. This is the process of combining physical or logical channels to essentially create a larger pipe (data channel) by sending traffic over multiple channels simultaneously. However, channel bonding more than two copper pairs may not be possible in real-world applications. There are additional technologies that leading system vendors in the VDSL space are developing to increase capacity as well. An example is called DSL Phantom Mode by Alcatel-Lucent and Phantom DSL by Nokia Siemens, combing several technologies in bonding several copper pairs along with noise cancelling techniques that can increase data rates of VDSL [EMM1].

VDSL2 Summary Features Set:

- Spectrum band plan: upstream and downstream band up to 17 & 30 MHz
- Modulation: DMT (up to 15 bits per carrier)
- FEC: Trellis code + Reed Solomon
- Frequency division duplexing (FDD)
- Techniques to increase capacity:
    - Deploy fiber deeper (<2500 often less)
    - Reduce distance from DSLAM and home
    - Enable all spectrum
    - Enable vectoring (noise cancellation) data rate increase ~150%
    - Enable bonding + vectoring data rate increase 100% down & 25% up
- Typical Architecture:
    - Fiber to the node / cabinet (FTTN/C)
    - Serving 300 HHP
    - Ground mounted and plant powered
    - <2500 Meters most often <1000 Meters
    - Distributed access architecture (DAA) only called remote mini-DSLAM

G.fast Solution

The latest in copper technology is called G.fast and is intended for deep fiber applications, called fiber-to-the-distribution point (FTTdp) where the distribution point is about 200 meters or less away from the home. This is an extended frequency approach using 106 MHz and 212 MHz profiles unlike the 30 MHz spectrum limit of VDSL2. G.fast is not intended to replace VDSL2 copper links greater than 250 meters. G.fast speeds promise up to 1 Gbps, but typical speeds may be 150 Mbps for 250 meters

[EMM1], 200 Mbps for 200 meters [EMM1] and 500 Mbps for 100 Meters [EMM1]. Capacity will vary on spectrum used and distance.

G.fast Summary Feature Set:

- Spectrum band plan
  - Start frequency: 2.2, 8.5, 17.664, or 30 MHz
  - End frequency: 106 & 2-212 MHz
- Modulation:
  - DMT, 2048 sub-carriers, sub-carrier spacing 51.75 kHz, ≤12 bits/sub-carrier
- FEC: Trellis code + Reed Solomon
- Time division duplexing (TDD)
  - Downstream and upstream capacity shared
  - Downstream/upstream asymmetry ratio
    - Mandatory: 90/10 to 50/50
    - Optional: from 50/50 to 10/90
  - Delay increased with distance between FTTdp and customer
- Backward compatible with VDSL2
- Coexistence with xDSL
- Techniques to increase capacity:
  - Deploy fiber deeper
  - Reduce distance from G.fast dPU and home
  - Enable full spectrum
  - Enable vectoring and bonding
  - Type of gauge of copper wires
  - Capacity is reported as down + up
- Typical architecture:
  - Fiber to the distribution point (FTTdp)
  - Fiber and G.fast serving 8 – 16 homes
  - Pole mounted (often) or pedestal
  - Reverse power feed from the customer home
  - <250 Meters between FTTdp and home
  - Remote G.fast distribution Point Unit (16 ports)

Coax to the Home (CTTH) using HFC and DOCSIS

The cable operator may have six (6) to seven (7) miles of coaxial cable comprising the service area of a node. The distance will result in more active equipment such as amplifiers and more passives such as taps. However at the MDU location, the number of households passed (HHP) or customers in the service area requires less coax, less actives, and fewer passives. The coaxial cable may use more spectrum than currently required. If the spectrum is extended above 1 GHz it is possible to provide even more data capacity and 10 Gbps of data capacity is not out of the question. In addition, the mix of spectrum usage can be changed, for example the allocation of downstream spectrum and upstream spectrum. DOCSIS network capacity is determined by the frequency or spectrum allocated by the service provider. Distance does not play a role in DOCSIS when it comes to network capacity, unlike VDSL2. The DOCSIS standards define that the distance between the cable modem termination system (CMTS) and the cable modem customers may reach 100 miles or roughly 160 km and 80 km with DOCSIS 3.1. The DOCSIS standard allocates separate spectrum for upstream and downstream usage, which is known as frequency division duplexing (FDD).

Summary of DOCSIS Releases:

DOCSIS 1.0 March 1997

- Beginning of data over cable system interface specification (DOCSIS)
- Defined support for high speed data over HFC

DOCSIS 1.1 April 1999

- Adds state of the art QoS techniques for priority services (e.g. VoIP)

DOCSIS 2.0 December 2001

- Increased upstream modulation format for more b/s/Hz
- Adds new physical layer (PHY) for the upstream Synchronous Code Division Multiple Access (SCDMA)
- Defined a state of the art advanced media access layer (MAC) (even to this day)
- Enabled two (2) dimensional upstream bandwidth allocation and/or simultaneous transmission within the same channel for quality of service (QoS) and quality of experience (QoE)

DOCSIS 3.0 August 2006

- Added IPv6 & multicast QoS
- Expanded 2D upstream scheduling now across multiple channels
- Increases data capacity with channel bonding similar to other technologies
- Kept PHY layer modulation formats & old forward error correction (FEC) (DOCSIS 3.0 speed limit)

DOCSIS 3.1 October 2013

- Enables backward compatibility (as opposed to coexistence)
    - Avoids spectrum tax (allocating separate spectrum for legacy and new)
    - Leverage DOCSIS MAC across legacy single carrier (SC) PHY & new orthogonal frequency division multiplexing (OFDM) PHY
    - Enable single carrier QAM (SC-QAM) and OFDM to share a bonding group
- Data rate capacity increases
    - Enables 10+ Gbps downstream capacity
    - Enables 1+ Gbps upstream capacity

- The maximum is unbounded (10 – 20 Gb/s or even higher)

- Modernize the PHY Layer (to increase bits per Hz)
  - Support legacy DOCSIS PHYs plus
  - Downstream & upstream modulation formats (16384 QAM / 4096 QAM)
  - Adds downstream orthogonal frequency-division multiplexing (OFDM)
  - Adds upstream orthogonal frequency-division multiple access (OFDMA)
  - Adds error correction technology
  - Outer FEC: Bose-Chaudhuri-Hocquenghem (BCH) codes
  - Inner FEC: Low-Density Parity-Check (LDPC) codes
  - The changing of the FEC in DOCSIS 3.1 from DOCSIS may result in:
    - Gain could be up to two modulation orders in the same SNR environment for the ATDMA upstream and EuroDOCSIS downstream annex A
    - Gain could be close to a single order for the DOCSIS J.83 annex B downstream
- Defines new cable spectrum band plan
  - Upstream may extend to 200 MHz (D3.0 defines 5-85 MHz)
  - Downstream may extend to 1.2 GHz or 1.7 GHz (D3.0 defines 1 GHz)

Overview of PON Terms and Technologies

The IEEE and SCTE have also defined PON standards for PON as well. Below are some of the terms and definitions used in this paper. A summary of the previous and current releases of PON standards is captured in Figure 2, and additional description of these standards is listed below.

ODN: Optical distribution network (ODN), referring to the outside plant (OSP). Items include fiber and splitters. The ODN is traditionally all-passive, thus no powered equipment is in this network segment.

OLT: Optical line terminal (OLT), located at the headend/central office (HE/CO). This network element controls the downstream and upstream transmission. The downstream is broadcast to each premise, and the upstream transmission uses a multiple access protocol, called time division multiple access (TDMA). The OLT manages traffic to ensure bandwidth amount and priority for specified services. This is like a Cable Modem Termination System (CMTS) in the cable network.

ONU / ONT: Optical network unit (ONU), located at the Customer Premise Equipment (CPE) (term associated with IEEE EPON). The optical network terminal (ONT), located at the CPE (term associated with FSAN / ITU-T version of PON)

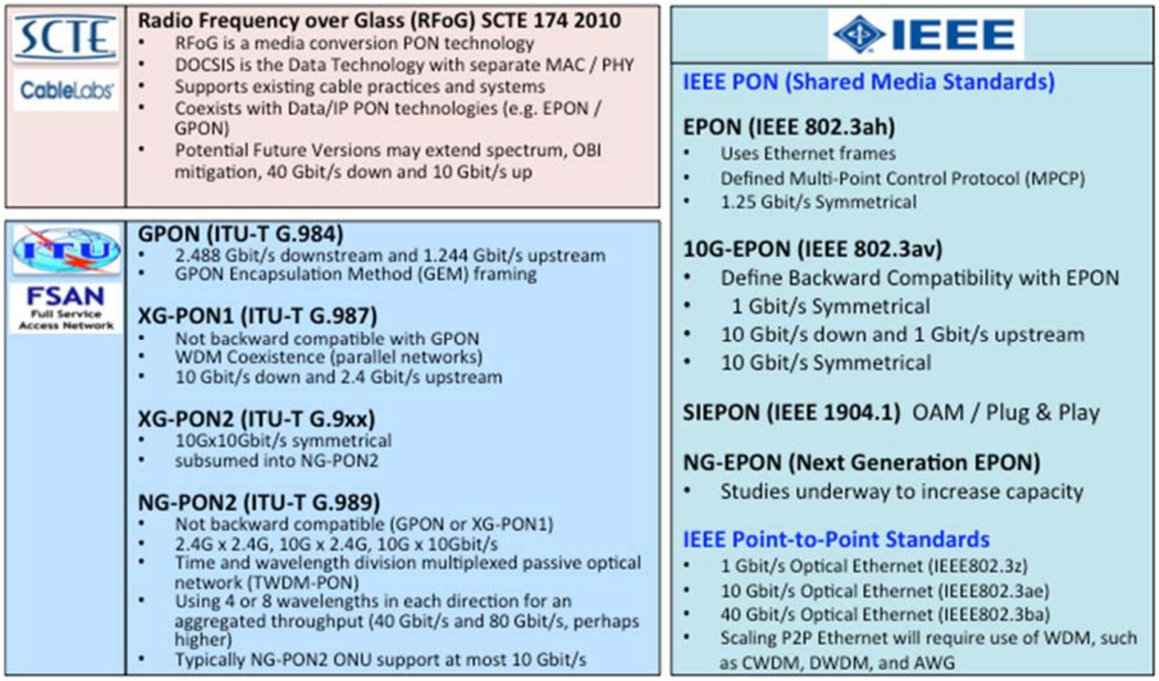

Figure 2 - Summary of Fiber to the Premise Technologies

FSAN/ITU-T GPON Family

The use of standards-based PON technologies began in the mid 1990's by the FSAN, which is a group comprised by major telecommunications service providers and system vendors. The International Telecommunications Union ITU-T standardized several versions of PON technologies and the major highlights for these specifications are listed below [EMM2].

ITU-T G.984 Series – GPON (Gigabit PON)

This is an evolution of the BPON standard. It supports higher rates, enhanced security, and choice of data encapsulation mode, either ATM or GPON encapsulation method (GEM), although nearly all systems utilized GEM. This had an excellent line encoding method called non-return-to-zero (NRZ), well defined optical standards, and support for data services and time division multiplexing (TDM) service via circuit emulation service over packet (CESoP) and native TDM. Some key features are listed below:

- 2.488 Gbps downstream x 1.244 Gbps upstream
- Additional PON management overhead varies and needs to be considered
- 2.488G DS Wavelength at 1490nm ±10 (1480nm to 1500nm)
- 1.244G US Wavelength at 1310nm ±50 (1260nm to 1360nm) known as Wideband G.984.2 (year 2004)
- 1.244G US Wavelength at 1310nm ±40 (1270nm to 1350nm) known as Reduced (DFB) G.984.5 (year 2007)

- 1.244G US Wavelength at 1310nm ±20 (1290nm to 1330nm) known as Narrowband G.984.5
- Since 984.5 was released narrowband optics have been used to accommodate future upstream wavelengths

ITU-T G.989 Series (NG-PON2 or TWDM-PON)

The G.989 series is the latest standard underway and supports 10 Gigabit symmetrical and other speed tier options as well as support for multiple wavelengths across the PON. Some key features are listed below:

- Not backward compatible with GPON or XG-PON1, only WDM Coexistence
- a.k.a. Time and wavelength division multiplexed passive optical network (TWDM-PON)
- 2.488 Gbps downstream x 2.488 Gbps upstream
- 9.953 Gbps downstream x 2.488 Gbps upstream
- 9.953 Gbps downstream x 9.953 Gbps upstream
- 9.953 Gbps before encoding and FEC 8.669 Gbps
- 2.488 Gbps before encoding and FEC 2.290 Gbps
- Additional PON management overhead varies and needs to be considered
- Supports four (4) to eight (8) Wavelengths: downstream 1596-1603nm / upstream 1524-1544nm
- Using four (4) to eight (8) wavelengths in each direction for an aggregated throughput (40 Gbit/s and 80 Gbit/s, perhaps higher)
- Typically an NG-PON2 ONU shall be able to support at most 10 Gbit/s
- Using four (4) to eight (8) wavelengths in each direction independently as separate PON systems on the same fiber or ODN, used to reduce service group size per PON MAC domain

IEEE EPON Family

The Institute of Electrical and Electronics Engineers (IEEE) 802 group defines a family of IEEE standards dealing with local area networks and metropolitan area networks. This standards body defined the Ethernet Protocol that is used in networking throughout the world. The IEEE and specifically the 802-working group defined several point-to-multipoint (P2MP) passive optical network (PON) standards referred to as 802.3ah and 802.3av [EMM2].

IEEE 802.3ah – EPON or GEPON (Ethernet PON)

EPON is an IEEE/ Ethernet in the First Mile (EFM) standard for using Ethernet for packet data. 802.3ah is now part of the IEEE 802.3 standard. The IEEE standardized 1G-EPON in 2004. Key features include:

- 1.25 Gbps downstream x 1.25 Gbps upstream

- 1.25 Gbps after 8B/10B encoding and no FEC yields 1 Gbps
- Additional PON management overhead varies and needs to be considered
- 1.25G DS Wavelength: 1490nm ±10 (1480nm to 1500nm)
- 1.25G US Wavelength: 1310nm ±50 (1260nm to 1360nm) known as Wideband G.984.2
- 1.25G US Wavelength: 1310nm ±20 (1290nm to 1330nm) known as Narrowband as defined by ITU-T G.984.5
- Narrowband is not defined in the IEEE but is used worldwide and uses the same optics as GPON

IEEE 802.3av 10G-EPON

10G-EPON (10 Gigabit Ethernet PON) is a standard that also supports the previous standard called 802.3ah EPON, thus is backward compatible. 10G-EPON may use separate wavelengths for 10G and 1G downstream, called dual rate mode, if desired by the service provider. The upstream defines support for time division multiplexing (TDM), which allows a single wideband receiver (1260 nm -1360 nm) in the OLT to receive both 10G and 1G upstream wavelengths. The 10G-EPON systems will support two MAC domains and a single return path dynamic bandwidth allocation (DBA) that will support the TDM mode. This allows 10G and 1G bursts at different periods of time. The EPON ecosystem also enables the support for WDM coexistence like GPON and XG-PON, whereby EPON and 10G-EPON wavelengths in both directions may exist on the same PON. The IEEE standardized 10G-EPON in 2009. Key features are below:

- 1 Gbps downstream x 1 Gbps upstream
- 10 Gbps downstream x 1 Gbps upstream
- 10 Gbps downstream x 10 Gbps upstream
- 10.3125 Gbps before encoding and forward error correction (FEC) 8.710 Gbps
- Additional PON management overhead varies and needs to be considered
- 10 Gbps DS Wavelength at 1577.5nm ±2.5 (1575nm to 1580nm)
- 10 Gbps US Wavelength at 1270nm ±10 (1260nm to 1280nm)
- 1 Gbps down and up, same options as above

SCTE IPS910 RFoG (RF over Glass)

RFoG (RF over glass) is an SCTE interface practices subcommittee standard defined in SCTE 174 2010 developed for point-to-multipoint (P2MP) operations. RFoG has a wavelength plan compatible with data PON solutions, such as EPON or 10G-EPON, provided RFoG uses 1610 nm upstream instead of 1310 nm upstream wavelength. RFoG offers FTTH PON-like architecture for MSOs without having to select or deploy a PON technology. RF-over-glass (RFoG) delivers triple play cable services through a FTTH style network infrastructure (i.e. fiber-to-the-home). Essentially RFoG is a layer 1 media conversion approach for fiber to the premise that uses hybrid fiber coax (HFC) technologies and extends the fiber to the home when a mini node, called an RFoG ONU, is placed at the home and performs media conversion from optical to coax.

In RFoG, the coax portion of the network is just at the customer premise, allowing traditional cable installation practices to be leveraged. The use of traditional cable headend equipment for video and data (DOCSIS) network uses RF headend signal processing connected to separate headend RFoG optical transport devices. The RFoG transmitter and receivers do not have a MAC or PHY layer scheduler as found in typical PON technology, therefore this is not a data PON technology. To enable coexistence with traditional data PON systems, RFoG uses a 1551 nm forward (downstream) optical transmitter and a 1610 nm receiver (upstream) at the headend. The RFoG ONU provides the optical termination at the subscriber home and allows traditional cable CPE devices such as set-top boxes (STB), DOCSIS modems, and VoIP eMTAs to be used at the subscriber premise. RFoG allows MSOs to offer FTTP, while leveraging the entire existing back office systems, such as billing, provisioning and network management. A major problem found in RFoG technology is called optical beat interference (OBI) where the R-ONU transmissions collide in the optical domain, which disrupts communications and impacts performance.

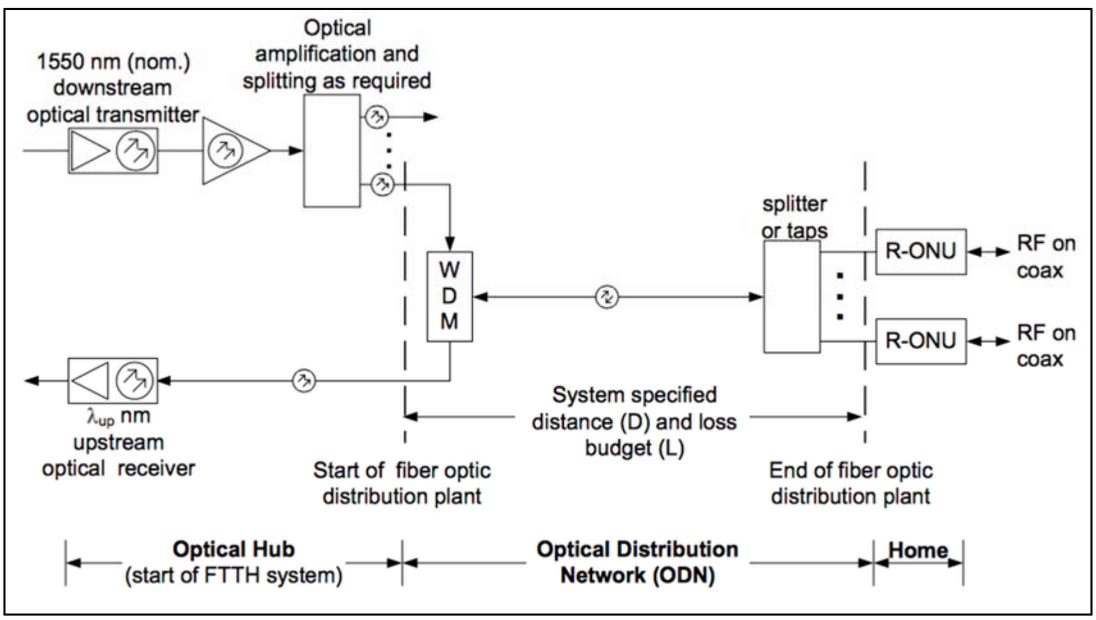

Figure 3 - RFoG Reference Architecture per ANSI/SCTE 174 2010

- SCTE RFoG Architectures (as shown in figure 3) may use a passive optical network (no electronics) or may use an active optical network (use of active electronics in the ODN).
- Typical Drivers for actives (electronics) in the ODN for RFoG include:
  - Extend optical reach in the downstream and upstream (from 20 to 60 km)

- Convert the RFoG upstream RF signals from analog to digital signals format for digital return
- Use of WDM technology across the ODN to maximize the number of RFoG PON service groups

Hybrid Passive Optical Network (HPON)

A new architecture for cable fiber-to-the-home of even fiber-to-the-curb and coax-to-the-home, is called hybrid passive optical network (HPON) uses standard ANSI/SCTE 174 2010 RFoG ONUs (R-ONU) and eliminates optical beat interference (OBI). HPON contains active or powered elements in the outside plant called HPON optical switch that configured in a physical star topology serves as a central aggregation point for directly connected standard RFoG ONUs. The HPON optical switch may have a direct connection to the standard amplitude modulated transmitters and receivers in the cable operators headend / hub location.

Definition of HPON:

- HPON technology prevents from happening a major problem found in RFoG technology known as optical beat interference (OBI)
- Prevents OBI with the addition of an active in the Optical Distribution Network (ODN), this active is called HPON Optical Switch (shown in figure 4)
- Implements optical collision avoidance (OCA) to prevent OBI completely
- The combination of the HPON Optical Switch and star physical topology prevents OBI
- Supports fully backward compatible with ANSI/SCTE 174 2010 RFoG equipment deployed at both the home and at the headend
- Supports any ANSI/SCTE 174 2010 RFoG ONU (R-ONU) and amplitude modulated (AM) headend optical transmitters and receivers
- Transport any RF signal, such as analog video, digital video, DOCSIS SC-QAM, DOCSIS OFDM, and future RF technologies
- Is a media conversation PON technologies (like RFoG) and these are unlike data PON technologies (e.g. GPON and EPON) that use MAC and PHY layers to manage multiple access system communications to preventing optical collisions

Architecture of HPON:

- HPON is a point to multipoint fiber-to-the-home system optimized for compatibility with hybrid fiber-coax (HFC) networks
- HPON optical hub can be placed in existing RFoG deployments to eliminate OBI on in new HPON deployments.
- HPON eliminates OBI with the addition of an active network element in the optical distribution network (ODN), this active is called HPON Optical Switch

- The combination of the HPON Optical Switch and star physical topology to the R-ONUs prevents optical collisions or OBI
- The HPON optical switch will likely be at the location in the ODN where typically an optical splitter would have been located
- Cable operators may select an HPON optical switch that may also support non-RFoG functions, like an EPON extender, EPON pass-thru, analog to digital optics, etc.

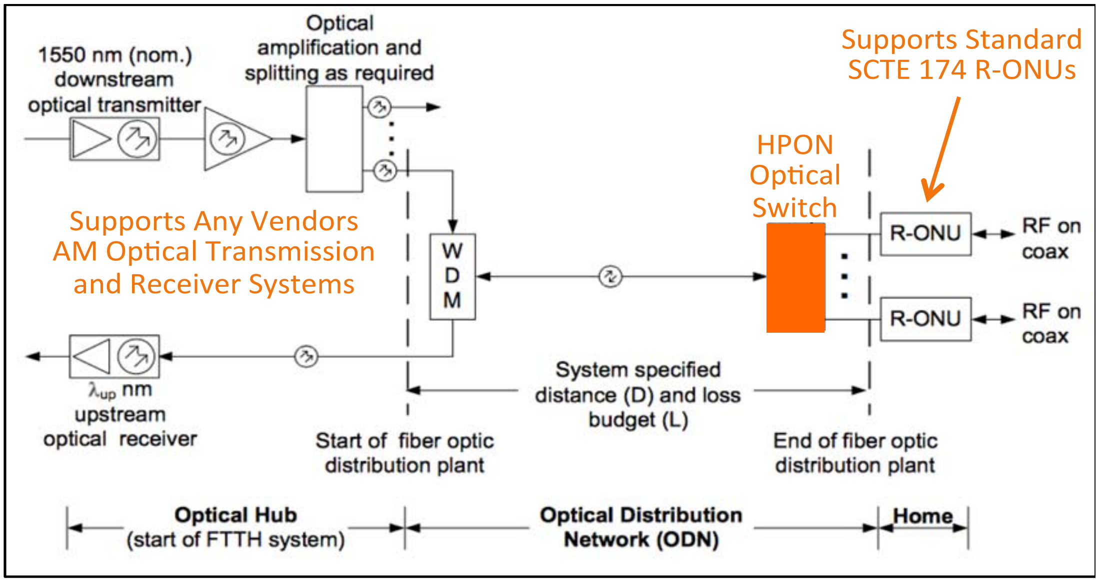

Figure 4 - HPON Reference Architecture

HPON Reference Architecture (as shown in figure 4):

- HPON uses an Active Optical Network (use of active electronics in the ODN)
- HPON Drivers include:
  - Prevention of Optical Beat Interference (OBI)
  - Extend optical reach Long Reach and Large Splits
  - Up to 40 km and 1024 Splits today, more possible tomorrow
  - Fiber to the Curb/Deep HFC for CTTH
  - FTTH solutions leveraging existing MSO systems

How HPON Works:

- HPON is a media conversation PON technologies (like RFoG) and these are unlike data PON technologies (e.g. GPON and EPON)
  - Media conversion PON technology performing only optical-to-electrical or electrical-to-optical conversion
  - Source RF signals are placed into RFoG network device where media conversion between the coaxial and fiber network is performed

  - Media Conversion PONs operate independent of the RF data MAC and PHY layer access equipment, thus the optical domain is unmanaged
  - Data PON technologies define MAC and PHY layer access equipment and communications for a managed multiple access system (avoiding optical collisions)
- RF carrier is received at the AM optical transmitters with linearly varying voltage input signal (modulating) directly translates into a corresponding light intensity (optical power) of the laser for optical transmission.
- Upstream processing may vary by implementation to avoid optical collision between multiple users

TELCO WIRELINE ACCESS NETWORK EVOLUTION

In considering the technologies described in the section above there are many alternatives that telephone and cable operators can chose as they evolve their networks. Some of the technologies are specific to the existing network, such as copper twisted pair and coaxial cable, while the use of fiber to the home is a chance that both types of operators may select the same technology or similar approach. Figure 5 illustrates a possible migration path that some telecommunication operators have taken to evolve their copper twisted pair network. As shown in the figure, the evolution path places fiber closer to the subscriber to within 100 meters and ultimately to the subscriber's home or unit. Some telecommunication operators have skipped the evolution path and have gone straight to fiber to the home. The telecommunication operator twisted pair network has far less throughput capacity relative to coaxial cable and fiber, placing telco in a different position than cable operators with regards to fiber to the home. The use of copper twisted pair as shown in the capacity section has far less capacity than the coax and fiber alternatives, thus limiting the maximum or top tier data service speed that could be offered.

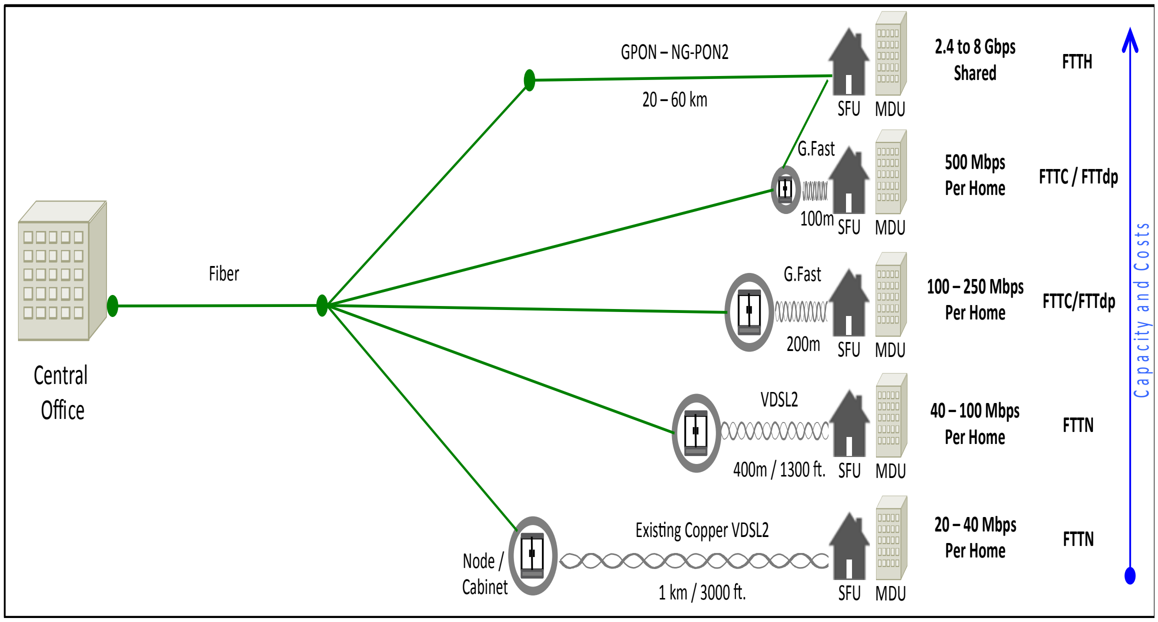

Figure 5 - Telco Wireline Access Network Evolution

AT&T U-verse® Fiber to the Node with VDSL2 and Preexisting Copper Analysis

As shown in figure 5, the use of fiber to the node (FTTN) may extend to a node or cabinet location that contains VDSL2 terminating equipment may be within 3,000 feet or 1 km of the subscribers home. This will enable 25 to 37 Mbps of data throughput using preexisting copper phone lines. [CLAR] The cost data in figure 6 was sourced from Fibre Investment and Policy Challenges, OECD Workshop, Stavanger, Norway 10-April-08, Richard N. Clarke, Assistant Vice President, AT&T - Public Policy, Page 17. The published material did not contain a break out of the capital components that comprised the enablement and cost to connect areas, though a list of some of the areas we provided.

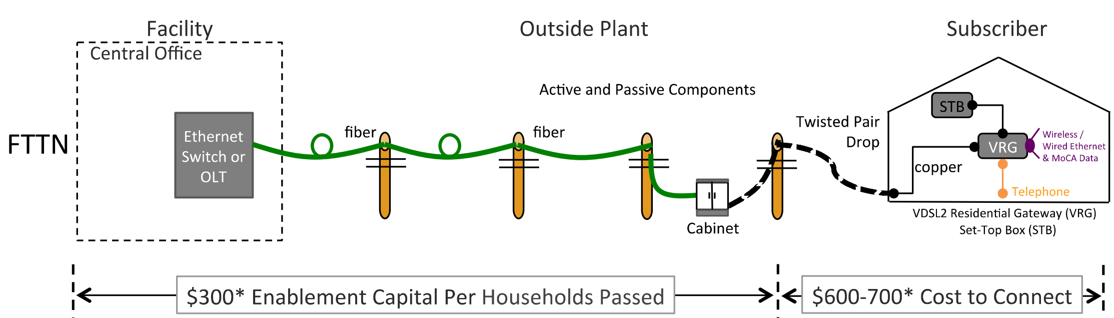

Figure 6 - AT&T U-verse® Fiber to the Node with VDSL2

Enablement Capital (Cost to Pass a Home)

- Capital Components
  - Ethernet Switch,
  - Optical Tx/Rx
  - Video Equip not shown
  - Labor Costs
  - Optical Cable, Construction, Cabinet and Installation
  - VDSL2 video multicast capable nodes
  - We are uncertain if the network equipment at the CO or VDSL2 cabinet is sized for a specified subscriber penetration rate.
  - If it is less than sized for 100% take rates then cost for enablement will increase.
  - In 2008 stated in the low $300 HHP range [CLAR]
- Variables Impacting Capital
  - Assumes fiber to within 3000 ft. (1 km) of the VDSL node subscribers
  - Cabinet location impacts VDSL2/G.Fast capacity and the closer to serving area greater the cost due to the deployment of more fiber and increase in the number of cabinet or node locations
  - Amount of aerial versus underground is a major factor
  - Distance between cabinet and customer impact capacity
  - Labor cost and methods vary regionally and over time

Success Capital (Cost to Connect a Home)

- Capital Components
  - $0 Drop cable / labor assumed existing
  - VDSL2 Residential Gateway (VRG)
  - Internet Protocol – Set-top Box (IP-STB) (assumed 1 in the price target)
  - Installation of NID, gateway, and STB
  - In 2008 stated in the between $600 - $700 range [CLAR]
- Variables Impacting Capital
  - Additional set-top boxes per subscriber will increase cost to connect
  - Material and equipment costs vary
  - Variable installation time and labor rates

Verizon FiOS® Fiber to the Home (FTTH) with GPON

As shown in figure 5, the use of Fiber-to-the-Home (FTTH) was selected by Verizon and deployed under the product name FiOS. The Verizon FiOS costs used in the material was from a published USA Today March 26, 2010 article titled “Verizon winds down expensive FiOS expansion” that was authored by Peter Svensson of the Associated Press. The capital cost numbers shown for enablement cost of $750 and cost to connect of $600 were sourced from that article [SVEN]. The composition of the cost was not provided so the components shown in figure 7 and those listed below in the description may not represent those that make up the costs. Every attempt has been made to illustrate the likely capital composition enablement and success capital.

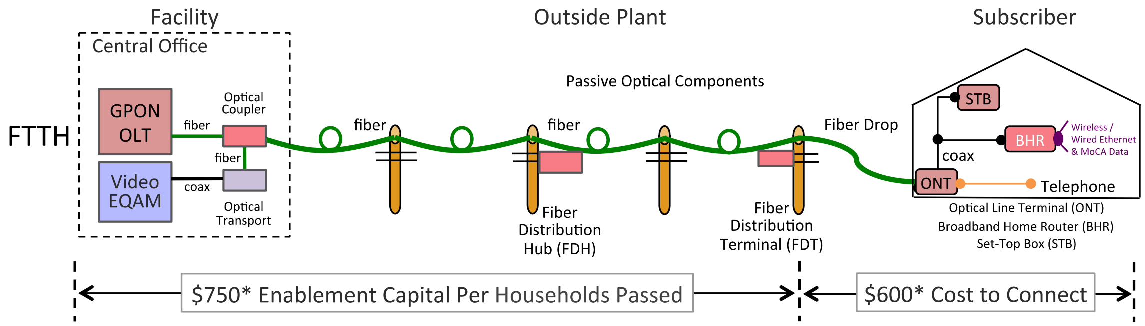

Figure 7 - Verizon FiOS® Fiber to the Home (FTTH) with GPON

Enablement Capital (Cost to Pass a Home)

- Capital Components
  - GPON OLT, EMS, passives, racks, cabling, power, and labor costs
  - GPON OLT may be sized for a specific sub take rate and cost could rise
  - Fiber optical cable costs
  - Distribution hubs, terminal, passives, connectors
  - Construction and installation labor
  - It is not know the sizing of the Fiber Distribution Hub or Splitter Hub this may not be sized for 100% take rate or even 50% this would increase enablement capital per HHP to add subscribers
  -

- Variables Impacting Capital
  - OLT spending as part of HHP enablement capital may increase due to take rates and we have no data confirming the OLT sizing
  - Uncertain of the HHP sizing Fiber Distribution Hub or Splitter Hub
  - Amount of aerial versus underground is a major factor
  - Home Per Mile is a major factor
  - Distance between central office and subscriber
  - Labor cost and methods vary regionally and over time

Success Capital (Cost to Connect a Home)

- Capital Components
  - Drop fiber and labor costs
  - Optical Network Terminal (ONT)
  - Broadband Home Router (BHR)

  - Digital Cable STB with MoCA (assumed 1 in the price target)
  - Installation of ONT, BHR, and STB Costs

- Variables Impacting Capital
  - Additional Set-top boxes per subscriber will increase cost to connect
  - Material and equipment costs vary
  - Variable Drop Length (unknown)
  - Variable installation time and labor rates

Telco Network Investment Comparison

As seen in figure 5 of the telco wireline access evolution AT&T and Verizon chose completely different paths and as shown in both figure 6 and 7 the costs structures are just as different. Figures 8 and 9 both show enablement capital and success capital. As shown in figure 8, enablement capital is shown as the cost to pass a home, thus if there were zero customers this is the sunk costs the carrier would spend and this cost component is where most business would prefer to be as low as possible while still meeting their objectives. The cost to connect a home, success capital is the cost where most business would prefer to invest their capital as this is spent in serving a paying customer. One could suppose that a business may prefer to push success capital to the consumer, however to win a customer many carriers provide the success capital equipment and some may earn rental revenue for doing so.

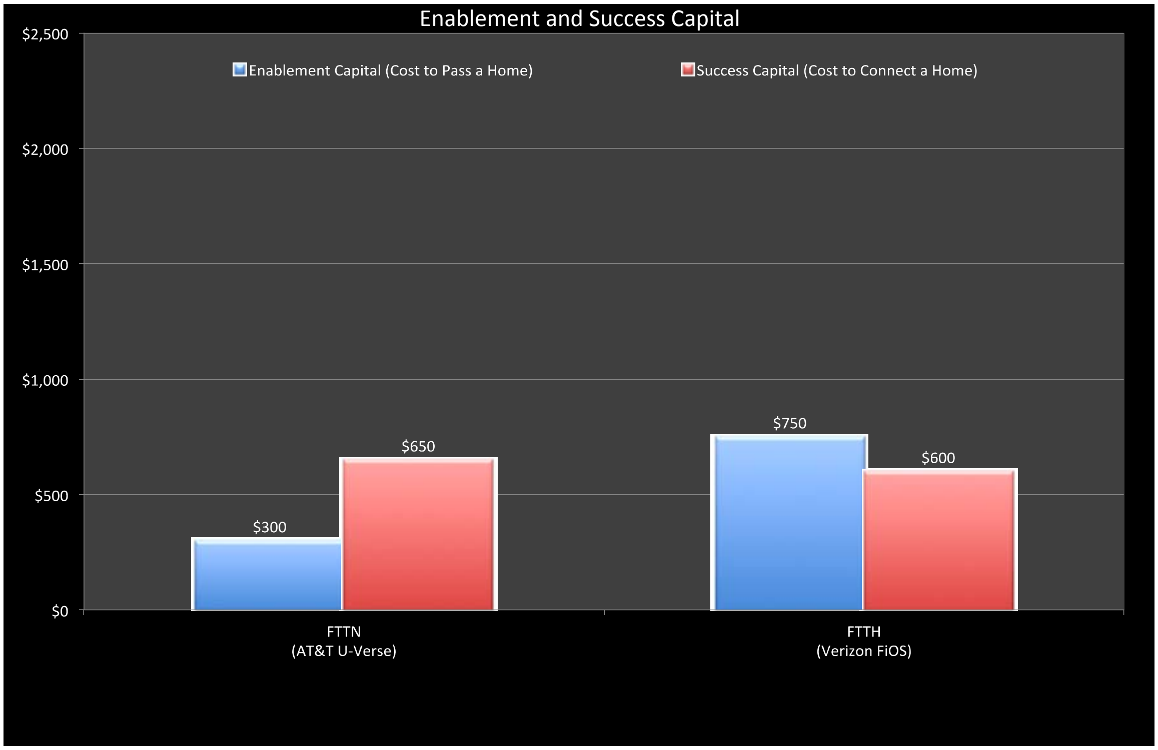

Figure 8 - Telco Enablement and Success Capital Comparison

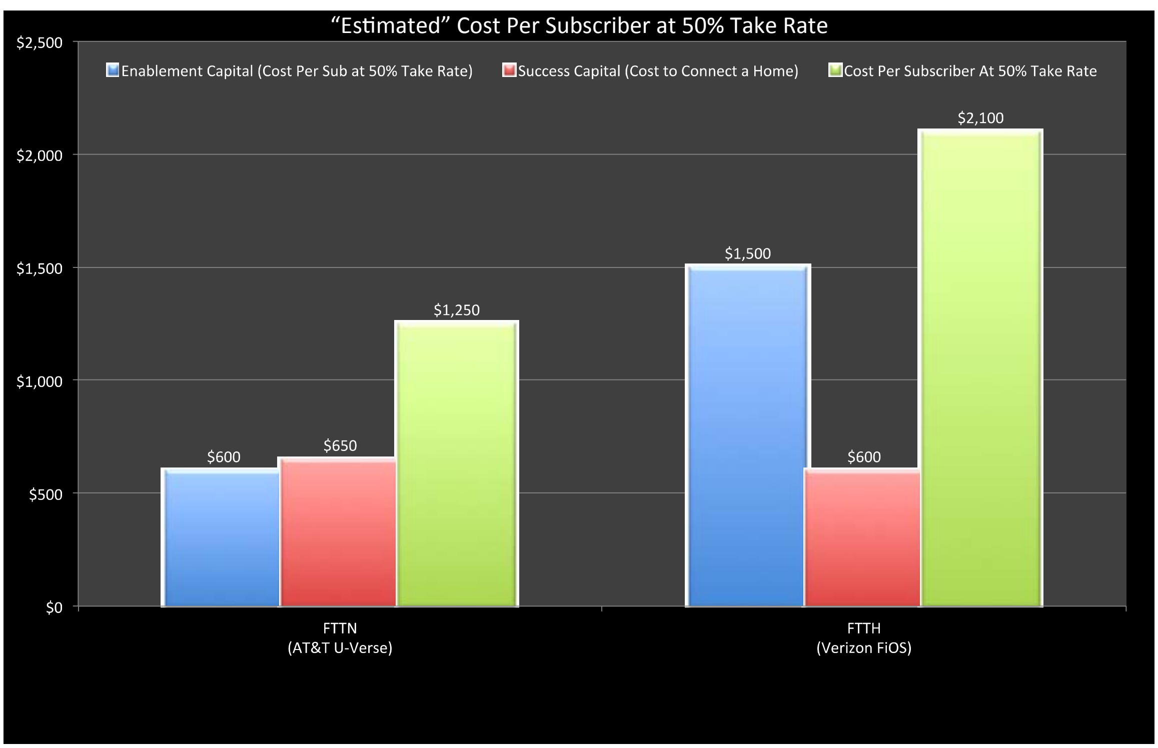

Figure 9 - “Estimated” Cost Per Subscriber at 50% Take Rate

The costs per subscriber at 50% take rate are estimates because it is unknown if the enablement capital data used for the AT&T and Verizon costs include enough capacity to reach a 50% take rate. This assumes that the enablement capital will support a 50% take rate of the triple play service. In figure 9 the cost per subscriber illustrated the impact of high enablement capital per HHP, even though both had similar success capital values in these models, AT&T at $650 and Verizon at $600. What is not known are the actual costs the carriers use today. Additionally, what is not captured is the total cost of ownership (TCO) over time comparing the evolution of the twisted pair network evolution versus the fiber to the home revolution.

CABLE WIRELINE ACCESS NETWORK EVOLUTION

In considering the technologies described in the section above there are many alternatives that cable operators can chose as they evolve their networks. Figure 10 is an illustration of possible evolution paths a cable operator could take, but some of the steps may be skipped. Also there is not a timeline given so this could take many years and happen over a decade or more.

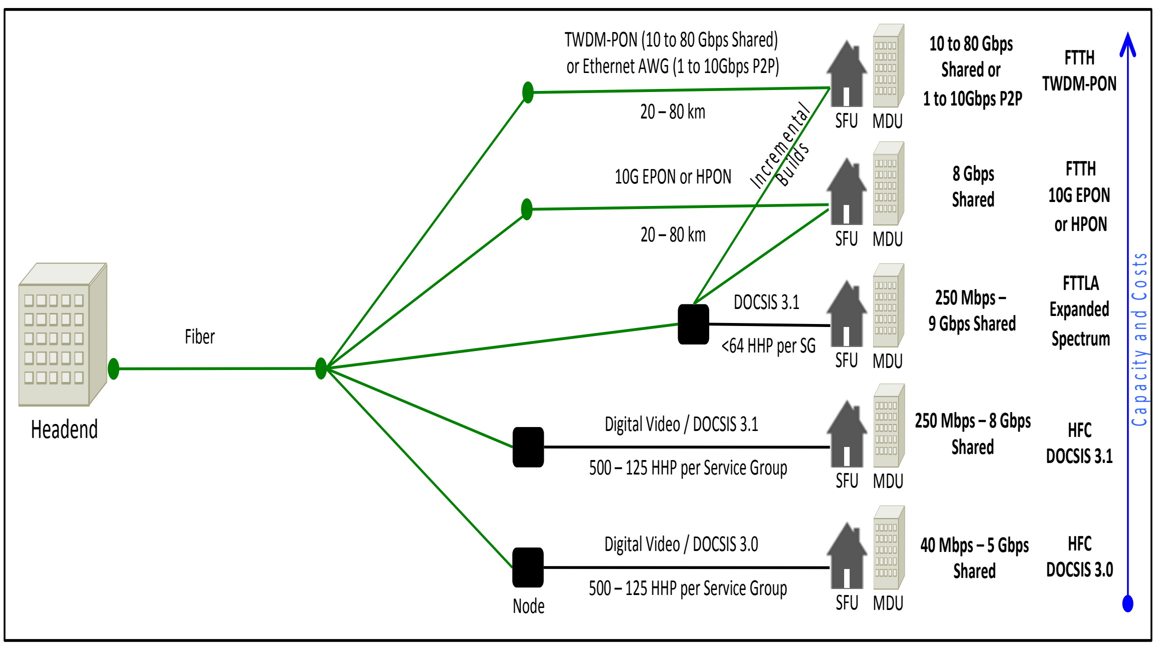

Figure 10 – Cable Operator Wireline Access Network Evolution

Cable Operator Network Migration Options

The figure above captures some of the migration options and the list below is an attempt to illustrate the position that MSOs are taking for new builds or greenfield application, existing network migration where they already have Coax-to-the-Home (CTTH), and a list of the range of migration options that the MSOs may consider.

- New build or greenfield will continue to move to fiber to the home
- Existing network migration
  - Traffic and service tier growth as a result of competition is the main driver!
  - Paths vary widely within and among MSOs worldwide
  - Multiple dwelling unit (MDU) vs. single family unit (SFU) may have different paths
  - Home densities per mile is a factor for both cost and thus selection of path
  - An MSO's view of capital allocation (massive upfront to surgical just in time)
- A range of migration options
  - Optimize the existing network (encoding, b/s/Hz, move to IP/ DOCSIS)
  - Business as usual (BAU) node splits and maintain existing spectrum
  - Spectrum expansion and change (system upgrade)
  - Fiber deep: Spectrum expansion & change, deploy fiber for Node+0, 30-60 HHP)
  - Fiber to the curb (FTTC) "or" last amplifier (FTTLA) "or" fiber to the tap (FTTT)
  - Fiber to the home/unit (FTTH/U) using HPON or 10G EPON (or combinations)
  - And many more in between!

Overview of the Cable Migration Uses Cases

The cable migration use cases selected in this paper may not represent the path a MSO may take in the near term or at all. These use cases are all based on a common set of assumptions based on the same service area characteristics so that we may measure the different use cases given a common set of underlying assumptions. The list below highlights some of the key assumptions and these assumptions may be similar to some MSO environments, which are not meant to represent a use case representing an entire MSO. A cable operator has a mix of environments that will impact the costs of each use case listed below. The key variables that may increase or decrease the investment include:

- Homes per mile
- Distance of fiber spans to new node or to the households
- Amount of aerial and underground plant
- Coax coring techniques
- Home in the entire serving area
- Many more factors.

Key Assumptions:

- Please read the disclaimer regarding the analysis
- The use cases represent a few migration paths
- The use cases examine a single area with the following characteristics:
- Total Plant (Miles): 14.1
- Total Serving Area: 1060 HHP
- HFC Optical Serving Area: 530 HHP or 265 HHP
- HPON Optical Serving Area: 256 HHP
- Homes per Mile: 75
- Aerial / Underground: 100% Aerial

The assumption of 100% aerial plant is a major assumption and will make these uses cases have lower enablement capital and in the case of FTTH have lower success capital as well. It should be noted that new and innovative methods that are just recently emerging and being tested might enable underground plant transition to fiber far less costly than traditional methods. These use cases assume a brownfield or network serving area already wired with fiber optic cables to the neighborhood and coaxial cable to the home. The portions of the underground plant may be able to use the innovative “coax coring” techniques that remove the coaxing center core and replace it with fiber optics cable and even copper lines to distribute power to remote devices. Though these use cases consider 100% aerial future use cases should consider underground and use of coax coring as this may provide a far better economical path than previously consider for underground plant markets. We were aware of this innovation and testing underway and we decided not to publish numbers based on traditional methods and costs where underground is required. Removal of the existing coaxial cable is not considered.

Additionally, all of the use cases that require DOCSIS for IP/data delivery consider that the MSO will be driving for GPON type capacity while using the existing CTTH network. The use cases requiring DOCSIS use CCAP pricing estimates based on 64 channels per DOCSIS service group at a price per channel of $399.00, which is based on the Infonetics Q4/2014. The actual price per channel an MSO may pay could be less when assuming the licensing channel capacity as activated.

Use Case 1: Today's Existing Network, Spectrum Split, 530 HHP Node and then Add 2.4 Gbps of IP/DOCSIS Capacity

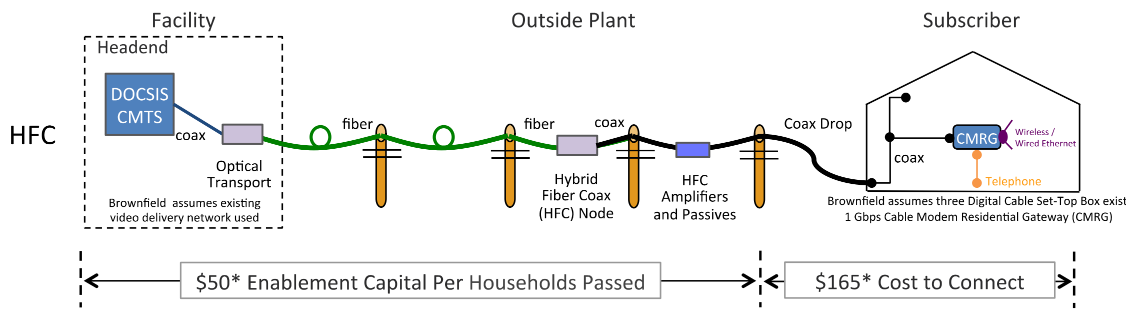

Figure 11 – Use Case 1 Today's Existing HFC with 2.4 Gbps of DOCSIS

* Estimated Capital Cost assumes existing HFC and connections to the subscriber homes with 530 HHP DOCSIS Serving Group sharing 2.4 Gbps of Data (GPON data rate)

Enablement Capital (Cost to Pass a Home)

- Capital Components
  - D3.0/3.1 CCAP with 48 SC QAM + 96 MHz D3.1)
  - Assumes no existing CCAP in place
  - The use cases requiring DOCSIS use CCAP pricing estimates based on 64 channels per DOCSIS service group and at the price per channel rate of $399.00, which is based on the Infonetics Q4/2014.
  - The actual price per channel an MSO may pay could be less when assuming all of the licensing channel capacity is activated.
  - Assumes existing network, spectrum split, and 530 HHP node
  - Assumed preexisting: fiber optical cable and coaxial cable costs, HFC nodes, coax amplifiers, coax passives, connectors

- Variables Impacting Capital
  - Enabling all channels per port and move to D3.1 will likely see lower price per channel & megabit
  - Excellent cost per sub
  - Leveraging existing outside plant and spectrum thus there are no variables to consider on the OSP.

Success Capital (Cost to Connect a Home)

- Capital Components
  - $0 drop cable / labor (assumed existing)

- $0 digital cable STB assumed 3 per home (assumed existing)
- $0 cable modem for non 1 Gbps subs (assumed existing)
- Includes cost for 1 Gbps cable modem residential gateway and installation

- Variables Impacting Capital
  - Material and equipment costs vary
  - CPE equipment type, selection & costs
  - Variable Drop Length (Assumed 150 feet)
  - Amplifier equipment needs
  - Variable installation time and labor rates

Use Case 2: Spectrum Upgrade 1 GHz / 85 MHz move from 530 to 265 HHP Node and Add 2.4 Gbps of IP/DOCSIS Capacity per Node

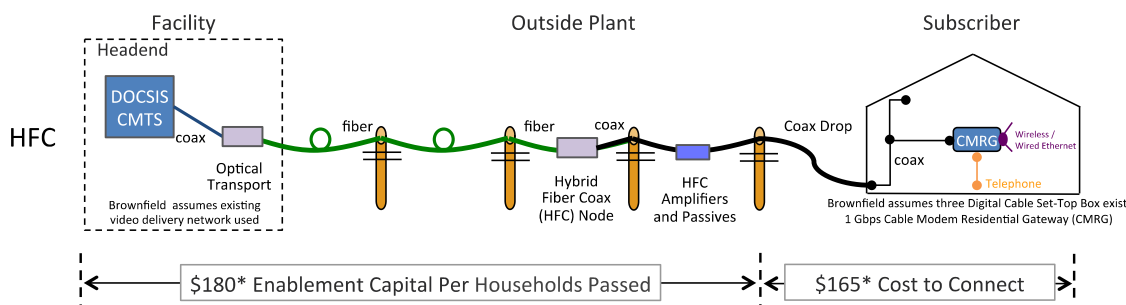

Figure 12 – Use Case 2 Spectrum Upgrade / Change Smaller Service Group

* Estimated Capital Cost assumes existing HFC and connections to the subscriber homes with 265 HHP DOCSIS Serving Group sharing 2.4 Gbps of Data (GPON data rate)

Enablement Capital (Cost to Pass a Home)

- Capital Components
  - D3.0/3.1 CCAP with 48 SC QAM + 96 MHz D3.1)
  - Assumes no existing CCAP in place
  - The use cases requiring DOCSIS use CCAP pricing estimates based on 64 channels per DOCSIS service group and at the price per channel rate of $399.00, which is based on the Infonetics Q4/2014.
  - The actual price per channel an MSO may pay could be less when assuming all of the licensing channel capacity is activated.
  - Node Split from 530 HHP physical node to 265 HHP (New Node location is strategically placed to balance the HHP node)
  - Node Split requires additional enablement capital for optics, nodes, fiber construction & installation labor to new node location

  - Spectrum Change means new headend optics and digital receivers as well as upgrading existing amplifiers
- Variables Impacting Capital
  - Enabling all channels per port and move to D3.1 will likely see lower price per channel & megabit
  - Excellent cost per subscriber
  - Node splits cost are impacted by use of aerial vs. underground
  - An MSO will extend fiber from the current 500 HHP location to the new node location, thus they will not have to run fiber from the HE to the new node location(s)
  - Labor cost and methods vary regionally and over time can be +/-

Success Capital (Cost to Connect a Home)

- Capital Components
  - $0 drop cable / labor (assumed existing)
  - $0 digital cable STB assumed 3 per home (assumed existing)
  - $0 cable modem for non 1 Gbps subs (assumed existing)
  - Includes cost for 1 Gbps cable modem residential gateway and installation
- Variables Impacting Capital
  - Material and equipment costs vary
  - CPE equipment type, selection & costs
  - Variable Drop Length (Assumed 150 feet)
  - Amplifier equipment needs
  - Variable installation time and labor rates

Use Case 3: FTTH using HPON Spectrum 1 GHz / 85 MHz "plus" DOCSIS with 265 HHP Serving Group sharing 2.4 Gbps

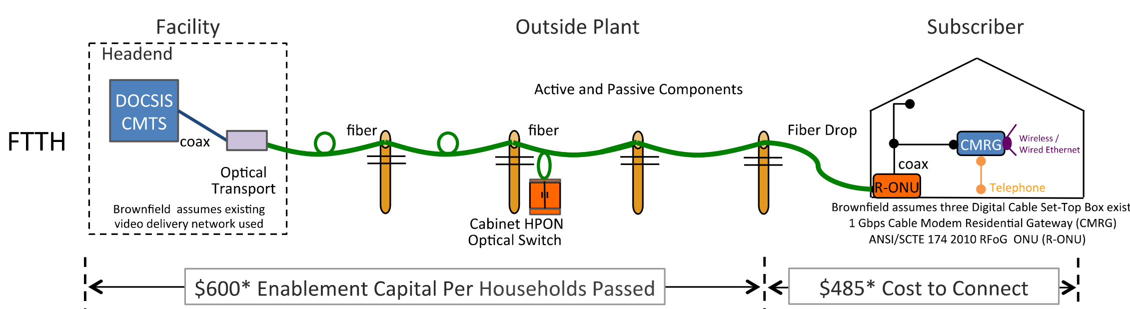

Figure 13 – Use Case 3 FTTH using HPON and DOCSIS 2.4 Gbps

* Estimated Capital Cost assumes existing HFC, 265 HHP DOCSIS SG sharing 2.4 Gbps, HPON support existing CPE products like Analog, STB, EMTA, and the model assumed a 1

Gbps DOCSIS modem is added but not required if the Customer does not take the 1 Gbps service tier.

Enablement Capital (Cost to Pass a Home)

- Capital Components
  - D3.0/3.1 CCAP with 48 SC QAM + 96 MHz D3.1)
  - Assumes no existing CCAP in place
  - The use cases requiring DOCSIS use CCAP pricing estimates based on 64 channels per DOCSIS service group and at the price per channel rate of $399.00, which is based on the Infonetics Q4/2014.
  - The actual price per channel an MSO may pay could be less when assuming all of the licensing channel capacity is activated.
  - The MSO will not need to run new fiber from the headend or hub to the home, but rather extend the existing fiber at node locations
  - HPON is sized for 50% take rate upfront though 100% is possible
  - Assumed a fiber will be pre run to all existing tap location as part of enablement capital, this could be termed as fiber-to-the-curb
  - Running fiber from the tap location to the home is success capital
- Variables Impacting Capital
  - Enabling all channels per port and move to D3.1 will likely see lower price per channel & megabit
  - Excellent cost per sub
  - Running fiber to all tap locations that may have 4 HHP will put fiber just 150 feet or less away from every subscriber
  - This assumption place fiber closer than FiOS (64 HHP) but we assume at least 1 customer exists off of each tap and thus justifying this fiber build to the tap location.
  - Use of underground cable

Success Capital (Cost to Connect a Home)

- Capital Components
  - $0 digital cable STB assumed 3 per home (assumed existing)
  - $0 cable modem for non 1 Gbps subs (assumed existing)
  - Includes cost for 1 Gbps cable modem residential gateway and installation
  - Fiber Drop Cable
  - R-ONU and installation
- Variables Impacting Capital
  - Material and equipment costs vary
  - Variable drop length (Assumed 150 feet)
  - Variable installation time and labor rates

Use Case 4: FTTH using HPON enabling Legacy Video “and” 10G EPON Symmetrical for All IP based Services

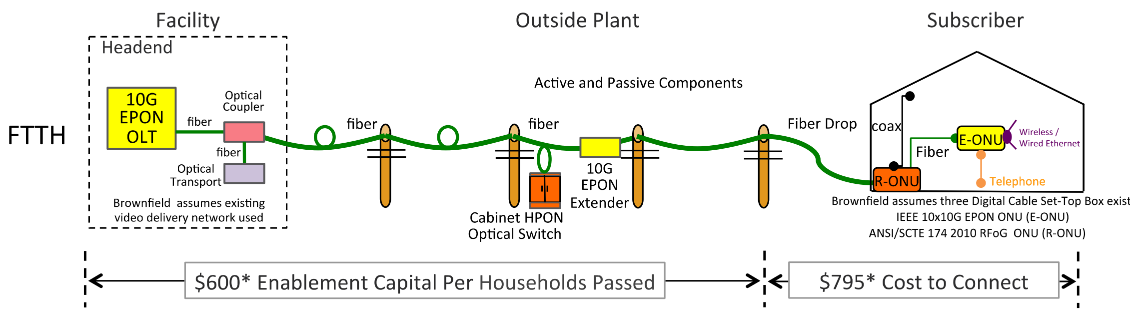

Figure 14 – Use Case 4 FTTH using HPON for Legacy Video and 10G EPON for Data

* Estimated capital cost assumes 10G symmetrical, use of DWDM PON extender for 64 HHP per port, leverage existing MSO video end-to-end enabled by HPON & RFoG.

Enablement Capital (Cost to Pass a Home)

- Capital Components
  - Includes HPON system components to enable existing video services using analog and/or digital cable to TV and digital cable STBs already in the home
  - Includes 10G EPON OLT and will be configured to support PON extender
  - DOCSIS is not used for data transport for any service
  - Leverage existing DOCSIS back office and video infrastructure
  - The MSO will not need to run new fiber from the headend or hub to the home, but rather extend the existing fiber at node locations
  - EPON is sized for 50% take rate upfront though 100% is possible
  - Assumed a fiber will be pre run to all existing tap location as part of enablement capital, this could be termed as fiber-to-the-curb
  - Running fiber from the tap location to the home is success capital
- Variables Impacting Capital
  - Leveraging existing video is an options with forward video overlay lambda and a video return lambda for STB return this will require an HPON or RFoG network and R-ONU
  - Running fiber to all tap locations that may have 4 HHP will put fiber just 150 feet or less away from every subscriber
  - This assumption place fiber closer than FiOS (64 HHP) but we assume at least 1 customer exists off of each tap and thus justifying this fiber build to the tap location

Success Capital (Cost to Connect a Home)

- Capital Components
  - $0 digital cable STB assumed 3 per home (assumed existing)
  - Fiber drop cable
  - ANSI/SCTE based RFoG ONU
  - IEEE based 10 Gbps x 10G ONU
  - Installation for all components
- Variables Impacting Capital
  - Saves some success capital for leveraging the existing digital cable STBs in the home
  - Material and equipment costs vary
  - Variable drop length (Assumed 150 feet)
  - Variable installation time and labor rates

Use Case 5: FTTH using 10G EPON Symmetrical for All IP based Services including Full IPTV Deployment

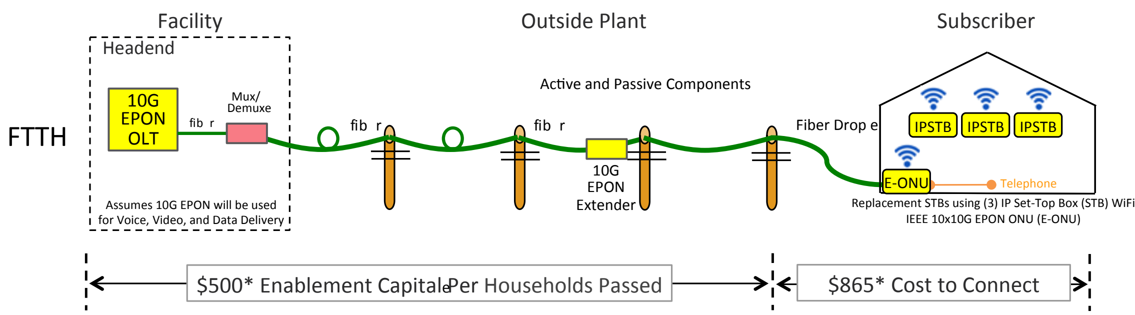

Figure 15 – Use Case 5 FTTH using 10G EPON Symmetrical For All MSO Services

* Estimated capital cost assumes 10G Symmetrical, use of DWDM PON extender for 64 HHP per port, requires IPTV and includes transport of video using 10G EPON

Enablement Capital (Cost to Pass a Home)

- Capital Components
  - Includes 10G EPON OLT and will be configured to support PON extender
  - Leverage existing DOCSIS back office and 10G EPON for IPTV
  - The MSO will not need to run new fiber from the headend or hub to the home, but rather extend the existing fiber at node locations
  - EPON is sized for 50% take rate upfront though 100% is possible
  - Assumed a fiber will be pre run to all existing tap location as part of enablement capital, this could be termed as fiber-to-the-curb
  - Running fiber from the tap location to the home is success capital
- Variables Impacting Capital
  - Assumes all IP video over 10G EPON

- Some video equipment may be repurposed like bulk encryption
- Running fiber to all tap locations that may have 4 HHP will put fiber just 150 feet or less away from every subscriber
- This assumption place fiber closer than FiOS (64 HHP) but we assume at least 1 customer exists off of each tap and thus justifying the fiber build to the tap location.

Success Capital (Cost to Connect a Home)

- Capital Components
  - Replace existing brownfield three digital cable set-top box with 3 IPTV set-top boxes
  - Fiber drop cable
  - IEEE based 10 Gbps x 10G ONU
  - Installation for all components
- Variables Impacting Capital
  - Migration to IP set-tops will increase connect costs but reduces if IP-STB are in place
  - Material and equipment costs vary
  - Variable drop length (Assumed 150 feet)
  - Variable installation time and labor rates

Fiber-To-The-Tap Systems with Extended-Spectrum HFC System using HPON

A fiber to the tap system could be used to extend fiber to the curb or very close to the subscriber's home but leverage the existing coax in the neighborhood and drop. These short spans of coax may permit DOCSIS 1.7 GHz or 4 GHz or 8 GHz to be used to create massive amounts of capacity leveraging the coax already in the ground wire to every home.

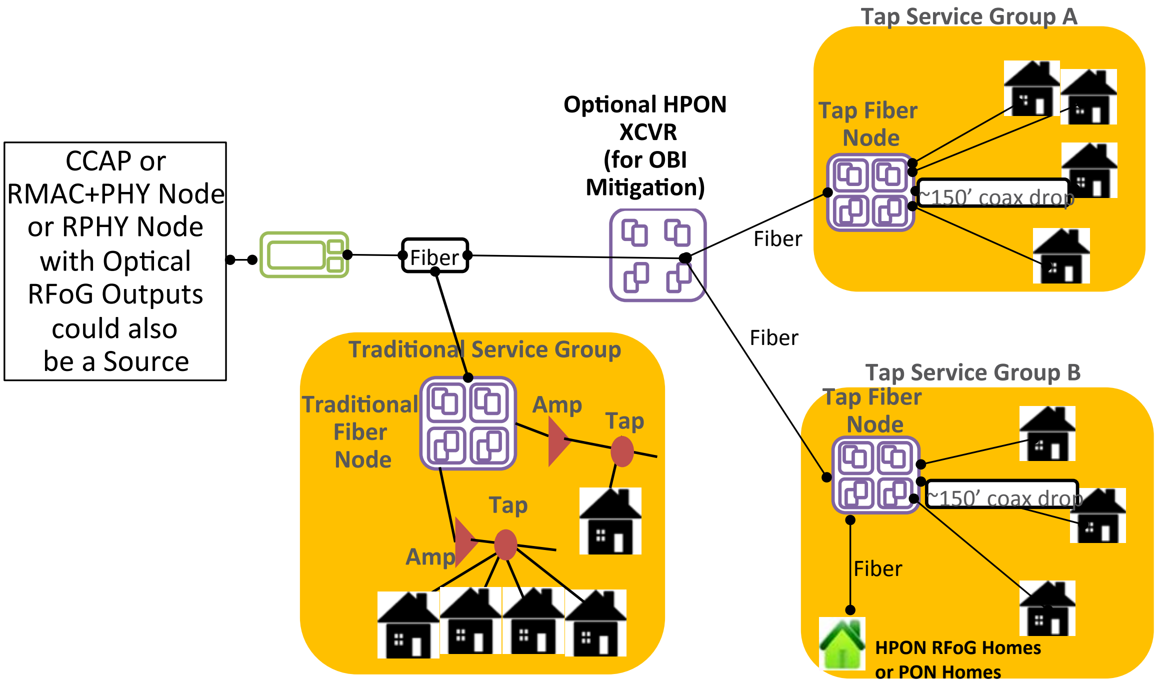

Figure 16 – Fiber-To-The-Tap Systems with Extended-Spectrum HFC System using HPON

Cable Operator Possible Use Case Investment Comparisons

As seen in figure 10 of the cable operator wireline access evolution these five use cases represent a sample of the possible paths the may be implemented. The use cases represent the completely different paths and as shown in both figure 10 and illustrated with additional details in the use cases. Figures 17 and 18 both show enablement capital and success capital. As shown if figure 17, enablement capital is shown as the cost to pass a home, thus if there were zero customers this is the sunk cost the carrier would spend.

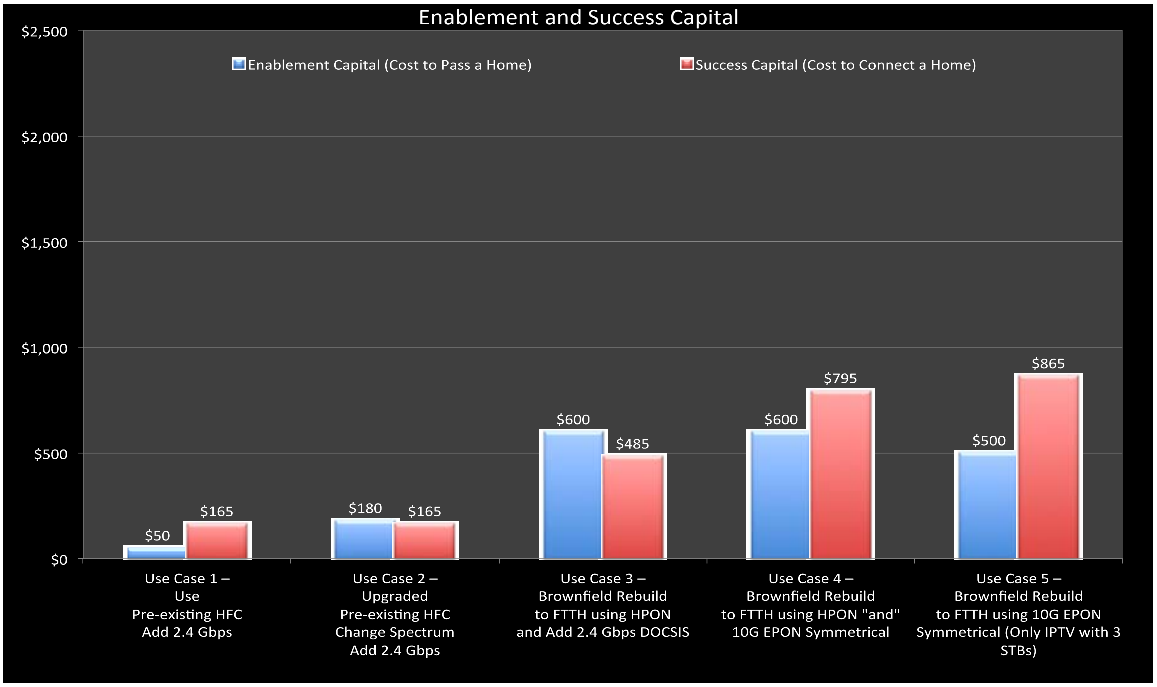

Figure 17 - Use Case Enablement & Success Comparison

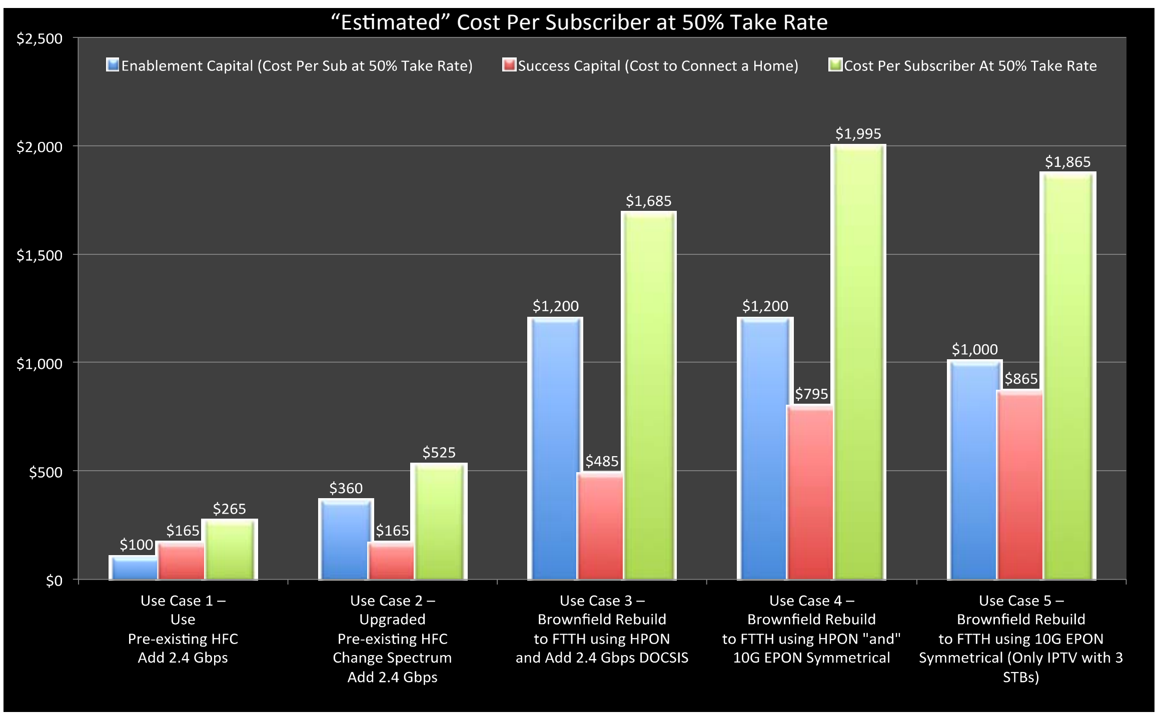

Figure 18 - Use Case Cost Per Sub at 50% Take Rate

Figure 18, illustrates the costs per subscriber at 50% take rate of the triple play service. In figure 18 the cost per subscriber illustrates the impact of high enablement capital per HHP. What is not shown is the total cost of ownership (TCO) comparing these use cases.

DATA CAPACITY COMPARISONS

Figure 19 compiles the material found in the previous sections to allow for a side-by-side comparison of the technology choices in the wireline space. Located at the top of each figure defines the technology types. An obvious conclusion as seen in the figures below is that HFC and DOCSIS have far greater capacity than the copper twisted pair solutions, where both would compete to leverage existing wiring. Some service providers are re-wiring their access networks with fiber to the home and utilizing various PON technologies identified in Figure 19. Estimates are based on physical layer (PHY layer) after encoding and forward error correction (FEC) overhead if used and no other overhead is assumed.

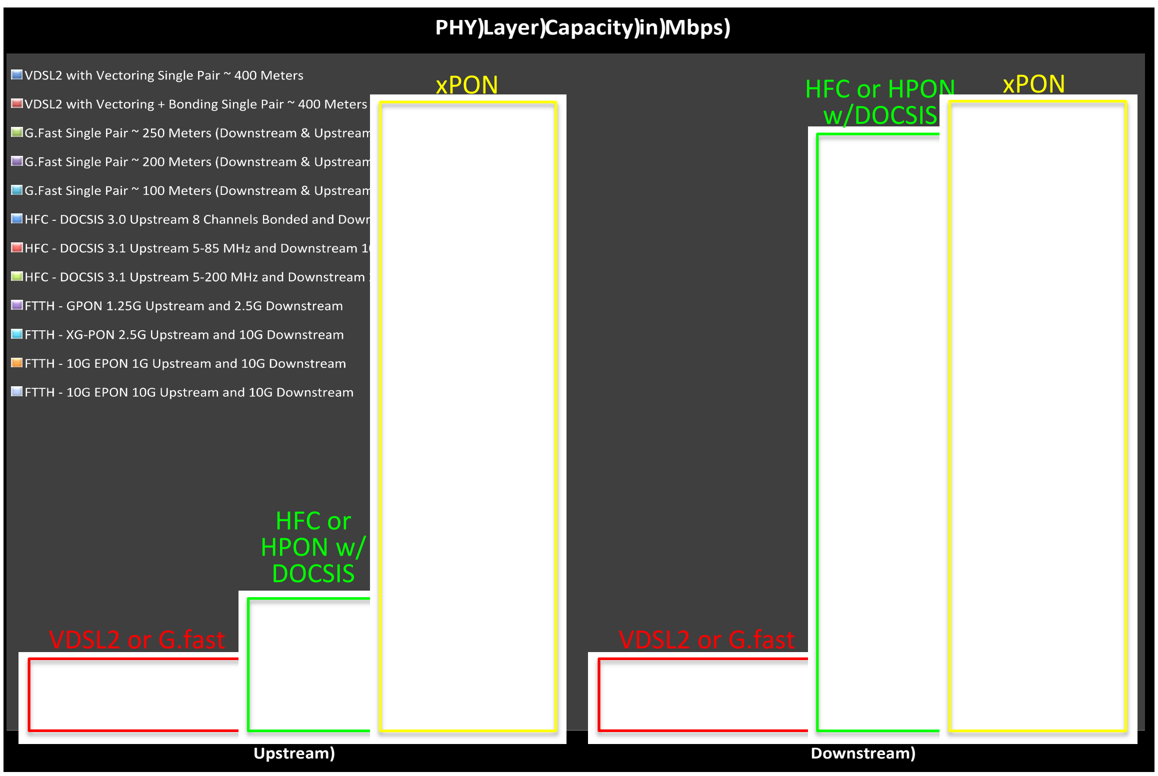

Figure 19 - Access Network PHY Capacities

PHY layer rates after encoding and FEC (if used), however the copper solutions estimate capacity. DOCSIS 3.1 assumes an average of 2048-QAM in the downstream and 1024-QAM in the upstream.

CONCLUSIONS AND RECOMMENDATIONS

Investment Assessment Summary

- **Network Evolution (CTTH)**
  - Copper/coax to the home has nearly 100% connects
  - Leverage the existing drops twisted pair / coax
  - Fastest time to market / minimal impact to neighborhood
  - Analysis shows the lowest cost solution
  - Lowest enablement, success capital, & per subscriber cost
- **Network Revolution (FTTH)**
  - Substantial overbuilding what exists
  - Highest "upfront" enablement, success capital, per subscriber
  - Total cost of ownership least understood
  - Highest capacity solutions

Evolution vs. Revolution Summaries

- **Evolution – Leverage Existing Copper/Coax Network to the Home**
  - Evolve and upgrade the data technology MAC/PHY technology
  - Upgrade to increase spectrum
    - Telco 1 MHz, 2 MHz, 17 MHz, 30 MHz, 106 MHz, 212 MHz, ???
    - Cable 300 MHz, 550 MHz, 750 MHz, 1000 MHz, 1218 MHz, ???
    - Cable fiber-to-the-tap may permit DOCSIS 1.7 GHz or 4 GHz or 8 GHz
  - Invest in building fiber and deploying more nodes/cabinets closer to the subscriber
  - Technology upgrades, more spectrum, closer fiber to the homes means more capacity
  - Leveraging existing network lowest enablement but requires continued investment
  - Enablement and success capital allocation can be surgical where/when needed
  - Having an active outside plant likely means higher operational costs compared to PON
- **Revolution – Overbuild Network with Fiber to the Home (FTTH)**
  - Heavy upfront investment in enablement and success capital to build FTTH
  - Capacity that may last for decades with additional capacity a wavelength away

  - Continued data technology investment BPON, GPON, NG-PON2 increases capacity
  - All optical and likely all passive optical network means less operation expense

Key Overall Summaries for Cable Operators

- HFC data capacity remains competitive against modern xPON (upstream remains a challenge)
- HFC serves more homes and customers with far less capital
- HFC is extremely cost effective when compared any access layer technology
- Upgrade 1 GHz+ / 85 MHz with 2.5G DOCSIS extremely cost effective
- Cable Migration to FTTH 10G EPON has lowest enablement capital
- Enablement and success cost per bit favors FTTH 10G EPON solutions
- cable fiber to the last active or fiber to the tap with HPON leverage CTTH positioning fiber close enabling 10G EPON for selective customers

- Important factor like operational costs were not considered

Recommendations

- **Extending the Life of CTTH and preparing for FTTH Transition**
  - Consider:
    - Maximizing existing spectrum and adding more DOCSIS are cost effective choices
    - A spectrum upgrade to 1 GHz or higher when you touch the plant as this will bring the entire network to parity (from CCAP, optics, amps, taps, and CPE)
    - When drop replacements are needed consider Siamese drop (coax and fiber) as this could prepare for the transition to FTTH
    - Node splits drives fiber deeper in the neighborhood at lower capital costs than FTTH
  - Solves:
    - Capacity and service challenges at far less cost.
- **Meeting the Extremely High Data Rate Challenge**
  - Consider:
    - This analysis shows the HFC/DOCSIS meeting 1 Gbps+
    - Extremely high downstream, upstream, and even symmetrical services are purchased by a small percentage of subs
    - Building FTTH for those subscribers only
  - Solves:
    - Billboard Speed Issue

- Preserves HFC for the masses
- Pushes fiber closer to the subscriber.

DISCLAIMER

All economic estimates may not represent actual build and equipment costs. The cost estimates for Verizon were based on a 2010 Associated Press article and AT&T published material. The Cable HFC and FTTH economic estimates contain inputs from a third party and ARRIS for construction, installation, labor, materials, current and future equipment estimates as well as our assumptions of network architecture and topology. These use cases were compiled independent from the cable operators. The use cases are based on an extremely small sample size and actual build costs may vary widely market by market. This material is for information and illustrative purposes only and should not be considered or derived as actual results. It is not, and should not be regarded as actual cost estimates. Comparisons between Verizon, AT&T, and these use cases should not be considered as a direct comparison because the assumptions are not known and certainly not aligned. In addition, all of these estimates assume to varying degree different starting points or rather previous investments, which may not be represented in these costs as these are sunk costs. The core purpose of this data is to show relative difference for a particular set of use case migration options and should be used for discussion purposes only. The estimates expressed in this material are subject to change without notice. Reasonable people may disagree about the opinions expressed in our analysis and results. There are many other factors that were not considered that may impact the estimates and illustrate a significantly different result. It is strongly recommended that individuals and companies perform their own analysis based on their environment and costs.

TECHNICAL ACKNOWLEDGEMENTS

The author would especially like to thank the contribution of Fred Slowik, Jon Bordner, Stuart Eastman, Steve Hersey, Charles Cheevers, Venk Mutalik, and Scott Ishler, because without their assistance this paper could not have been completed.

ABBREVIATIONS

10G-EPON	10 Gigabit Ethernet PON
2D	Two Dimensional
APON	ATM (Asynchronous Transfer Mode) Passive Optical Network
BAU	Business as usual
BCH	Bose-Chaudhuri-Hocquenghem
BPON	Broadband Passive Optical Network
CAA	Centralized Access Architecture
CAT5	Category 5 Cable
CESoP	Circuit Emulation Service over Packet
CMTS	Cable Modem Termination System
CO	Central Office
CTTH	Coax-to-the-Home
CTTU	Coax-to-the-Unit
CWDM	Coarse Wave Division Multiplexed
D3.1	DOCSIS 3.1
DAA	Distributed Access Architecture
DBS	Digital Broadcast System
DFB	Distributed Feedback Laser
DOCSIS	Data Over Cable System Interface Specification
DPG	DOCSIS Provisioning of GPON
DPoE	DOCSIS Provisioning of EPON
DS	Downstream
DSL	Digital Subscriber Line
DTA	Digital Terminal Adapter
EFM	Ethernet in the First Mile
EPON	Ethernet Passive Optical Network (aka GE-PON)
FCC	Federal Communications Commission
FDD	Frequency Division Duplexing
FEC	Forward Error Correction
FSAN	Full Service Access Network
FTTB	Fiber-to-the-Building/Business
FTTC	Fiber-to-the-Curb
FTTdp	Fiber-to-the-Distribution-Point
FTTH	Fiber to the Home
FTTN	Fiber to the Node
FTTP	Fiber to the Premise
FTTU	Fiber-to-the-User

FTTx	Fiber To The x (FTTH Home, FTTB Business, FTTP Premise, and FTTC Curb)
Gbps	Gigabits per Second
GEM	GPON Encapsulation Method
GEPON	Gigabit Ethernet - Passive Optical Network (aka EPON)
GPON	Gigabit-Passive Optical Network
HE	Headend
HFC	Hybrid Fiber Coax
HHP	Households Passed
HPON	Hybrid Passive Optical Network
HSD	High Speed Data
HSI	High-speed Internet
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IPTV	Internet Protocol TV (video) over IP networks
ITU	International Telecommunication Union
LDPC	Low-Density Parity-Check
MAC	Media Access Layer
Mbps	Megabit per Second
MDU	Multiple Dwelling Unit
MoCA	Multimedia over Coax Alliance
MSO	Multiple System Operator
MTA	Multimedia Terminal Adapter
NOC	Network Operations Center
NRZ	Non-Return-to-Zero
OBI	Optical Beat Interference
OCA	Optical Collision Avoidance (
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiplexing Access
OLT	Optical Line Terminal
ONT	Optical Network Terminal
ONU	Optical Network Unit
OSP	Outside Plant
OTT	Over-the-Top
P2MP	Point-to-Multipoint
P2P	Peer-to-peer
PHY	Physical Layer
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience

QoS	Quality of Service
RFoG	RF Over Glass
SC	Single Carrier
SCTE	Society of Cable Telecommunications Engineers
STB	Set-Top Boxes
TDD	Time Division Duplexing
TWDM	Time and wavelength division multiplexed passive optical network
TDMA	Time Division Multiple Access
US	Upstream
VDSL	Very High Bitrate DSL
VDSL2	Very High Bitrate DSL2
VHSI	Very High-Speed Internet
VoD	Video-on-Demand
VRG	VDSL2 Residential Gateway
WDM	Wavelength Division Multiplexing
WDM-PON	Wavelength Division Multiplexing PON

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