LESSONS FROM TELCO & WIRELESS PROVIDERS: EXTENDING THE LIFE OF THE HFC PLANT WITH NEW TECHNOLOGIES

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Abstract

This paper draws on lessons from the past (within the telecommunications space) to predict some of the new technologies that may be considered by Multiple System Operators (MSOs) as they move forward into a service provider world of the future. It is a future that will undoubtedly demand more and more bandwidth to be offered to subscribers over time.

After presenting some historical data on the evolution of telecommunications systems and some new traffic engineering information on bandwidth growth trends, the paper will attempt to identify the life-span of the current Hybrid Fiber/Coax (HFC) infrastructure through which most Voice, Video, and Data services will be provided in the future. Potential techniques for extending that life-span will also be explored. It will be shown that with appropriate management, the life-span of the current HFC network can likely be extended well into the 2030s or 2040s (or beyond).

The paper then explores some of the key technologies that may be utilized in concert with or in lieu of the existing HFC network during this period.

Most of the predictions in this paper will draw heavily on the historical lessons that can be learned from the network evolutions that have taken place within the Telco & Wireless industry during the past two decades. The paper will attempt to show why these lessons may be applicable to the future evolutions that are likely to take place in the Cable industry.

BACKGROUND

Introduction

Correctly predicting the future is a difficult, but critical task for any company. This is especially true when an industry is facing a time when transitions in technologies are being considered- with the potential end-of-life for one technology approaching and prospects for the birth of a new technology looming in the foreseeable future. Are there ways to extend the life of the existing technology? Are those extensions beneficial or not? If a transition is to take place, when should it take place? Should the transition be done quickly or gradually? Which technologies should be used during the transition? Which of many available technologies should carry the load in the future? All difficult questions that need to be answered as any industry approaches a "technology transition window."

Some in the Cable industry have argued that the HFC network that provides the access network backbone for MSOs is slowly beginning to approach one of those "technology transition windows." Some believe that the bandwidth demands of subscribers in the near future may exceed the capacities of their existing HFC infrastructure, and they are trying to prepare for that eventual occurrence.

Are these arguments that the HFC plant is approaching obsolescence correct? If so, will the HFC network need to be replaced in the 2010s? In the 2020s? In the 2030s? In the 2040s? Beyond that date? Should a transition to a new technology occur after DOCSIS 3.1

and Distributed Access Architecture deployments, or should the new technologies supplant DOCSIS 3.1 and Distributed Access Architectures. Should the new technologies be introduced in parallel with existing technologies? How should the transition be orchestrated- quickly or gradually? What technology or group of technologies will replace the current technologies? Will it be Passive Optical Networks (PONs) or Radio Frequency over Glass (RFoG) or Point-to-Point Ethernet? Will it be something else?

As stated above, these are all difficult questions to answer, but answering them in the right way is critical for every MSO. And it should not be shocking if different MSOs answer these questions differently and select different paths, because in many cases, the "correct" answer is heavily dependent on many different and interesting factors.

1) What is the starting point- i.e., what is the status of the MSO's current HFC infrastructure?
2) What is the desired ending point - i.e., what technologies does the MSO wish to use in the future?
3) How quickly can they transition? (Note: This usually becomes an economic question, requiring the MSO to perform a Business Case Analysis on the various transition plans).
4) What are the capabilities and costs of the different technologies under study?
5) What improvements are expected in the different technologies under study?

The authors will explore many of these topics and attempt to make predictions within this paper. However, it is clear that any predictions on the future require some amount of information to help guide those predictions. The authors decided to do what many researchers have done to predict the future, by looking at the past. Perhaps answers to these questions can be found by looking to history and exploring similar evolutions in history to see how they played out.

But are there any examples in history where large service providers using copper-based technologies found themselves at a point where bandwidth requirements of the future looked like they would stress the capabilities of their copper-based technology? If so, is there anything to be learned from the manner in which they dealt with the situation. The authors believe that the answer to both of these questions is yes. And because of that, the paper will now take a brief look at the recent history of the Telco & Wireless industry.

TELCO HISTORIES

A Brief History Of The Telco Industry's Voiceband Modem Evolution (1950's to 1998)

The wireline telephone systems of today's Public Switched Telephone Networks (PSTN) have deep roots in history. They are actually close descendants of the telegraph systems that also used wires to transmit signals across long distances in the early-to-mid-1800s.

Throughout the mid-1800s, many researchers were looking at new technologies that would ultimately be useful for telephone transmissions of voice signals across a wire. With the granting of patent number 174,765 by the U.S. Patent Office on March 7, 1876, Alexander Graham Bell's ideas were pushed forward as a seminal approach to the transmission of voice signals over wires. The first overhead telephone lines were set up between houses in Boston using iron and steel wires with an earth (ground) return. The use of copper wires for the telephone transmission became possible in 1877 with Thomas Doolittle's invention of a process to hard-draw copper into durable wires. From that point on, copper wires were used for most telephone systems. Alexander Graham Bell patented two-wire, twisted-pair circuits in

1881, leading to lower-noise transmissions. This permitted long-distance copper lines to be used to connect New York to Boston in 1884 and New York to Philadelphia in 1885. Bundling of these two-wire circuits inside of cables to carry many parallel lines became common-place by 1890. By 1900, most of the U.S. telephone system was connected using twisted-pair cables. Multiplexing of multiple phone conversations on a pair of wires, improving the insulation, and improving the cable sheath became the focus of many innovations during the 1880, 1890, 1900, and 1910 decades. While many other improvements have been made since then, it is interesting to note that (for all practical purposes) telephone wires between the telephone central office and the home have changed very little in the past 100+ years. (Note: By comparison, the higher-performance coaxial cables used within the Cable industry were only invented in 1942, so the Cable industry's coax will likely have a much longer life ahead of it if it matches the total lifespan experienced by twisted pair wires. One may wonder why it shouldn't experience a similarly long life with its increased performance levels relative to twisted pair). [COPP] [EASY]

The two-wire copper wires that make up the copper loop for Telcos have thus been used to transport voice signals for more than 100 years. However, a new type of signal began to appear on these copper wires in the 1950s (~60 years ago). It was during that decade that the U.S. Air Force's Ballistic Missile Early Warning System (later called SAGE) began to use telephone lines to transmit signals between radar stations in Canada and IBM 790 computers in the U.S. These signals needed to have spectra that could be carried by the traditional voiceband spectrum of 0-3.3 kHz (the passband of the telephone lines). As a result, modems (modulator-demodulator systems) were used to convert binary information from the computers into analog signals with appropriate amplitude and frequency characteristics. These original Air Force modems could transmit at data rates of 75 bits per second, and eventually achieved speeds of 750 bits per second. They were predominantly unidirectional or half-duplex transmissions, though.

In 1958, the bi-directional modem concept was commercialized by AT&T with the creation of the Bell 103 modem. This modem was based on Frequency-Shift-Keying (FSK) and permitted full-duplex transmission (the transport of signals in both directions at the same time). It also permitted a data rate of 300 bits per second (which was considered adequate for business and scientific applications of the time).

As researchers at universities began exchanging data between computers, the demand for modems grew. The demand for more modem bandwidth also began to grow. AT&T soon developed the Data Set 202 modem, which provided a higher data rate of 1200 bits per second. In 1962, they released the Data Set 201 modem with 2400 bit per second performance. (Note: The Data Set 201 modem was required to work on specially-conditioned leased or private lines). In 1965, Robert Lucky (of AT&T Bell Labs) invented adaptive equalization, which helped mitigate against channel frequency response issues. In 1968, a non-AT&T company called Milgo released the 4400/48 modem that could operate using proprietary protocols at 4800 bits per second over minimally-conditioned telephone lines. In 1971, Codex added many innovations using suppressed-carrier single side-band modulation with their 9600 modem that could operate at 9600 bits per second. That was followed by the world's first PC-based modem (the 300 bps 80-103A) was created by Dale Heatherington and Dennis Hayes in 1977.

Improvements continued throughout the next decade, and standardization became more desirable over time so that modems from different vendors could communicate with one another. This standardization effort became especially important as more home-based subscribers began using modem technology with Tim Berners-Lee's introduction of the three fundamental World Wide Web protocols (HTML, URI's, and HTTP) in 1989. [WEBF]

By 1991, the ITU-T V.32 and V.32bis standards were created, permitting modem transmissions at data rates of 9600 bits per second and 14,400 bits per second, respectively. These standards made heavy use of new technologies such as echo cancellation and Trellis-Coded Modulation (TCM). Then the ITU-T V.34 standard created modems that could support data rates of 33,600 bits per second by capitalizing on silicon technology improvements and measuring the characteristics of the telephone line and tuning transmission parameters.

In the 1998-1999 timeframe, the ITU-T committees were putting the finishing touches on a new set of standards called ITU-T V.90 and ITU-T V.92. These two specifications utilized an incredible number of recent innovations in communication theory (such as Quadrature Amplitude Modulation (QAM), pre-coding, and spectral shaping), and the specifications were to be based on the best technology available at the time. The specifications drew heavily from two competing and proprietary modem designs that had been created a few years earlier. These included the K56flex proposal from Rockwell and Lucent and Motorola and the X2 proposal from US Robotics. V.90 modems would permit download speeds of up to 56,000 bits per second and upload speeds of up to 33,600 bits per second. V.92 modems would permit download speeds of up to 56,000 bits per second and upload speeds of up to 48,000 bits per second.

These incredibly high data rates supported across the analog wires propelled the speeds to values that would come close to the digital bandwidth capacity available on the digital DS-0 circuits that were utilized in the trunk connections between digital switching systems in different telephone central offices. Because of this and because of the complexity of the resulting modem chips, the V.90 and V.92 modem technology was also called "V.Last". This nickname was used because many of the researchers associated with the telephone line modem technologies believed that V.90 and V.92 might be the end of the line for the (then) forty-year-old modem technology improvements that had roughly begun back in 1958 with the Bell 103 modem definition. Many researchers believed that for the support of future broadband data services, copper telephone lines were essentially becoming obsolete. At that particular point in time, their view of the evolution of modem technology on copper telephone lines was probably driven strongly by the chart shown in Fig. 1a. There were two data rate growth spurts, with a long 20-year period of relative stagnation (from 1971 to 1991) between the growth spurts. Most were probably preparing for another period of stagnation. The only research looking at increasing the data-rate on the copper telephone lines proposed moving the transmission spectrum above the 3.9 kHz voiceband, and many researchers believed that the transfer functions of the transmission media above that voiceband limit were challenging at best. There would be spectral regions filled with amplitude and phase variations that would greatly distort any high data-rate signals. Voiceband modem designers were constrained in both power and frequency levels (as shown in Fig. 1b)- with power limits from the FCC and codecs and with frequency limits from codecs and ring detectors. This led to a belief that spectral regions above 3.9 kHz on copper lines were a "No-Man's Land" for broadband services, as shown in Fig. 1b. [BRIT] [MODE] [NETH] [HIST] [DIAL] [56KB]

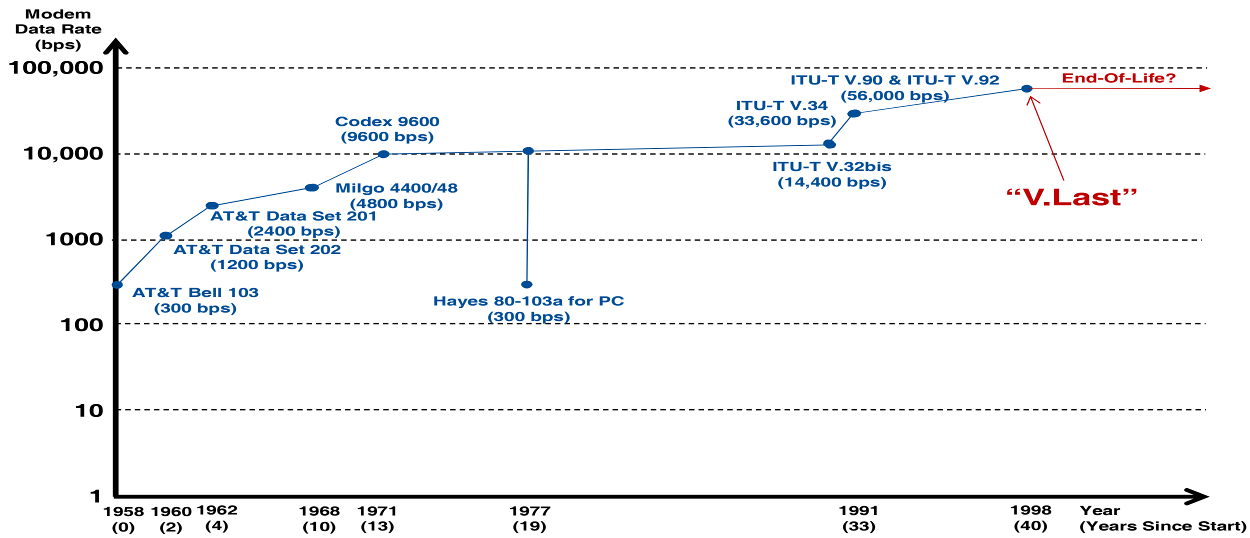


Fig. 1a- Telephone Line Voiceband Modem Data Rates vs Time

Due to these concerns about the end-of-life of broadband data services on copper telephone lines, many Telco executives and researchers began to look at new technologies that might be able to deliver the expected data rates of the future. The Telco industry had entered a window of time that was labeled as the "technology transition window" earlier in this paper. The entire Telco industry needed to develop a new game plan to ensure that they would not become irrelevant as an Internet Service Provider going forward into the future.

The steps and decisions made by various Telcos between 1998 and the present time will be the key focus of the remainder of this paper, because it is the belief of the authors that the Cable industry can learn from their successes and failures during their "technology transition window."

During the past twenty years, Telcos have been undergoing a lengthy transition in technologies, as they have slowly migrated from copper loop plants to fiber and/or wireless infrastructures. The decisions that they made during that twenty-year journey

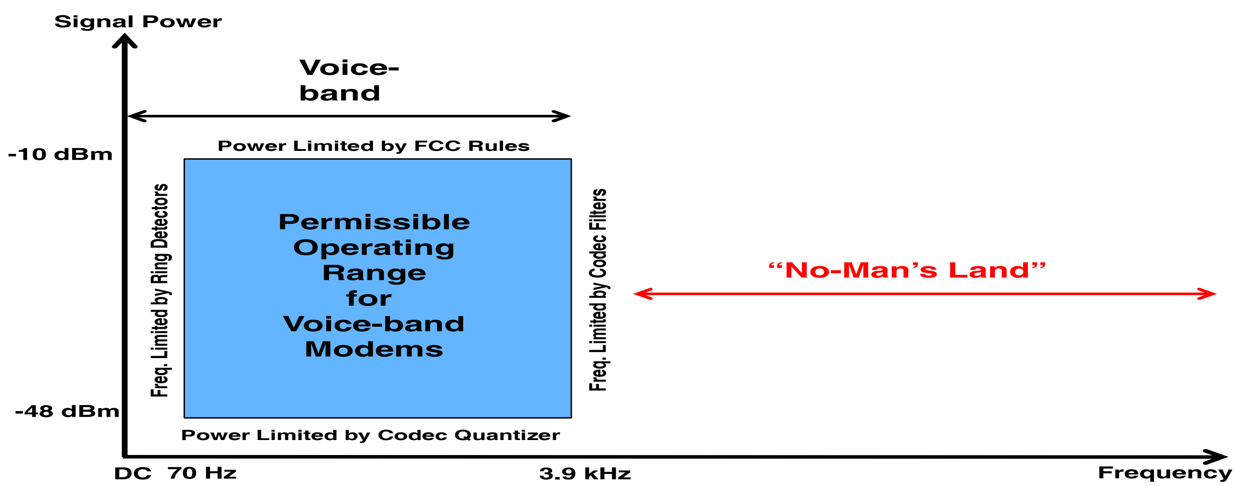


Fig. 1b- Old Views on Useable Spectrum for Copper Twisted Pair

may be instructive to MSOs as the Cable Industry begins to wrestle with questions about the longevity of its own existing technology infrastructure: the HFC network. The paper will begin by briefly looking at what Telcos have done between 1998 and the present time.

The Challenges That Faced The Telco Industry in 1998

The Telco Industry found itself in a complex situation during the 1998 time-frame. Many within the Telco industry believed that modem performance levels over copper lines may not see data rate improvements that would keep up with the bandwidth demands of subscribers. At the same time, the Telco Industry was encountering a new Service Provider competitor in the form of Cable MSOs. With the release of the DOCSIS 1.0 specification in 1997 and the first CableLabs certification of modems and CMTSs in 1999, high-speed data services with shared 30 Mbps channels (over HFC plants) were becoming a challenging competitor to telephony modem technology (which at the time, appeared to be limited to much lower ~56 kbps service levels).

Because of these challenging trends, Telco executives needed to re-invent their companies and had to make some important decisions on how to move forward. Although each operator might have followed slightly different game plans with slightly different technologies and slightly different schedules, the Telco industry (in general) could be said to have followed a three-pronged path. They ultimately decided to invest in three different last-mile technology paths for broadband data services going forward. Those paths included:

a) Broadband data services over fiber-based Passive Optical Networks (PONs)
b) Broadband data services over the growing Wireless (Cellular) infrastructure
c) Broadband data services using newly-evolving Digital Subscriber Line (DSL) technology running over the traditional copper telephone lines.

Between 1998 and the present time, each of these three Telco technology areas saw impressive change and growth. These changes are briefly outlined in the following three sections.

A Brief History Of The Telco Industry's PON Evolution (1998 to Present)

In the 1990s, PON was a relatively new point-to-multipoint fiber-based technology that was beginning to see the light of day- it was coming out of the labs and moving into early products and deployments. This timing was fortuitous for many Telcos who were hunting for their next-generation access technologies that might replace copper wire. PON became one of the key areas of focus for those involved in replacement activities. The evolution of PON was helped by early standards work. But it was somewhat slowed by a battle between two different standards efforts (one in ITU-T, and another in IEEE).

One of these standards efforts was originated by an organization of mostly Telco service providers and vendors. This group was called the Full Service Access Network (FSAN) working group, and they then partnered with the ITU-T organization to publish the G.983.1 spec on January 13, 1995. It described an Asynchronous Transfer Mode-based (ATM-based) transport system over fiber, and it was called ATM PON or APON. This APON system permitted operation of a single PON over ~20 km with up to 32 Remote Nodes. It supported 155 Mbps service in the downstream and 155 Mbps service in the upstream. On a single fiber, the APON would operate at 1.55 um wavelengths for downstreams and 1.3 um wavelengths for upstreams. Dual fiber systems were also permitted and would operate at 1.3 um wavelengths for both downstream and upstream transmissions. [OPTI]

With the failure of ATM to gain widespread market acceptance, the specification was quickly modified to create a more Ethernet-friendly version known as Broadband PON or BPON. It supported both 155 Mbps service and 622 Mbps service in the downstream and 155 Mbps service in the upstream. When shared across 32 Remote Nodes, this could yield an average bandwidth of 155 Mbps/32 = 4.8 Mbps per subscriber (a bandwidth that was 85 times greater than that which was achievable by copper wire modem technology). [FREN]

FSAN and ITU-T then began work on a new specification aimed directly at providing service for the highly-coveted 1+ Gbps market. This specification (known as G.984.x or GPON) began development in 2001 and produced final documents in the 2003/2004 time-frame. This permitted first interops of equipment to occur in January of 2006 and first equipment deployments to occur in 4Q07. The GPON specification permitted a 20 km physical reach (60 km with special optics) out to 128 Remote Nodes, and it supported 622 Mbps downstream/622 Mbps upstream operation, 1.25 Gbps downstream/1.25 Gbps upstream operation, and 2.5 Gbps downstream/1.25 Gbps upstream operation. On a single fiber, the GPON would operate at 1.48-1.5 um wavelengths for downstreams and 1.29-1.33 um wavelengths for upstreams. Heavy deployments of GPON began in 2008 and 2009. [TELC]

In 2005, the FSAN and ITU-T began work on another new specification aimed at providing 10 Gbps service. The first specification to result from this effort was the ITU-T G.987 or XGPON1specification. XGPON1was released in the 2009/2010 time-frame, and it permitted a 20 km physical reach (40 km with special optics) to 128 Remote Nodes, and it supported 10.3125 Gbps downstream/1.25 Gbps upstream operation. On a single fiber, the XGPON1 would operate at 1.575-1.58 um wavelengths for downstreams and 1.26-1.28 um wavelengths for upstreams. [HOOD]

XGPON1only gained small market acceptance, so efforts quickly began within FSAN and ITU-T on its successor specification, which is known as ITU-T G-989 or NG-PON2. The first release of the first document for this specification occurred in 2013, and releases of other documents are expected in the future. NG-PON2 supports many different modes of operation based on Time and Wavelength Division Multiplexing (TWDM). Typical modes of operation in early deployments may be supporting 9.953 Gbps downstream/9.953 Gbps upstream operation. However, future versions (based on WDM) may support 40 Gbps downstream/9.953 Gbps upstream operation. It is designed to support up to 256 Remote Nodes, but normal operation will likely see 32-64 Remote Nodes in service. Reaches may range from 20 km to 60 km, depending on split ratios. On a single fiber, the NG-PON2 would operate at 1.596-1.603 um wavelengths for downstreams and 1.524-1.544 um wavelengths for upstreams. These systems are not yet available. [G989]

In parallel with the FSAN and ITU-T specification efforts, the IEEE has a similar effort underway to create a parallel set of standards which are unfortunately incompatible with the FSAN/ITU-T standards.

The IEEE Ethernet in the First Mile (EFM) working group began their PON specification effort in January 2001, with an aim to create a method of delivering 1 Gbps Ethernet service over point-to-multipoint fiber systems. Since they were based on Ethernet from the start, these systems are typically called Ethernet

PON or EPON systems. The resulting specification was called IEEE 802.3ah or EPON, which was released in 2004. It supported 1.25 Gbps service in the downstream and 1.25 Gbps service in the upstream. It is designed to support up to 64 Remote Nodes (although more may be possible). Reaches may range from 10 km to 20 km, depending on split ratios. On a single fiber, the EPON would operate at 1.48-1.5 um wavelengths for downstreams and 1.26-1.36 um wavelengths for upstreams. These systems began to see real deployments in 2005. [KRAM] [TECH]

The IEEE's second PON specification effort was begun in 2006 (as the 10G-EPON Task Force) and led to the creation of the IEEE 802.3av or 10G-EPON specification, which was released in 2009. A related specification defining system interoperability requirements was the IEEE P.1904.1 or SIEPON specification, which was released in 2012. Yet another related specification defining longer reach optics was the IEEE 802.3bk specification, which was released in 2013. It supported 10.3125 Gbps service in the downstream, and 10.3125 (or 1.25) Gbps service in the upstream. It is designed to support up to 64 Remote Nodes (although more may be possible). Reaches may range from 10 km to 20 km, depending on split ratios. On a single fiber, the EPON would operate at 1.575-1.58 um wavelengths for downstreams and 1.26-1.29 um wavelengths for upstreams. These systems were beginning to see real deployments in 2014, and the IEEE is beginning considerations on the next-generation of EPON standards that will likely use WDM techniques to offer even higher bit-rates. [10GE] [ETHE]

With all of the above PON options, the quoted bit-rates are all "raw bit-rates" that would have to be reduced if one wanted to account for the overhead from various forms of line encoding (8B/10b or 64b/66b were common) and MAC framing. Thus, the actual bit-rates available to subscribers would have to be reduced from these "raw bit-rates."

It should come as no surprise that the Telco markets have been bifurcated, as different Telcos have decided to follow different paths with different roll-out strategies. In general, North American and European and South American markets have tended towards the use of the FSAN and ITU-T standards, whereas China and other APAC markets have tended towards the use of the IEEE standards. [HARA]

Nevertheless, one can track the general bandwidth trends provided by the evolving PON technologies. These trends are captured in Fig. 2.

A Brief History Of The Telco Industry's Wireless Broadband Evolution (1998 to Present)

The rapid evolution of improvements found in cellular phone technology and the related wireless broadband technologies during the past 35 years have been legendary. The pace at which improvements have taken place in cellular/wireless broadband technology is quite remarkable, and it has spawned an array of technologies whose names look like alphabet soup.

Due to the large number of cellular/wireless variants that have evolved over time within different regions of the world, the paper will not attempt to track every evolutionary step. Instead, the authors will track large steps to see how this form of Telco service evolved over time.

Cellular phone technology can trace its humble origins to the first generation (1G) analog systems that began to be deployed in the late 1970's and early 1980's. NTT operated the first analog cellular system in 1979. Soon after that, NMT, AMPS, and TACS were three early cellular systems that found deployments in northern Europe, North America/Latin America, and UK/China/Japan, respectively. Frequency modulation and Frequency-Division-Multiple-Access were common in many of these systems. Directional antennae and frequency re-use also became common technologies within these early systems. By 1993, it became apparent that extra bandwidth on the analog AMPS networks could be used to allow the low-bit-rate transmission of IP packet data to cellular phones (primarily for messaging). The maximum data-rate supported on these Cellular Digital Packet Data (CDPD) networks was ~19.2 kbps. This data-rate was much lower than the 56 kbps data-rates that were provided by telephone line modems of the time.

spectral efficiencies of these 2G cellular systems and increases in spectral widths (created by expanded frequency license sales) permitted much higher data-rates and more simultaneous phone calls to be carried over the cellular frequencies. With the advent of 2.5G cellular systems, GSM added General Packet Radio Service (GPRS) support in ~2000 to permit packetized data to be transmitted at the higher data-rates of 56 kbps. Then further enhancements led GSM systems to develop Enhanced Data Rates for GSM Evolution (EDGE), which provided even higher data-rates of 236 kbps.

In 2001, Telcos deployed third generation (3G) cellular systems that began to focus on providing more efficient packet transfers over the wireless interface. The ITU (in conjunction with the 3GPP project) helped to define the International Mobile Telephone-2000 (IMT-2000) standard to help guide this effort. The ETSI organization in Europe created the Universal Mobile Telecommunication System (UMTS) standard from the IMT-2000 work. In the U.S., the IMT-2000 work was modified to create the cdma2000 standard. High-Speed Packet Access (HSPA) was added to the UMTS systems to permit data transmission at data-rates of at least 200 kbps. 384 kbps was a

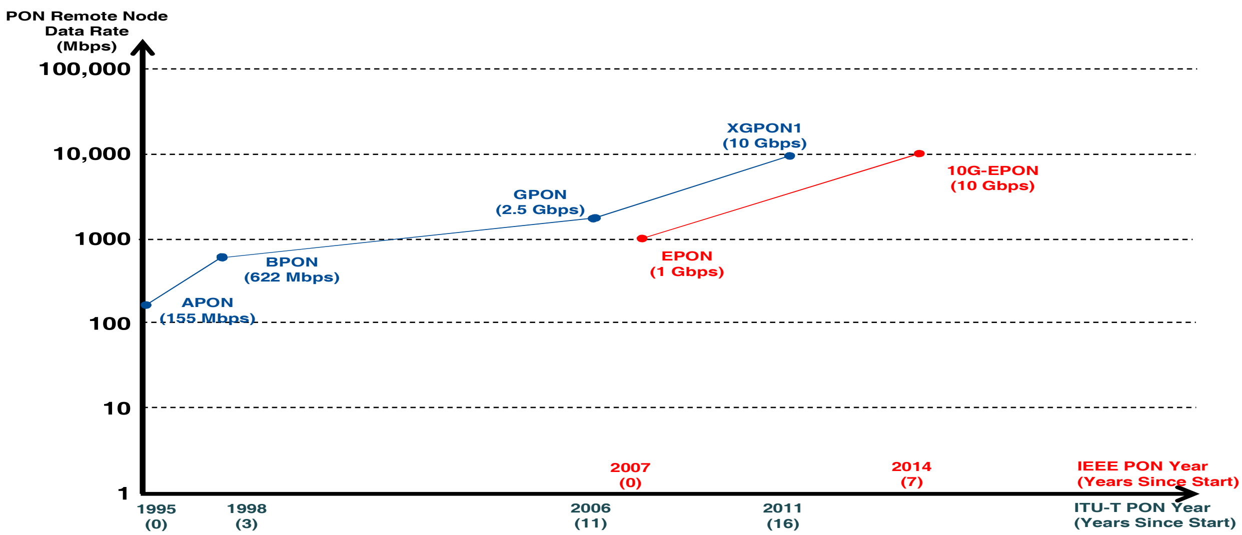


Fig. 2- PON Maximum Downstream Data Rates vs Time

Second generation (2G) cellular systems were introduced in the late 1980's. This new technology helped to transition the cellular market from analog to digital modulation techniques (ex: Time Division Multiple Access and Code Division Multiple Access (CDMA)). Many different types of systems were defined, including Global System for Mobile Communicattions (GSM), IS-54, IS-95 (aka CDMA One), IS-136, and Personal Digital Cellular (PDC). Improvements in the common data-rate for the HSPA systems. A similar data transmission variant known as Evolution Data Optimized (EV-DO) was included in cdma2000 systems. [1G4G]

The 3rd Generation Partnership Project (3GPP) project carried the torch into the fourth generation of cellular systems (known as 4G). The 4G systems would focus on unifying the different technologies that had developed in the cellular space, and it would also attempt to provide higher data-rates, lower latencies, and greater levels of security. Given the name Long Term Evolution (or LTE), the spec opted to utilize Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input-Multiple Output (MIMO) antenna technologies. The first LTE systems were deployed in Stockholm and Oslo on December 2009, but they were not fully compliant with the 4G specs, and were therefore called 3.9G systems. More spec-compliant 4G systems began to be deployed in the 2011-2014 time-frame. [EVOL] These systems offered typical downlink data-rates of 5-12 Mbps, which permitted them to be utilized for the transmission of IP Video streams. [LTES]. Recent augmentations to the spectrum by some Telco service providers are permitting subscribers to experience 30 Mbps peak downlink data-rates (as of 2014). [PEAK]

The 3GPP project standardized a new specification known as 3GPP Release 10 in March of 2011. That specification is also called LTE-Advanced, and will likely serve as the definition for the next generation of broadband wireless services. LTE-Advanced will include many new features, including Coordinated Multi-Point transmission and reception (aka CoMP), MIMO techniques, bandwidth up to 100 MHz, cognitive radio, and Self-Optimizing Network (SON) techniques, and coordinated management of macrocell and picocell and femtocell transmissions to optimize performance. [LTEA]

The general bandwidth trends provided by the evolving cellular/wireless broadband technologies are illustrated in Fig. 3. (Note: There are many variants that could be added to this figure which would change the shape of the curve. However, this curve is adequate for providing general trends).

A Brief History Of The Telco Industry's DSL Evolution (1998 to Present)

While Telcos focused much of their post-1998 investment on other technologies (such as PON and Cellular), there was still a lot of wired Telco plant already deployed in the world. This infrastructure could be utilized to deliver broadband services if enabling technological break-throughs could be found to permit more bandwidth to be transmitted. Techniques to break through the 56 kbps modem bandwidth ceiling were needed. Fortunately, there was ground-breaking innovation being pumped into the old telephone line modem technology- even after 1998. Most of this work was focused on a new technology that came to be known as DSL technology.

The primary difference between DSL and its predecessor copper line technology (dial-up modems) is that DSL attempted to operate without interfering with traditional voice signals that are still operating in the voiceband spectrum below 3.9 kHz. Thus, a voice call and Broadband Internet service could co-exist on the copper loop. In addition, DSL transmissions do not require a telephone connection to be established (and paid for), so it was viewed as an "always-on" technology that could be used continuously without fear of creating large phone bills.

As a result of this basic change, DSL permitted (and required) its loop signals to be bandpass signals residing above 3.9 kHz in the spectrum. These bandpass signals only needed to take on this form for transit across the copper telephone loop, because equipment in the Telcos Central Office would immediately convert the DSL signals into traditional Internet signals (Ethernet or ATM over Synchronous Optical Network or SONET technology) for ultimate transmission through the Internet. This fundamental change in approaches opened the door to many innovations, because the bandpass signals were not constrained to operate within 3.9 kHz of spectrum.

Since the higher-frequency DSL signals cannot pass through loading coils found in many telephone loops, the loading coils are usually removed to permit DSL service to operate. (Note: The removal of these loading coils can make voice service unusable over long distance loops, so there are distance limits placed on the reach of DSL loops. This eventually led to the creation of DSL Access Multiplexers, or DSLAMs, that are placed closer to homes, cutting down on the overall length of most telephone loops).

The first generation of DSL essentially began in 1988, when a group of engineers at Bellcore filed a patent application for a broadband technology that placed the broadband signals on a twisted pair loop above the 3.9 kHz voiceband. The patent proposal argued that the downstream and upstream bandwidth capacities could be asymmetrical, since most data might be transmitted towards the home rather than away from the home.

By 1991, a de facto standard for High-speed Digital Subscriber Line (HDSL) technology was completed by Joe Lechleider of Bellcore, drawing on many of the ideas (such as line equalization) from the Integrated Services Digital Network (ISDN) and T1 technologies that had been used to transport digitized voice signals across the Telcos long-distance telephony networks. It was a two-line system that transported 800 kbps on each line, offering a total of 1.6 Mbps of bandwidth capacity for two-mile loops (limited mostly by crosstalk). It was deployed to a relatively small number of subscribers (since it was limited by the undesirable requirement for two lines), and it was rapidly replaced by the next generation of DSL technology known as Asymmetric Digital Subscriber Line (ADSL).

ADSL had several different and competing proposals for modulation technologies. Carrier-less Amplitude Phase Modulation (CAP) and QAM were proposed by some companies, whereas Discrete Multi-Tone

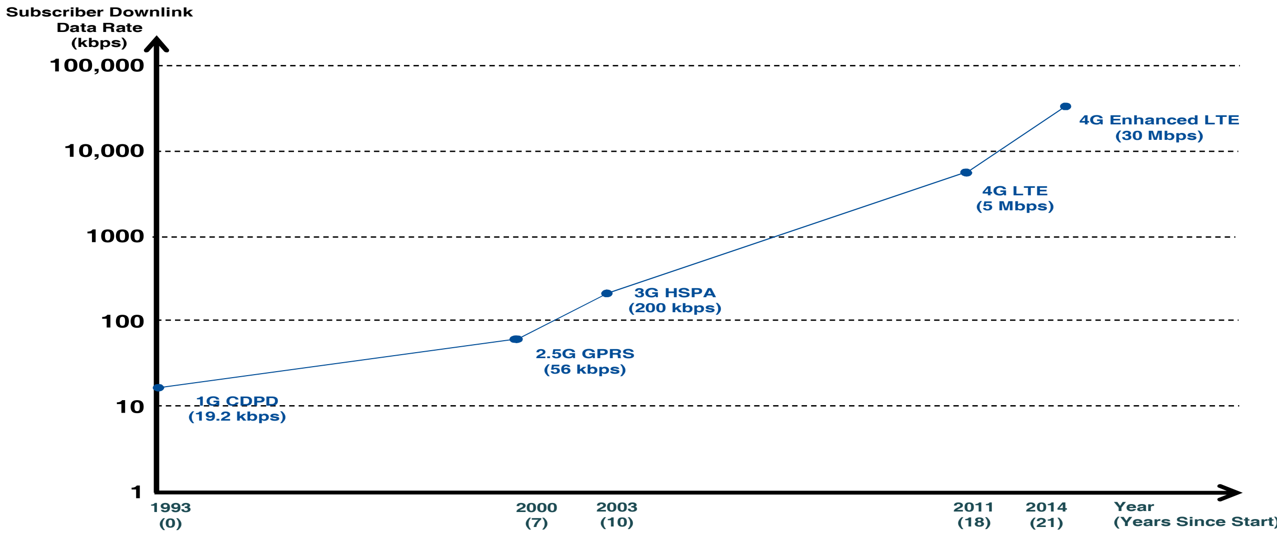


Fig. 3- Wireless Broadband Downlink Data Rates vs Time

(DMT) was proposed by other companies. Eventually, bake-offs showed that DMT performed better by being able to adjust each of its narrow carriers to conform to the varying Signal-to-Noise Ratios in each portion of the loop spectrum. In 1993, John Cioffi's company (Amati) was the first company to produce a working 6 Mbps ADSL product. By 1995, the ANSI T1.413.1995 standard existed, and 6.4 Mbps downstream/800 kbps upstream ADSL modems were being deployed using a 1.1 MHz spectrum, as shown in Fig. 4. An ITU spec for ADSL, known as ITU-T G.992.1, was also ratified in 1999.

Improvements to the ADSL technology eventually led to the ADSL2 spec known as ITU-T G.992.3. These ADSL2 modems operated at 12 Mbps (in the downstream) and 1 Mbps (in the upstream) using new technologies such as improved modulation formats and bonding of multiple lines. Deployments began in 2003.

The ADSL2+ spec (known as ITU-T G.992.5) was then ratified in 2003. These modems operated at 24 Mbps in the downstream and 1 Mbps in the upstream. It accomplished this by doubling the downstream frequency band to be 2.2 MHz wide, and it also added crosstalk mitigation techniques. Deployments began in 2005.

A new spec using slightly different technologies was then created. It was called Very-high-bit-rate Digital Subscriber Line (VDSL), and became the ITU-T G.993.1 spec in 2004. It offered 55 Mbps downstream and 15 Mbps upstream service. Early deployments began in 2004.

By 2005, improvements to the VDSL technology led to the VDSL2 spec known as ITU-T G.993.2. These VDSL2 modems operated at 55 Mbps (in the downstream) and 30 Mbps (in the upstream) for long-reach loops. Alternatively, they can be operated at 100 Mbps (in the downstream) for short-reach loops. VDSL2 utilizes up to 17 MHz of spectrum on the twisted-pair loop. Vectoring technologies (to mitigate crosstalk) and bonding technologies (to use multiple lines into a house) were used within this technology. Early deployments began in 2008. [DIGI] [DSLT] [CIOF]

In 2014, a new DSL set of standards known as ITU-T G.9700 and ITU-T G.9701 were adopted. They are also known as G.Fast. G.Fast is being designed to support a 150 Mbps to 1 Gbps service over loop lengths of 250 meters or less. It can utilize up to 212 MHz of spectrum on the twisted-pair loop, which is much more spectrum than previous DSL spectra. (It is much more spectrum than the early ADSL systems, as shown in Fig. 5a). It also uses Time Division Duplexing (instead of the Frequency Division Duplexing techniques used in previous DSL versions). Deployments of G.Fast are expected to begin in 2016. [GFAS]

When comparing the different DSL spectral efficiencies and spectral widths of ADSL vs. G.Gast, it becomes clear that Telcos have made much more use of spectral width increases and have relied less on spectral efficiency improvements. In fact, they seemed to be willing to accept drops in spectral efficiencies over time (probably due to the lower SNRs found in the regions of the spectrum where they expanded into). However, to continually remain competitive and extend their spectral width, it appears that the Telcos were quite willing to sacrifice network reach. This is somewhat illustrated within Fig. 5b, which includes data from several sources. [WHAT] [GFAS] [VDSL]

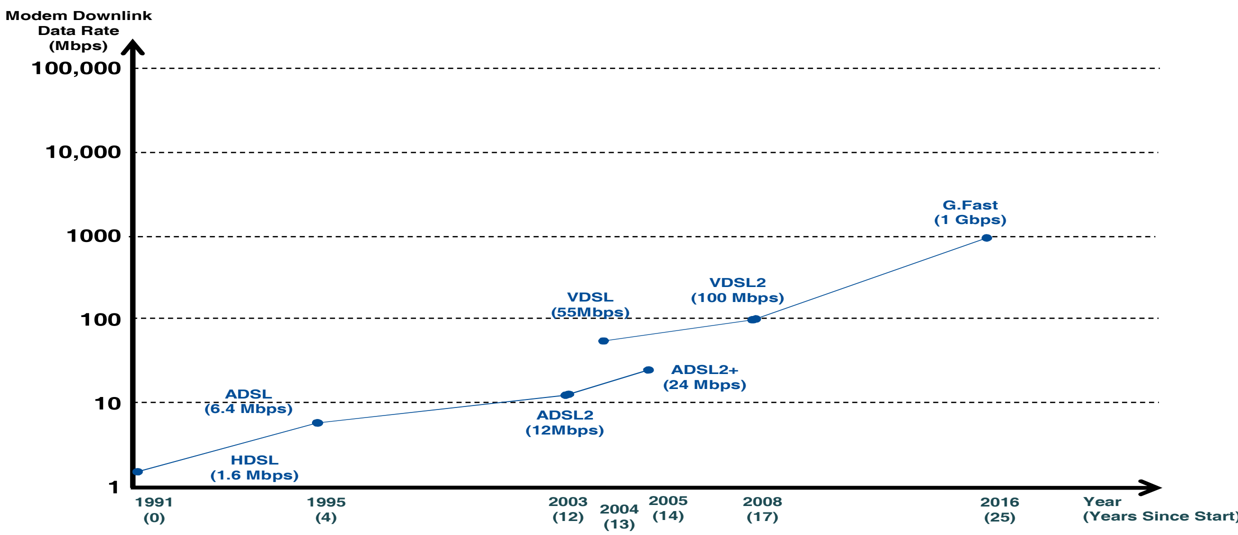


Fig. 4- DSL Downlink Data Rates vs Time

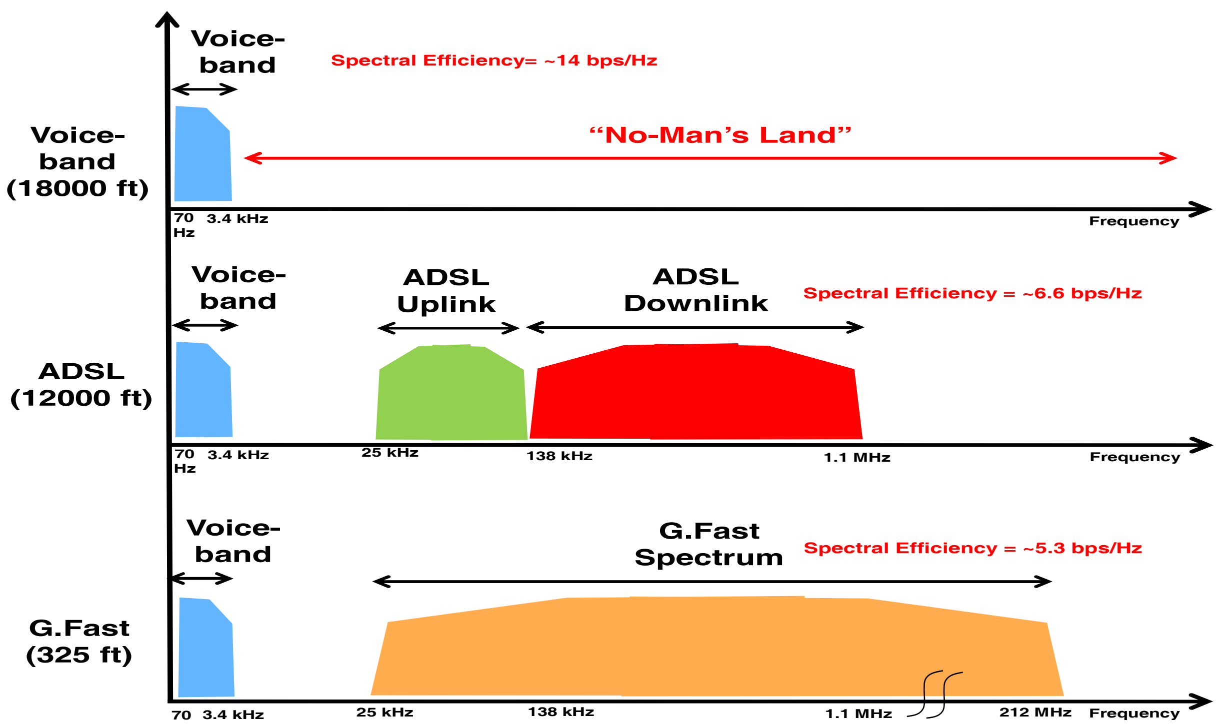


Fig. 5a- New Views on Useable Spectrum for Copper Twisted Pair

DSL ultimately became the predominant broadband technology deployed in Europe and many other parts of the world. Fig. 4 illustrates the bandwidth trends that led to this success. The growth in data-rates since 1998 are remarkable- especially for a twisted-pair copper line infrastructure that was predicted to be near its end-of-life when 56 kbps V.Last technology became available in 1998. The 2016 G.Fast data-rates of 1 Gbps will be approximately 17,857x faster than the V.Last data-rates of 56 kbps. In the 25 years from 1991 to 2016, DSL experienced an average CAGR in data-rates of 29.37%.

It is interesting to compare this CAGR to the CAGR values of other technologies that were studied. These comparisons are shown in Table 1. The data-rate CAGRs range from

Technology	DS Spectral Efficiency	DS Spectral Width	DS Bit-Rate	DS Reach
ADSL (1995)	1.3 bps/Hz	1.1 MHz	1.5 Mbps	18,000 ft
ADSL (1995)	5.8 bps/Hz	1.1 MHz	6.4 Mbps	12,000 ft
VDSL (2004)	7.8 bps/Hz	7 MHz	55 Mbps	1,000 ft
G.Fast (2016)	4.7 bps/Hz	212 MHz	1 Gbps	325 ft

Fig. 5b- Spectral Efficiency and Spectral Width and Bit-rate and Reach for Various DSL Technologies

~14% (for Voiceband Modems) to ~42% (for Wireless Broadband). GPON and DSL both experienced data-rate CAGRs of ~29%. In all cases, definite improvements were seen in the different technologies. It is intriguing to see that DSL provided an average data-rate CAGR of 29% per year, even after Voiceband modems had reached their end-of-life.

Technology	Years	Total Data-rate Increase	Average CAGR
Voiceband Modems	40	186.67	13.97%
GPON	16	64.52	29.75%
Wireless Broadband	21	1562.50	41.93%
DSL	25	625.00	29.37%

Table 1- Data-rate Growth Rates

TRAFFIC ENGINEERING FOR THE CABLE SPACE

A Quick Prediction Of Cable Traffic Engineering For The Future

When will the Cable Industry’s current delivery infrastructure (the HFC plant) reach its end-of-life? Is the Cable Industry at a point where it is ready to enter a “technology transition window” similar to the one experienced by Telcos in the 1998 time-frame? Will Cable MSOs need to immediately embrace new technologies to replace their HFC Plant? Or will they find new techniques to extend the end-of-life of their existing HFC plant in ways that mimic what Telcos were able to do with DSL technologies on their copper loops?

These are all difficult, but important questions that need to be answered. In this paper, the authors will attempt to analyze the decisions made by Telcos over the past 17 years to predict what Cable MSOs might do in the coming future.

However, before looking at past Telco decisions, it would be beneficial to first perform some traffic engineering calculations to predict the amount of bandwidth capacity that will be required within Cable Service Groups of the future. One can then compare those predicted bandwidth capacity requirements to the bandwidth capabilities provided by the HFC plant (with various modifications), and guesses can be created on the expected life-span of the existing HFC Plant.

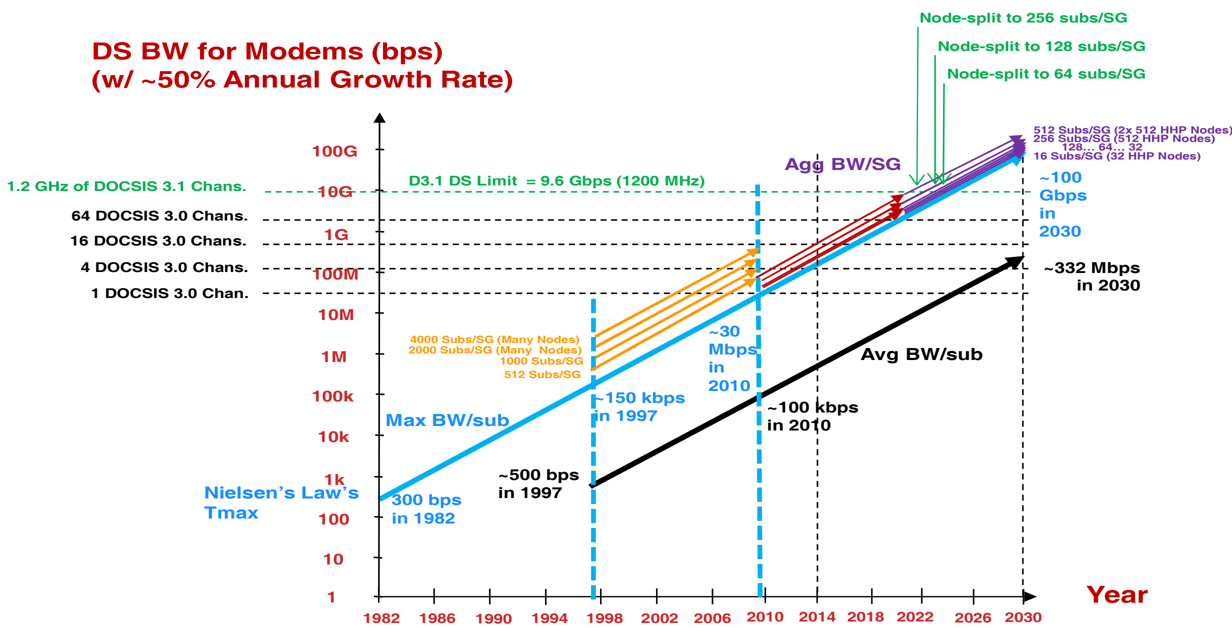


Fig. 6- Bandwidth Trends with 50% CAGR in Future

Recent studies have shown that the required bandwidth capacity for a particular service group can be estimated by knowledge of the Maximum Per-Subscriber Bandwidth Offering (Tmax), the Average Busy-Hour Per-Subscriber Bandwidth Consumption (Tavg), and the number of subscribers (Nsub) in the service group. [CLOO]

Within that study, it was shown that to provide reasonably good Quality of Experience levels to subscribers within a service group, the bandwidth capacity requirements (C) for the service group could be roughly specified by the following formula:

$$C >= Nsub*Tavg + 1.2*Tmax. \qquad (1)$$

It should be noted that other more complex (and more accurate) formulae are also under study [EMM1], but this simple formula will be utilized within this paper to make some key points.

Using formula (1) and predictions about Nsub and Tmax and Tavg trends into the future, one can plot the required bandwidth capacity levels for various sized service groups.

This is done in Fig. 6 for a future where Tmax and Tavg continue to grow with a 50% CAGR (as they have done for the past decades). This is also done in Fig. 7 for a future where Tmax and Tavg grow with a lower 30% CAGR. This lower 30% CAGR is predicted by some MSOs who believe that IP Video streaming created the last big boost in bandwidth over the last several years and that no new applications will likely show up in the near future to continue pushing that 50% pace. Other MSOs still believe that the CAGR will continue at a 50% pace, driven (perhaps) by an upcoming move to 4K video streaming and then to Virtual Reality streaming.

In either case, the plots of Fig. 6 and 7 both illustrate that the HFC plant still has quite a bit of life left in it. In general, MSOs could use DOCSIS 3.1 across a 1.2 GHz plant and sustain the growth rates (with the assistance of a few node-splits) all the way until the mid-2020's (for a 50% CAGR) or the late-2020's (for a 30% CAGR) before the highest Service Tier hits the limit.

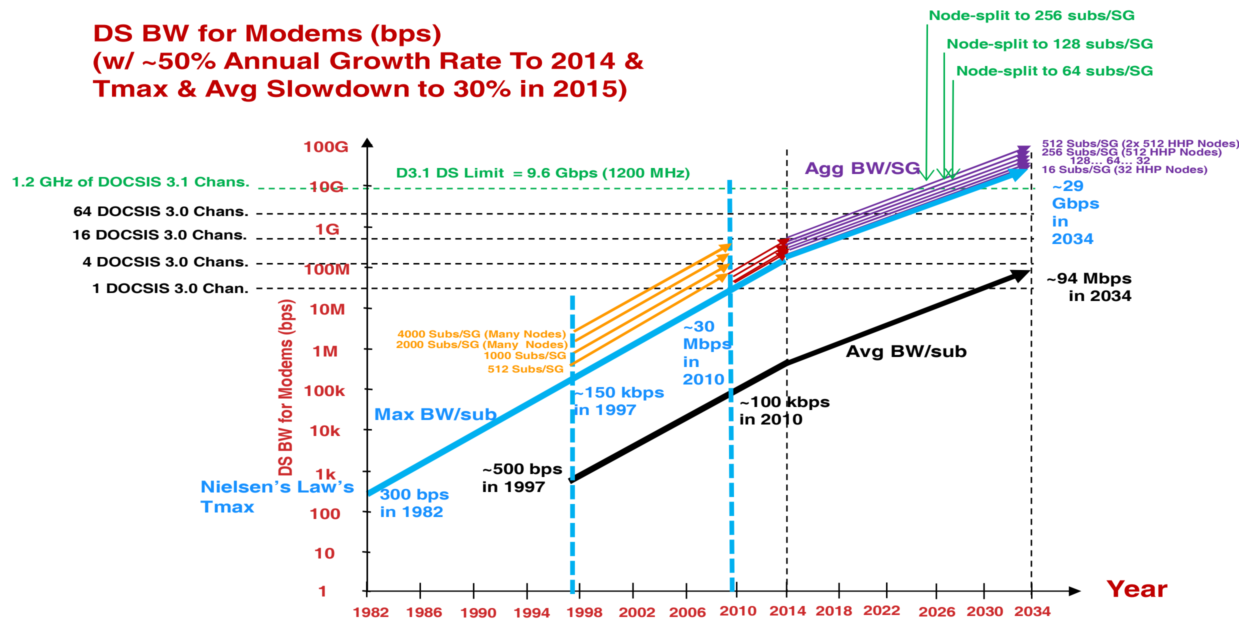


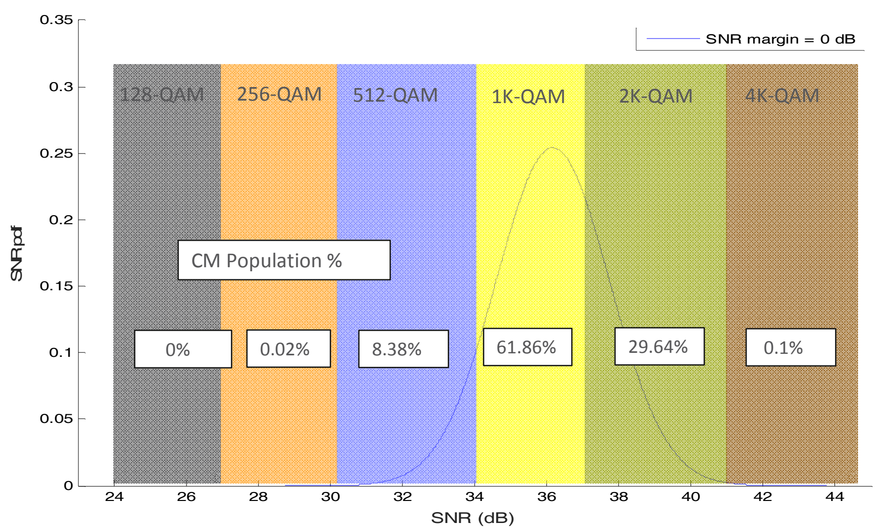
Fig. 7- Bandwidth Trends with 30% CAGR in Future

There is quite a bit of useful information provided by the plots in Figs. 6 and 7. The plot has the Downstream Bandwidth displayed in a logarithmic fashion on the y-axis, and it has the years ranging from 1982 to 2030 on the x-axis

The first curve to explore is the light blue curve, which shows Nielsen's Curve that identifies the expected Tmax values on a year-by-year basis. This curve illustrates that MSOs will likely have to provide higher and higher Tmax values to their subscriber pool on a yearly basis. If these trends continue at a 50% CAGR, then Nielsen's Curve predicts that the Tmax value for a high-end modem may be on the order of 100 Gbps by 2030. The 30% CAGR predicts that the Tmax value may approach 29 Gbps by 2030. One may wonder what applications could possibly require that kind of bandwidth 15 years from now. The honest answer is that the authors do not know what those applications will be—nobody does. But it is probably fair to say that the college students of today will help to invent those impossible-to-identify applications. It is, however, quite feasible that these applications may include 4K/8K IP video streaming, machine-to-machine applications, IoT applications, virtual reality systems, and futuristic holographic display systems.

The second set of curves of interest (in Figs. 6 and 7) that should be explored is the curve set illustrating Average Bandwidth Consumption rates as a function of time. The dark black curve illustrates the approximate average per-subscriber bandwidth consumed by a single subscriber during the busy-hour period of time (8pm-9pm). This curve displays an average value using contributions from both active and inactive users, so the average values (Tavg) end up much lower than the Tmax values. In fact, the Tavg values for a single subscriber tend to be ~300 times lower than the corresponding Tmax values within a given year! However, with a 50% CAGR, the plotted values will grow to be ~332 Mbps by 2030. With a 30% CAGR, the plotted values grow to be ~94 Mbps by 2030.

While a curve for a single subscriber is interesting, it is not very useful for traffic engineering analyses that must examine and predict aggregate traffic patterns for many subscribers in a shared pool (like a Service Group). The single subscriber curve can, however, be scaled upwards in a linear fashion to yield the average bandwidth for a larger pool of subscribers that can share the DOCSIS HSD channels within a Service Group (SG). When that scaled bandwidth is added to 1.2*(Tmax), the authors end up getting the amount of bandwidth predicted by formula (1). The orange, maroon, and purple curves display the scaled-up bandwidth requirements for many different sized Service Groups. It should be noted that two adjacent, parallel lines of any particular color (orange, maroon, or purple) are exactly one node split apart from one another in terms of the bandwidth capacity required to support the Narrowcast services.



Spectral efficiency (bps/Hz)						
8K:	5.628	6.432	7.236	8.040	8.844	9.648
4K:	5.216	5.961	6.706	7.451	8.196	8.941

Fig. 8a- Histogram of SNRs on Typical HFC Plants & Corresponding QAM Order

The dashed horizontal lines mark various bandwidth levels for different numbers (and types) of DOCSIS QAM channels. The green, dashed, horizontal line is the maximum amount of useable bandwidth capacity that would be available if the MSO were to donate ~100% of the 1.2 GHz HFC network bandwidth to DOCSIS 3.1 operation. The resulting bandwidth capacity of ~9.6 Gbps assumes above-average Downstream SNRs averaging ~40 dB and permitting an average DOCSIS 3.1 modulation order of 2048QAM with 8.8 bps/Hz spectral efficiencies across ~1100 MHz of the 1200 MHz spectrum. Fig. 8a shows how this level of performance is possible for *clean* plants in today's HFC network. [ALB1] (Note: It is the belief of the authors that providing an isolation between the access network and the home network can help ensure that many connections to homes could achieve 40 dB SNRs or better).

This level of bandwidth capacity (9.6 Gbps) would support most Narrowcast services until the time-frames indicated by the vertical green arrows within the figures (when the purple curves rise above the 9.6 Gbps threshold level). As can be seen in Fig. 6, this scenario would carry MSOs on their current HFC plant until the mid-2020's (for CAGRs of 50%). In Fig. 7, this scenario would carry MSOs on their current HFC plant until the late-2020's (for CAGRs of 30%).

It is important to note that this traffic analysis is based on Nielsen's Law. As a result, it is focused on the highest speed tier offering (sometimes referred to as the Billboard rate or tier). A study [ULM1] carried out with several large MSOs shows that the number of subscribers within the top Billboard tier actually account for 1% (or less) of the existing cable customers. Another important discovery from this study is that the lower bandwidth Service Tiers are also growing at proportionately lower CAGRs. This is shown within the plot of Fig. 8b.

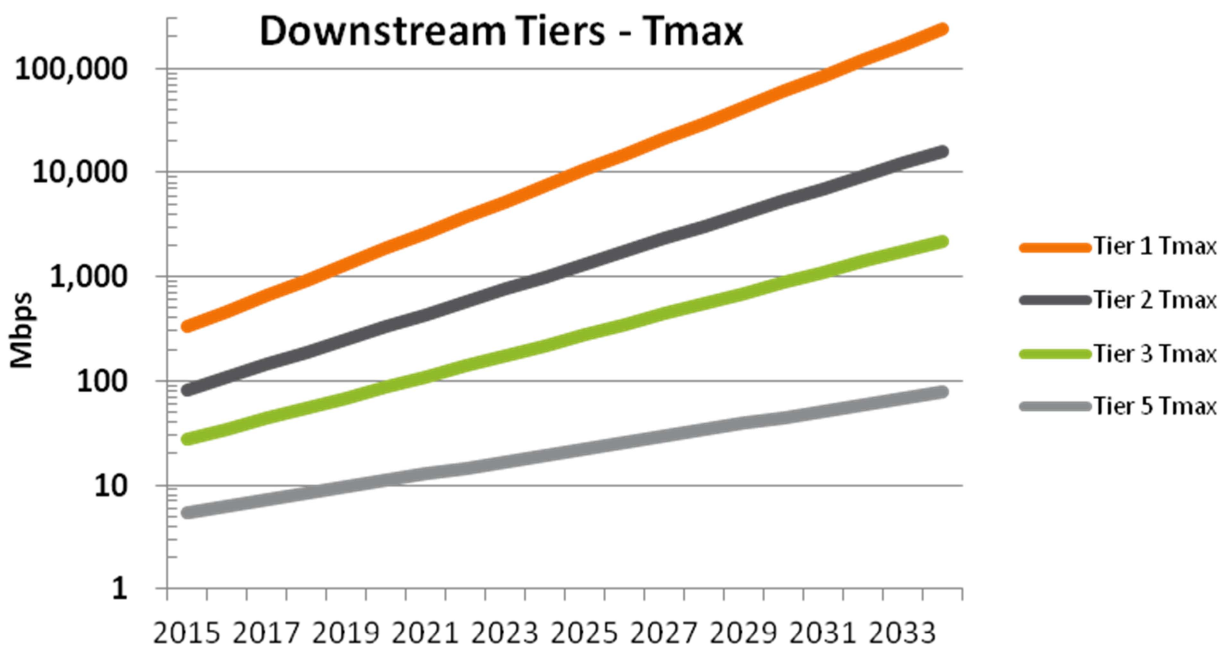


Fig. 8b- Tmax Trends for Different Service Tiers

While the orange Top Tier (Tier 1) is growing at 50% CAGR, it represents only 1% or less of the customer base. Meanwhile the lowest tiers (green & gray) are experiencing lower CAGRs, and they also account for the vast majority of the customers (in the range of 75%-90%+).

From this perspective, the vast majority of subscribers will likely be able to remain on the HFC plant for a much longer period of time than Performance Tier subscribers, while the Performance Tiers (e.g. 1% to 20% of subs) will likely hit the available bandwidth ceiling in the next decade or two. This is similar to what has been seen in the Telco space. While new DSL technology has come along (e.g. VDSL, G.Fast), this is typically being deployed to a limited number of elite customers, whereas the majority of the customer base continues to run on the older DSL technologies. Similarly, the latest and greatest wireless technologies are also rolled out slowly to a limited number of customers for a number of years before the aggregate masses are given access to the new technologies.

So, turning back to Fig. 6 and Fig. 7, one may wonder whether the green-arrow epochs in the late 2020's (where the required bandwidth exceeds the HFC bandwidth capacity) marks the the true ending of the HFC plant? Will that force MSOs to enter a "technology transition window" prior to that time to permit a transition to new technologies and away from the HFC plant by the late 2020's? Is there anything that can be done to extend the life of the HFC plant beyond this late 2020 time-frame? The authors will attempt to answer these question in the following sections.

LESSONS LEARNED FROM THE TELCO AND WIRELESS PROVIDERS

Identifying Categories Of Lessons

In many of the previous sections, the authors outlined a brief history of various Telco and Wireless service providers. The focus was on the technologies that they used during their "technology transition windows" and the bandwidth capacities that they were able to achieve using those technologies.

In this section, the focus will change. Instead of looking at technologies, the authors will focus on some of the lessons that might be learned by looking more closely at what decisions were made by the Telco and Wireless providers as they evolved their networks.

There are both obvious lessons and subtle lessons that can be found if one keeps an open mind. In particular, there may very well be many actions taken by by Telco and Wireless providers as they transitioned their networks that may be candidates for use by MSOs as they move forward into their own future (which will undoubtedly include some modifications to their networks). Some of these ideas may be interesting to MSOs. On the other hand, some others may not be as palatable or practical. But the authors will outline all of them, because sometimes even some of the most outlandish ideas may prove to be valuable tools when push comes to shove and novel solutions are required.

Thus, the following sections will list many of the potential lessons observed by the authors as they researched the history of the various Telco and Wireless providers. Each of these lessons will be placed into one of three categories:

- Category A: Lessons with a high probability of being used by MSOs
- Category B: Lessons with a medium probability of being used by MSOs
- Category C: Lessons with a low probability of being used by MSOs

Lessons learned from the Telco and Wireless providers' past actions will be mapped into each category, and the proposed lesson will be coupled with a potential action that could be considered by MSOs. Obviously, the particulars of the past Telco and Wireless actions will need to be modified to be compatible with the future circumstances of MSOs, but the resulting observations should nevertheless prove to be interesting.

Category A: Lessons With A High Probability Of Being Used By MSOs

There were several lessons learned from Telco and Wireless providers that appear to be quite adaptable to the future that MSOs may face. These lessons are outlined within this section.

Lesson A1: Use Orthogonal Frequency Division Multiplexing (OFDM) and Low Density Parity Check (LDPC) Codes. This permits higher spectral efficiencies that approach the Shannon Limit for transmission systems. These types of approaches have been used for years in both Wireless and DSL systems.

Obviously, these techniques are already being planned for future DOCSIS 3.1 systems, and therefore will be used by MSOs.

Lesson A2: **Assign different modulation orders to subscribers with different Signal-to-Noise Ratios (SNRs) to optimize throughput.** This has been done for years in both DSL and Wireless.

With the advent of Multiple Modulation Profiles in DOCSIS 3.1, these techniques are also being planned for future use within DOCSIS 3.1 systems. As a result, they will undoubtedly be used by MSOs in the very near future.

Lesson A3: **Maximally utilize Moore's Law improvements in silicon and new linearizers/equalizers to permit signal reception with lower SNR and higher distortion.** These types of improvement led to the continual bandwidth increases that have been evident in PON, Wireless, and DSL systems over many years.

Obviously, these improvements in the available technologies are difficult to predict, but there is a reasonably high probability that they will continue to occur into the future. It is not so much a question on "if" the industry will see advances, it is more a question on how fast and when those advances will be available. Thus, MSOs should plan to capitalize on them. As an example, it seems quite possible that continuous improvements in equalization and non-linear distortion cancellation techniques may permit even more advanced corrections of complex high-frequency distortions in the future. This may permit higher and higher frequencies to be transmitted and received on the HFC network. Fiber limits due to nonlinear optical noise and "copper plant" limits due to nonlinear amplifiers may be able to be pushed aside by new pre-processing and post-processing algorithms.

Lesson A4: **Use IP Video as a transport technology for television programming.** Telcos received greate benefit from migrating their infrastructure from analog voice to Voice over IP (VoIP). They have also adopted IP Video transport over DSL and PON for its benefits. The benefits of IP Video include the use of a single back-office infrastructure for delivery to all devices, the ability to transmit across any type of network (to endpoints both inside and outside the home), the statistical multiplexing gains of packet-based delivery on high-bandwidth channels, the availability of high-compression, low-bit-rate video codecs (such as H.264 and HEVC), and the increased bandwidth efficiency gains resulting from Adaptive Bit-Rate (ABR) algorithms which can dynamically change video resolutions.

These approaches are likely to be utilized by MSOs to transmit IP Video signals over DOCSIS channels in the future.

Lesson A5: **Migrate appropriately-selected customers to Fiber-To-The-Premise (FTTP) service as their growing bandwidth needs necessitate this alternative service.** Telcos have successfully targeted new technologies to selecte customers, while keeping the bulk of their customers on older, existing technologies as long as possible to maximinze their return on investments.

FTTP promises much higher bit-rates to subscribers in the long-run, and Telcos have migrated high-end users to FTTP technologies for years as their bandwidths grew to exceed the capacities of twisted-pair wires.

These FTTP approaches are likely to be the end game for most service providers-including MSOs in the distant future. FTTP will therefore be a part of every MSOs plan as they migrate into the future. While the current HFC infrastructure can support most customers needs into the late 2020's and beyond, an eventual move to these FTTP technologies is likely to be a part of the deep MSO future. Unlike Telcos, MSOs have the benefit of being able to choose from several permissible FTTP technologies, including Traditional RFoG, Extended-Spectrum RFoG, and PON. Each approach has its own advantages and disadvantages.

GPON and EPON currently offer 10 Gbps Downstream capabilities with a promise of increased bandwidth capacities in the future. xPON technologies also offer scaling benefits due to their use in both the MSO and Telco spaces.

Traditional RFoG (with its DOCSIS 3.1 modulation orders carried inside of 1.2 GHz or 1.7 GHz spectral widths) could offer 10-15 Gbps Downstream capabilities and permits interoperability with existing customer-premise equipment.

Extended-Spectrum RFoG would eliminate the 1.7 GHz boundary of DOCSIS 3.1, and it would utilize higher spectral widths that could permit (say) 25-50 Gbps Downstream capabilities in the future. The higher bit-rates provided by Extended-Spectrum RFoG could be realized in both the Downstream and Upstream directions due to the fact that separate lamdas are used to transport the two types of signals. With separate RFoG wavelengths allotted for Downstream and Upstream transmissions, it may be possible to fill an 8 GHz Downstream spectrum and a1.2GHz Upstream spectrum with high bps/Hz signaling, including or exceeding 1024QAM. This would yield up to ~10Gbps in the Upstream concurrent with up to ~50Gbps in the Downstream.

Ultimately, cable operators might want to consider this type of Hybrid-PON (HPON) architecture that can simultaneously support a mix of these different FTTP technologies. This would offer the MSOs the best of all worlds and the maximum amount of future-proofing.

<u>Lesson A6</u>: Modify home networks to help increase the capacity of the access network. Telcos showed a strong willingness to do this for their DSL deployments, where they found it necessary to (for example) install DSL filters into the resulting home networks.

Approaches such as these may be applicable to MSOs in the future. For example, recent analyses have shown that the maximum achievable head-end to amplifier on some HFC plants may support very high modulation orders including 4096QAM while some HFC plants may support a maximum 1024QAM to the amplifier. [EMM2] However, the propagation of the signals from the head-end to the cable modem (through the home network) can oftentimes degrade the SNRs to much lower levels that will only support 1024QAM (or even less). [EMM2] [ALB2] These scenarios are captured in Fig. 9a and Fig. 9b. The resulting conclusion is that MSOs (like Telcos) may find benefits from physically separating their access network from their home networks. This may be accomplished using 2-port gateways at the portal into the home for the DOCSIS systems of the future.

<u>Lesson A7</u>: Use different access technologies in parallel to match appropriate bandwidth capacity to each subscriber. Telcos have been doing this in extreme ways ever since they introduced cellular network services (for mobile subscribers) and fiber network services (for high-bandwith subscribers) on top of their already-existing twisted-pair services (for normal-bandwidth subscribers). In many regions of the world, Telcos are managing all three of these services within the same region. They are even looking to expand to another

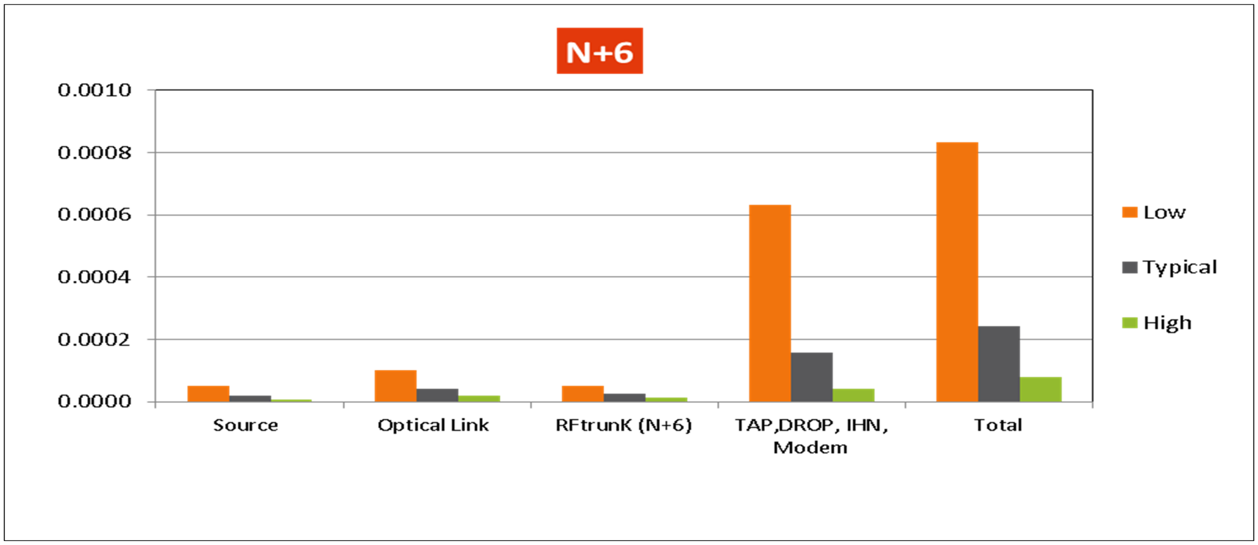


Fig. 9a- 1/CNR (linear scale) for different segments composing the N+6 network (centralized architecture)

form of more localized wireless service through the use of LTE-U technologies. While the parallel use of these technologies leads to increased operational complexities, the use of centralized, software-based management platforms has simplified the management of these various access technologies.

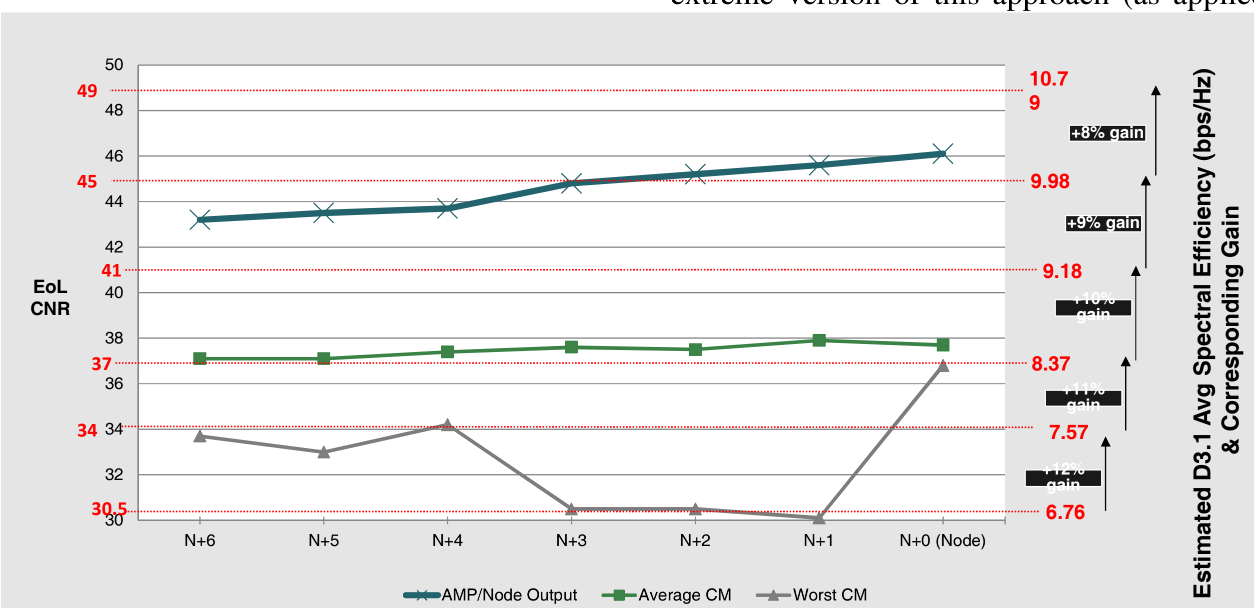


Fig. 9b- EOL CNR & Spectral Efficiency at various points in HFC Plant

MSO's may very well find themselves in a similar predicament as they move forward in time. They will likely have the HFC network operating for many years to come. In addition, they may be managing new fiber-based solutions (using PON or RFoG) as well as new wireless-based solutions (using WiFi or LTE-U). Each service will be paired with appropriate subscribers based on the bandwidth needs of each subscriber. An extreme version of this approach (as applied by an MSO) might include the use of Coax, Fiber (PON or RFoG), and WiFi/LTE-U all entering the home in parallel, as shown in Fig. 10. While extreme, it is nevertheless quite

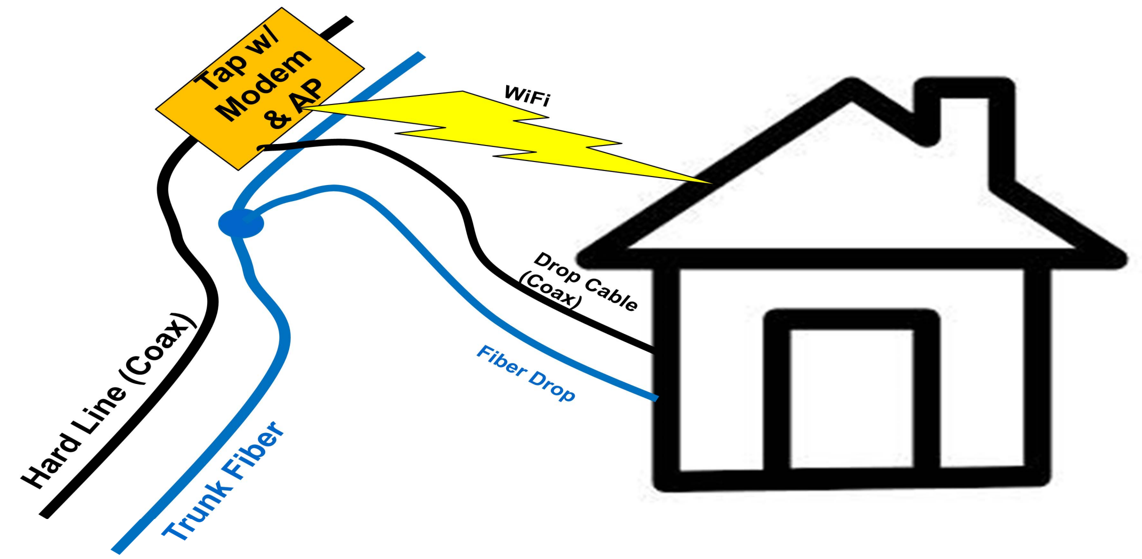


Fig. 10- Parallel Access Technologies Into The Home

possible that the natural evolution of the Cable plant could lead to a situation where all three of these technologies will be available to the MSO for driving bandwidth into the home. DOCSIS Provisioning of EPON (DPOE) and DOCSIS Provisioning of GPON (DPOG) obviously help to manage several of these different technologies using a common DOCSIS management infrastructure. Perhaps a DOCSIS Provisioning of WiFi (DPOW) definition will further expand the benefits of that common DOCSIS management infrastructure in the future.

<u>Lesson A8</u>: Use centralized, software-based management of network infrastructure platforms (ex: IMS & SDN). Telcos moved in this direction with their Intelligent Network (IN) efforts for fixed networks. They continued to support this approach with the development of the IP Multimedia Subsystem (IMS) to support Internet traffic on the traditional telecommunication networks. They then began showing early interest in Software Defined Networks (SDNs) to manage all network elements from a single logical control element. All of these approaches share some common elements. They all are based on open standards; they all attempt to subdivide control and dataplane functionality into separate sub-systems; and they all attempt to permit providers to more easily manage solutions from multiple vendors.

Portions of the IMS protocols (ex: SIP) have already been utilized by MSOs. In addition, SDN approaches are currently being studied by MSOs, and the MSOs may find similar benefits in their application of these types of technologies in the near future. These centralized, software-based management systems could be useful in managing the complexity of multiple access technologies or multiple Remote Gadgets in the future.

<u>Lesson A9</u>: Use Distributed Access Architectures to help deliver services. Telcos have used this approach quite successfully with DSL services. DSLAMs were placed outside of central offices to provide the final connections to the subscriber. High-bitrate fiber connections were typically used for connectivity to the DSLAMs.

MSOs may choose to move in this direction as well. Studies on various Remote Gadgets or Distributed Access Architectures (ex: Remote CCAP, Remote PHY, Remote MAC+PHY) are already under way.

<u>Lesson A10</u>: Use Carrier-Class equipment to ensure high service availability. Telcos have always taken high availability to be a keystone of their wired service offering. The wired telephone network has always been considered a "lifeline service" whose operation was critical to the survival of subscribers during life-threatening events.

MSOs are also working to build a Carrier-Class network. These efforts will undoubtedly pay off as subscribers are likely to continue to demand that level of service in the future.

<u>Category B: Lessons With A Medium Probability Of Being Used By MSOs</u>

There were several lessons learned from Telco and Wireless providers that may be interesting to MSOs in the future. Some MSOs may find these medium probability lessons to be interesting. Others may not find them useful. These medium probability lessons are outlined in this section.

<u>Lesson B1</u>: Expand channel spectrum to maximize channel capacity. In their DSL bandwidth expansions, it seems that Telcos realized early on that a K times increase in spectral width will oftentimes yield higher overall bandwidth capacities- even with a corresponding $1/(K+\varepsilon)$ decrease in power spectral density, implying that the total channel power is held constant. (Note: The ε value in the power spectral density formula above is included to account for any additional signal power loss due to increased signal attenuation or due to amplifier/active element distortions sometimes found in the higher frequency portion of the spectrum where the spectral expansion usually takes place).

A similar application of this rule in the MSO space would imply the use of Extended-Spectrum DOCSIS 3.1. This would ignore the current limits of 1.2 GHz or 1.7 GHz on DOCSIS 3.1, and extend the spectrum beyond those limits. For example, if a DOCSIS 3.1 system is already operating with (say) 4096QAM in 1 GHz of spectrum, then the application of a K=4x spectrum increase (with ε=0) would result in a spectrum expansion of 4x to 4 GHz of spectrum. However, if total signal power levels are maintained at the same level, then the power spectral density reduction would be ~6+ dB (in power per MHz). The ~6 dB reduction might therefore require the MSO to reduce their modulation order by two levels from 4096QAM (with a12 bps/Hz raw spectral efficiency) to 1024QAM (with a 10 bps/Hz raw spectral efficiency). This yields a 10/12 reduction in spectral efficiency. Even with this decreased modulation order, the gains from the spectral expansion out-weigh the losses from the lower modulation order, and the overall increase in bandwidth capacity would be given by 4*(10/12) = 3.33x, as shown in Fig. 11a. This increase would obviously be decreased for values of ε greater than zero (due to increased attenuation or distortion in the new spectrum), but nevertheless there might still be a sizable increase in bandwidth capacity resulting from the spectral expansion (as experienced by the Telcos). Whether this effect is beneficial to MSOs or not would undoubtedly be a function of the cost of the upgrade as well as.

Historically, MSOs have resisted plant upgrades that require them to expand the plant spectrum. Even as they are currently discussing spectral expansions for DOCSIS 3.1, most MSOs seemingly avoid consideration of spectral widths that might exceed 1.2 or 1.7 GHz. Telco history implies that MSOs may want to consider using this Extended-Spectrum expansion in all three of the media on which they will likely be transmitting signals in the future- on the HFC plant, on FTTP plant, and over Wireless.

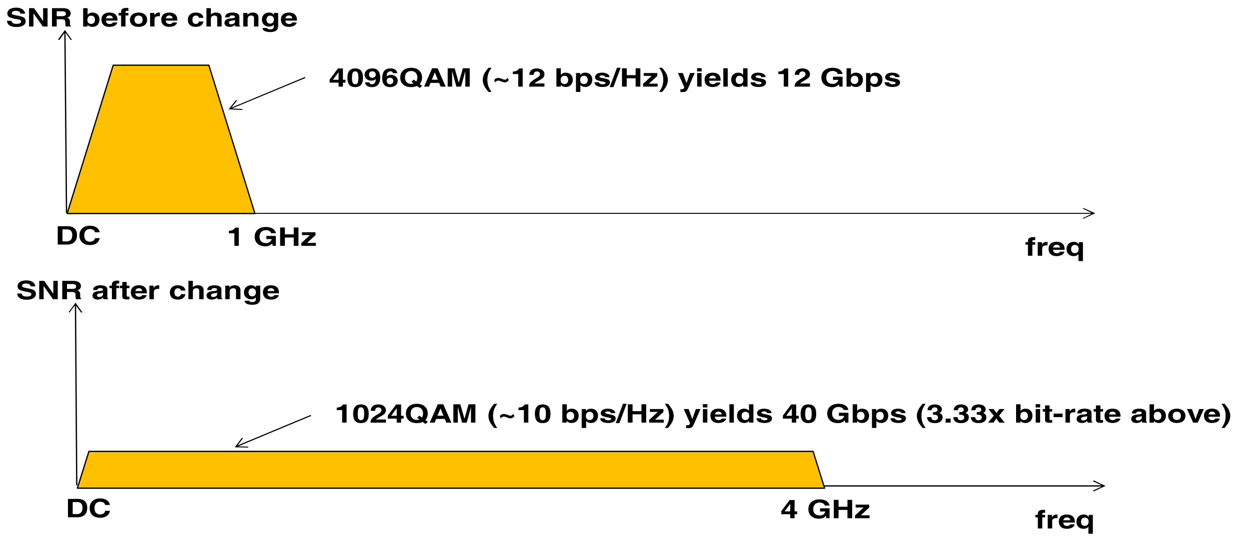


Fig. 11a- Benefits of Spectral Expansion

<u>Lesson B2</u>**: Increase the reach of digital fiber runs and decrease the reach of the twisted-pair (copper) access network to decrease attenuation and maximize SNR and increase QAM Modulation levels.** This practice was very common in the DSL space, and it was often implemented in conjunction with the spectrum expansion described in the previous lesson. Over a 21-year window of time, Telcos reduced their copper loop reach from 18,000 feet to 325 feet, while oftentimes adding more Ethernet or PON fiber length to reach the deeper DSLAMs. Each of the distance reduction operations enabled another round of spectral expansion and bandwidth capacity improvements to be supported on the existing twisted-pair infrastructure.

MSOs are already employing this technique (to some extent) with Fiber Deep architectures that extend the reach of the fiber and decrease the reach of the coaxial connections within the HFC network. However, they could choose to go to more extreme fiber depths (and shorter coaxial runs) to better mimic the actions of the Telcos. For example, Fig. 11b shows the potential of a Very Deep Fiber architecture with shared coaxial runs that might be limited to coaxial distances of less than 1000 feet.

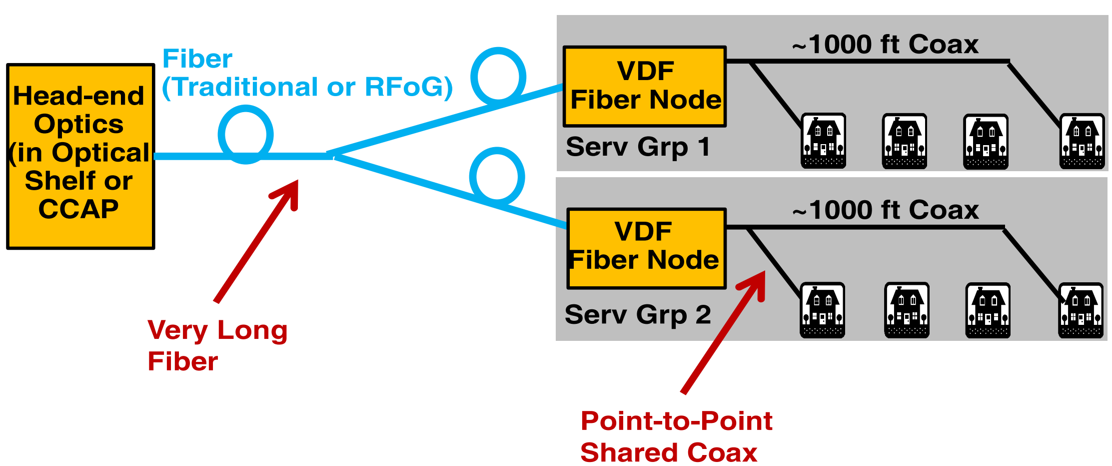


Fig. 11b- Very Deep Fiber (VDF) Shared Coax Technology

<u>Lesson B3</u>: Use "Selective Subscriber Shedding" to move heavy users to alternative transport technologies. This approach proposes to identify heavy users and move them off of the primary infrastructure onto an alternative infrastructure. This approach intrinsically leads to improvements in the performance of the primary transport technology. It is beginning to be used by Wireless providers as they create alternative technologies (picocells and femtocells) to carry heavy localized traffic without congesting the capacity on the primary macrocells in their Wireless infrastructure. The creation of the picocells and femtocells is essentially being done to protect the performance of their primary infrastructure investment (the macrocell). It basically allows heavy users to be moved to the small cells and reduces congestion on the marcrocells.

It is possible that MSOs may also want to adopt this policy for protecting the service level on their primary infrastructure investment (the HFC network) going forward. In particular, MSOs may want to provide an alternative infrastructure (such as a FTTP system or a Fiber-To-The-Curb (FTTC) system based on RFoG or PON) to which they can connect their high-usage and/or high-end Service Level Agreement (SLA) subscribers. If these subscribers are serviced by the alternate infrastructure, then their traffic is removed from the general HFC network, leaving the remaining customers with higher bandwidth capacities that are available to be shared by a smaller number of people. If all of the high-end SLA customers are removed from the network, this also gives the added benefit that the required bandwidth capacity for the service group (as given by Eq. 1) is reduced, because the Tmax term in the formula would be reduced to the next lower SLA level. This fact is illustrated in Fig. 12a.

Fig. 12b shows the benefits that might be obtained from the careful application of Selective Subscriber Shedding. If subscribers are only shed to alternative technologies when available HFC bandwidth capacities become overloaded and if the service tiers have different Tmax values as shown in Fig. 8b, it becomes clear that MSOs could offer services to a large percentage of their subscribers on their existing HFC plants deep into the 2030 time-frame. [ULM1]

<u>Lesson B4</u>: Use automated handoffs to permit efficient movement of traffic between wireless and wired technologies. MSOs have now begun to support Voice over LTE (VoLTE) to Voice over WiFi (VoWiFi) handoffs that give subscribers better performance levels inside of buildings and also protect their primary infrastructure (i.e., the macrocell) from congestion. [HAND]

MSOs may want to provide similar technologies to their subscribers. Once WiFi is provided by the MSOs, this convenient service will undoubtedly help reduce subscriber churn. It can be offered for voice, video, and data services.

<u>Lesson B5</u>: Focus roll-outs of new wired technologies on aerial plant systems where costs are minimized. Telcos have oftentimes focused their new feature rollouts on the easier-to-modify aerial plant systems, and later decided whether to continue the rollouts on buried plant. It is a convenient and cost-effective way to quickly roll out services-especially those that require new hardware.

MSOs have followed similar paths, and may want to use the same tricks in their own networks within the future. They can perform the required hardware modifications for future rollouts of Deep Fiber systems or Remote Gadget systems or FTTP systems or other systems on aerial plant systems first wherever permissible. Costs are reduced by following this approach. Once proven, the MSOs can then decide if they want to extend the changes to non-aerial systems (based on Return On Investment calculations).

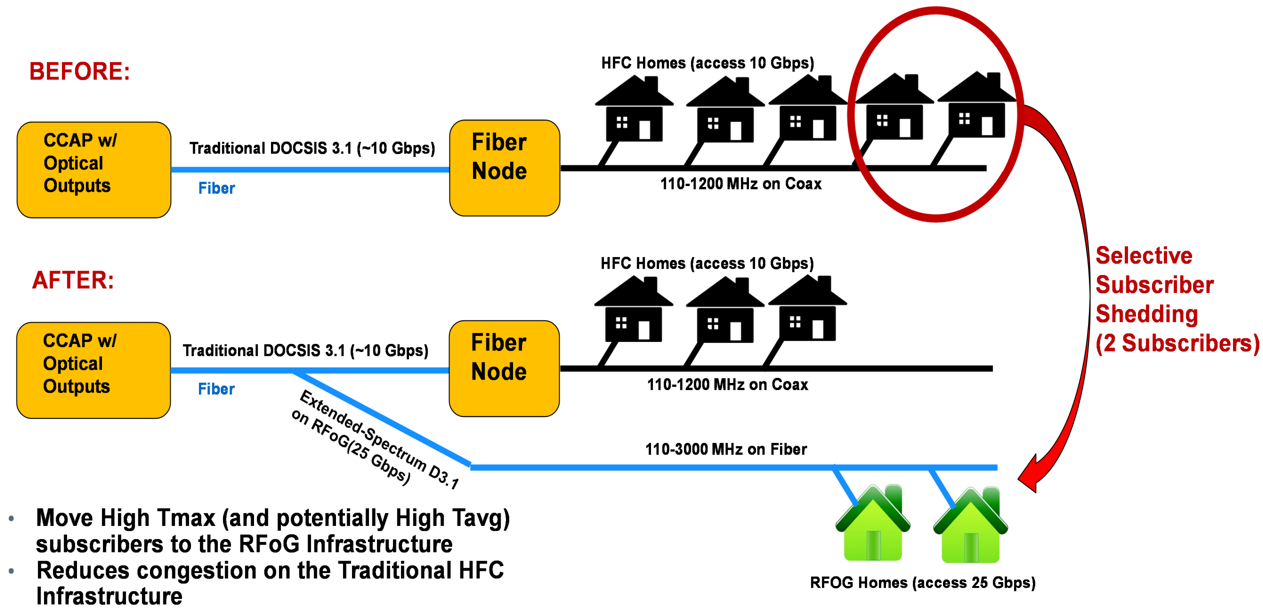


Fig. 12a- Selective Subscriber Shedding Example

Lesson B6: Use envelope-tracking, power-efficient amplifier sub-systems. These approaches have been optimized for applications within the LTE space, and Wireless vendors have placed great focus on distortion-correction within these systems. [JHAM]

These types of approaches may become applicable to cable head-end and access equipment in the future, because reductions in power consumption will become more and more important to MSOs over time.

Category C: Lessons With A Low Probability Of Being Used By MSOs

There were several lessons learned from Telco and Wireless providers that may be considered improbable (or even "crazy") for most MSOs to consider using in the future. Nevertheless, in the spirit of being open to all potential ideas and since it is feasible that some MSOs may find these low probability lessons to be interesting to explore, the lessons will be outlined in this section.

Lesson C1: Use fiber-to-copper media converters that are positioned extremely close to the homes to minimize twisted-pair (copper) attenuation. Telcos have been moving their DSLAMs and their G.Fast

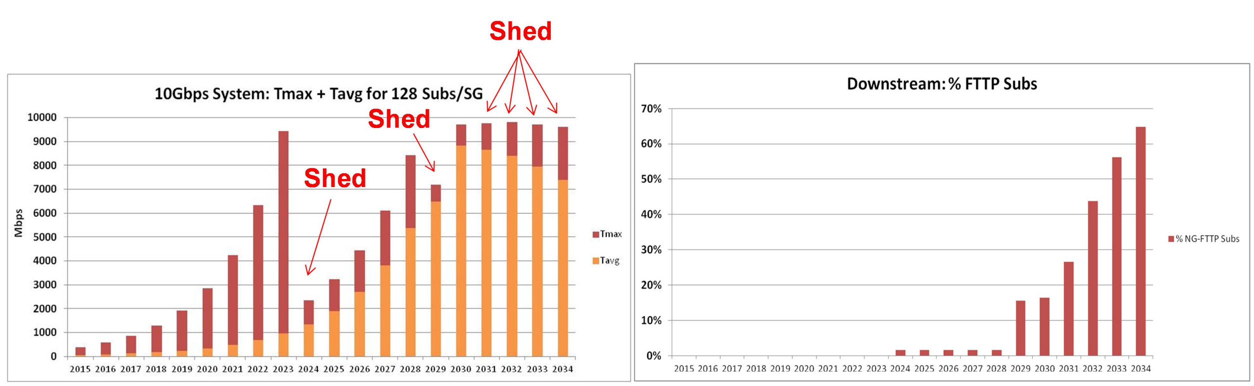


Fig. 12b- Bandwidth Required in HFC Service Group & Shed Subs in FTTH Service Group vs. Time

Distribution Points closer and closer to the home over time in an attempt to minimize signal loss and distortion in the twisted-pair portion of their transmission system. These moves have been costly, but the ability to continue to provide acceptable bandwidths to subscribers have warranted the moves, and the moves intentionally eliminated the expensive step of running new fiber connections all of the way to the house. As they make plans to move to their next generation of equipment (G.Fast), Telcos will be placing Distribution Points 300-600 feet from each house, and a single Distribution Point may only service 8-16 homes.

MSOs have also been moving their Fiber Nodes closer and closer to homes over time. However, Very Deep Fiber systems with coaxial reaches as short as 600 feet are seldom discussed or considered by most MSOs as they picture their future HFC networks in the 2020's. Perhaps those type of systems should be considered as MSOs move into the future. While this approach may seem extreme, it is feasible that some MSOs may find that business case analyses dictate that a similar path be followed for their HFC plants. In particular, for non-aerial plants in densely-populated urban areas where a plant re-build could require expensive city permits, the concept of continuing to re-use much of the already-deployed HFC coaxial infrastructure through backyards may prove appealing. This could lead MSOs to move Fiber Nodes much closer to the homes and having fewer and fewer homes per Fiber Node. The extension of the fiber required to support these Very Deep Fiber (VDF) systems could be accomplished in any one of several ways. It could be done by new trenching through existing easement areas. It could also be done in a less disruptive fashion using new technologies such as those that propose to core out the existing coax and create a conduit from the remaining plastic jacket where new fibers can be pulled [DEEP]. Whether MSOs will ever follow the lead of Telcos and have Fiber Nodes positioned within 600 feet of the houses and supporting only 8-16 houses is unclear. However, Very Deep Fiber (VDF) systems may very well find applications in the Cable space (for some MSOs) in the future.

Lesson C2: When necessary, draw electrical power from subscriber homes to power outside plant network equipment that is connected via copper connections to the homes. This approach (also known as reverse powering) is a controversial topic that is being considered by Telcos as they plan deployments of their G.Fast Distribution Points that are very close to the houses. The issue results from the fact that it is difficult to deliver power to the large number of Distribution Points that need to be positioned throughout the serviced neighborhoods. Whether subscriber-supplied power will be maketable or not is still up for debate. Those who argue that it may be marketable state that subscribers are already willing to supply the electrical power for their CPE equipment, and the Distribution Point could be envisioned to be an extension of the CPE equipment.

Only time will tell if this approach is marketable to consumers or not. If it is, then MSOs who choose to deploy Very Deep Fiber (VDF) systems could start to consider using electrical power delivered from the houses and over the coax as a source of power for their Very Deep Fiber Nodes.

Lesson C3: Use bonding of multiple physical connections into each home to boost the per-subscriber bandwidth capacity into the home. This approach to delivering a higher bandwidth service to homes has been common-place within the Telco space for many years. Two or more physical twisted-pair lines were oftentimes pulled into homes or businesses to offer multi-line voice service. In addition, ISDN used bonded twisted-pairs to offer higher bandwidth capacities. Different physical DSL lines have also been bonded by the Telcos in the past to increase total per-subscriber bandwidth capacity. In all of these cases, Telcos found it beneficial to physically pull a second line into the home to offer the required bandwidth capacity. [2LIN] [ISDN] [BOND]

MSOs have already realized the benefits of a limited amount of bonding through the use of channel bonding in DOCSIS 3.0 systems. That form of bonding permitted two or more channels on a *single* coax to act as a single logical channel, increasing the total bandwidth capacity injected into the home. However, DOCSIS 3.0 channel bonding was typically limited to operation on a single physical coax entering the home.

To better mimic the behaviors of the Telcos, MSOs would have to be willing to drop two or more coaxial cables into a single home. Each additional drop coax added to a home would obviously increase the Operation Expenses associated with the installation, but once installed, it would provide another spectrum's worth of bandwidth capacity into the home, as shown in Fig. 13.

Alternatively, one coax into the home could be dedicated to Downstream bandwidth while the second coax into the home could be dedicated to Upstream bandwidth, which would be quite compatible with Extended-Spectrum RFoG systems of the future. Another form of potential bonding that could be explored by MSOs in the future might be a bonding group created by the combination of the existing coaxial cable drop and a Fiber drop and a WiFi drop running in parallel into the home. Steering of packets across the three links of different technologies would have to be managed by a "super CCAP" box either in the head-end or in a Remote Gadget node. (See Fig. 14). Whether or not this type of Cable broadband delivery into the home is desirable to MSOs will undoubtedly be determined by business case analyses that look at the cost and the ultimate Return On Investment.

<u>**Lesson C4**</u>**: Use point-to-point (un-shared) copper connectivity into each subscriber's home to maximize each subscriber's bandwidth capacity.** This is not a new innovation recently discovered by the Telcos; this was the standard mode of operation since telephone service deployments were initially deployed in the 1800's- one home, one twisted-pair loop. (Note: Party lines did share twisted-pair loops, but they were not the norm for most Telco

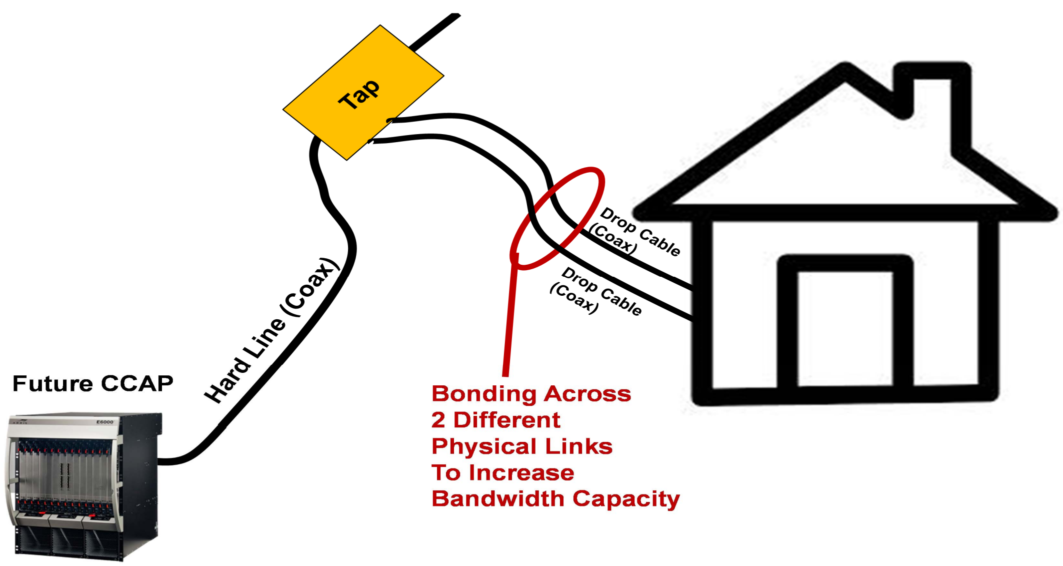


Fig. 13- Bonding Across Multiple Physical Links

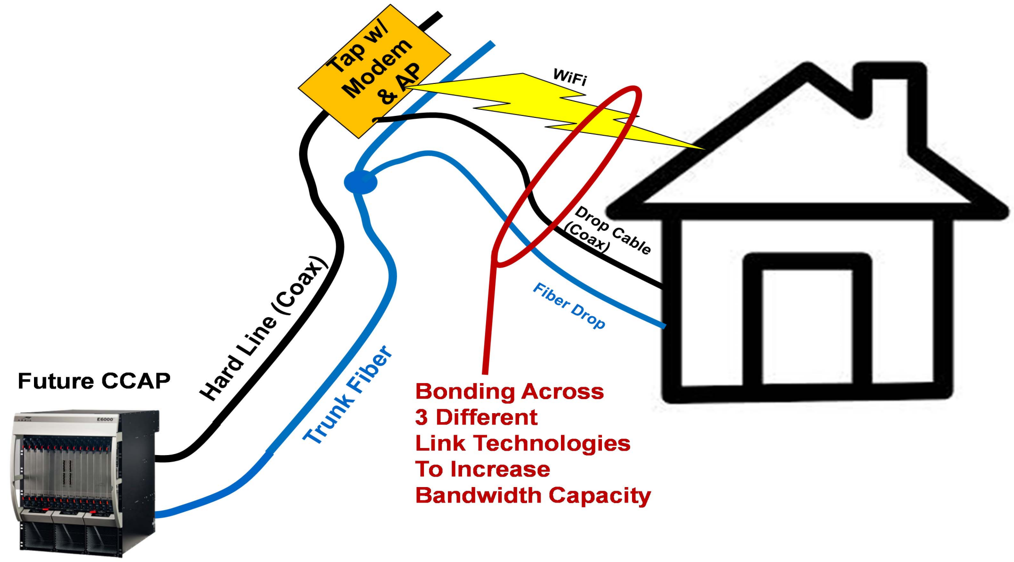


Fig. 14- Bonding Across Multiple Link Technologies

deployments). The disadvantage of un-shared copper connectivity was that many twisted-pair loops had to be deployed. However, the benefit of un-shared copper connectivity is that the bandwidth into a home is fully useable by the subscribers within that home. Thus, as the required per subscriber bandwidth capacity became larger and became more difficult to pass over a twisted-pair connection, Telcos were aided by the fact that the bandwidth on a single twisted-pair connection only needed to satisfy a single subscriber home. In addition, a "home-run" connection directly from the DSLAM or Distribution Point into an in-home modem minimizes signal degradation and micro-reflections.

MSOs may resist transitioning to this extreme form of point-to-point architecture that utilizes un-shared connections. It is very different from the current shared approach that has characterized HFC architectures since their inception. The transition would probably require large Operation Expenses to be committed to the transition. However, if MSOs did want to consider this approach as a means of capitalizing on that last 200 feet of coaxial drop cable that is already buried underground in the backyards of most homes, then they could choose to do it in at least one of two ways.

The first technique could use a "Drop from the Node" architecture that extends every point-to-point drop coax all the way back to a modified multi-drop Fiber Node, and the modified multi-drop Fiber Node would have to have a larger number of RF ports than is common today. (See Fig. 15).

This approach might be called the Very Deep Fiber (or VDF) point-to-point technology, and it is probably most applicable when an MSO has finally deployed a Node+0 architecture that eliminates all amplifiers within the coaxial portion of the network. For example, if future multi-drop VDF Fiber Nodes were moved deeper into the network and had (say) 32 homes connected to each multi-drop Fiber Node, then the multi-drop VDF Fiber Node would have to support 32 distinct and separate RF ports, where each RF port could feed an un-shared, point-to-point coaxial link to exactly one home. Each VDF Fiber Node could be assigned its own pair of lambdas on the fiber (for downstream and upstream transmissions), or RFoG OBI

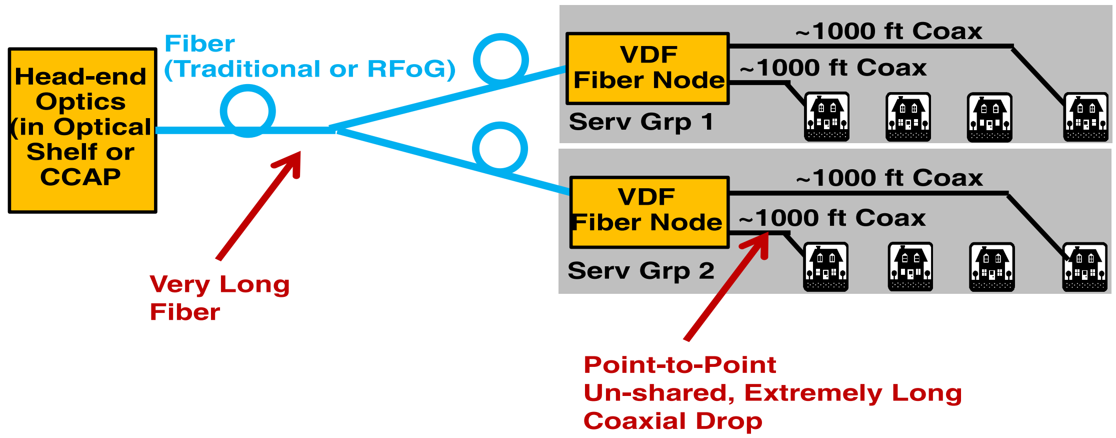


Fig. 15- Very Deep Fiber (VDF) Point-to-Point Technology

Mitigation techniques (such as Hybrid-PON technology) could be employed in the upstream direction. RFoG could then be used to permit multiple VDF Fiber Nodes to share a pair of lambdas on the fiber (which helps to conserve lambdas on the fiber). This VDF approach would obviously require the investment of a coaxial pull from each tap back to the multi-drop VDF Fiber Node (or the installation of a coaxial bundle from the multi-drop VDF Fiber Node to each of the tap locations). This VDF technique would have technique could use a “Fiber To The Tap” (FTTT) architecture that delivers the fiber all the way to the tap in the backyard. (See Fig. 16).

The approach might be called the Extremely Deep Fiber (or EDF) point-to-point technology. It would obviously require the investment of a fiber pull through the neighborhoods and would require the replacement of taps with small EDF Fiber Node-like devices. Each EDF Fiber Node

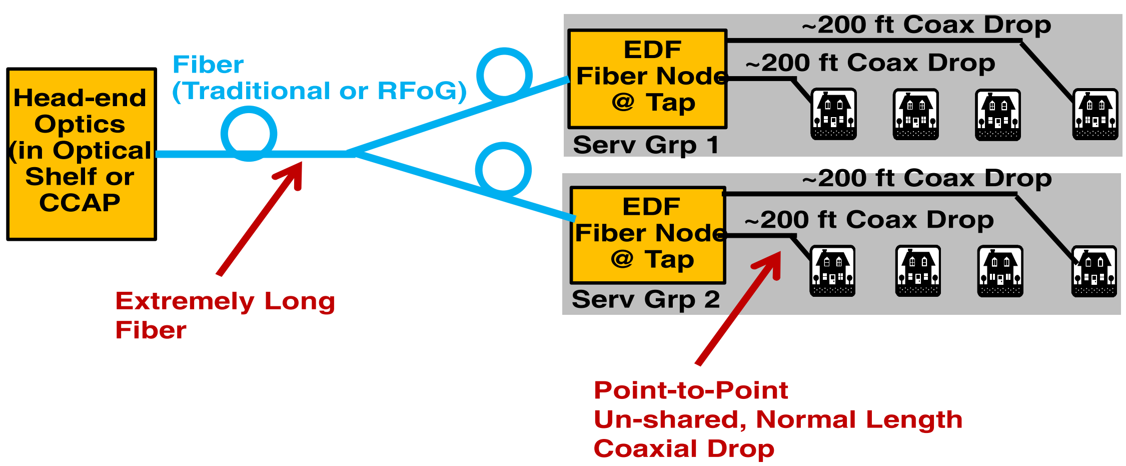


Fig. 16- Extremely Deep Fiber (EDF) Point-to-Point Technology

longer coaxial runs than a typical drop coax, so greater signal attenuation could become an issue with the VDF approach that could limit overall bandwidths.

The second technique circumvents the attenuation issues caused by the long coaxial runs of the first technique. This second could be assigned its own pair of lambdas on the fiber (for downstream and upstream transmissions). Alternatively, RFoG Optical Beat Interference (OBI) Mitigation techniques (such as Hybrid-PON technology) could be employed in the upstream direction and RFoG could then be used to permit multiple EDF Fiber Nodes to share a single downstream lambda and a single upstream lambda on the fiber (which helps to conserve lambdas on the fiber). [MUTA]

Although this EDF approach may not be appealing to some MSOs, other MSOs may find the idea interesting. As a result, the authors decided to briefly explore the point-to-point distance limits of typical coaxial drop connections in a little more detail. Several simplifying assumption can be made. These include:

1. The only sources of noise in the EDF-based point-to-point coaxial drop to the home is the Johnson-Nyquist thermal noise floor at the receiver and the receiver noise itself [JOHN]
2. The system temperature is 290K
3. The total power injected into each point-to-point link from the EDF Fiber Node source is maintained at a fairly reasonable level of (say) 50 dBmV with a CNR of 45 dB.
4. The transmitted power is uniformly distributed over the occupied spectrum (i.e. a flat Power Spectral Density). This is not necessarily the optimal PSD pattern as tilt added to the spectrum could help, but it does greatly simplify the calculations.
5. The coaxial drop cable is assumed to be RG-6. Its attenuation is calculated over an extended frequency range (beyond the normal recommended frequency range of 0-3 GHz) using standard formulae for resistive loss in the conductors and tan-d loss in the dielectric.
6. There is a "Coding Loss" of 4 dB associated with the particular physical layer channel code used (DOCSIS 3.1 OFDM). This is the difference between the performance (information capacity) of a perfect code, given by the Shannon-Hartley formula, and the performance of the channel code used. While highly optimized codes (e.g. Turbo Codes and some long-codeword LDPC variants) can in theory come within a fraction of a dB of the Shannon-Hartley limit, a more typical coding loss of 4 dB is appropriate when considering DOCSIS 3.1.
7. The receiver's input stage has a noise figure of 5 dB. Of course, low-noise amplifiers are available with much better noise figures than this, but 5 dB would be achievable using relatively low-cost components.
8. The receiver's demodulator has an implementation margin of 3 dB. Practical demodulators will generally not achieve theoretical performance for a variety of reasons (e.g. quantization noise, limited number of iterations in LDPC decoders, etc.); this margin ensures that the demodulator's MER exceeds the theoretical minimum MER required to decode a signal with particular modulation depth.
9. The physical layer has a "Temporal-Spectral Efficiency" of 90%. This refers to the loss of capacity associated with guard bands, pilots, signaling channels, and cyclic prefixes.
10. There is a capacity loss of 5% associated with framing overheads and MAC messaging.
11. The calculated capacity is the total bitrate in either direction; it may be split in any ratio between upstream and downstream traffic.

Using these simplifying assumptions, the resulting SNRs and supported modulation levels and resulting bandwidth capacities can be calculated for different spectral widths and different distances of typical RG-6 drop cables. The resulting bandwidth capacity is shown in Fig. 17a. The corresponding Modulation Order (in bps/Hz) are also shown in Fig. 17b, where the QAM order can be calculated from the Modulation Order using the formula QAM Order = $2^{(\text{Modulation Order})}$.

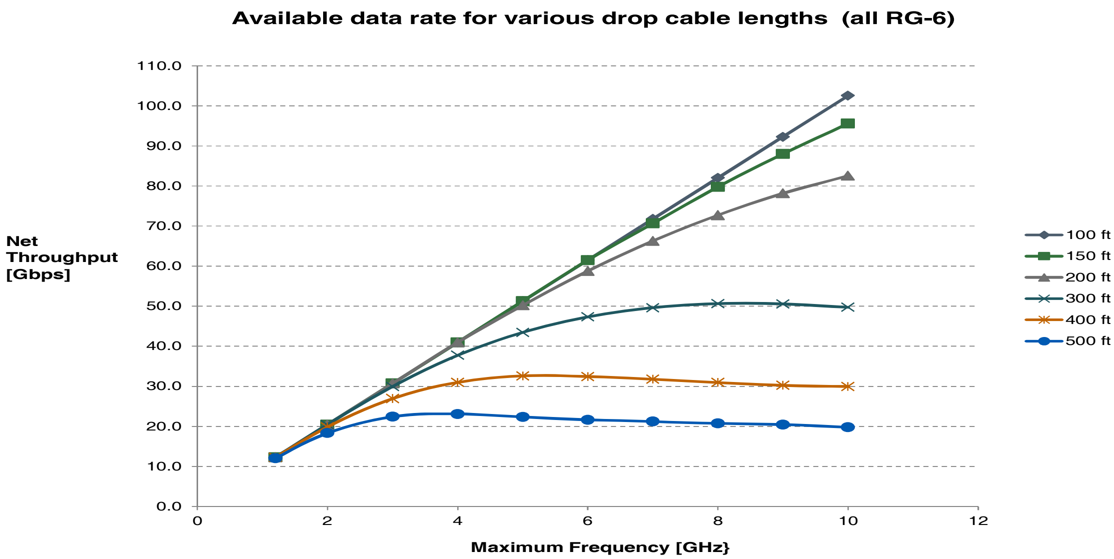


Fig. 17a- RG6 Coax Throughput Capacity vs Frequency (for Various Distances)

From these figures, it can be seen that (for the simplifying assumptions described above) there is a definite bandwidth capacity benefit (along with an unspecified cost) associated with the repeated doubling of the spectrum. This benefit is realized until the Modulation Order drops to a value of 1 (which corresponds to BPSK modulation).

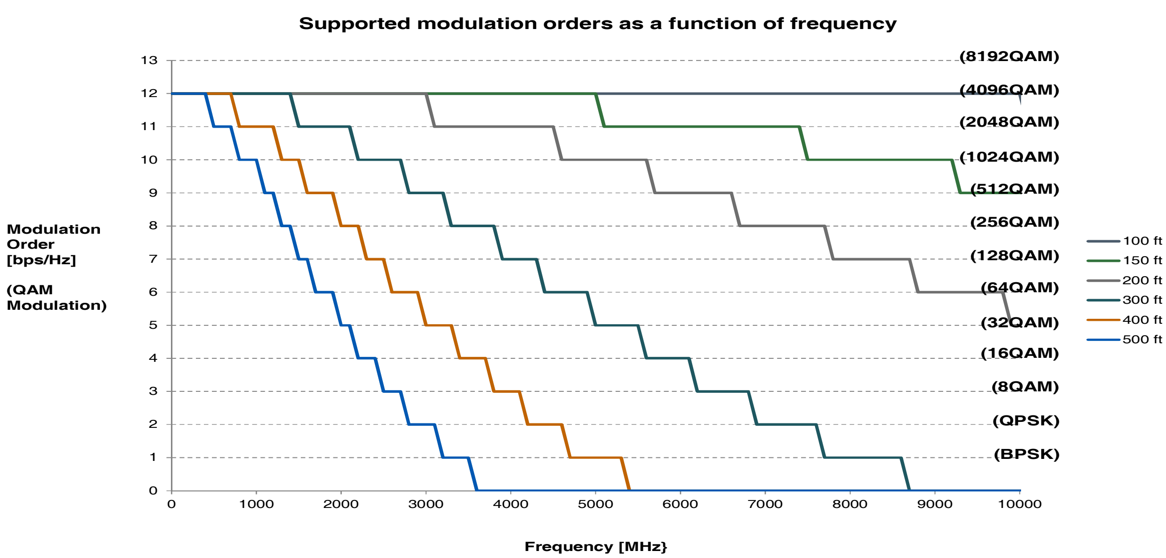


Fig. 17b- RG6 Coax Modulation Order vs Frequency (for Various Distances)

It is compelling to note the relatively high throughputs that seem to be achievable across a point-to-point RG-6 coax carrying DOCSIS 3.1 OFDM signals. As an example, a 500 ft. length of RG-6 carrying a 10 GHz-wide OFDM spectrum would apparently be capable of transmitting ~20 Gbps of throughput from the EDF Fiber Node to the home. A 300 ft. length of RG-6 carrying a 10 GHz-wide OFDM spectrum would apparently be capable of transmitting ~50 Gbps of throughput to the home. A 200 ft. length of RG-6 carrying a 10 GHz-wide OFDM spectrum would apparently be capable of transmitting ~80 Gbps to the home. A 100 ft. length of RG-6 carrying a 10 GHz-wide OFDM would apparently be capable of transmitting ~100 Gbps to the home. While second-order effects would likely reduce these bandwidth capacities to some extent, the message is clear. Support for relatively large throughputs are likely to be possible on reasonable lengths of drop cables into the homes.

Lesson C5: Offer Wireless-only and Wireless+Wired connectivity to subscribers inside of their homes. Telcos obviously moved to the support of Wireless connectivity many years ago with their cellular infrastructure, and they are augmenting their offerings with small cell offerings (ex: picocells and femtocells) as well as WiFi offerings. Many of their subscribers are "cutting the cord" on wireline service and eliminating the need for a wired infrastructure into their homes, choosing instead to use only the wireless cellular connections. Other subscribers are using both the wireless and the original wired infrastructure to receive services inside of the home.

While the current HFC wired infrastructure can support most customers needs into the late 2020's and beyond, an eventual move to these Wireless technologies is likely to be a part of every MSO's future. However, instead of using cellular phone and LTE technologies, MSOs may opt to use WiFi (or similar LTE-U) as their primary method of delivering the Wireless service. This may make sense, as all wireless providers are gradually moving to small cell (ex: picocell or femtocell) technologies in the future.

WiFi can be used in a similar fashion by MSOs who may have an almost ubiquitous coverage area in urban areas. This coverage can be provided by Access Points in every home gateway and potentially by Access Points placed in Fiber Nodes and amplifiers and taps along their HFC plant runs. This WiFi coverage can be further enhanced through the use of Very Deep Fiber (VDF) or Extremely Deep Fiber (EDF) technologies. When placed in taps, this WiFi technology could also be used to provide wireless drop capabilities that augment the normal coaxial drop cables. The channel bonding techniques described earlier could then be used to provide bonding across the coaxial and WiFi connections. [ALB3]

Lesson C6: Use Self Organizing Network concepts to manage multiple overlapping Wireless networks. Telcos are beginning to spend considerable time studying Self Organizing Network (SON) concepts to dynamically and automatically manage the transmission frequencies and power levels and directionality of each antenna in their 4G Wireless networks. SON technologies can be used to help with self configuration, self optimization, and self healing operations. These technologies will undoubtedly be beneficial for the management of small cell environments where overlapping antenna coverage areas are common.

MSOs may be able to capitalize on these same SON technologies within their dense WiFi networks. This will become especially true as higher numbers of antennae become available on future access points, paving the way for more directionality and more Multi-User Multiple Input-Multiple Output (MU-MIMO) arrangements are utilized. SON technologies will undoubtedly help manage the many overlapping WiFi networks that will exist in the home and the neighborhood of the future. [SONT]

CONCLUSIONS

What Has Been Learned?

There are many lessons that MSOs can potentially learn from the past history of Telcos. These lessons include:

- Lesson A1: Use Orthogonal Frequency Division Multiplexing (OFDM) and Low Density Parity Check (LDPC) Codes
- Lesson A2: Assign different modulation orders to subscribers with different Signal-to-Noise Ratios (SNRs) to optimize throughput
- Lesson A3: Maximally utilize Moore's Law improvements in silicon and new linearizers/equalizers to permit signal reception with lower SNR and higher distortion
- Lesson A4: Use IP Video as a transport technology for television programming
- Lesson A5: Migrate appropriately-selected customers to Fiber-To-The-Premise (FTTP) service as their growing bandwidth needs necessitate this alternative service
- Lesson A6: Modify home networks to help increase the capacity of the access network
- Lesson A8: Use centralized, software-based management of network infrastructure platforms (ex: IMS & SDN)
- Lesson A9: Use Distributed Access Architectures to help deliver services.
- Lesson A10: Use Carrier-Class equipment to ensure high service availability
- Lesson B1: Expand channel spectrum to maximize channel capacity
- Lesson B2: Increase the reach of digital fiber runs and decrease the reach of the twisted-pair (copper) access network to decrease attenuation and maximize SNR and increase QAM Modulation levels
- Lesson B3: Use "Selective Subscriber Shedding" to move heavy users to alternative transport technologies
- Lesson B4: Use automated handoffs to permit efficient movement of traffic between wireless and wired technologies
- Lesson B5: Focus roll-outs of new wired technologies on aerial plant systems where costs are minimized
- Lesson C1: Use fiber-to-copper media converters that are positioned extremely close to the homes to minimize twisted-pair (copper) attenuation
- Lesson C2: When necessary, draw electrical power from subscriber homes to power outside plant network equipment that is connected via copper connections to the homes
- Lesson C3: Use bonding of multiple physical connections into each home to boost the per-subscriber bandwidth capacity into the home
- Lesson C4: Use point-to-point (un-shared) copper connectivity into each subscriber's home to maximize each subscriber's bandwidth capacity
- Lesson C5: Offer Wireless-only and Wireless+Wired connectivity to subscribers inside of their homes
- Lesson C6: Use Self Organizing Network concepts to manage multiple overlapping Wireless networks

In several ways, the MSOs are entering a period of time that may be similar to the period of time that Telcos have just navigated. The HFC plant has a long life left in it, but MSOs will still need to carefully utilize the resources of their HFC plant to extend its life and maximize the return on this already-deployed investment. And as they extend that life, MSOs will also need to begin phasing in new technologies for their future.

MSOs will undoubtedly be able to use at least some of the tactics and techniques adopted by Telcos over the past several decades. These tactics and techniques permitted Telcos to extend the life of their twisted-pair plant while they also introduced new wireless and fiber-based technologies. The DSL techniques employed by Telcos on their twisted-pair loops allowed them to extend the life of their existing plant for at least twenty years beyond its originally-predicted end-of-life. If MSOs have similar levels of success with their HFC plants while they are introducing new technologies, then the MSOs may be able to extend the life of their HFC plants well into the 2030's or 2040' or beyond. It is quite likely that many MSOs will find themselves in a future environment similar to the environment of many Telcos today.

The HFC, RFoG, and HPON systems are likely to include some Extended-Spectrum DOCSIS solutions that can go beyond the 1.2 GHz spectral limits that are oftentimes discussed for DOCSIS 3.1 today. In fact, it is quite possible that many 10's of Gbps of bandwidth capacity could be provided using Extended-Spectrum DOCSIS solutions on all of these infrastructure types (HFC, RFoG, and HPON) in the future .

The Extended-Spectrum expansions permitted on the legacy HFC infrastructure will obviously be a function of the investmen

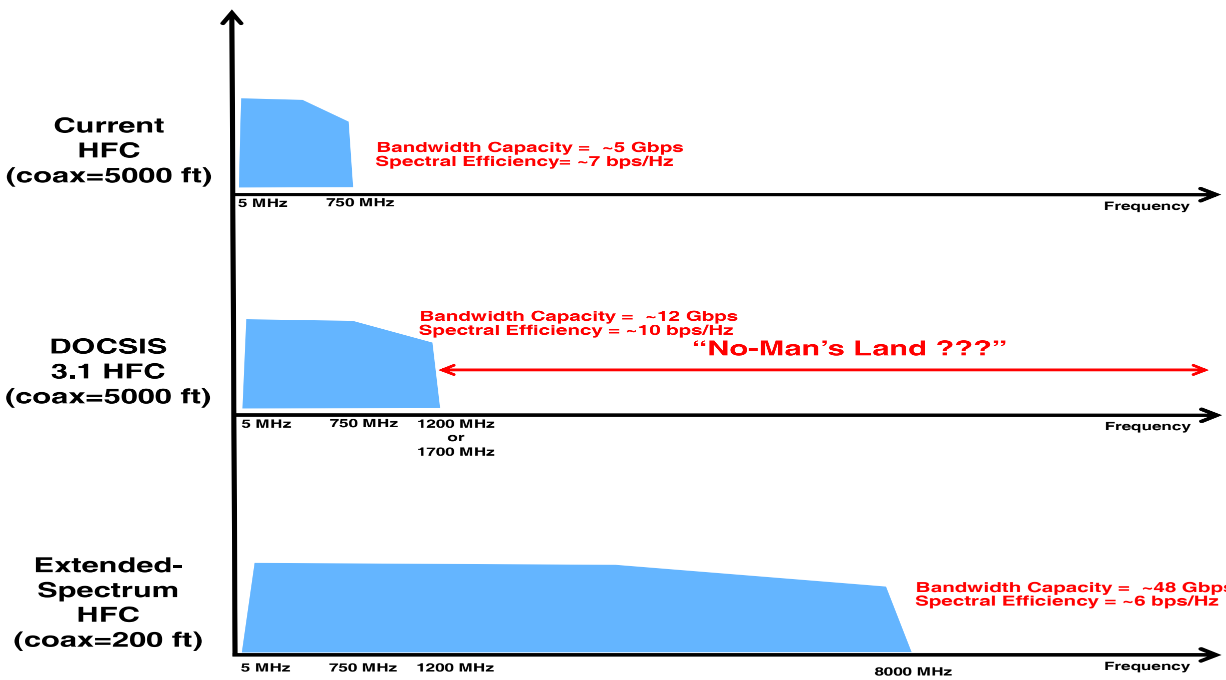


Fig. 18- Possible Future Views on Useable Spectrum for HFC Plant

levels that MSOs are willing to pour into the existing HFC plant. If they invest in it in a slow, continuous fashion (the way that Telcos did with their copper loop plant), then it is quite conceivable that the HFC plant of the future will contain very, very deep fiber runs and very, very short point-to-point coaxial drops to each home. These types of investments (if considered) could lead to an HFC evolutionary strategy described in Fig. 18. (Note: The expansion of HFC spectrum in Fig. 18 is quite similar to that which was seen for Telcos in Fig. 5a).

This futuristic world may see many medium-level SLA subscribers and low-level SLA MSO subscribers still being serviced from the legacy HFC infrastructure, while some high-level SLA subscribers will likely begin to be serviced on new FTTP infrastructures (based RFoG or HPON or PON). The high-level SLA subscriber may also be moved to new Very Deep Fiber HFC and Extremely Deep Fiber HFC infrastructures.

PON systems will also be utilized by MSOs in the future. These may be the technology of choice for the support of many business services subscribers. It may also be used by many MSOs for their residently subscribers as well. With PON systems also scaling to many 10's of Gbps in the future, these PON systems will also provide great bandwidth capacities for many FTTP subscribers.

In parallel with these HFC and RFoG and HPON and PON infrastructure improvements, a much more advanced WiFi or LTE-U Wireless network is also quite likely to develop within the MSO's network. This will be a dense system of Access Points that provide convenient connectivity to many of the subscribers in the future.

All of these paths mimic paths that have been taken by Telcos over the past several decades. As a result, it is quite possible that some of the lessons described within this paper may prove to be quite useful to MSOs in coming years.

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