# EXPLOITING HFC BANDWIDTH CAPACITY TO COMPETE WITH FTTH

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## *Abstract*

*Several different Fiber-to-the-Home (FTTH) architectures are starting to emerge and be deployed. Proponents of FTTH recognize the high cost of installation, but stress the capacity advantages over Hybrid Fiber Coax (HFC) networks. While it is true that optical fiber has almost unlimited capacity, the practical capacity of these networks are not superior to HFC networks in most cases. This paper presents capacity comparisons of popular FTTH architectures with that of a modern HFC network. In addition to this comparison, the paper also explores several methods for exploiting the significant unused capacity of HFC networks.*

*This paper presents CWDM downstream and upstream technologies that allow for low-cost segmentation of the optical serving area to the levels below 100 homes. As demonstrated this can be accomplished without additional fibers between the node and the headend or hub. This architectural modification of the HFC networks is also non- service interrupting and can provide capacities that meet or exceed today's PON architectures at a fraction of the cost.*

*Additionally the paper lies out how the HFC architecture can efficiently provide this additional bandwidth on a geographically granular basis, up to and including Fiber-to-the-Building where it makes sense for business applications or large multi-tenant buildings.*

## COMPETITION

### FTTH Deployments

Fiber to the Home (FTTH) has been deployed in varying degrees throughout the world. Each region has its own set of variables for choosing FTTH and what works in one country does not necessarily make sense in another.

Japan is leading the world in FTTH deployment. As of September 2005, Japan had 3.98 million FTTH subscribers and is adding 100K new subs a month. NTT is the largest carrier of FTTH and has reported that it will be investing $47 billion through 2010 to upgrade 30 million homes and businesses.[1] Even though FTTH is gaining subscribers, it is not having a material impact in areas where modern HFC networks exist. The HFC networks are typically offering 15 to 30 Mbps tiers combined with rich video offerings which satisfy most of the Japanese consumers.

Korea has the highest broadband penetration rate in the world, aims to have 100 Mbps service available to 5 million subscribers by 2007 and to 10 million subscribers by 2010 mainly over a FTTH network.[2]

Limited FTTH trials exist in Europe and are usually being introduced by local municipalities. As of Q2 2005, there were 166 FTTx trials/projects, 72% of which were initiated either by the municipal or the local power utility.[3]

Five countries are responsible for 97% of the activity, they are: Sweden, Italy, Denmark, and Norway.

Other than Verizon, FTTH deployment in the US has also mainly been rolled out by municipalities. Today FTTH has been trialed or rolled out in 652 communities across 46 states, but only accounts for 322,700 connected homes.[4] Nearly 50% of those projects do offer some form of triple-play services.

Verizon announced aggressive plans with the launch of FiOS. They reported to have 3 million homes passed by the end of 2005 and plans for another 3 million homes passed in 2006.[5] Several of these homes are apartment complexes which have not been wired for service. Subscriber success has not been clear in these markets. Most of the incumbent cable operators have preempted the FiOS offer of 15 Mbps by 2 Mbps with an equivalent or higher speed offer. Verizon has been quoted as achieving over 20% penetration in certain markets. It is unclear, however, whether this is an actual penetration number or a sales to contact number as the competing cable operators claim that Verizon has only actually achieved low single digits.

## HFC: Capacity Overview

FTTH perhaps has more marketing appeal than it does technical appeal. It is true that optical fiber's theoretical bandwidth capacity is nearly unlimited. It is also true that 10 Gbps per wavelength with 50 GHz can be commercial deployed for long haul networks today, providing 800 Gbps in the 1550 nm window. These technologies are not practical for access architectures for several reasons and as such the practical capacity of FTTH networks is very similar to that of modern HFC networks.

Traditional 870 MHz HFC networks are capable of over nearly 5 Gbps of downstream capacity and more than 150 Mbps of upstream capacity. European and Japanese cable systems are capable of 270 Mbps in their upstream and both US and international HFC networks can be configured in a Next Generation Network Architecture which can provide over 6 Gbps in the downstream and 360 Mbps in the upstream.

It must also be recognized these speeds can be accomplished at a fraction of the cost of FTTH networks.

## CWDM, DWDM Complement HFC

The optical links between the headend and the node match the capacity of the traditional telecommunications networks. Time Division, Wave Division and Frequency Division multiplexing techniques can and are all employed on this portion of the network. This allows for extremely efficient use of the optical fiber. Thanks to short distances limited noise contributions the CNR/SNR requirements of Shannon's bandwidth theorem can be easily met.

## HFC Network Capacity

The HFC network has significant capacity and is an excellent position to compete with FTTH networks Figure 1 and 2 compare the capacity of A,B,G, and E, PONS to HFC networks of varying node reductions.

As figure 1 indicates even a traditional 870 MHz HFC network with 500 home passed nodes has more downstream bandwidth per customer than most FTTH architectures today. After segmentation, downstream bandwidth can significantly exceed that of most PONs and upstream bandwidth can achieve parity.

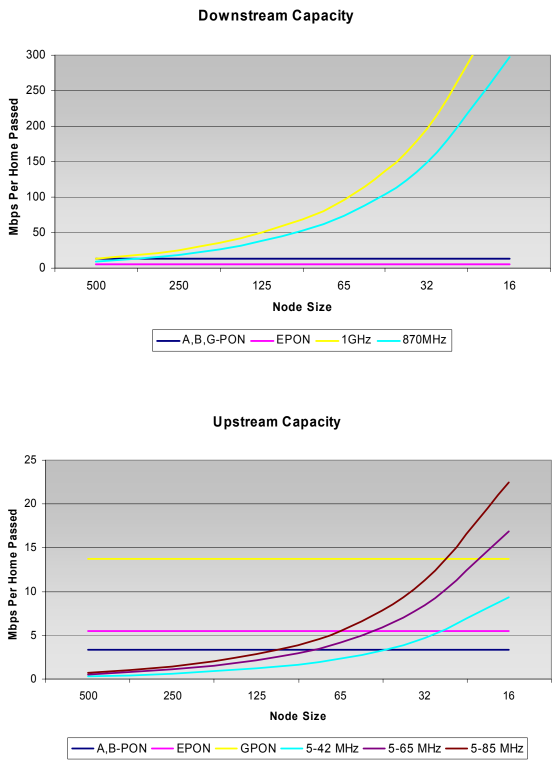


Figure 1. Bandwidth Capacity Comparison PON vs. HFC

In addition to HFC networks being able to eloquently evolve to increased bandwidth, it is also well suited to evolve to FTTx at any point based on demand. This demand can be very granular and thus the economics quite attractive. Key things to consider are the bandwidth limiting devices in the coaxial network and the distance limit for low-cost optics in the optical network. Typically the bandwidth limitions in the Coaxial networks are a result of RF actives. As fiber is deployed deeper, several options are available to overcome these limitations, including removing the RF actives all together.

## LINKS TO THE NODES

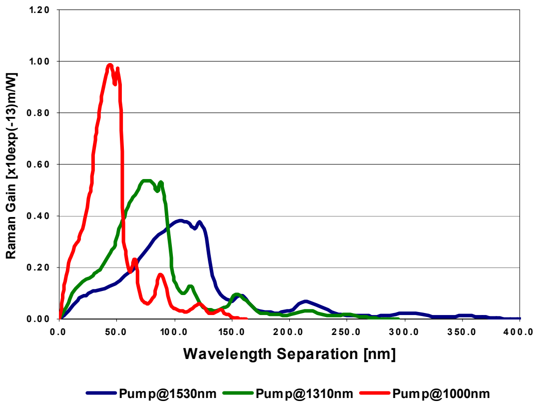
### Analog Links: CWDM vs. DWDM and Digital Baseband Technologies

DWDM capability of the optical links between headends and hubs has been documented in Figures 1, 2, 3, and 4. This technology is most suited for high-level aggregation (40 nodes can be fed from 3 fibers) over long distances thanks to cost-effective optical amplification. Designs reaching the ranging limits of the DOCSIS systems have been implemented and operated for several years. However, for shorter distances and segmentation applications more cost-effective techniques exist. The following reviews some of these techniques.

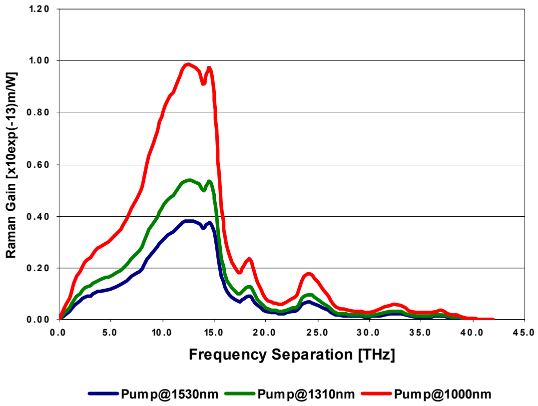
### Forward CWDM Links

The Coarse Wave Division Multiplexing (CWDM) technology, especially when used for FDM analog and QAM signals, encounter at least two major challenges. One of them is SRS-caused crosstalk between CWDM wavelengths on the same fiber. The other is high level of dispersion in SMF-28 or equivalent fiber above water peak. This fiber type is dominant in access networks today.

The theoretical description of the Stimulated Raman Scattering and its relation to the phenomena of Raman gain is well understood and is used in optical amplification. However, the same phenomenon leads to undesired amplification (shorter wavelength pass their energy to longer wavelengths) in multi-wavelength systems. If a wavelength is modulated, this amplification results in bi-directional (theoretically asymmetrical) crosstalk.



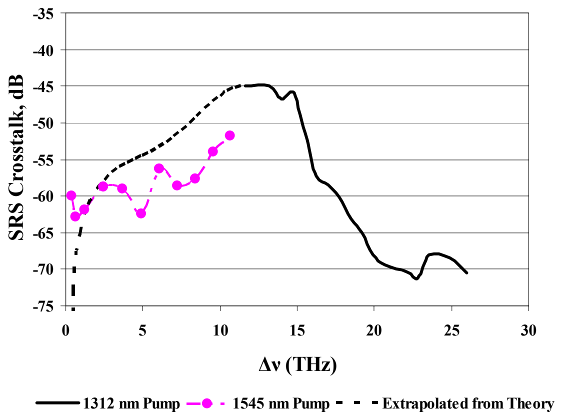
a) Raman Gain vs. Wavelength Separation



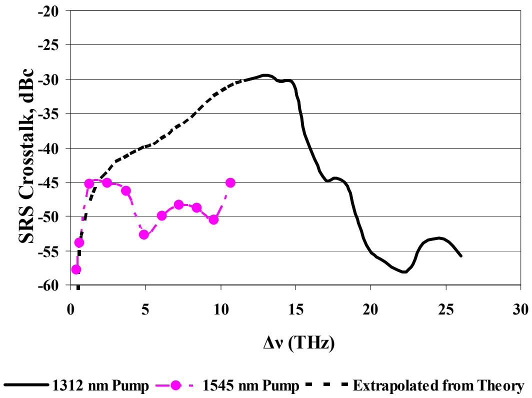
b) Raman Gain vs. Frequency Separation

Figure 2a & 2b. Raman Gain for Three Different Pump Wavelengths

Figure 2 shows the theoretical plots of the Raman gain. This theoretical relationship was closely matched during measurements of crosstalk at several pump wavelengths. (An example of the test results is shown in Figure 3.) Other contributions to crosstalk (e.g., XPM) at lower separations between wavelengths and higher RF frequencies cause the crosstalk values to deviate from the theoretical Raman gain relationship. (Detail descriptions of test methodologies and test results are beyond the scope of this paper.)



a) 499.25 MHz



b) 55.25 MHz

Figure 3. Crosstalk vs. Δv (Test Results for +10 dBm Pumps and 25.3 km of Fiber)

The crosstalk test results indicate that low frequency NTSC analog carriers of different content cannot be carried without the possibility of interference on any combination of two wavelengths unless they are separated by more than 30 THz. However, since QAM channels can tolerate higher level of interference, the crosstalk between CWDM wavelengths at higher RF frequency (where QAM channels are usually placed) can be low enough to allow carrying QAM channels of different content on different wavelengths. The test results were used to calculate the limits (under most conservative assumptions) of CWDM systems from QAM signal crosstalk point of view. Figure 4 shows cumulative crosstalk for a CWDM system when the fiber loading starts with 1270 nm and consecutive wavelengths are added (except water-peak wavelengths: 1310, 1390 and 1410 nm).

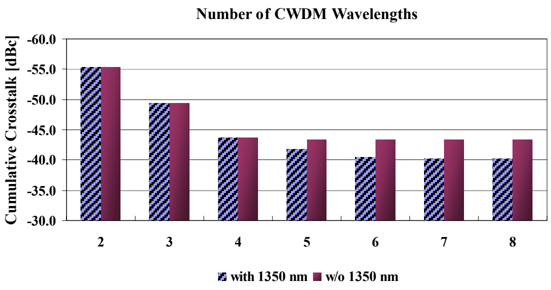


Figure 4. Calculated Cumulative Crosstalk at 499.25 MHz

Depending on the acceptable level of interference, a combination of several wavelengths with QAM loading of different contents above 500 MHz can be supported. Moreover, the higher the RF frequency, the lower the crosstalk.

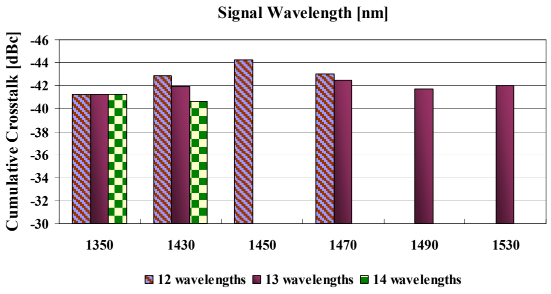


Figure 5. Cumulative Crosstalk for Multi-Wavelength Loads

Figure 5 shows that up to 12 CWDM wavelengths (up to 14 wavelengths could be acceptable) can be combined onto a single fiber as long as the NTSC analog video channels carry the same content and QAM channels are placed above 500 MHz. Unfortunately, Raman gain crosstalk is not the only impairment that can cause problems in analog optical links.

Dispersion

Dispersion in SMF-28 or equivalent type fibers can actually introduce stringent limits on the number of CWDM wavelengths carrying NTSC analog video channels in a single fiber. Figure 6 shows typical dispersion relationship for SMF-28 fiber.

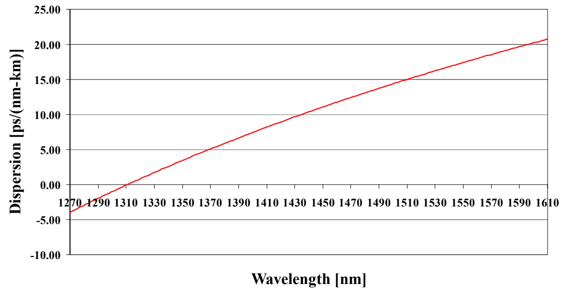


Figure 6. Dispersion of SMF-28 Fiber

The combination of high dispersion and laser chirp that is inherent in typical direct modulated lasers with FM efficiency of 100 MHz/mA will cause second order distortions (including CSO).

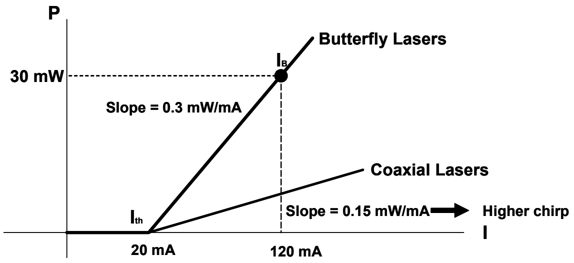


Figure 7. Typical Laser Characteristic

The total chirp will depend on the laser FM efficiency and slope (see Figure 7 for typical laser characteristic). Under the assumptions presented above, 30 mW lasers will have 10 GHz chirp (at 100% modulation) and 3 mW lasers will have 1

GHz chirp. Figure 8 shows what levels of distortions can be caused solely by laser chirp and dispersion at 1450 nm wavelength over 20 km of SMF-28 fiber.

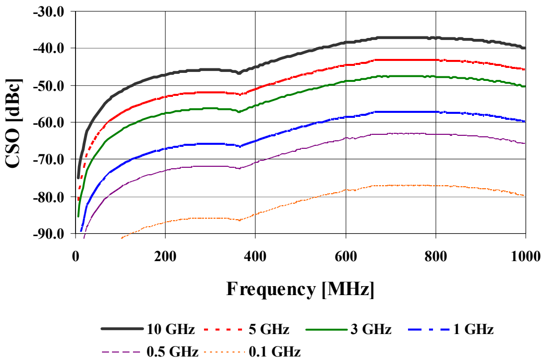


Figure 8. Second Order Distortion Caused by Dispersion at 1450 nm Wavelength in 20 km of SMF-28 Fiber

Figure 9 presents expected second order distortion levels at different wavelengths for different lasers in 20 km of SMF-28 fiber.

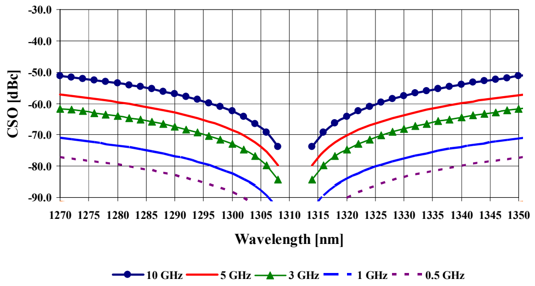


Figure 9. Second Order Distortions vs. Wavelength (20 km of SMF-28 Fiber)

If we assume that the contribution to the laser CSO from chirp/dispersion generated CSO cannot exceed –70 dBc (to avoid significant degradation of laser nonlinearity-generated CSO), then we can calculate the maximum number of CWDM wavelengths per fiber in the forward direction.

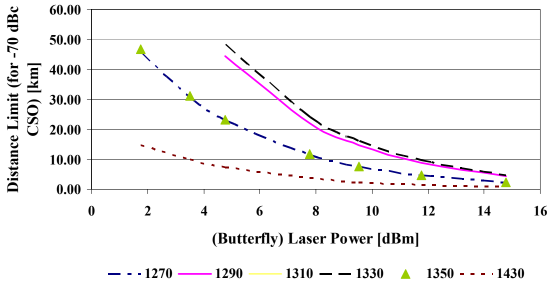


Figure 10. Dispersion CSO Distance Limits vs. Laser Power (Chirp)

Figure 10 presents the results of these calculations at 548.5 MHz, assuming FM efficiency of 100 MHz/mA for laser with characteristics presented in Figure 7. Under these assumptions, 6 wavelengths can be placed on a single fiber of 10 km length (loss budget permitting), 5 wavelengths on 15 km long fiber and 3 wavelengths on 20 km long fiber.

The SRS and dispersion considerations above were based on these assumptions:

1. The transmitter loading is hybrid analog/digital QAM

2. Analog channels on all wavelengths are the same.

3. Analog load consist of 77 NTSC video channels between 54 and 552 MHz.

If the number of channels or the loading type changes, the values in Figure 10 will change as well. In the extreme, with digital-only loading, the dispersion may be less limiting than Raman crosstalk (crosstalk is highest at the lowest frequencies, dispersion generated CSO is highest at 725 MHz) unless the low frequency QAM channels carry the same information on all wavelengths.

Dispersion Remedies

Under the assumptions used in the CWDM analysis, the limiting factor is dispersion combined with the laser chirp. To ease these limitations, the following can be implemented:

1. Lower chirp lasers used,
2. Dispersion compensation circuitry added in the transmitter for high-dispersion wavelengths,
3. Dual receiver configuration used in the node.

A detailed analysis of pros and cons for each of these solutions should decide about the selection of the optimal solution for a particular application. The remedies #1 and #3 can be easily implemented. Figure 11 shows a simplified diagram of the dual receiver links.

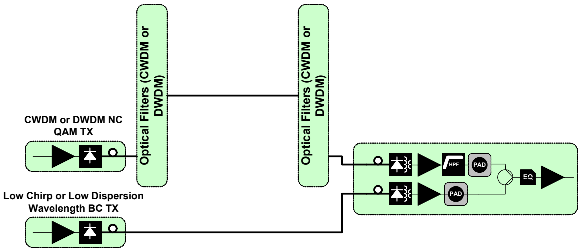


Figure 11. Dual Receiver System

One must note that even at 20 km, two fibers can feed 6 independent forward areas with 3 forward wavelengths per fiber and with the reverse signals counter-propagating on the same fibers that carry forward signals.

Analog Reverse Links

Analog reverse transmitters are lower power (typically 3 dBm or lower). Moreover, only digital (64 QAM max) channels are transmitted in the reverse links. For these reasons, SRS crosstalk can be disregarded. Similarly, CSO problems in DFB analog links can be disregarded (low chirp for low power laser), even in coaxial lasers. However, CSO in-links with FP lasers of much higher chirp must be analyzed at wavelengths above the water peak (1430 nm and longer). Even for –30 dBc C/I requirements, these links may be limited in distance.

Digital Baseband Links

Baseband digital links do not show problems attributed to the analog links. The power into the fiber for digital links is usually low (no Raman crosstalk problems) and dispersion does not lead to second order distortion. Instead, it results in pulse spreading but digital lasers are designed for a specific dispersion limits and digital technology developed many different remedies against dispersion (chromatic and PMD)

Several manufactures have been deploying digital baseband transport technology in reverse links. This transport allows for using both CWDM and DWDM technology to support reverse bandwidth up to 85 MHz (NGNA specified reverse upper frequency limit).

Moore’s Law provides for increased access to low-cost, high-data rate components. An example of this are Quad Fiber Channel and 10 Gbps transceivers, which are now readily available. This can add to the capacity of fiber between the headends/hubs and the nodes supporting digital reverse and providing additional bandwidth in the first mile plant.

The baseband digital link can share the forward and reverse fiber either in a counter-propagating manner or co-propagating manner if the frequency spectrum of the signals carried does not cause Raman crosstalk interference to other signals.

Applications for CWDM

Figures 13 and 14 present two examples of applying CWDM technology in the forward (analog transmitters) and reverse (with digital multiplexing of two reverse segments per wavelength) paths to segment fiber deep node clusters. The first implementation with the distance to the first node limited to 10 km uses full-load CWDM transmitters. The second implementation lends itself architecturally to a dual receiver configuration due to operator choice of Broadcast and Narrowcast equipment locations and the distance to the first node. The bandwidth capacity gains per household are presented in Figure 12 (refer also to Figure 1). Capacity per user will depend on the service penetration levels. The following assumptions were used:

1. Both clusters serve 500 households.
2. Initial sub split is 42/54 MHz; final sub split is 85/105 MHz.
3. Reverse used 16 QAM modulation initially and 64 QAM finally
4. Forward NC bandwidth is 192 MHz initially and 288 MHz finally.

The segmentation and other modifications listed above multiplied the forward NC bandwidth per household by a factor of 7.5 and the reverse bandwidth by a factor larger than 40. This still leaves 105 to 582 MHz bandwidth for broadcast signals. If this bandwidth is filled with digital 256 QAM signals, it will provide more than 3 Gbps broadcast capacity.

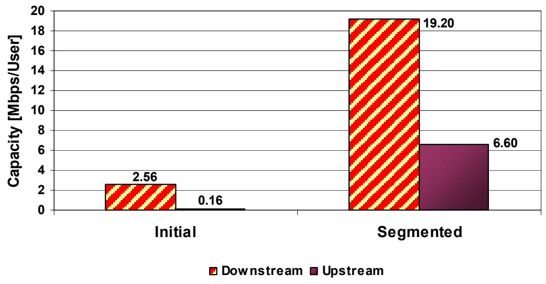
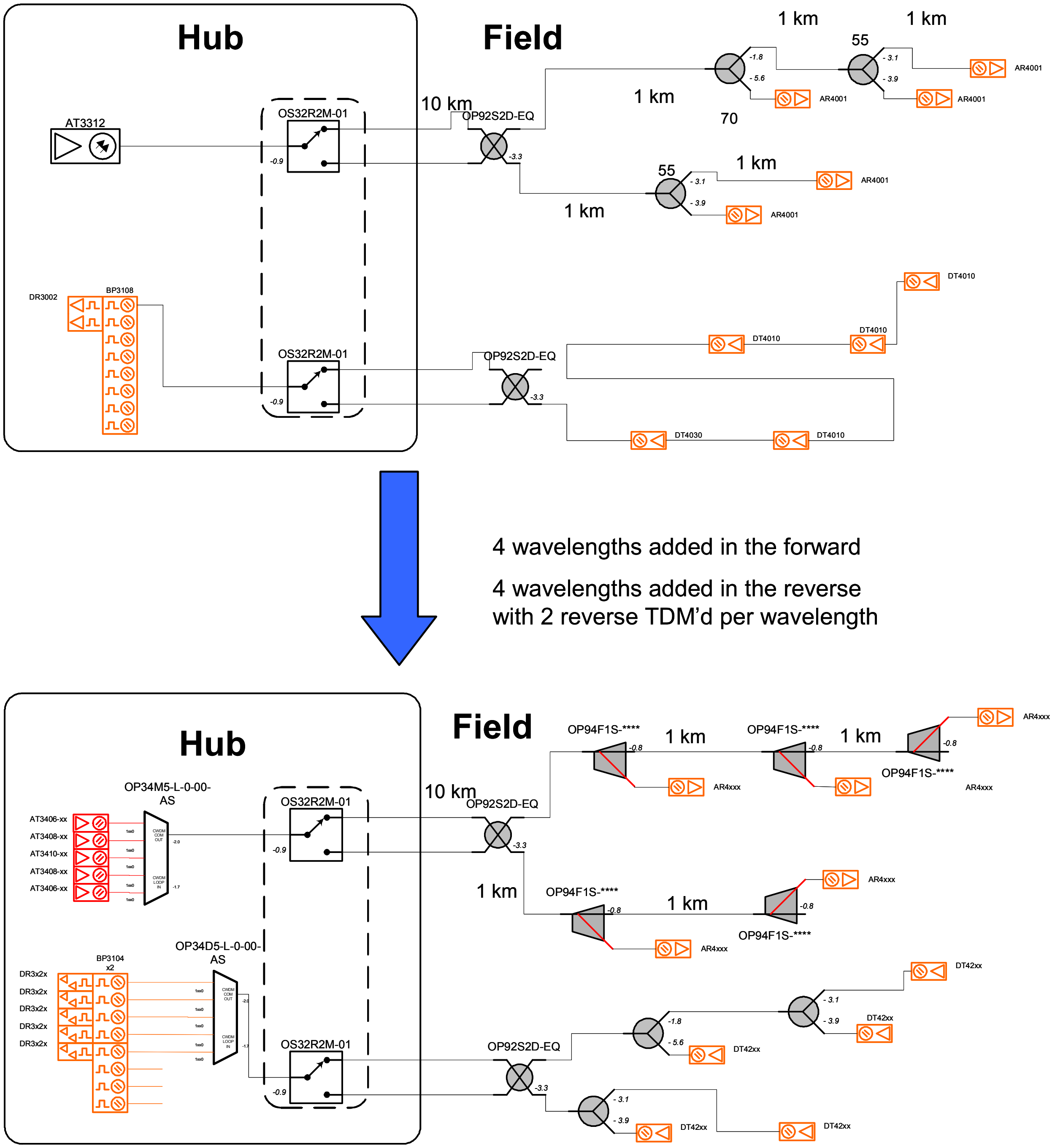


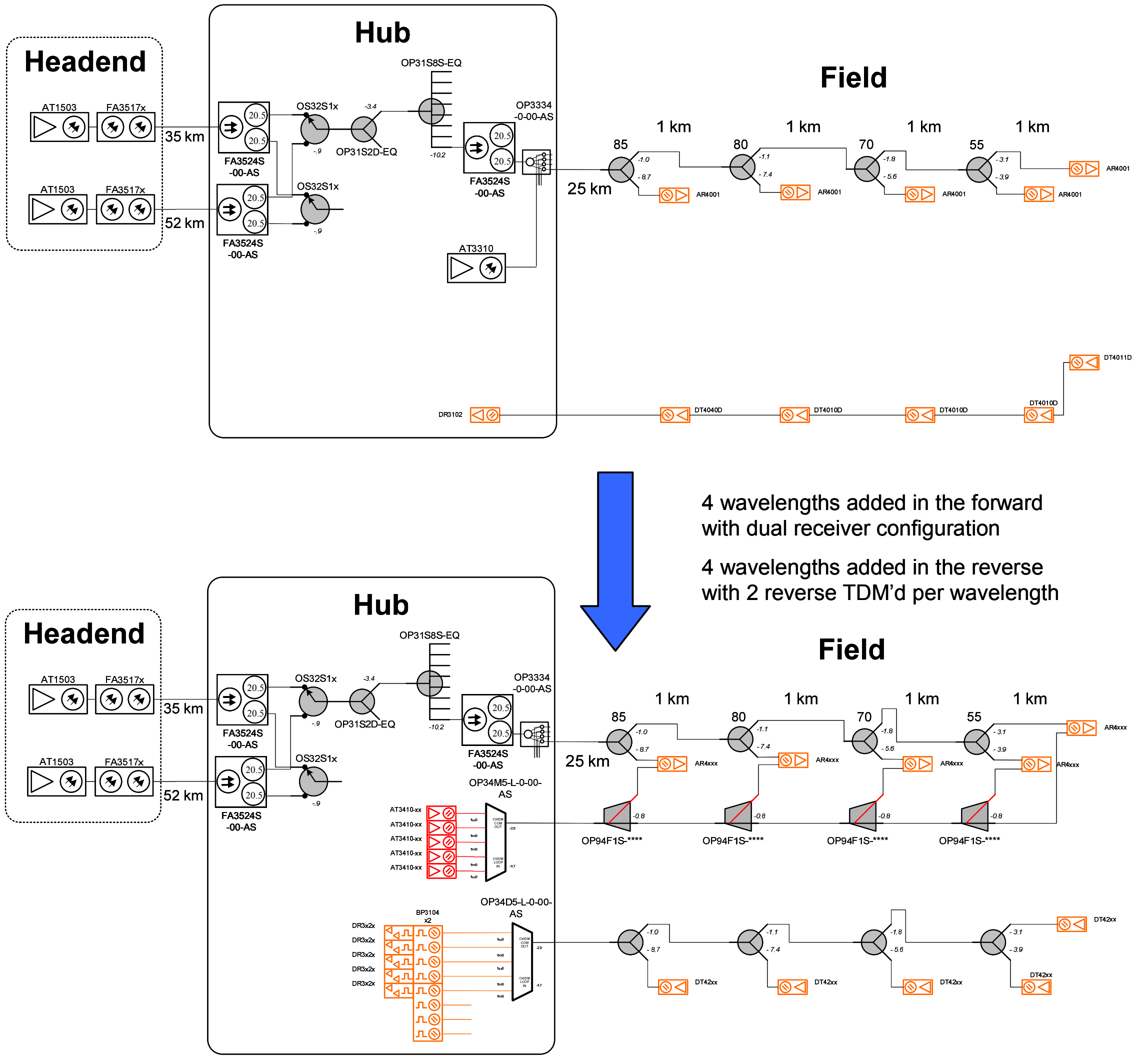
Figure 12. Bandwidth Capacity Gains per Household due to CWDM Segmentation Technology



4 wavelengths added in the forward

4 wavelengths added in the reverse
with 2 reverse TDM'd per wavelength

Figure 13. Segmentation with CWDM Technology: Forward with CWDM Full-Load Transmitters; Reverse with CWDM Digital Reverse with TDM'd Paths



4 wavelengths added in the forward with dual receiver configuration

4 wavelengths added in the reverse with 2 reverse TDM'd per wavelength

Figure 14. Segmentation with CWDM Technology: Forward with CWDM NC Transmitters and Dual Receivers; Reverse with CWDM Digital Reverse with TDM'd Paths

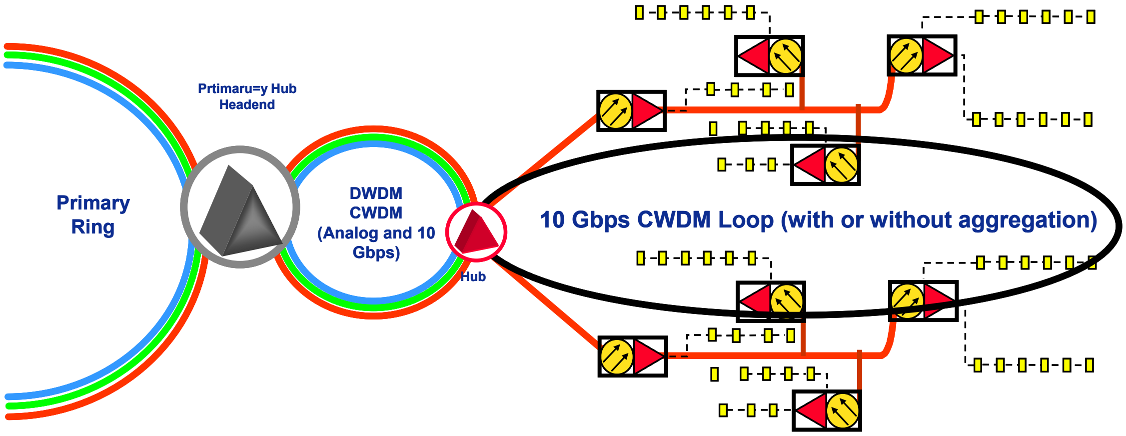


Figure 15. Digital 10 Gbps Transport Technology between Headend/Hub and Nodes

### Applications for Digital

Figure 15 presents a method of implementing digital baseband transport technology between headend/hub and the nodes. The multi-wavelength fiber capacity allows for filling up the unused CWDM and DWDM wavelengths in a counter-propagating or co-propagating manner to support bandwidth capacity enhancement in the first mile plant beyond those offered by traditional forward and reverse HFC technologies.

## FIRST MILE TECHNOLOGIES

HFC architectures have significant fiber capacity based upon these optical technologies. The challenge is delivering this capacity over the coaxial cable.

### Absolute Bandwidth and Bandwidth per User

The efforts of exploiting coaxial plant capacity progresses in two dimensions: bandwidth expansion and expansion of bandwidth per customer. In the first category are such efforts as:

1. Increasing system capacity towards 1 GHz with a combination of traditional analog video and digital QAM channels

2. Using spectrum above the existing nominal design limits of the broadband subsystem.

In the second category are efforts to:

1. Segment nodes into smaller serving areas by using fiber capacity and by extending fiber deeper into the coaxial plant to the point of eliminating RF actives after the optical node,

2. Replace analog channels with digital channels,

3. Improve digital signal efficiency by:

    a. Increasing QAM modulation levels for digital signals,

    b. Increasing coding capacity for digital video signals,

    c. Reclaiming broadcast digital bandwidth with switched digital architecture, and

    d. Increasing stat-muxing efficiency of digital video signals.

All these efforts can lead to reclaiming up to 288 MHz of forward bandwidth for narrowcast data signals. The hope is that DOCSIS 3.0 will allow using this bandwidth in a manner similar to FTTH where very high- capacity forward and reverse channels are shared among multiple users to improve statistical muxing gains.

### CMTS Cost

Today, DOCSIS CMTS channels typically serve between 500 and 1500 users with a single forward channel and multiple reverse channels. Average cost per user ranges from $5 to $20. Many sub-systems of the CMTS card are under-utilized, for example, typical reverse channel capacity exceeds forward channel capacity.

To match the capacity of APON and provide 640 Mbps downstream capacity and 150 Mbps of upstream capacity, 12 forward 6 MHz channels and 4 reverse 6.4 MHz channels are required. This accounts for the true network capacity of the APON architecture.

To match APON electronic costs of $300 per link, the DOCSIS CMTS configuration described above must drop to approximately $6,000. Note that GPON can provide higher capacity so the CMTS pricing will need to be even lower than this. The DOCSIS 3.0 CMTS configuration must include all components downstream of network interface (including QAM modulators and burst receivers) within the cost target indicated.

The HFC plant has significant advantage in its scalability. FTTH plant must be built from day one for the final penetration level due to loss budget requirements. The HFC plant can add equipment in the headend as the penetration levels increase. This will allow for taking advantage of declining prices and allows the operator to deploy bandwidth when and where it is needed.

## Gbps over Coax

If and where required, fiber can be extended to the last active (fiber deep deployments). This can be done efficiently and in a non-interruptive manner (no changes to the coaxial plant). With the actives eliminated from the coaxial network several options exist for increasing its capacity.

The coaxial cable spectrum is not limited to 870 MHz or 1 GHz. Most of the current deployments of HFC networks use 1 GHz passives and the passive section of coaxial plant can be easily used to 1.5 GHz and even to 3 GHz as long as it is not restricted by RF actives. This can allow for a use of the bandwidth above 870 MHz for point-to-multipoint (P2MP) technology deployment over passive coaxial plant.

Figure 16 presents one of many possible ways of spectrum utilization above the traditional HFC bandwidth. More optimal arrangements are being designed to simplify the implementation of this system and its integration with passive coaxial plant.

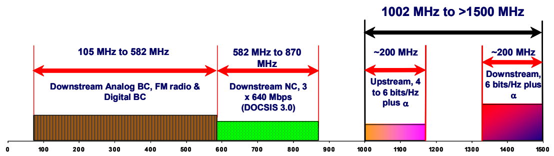


Figure 16. One of Possible Spectrum Utilization of Coaxial Passive Network

Beside physical layer, data and MAC layers are being developed to allow for adding Gbps capacity to the HFC capacity. The optimal solution would allow for several different data rates in forward and reverse to allow for adaptation to passive coaxial network conditions above the HFC operational frequency. It is mostly designed to take advantage of very short distances between the optical node and the farthest customer.

This technology can be deployed in a selective or opportunistic manner in areas where extreme capacity is required.

## Fiber on Demand

The digital capacity of fiber to the node can support much more bandwidth and many more applications. Moreover, the fiber in HFC network and especially in fiber deep HFC network is deployed to the proximity of the residential and business neighborhood. It is closer to the premises than the fiber in FTTN architecture where the node is designed to serve an area of 2,000 households. Therefore, at very low additional construction cost, a P2P (point-to-point) or P2MP fiber links can be deployed from the node to the premises.

Initial deployments of FTTP can serve businesses, schools and other public building with service expansion to SOHO premises and MDUs. These deployments can initially start with point-to-point (star) topology from the node to the premises. Modules providing an interface between the node digital uplink and standard FE or GigE are deployed in the optical node. They allow for installation of IEEE 802.3 standard compliant CPE devices and support 802.3ah capability. The CPE devices can be purchased off-the-shelf and self-installed by the customer or installed by an operator.

For residential deployments, an xPON compliant OLT is installed in the node and standard based ONTs are installed on customer premises. Note that the distance is significantly shorter than the distances in traditional FTTH deployments. This has a direct impact on loss budget and hence can result in selection of lower cost components and subassemblies.

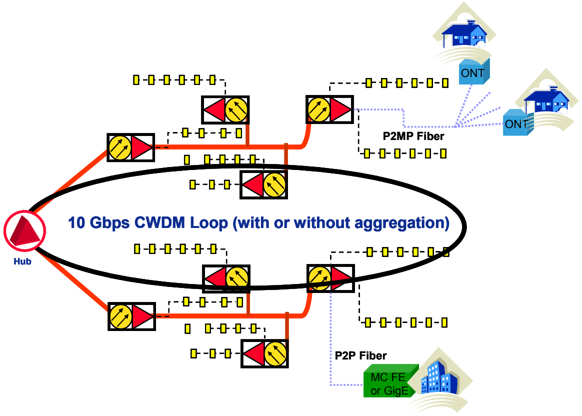


Figure 17. P2P and P2MP Opportunistic Deployments of FTTP in Fiber Deep HFC Networks

Both types of deployments can be implemented in an opportunistic manner, very similar to manner of deployment provided by many business service operators today. To further lower the future cost of deploying fibers, provisioning for fiber in the access plant during green-field construction can be implemented. A significant advantage of the evolutionary approach is the fact that all services supported by HFC are still being provided and the investment in all facilities and service equipment is fully utilized. Only when and where required or beneficial, is FTTP/FTTH from optical nodes deployed.

## SUMMARY AND CONCLUSIONS

### Node Uplink Capacity

The uplink in HFC nodes is based on the fiber optical technology and all developments that happen in this technology can be applied in those links. CWDM and DWDM for analog and QAM signals and for digital signals allow for exploiting the fiber capacity to its full potential. The optical nodes can be connected to the network via links that will not become a bottleneck for the traffic generated by the user connected to these nodes. The requirement is to deploy fiber deep enough into the access network so the first mile plant can put the uplink capacity to full use.

### Passive Coaxial Network Capacity

Coaxial network capacity is utilized only partially due to a simple fact that the loss of coax increases with frequency. In the past, the loss was compensated with RF amplifiers but at the same time RF amplifiers were limiting the bandwidth potential of the passive coax. With fiber deep into the HFC network, it is possible to support the traditional HFC bandwidth delivery to the customers without additional RF amplification between the node and the customer outlets. This traditional HFC bandwidth can provide increased capacity per user with the help of uplink technologies and DOCSIS and digital video technologies.

In passive coaxial network, the capacity above the traditional HFC bandwidth is now open to easy mining with advanced digital coding and modulation techniques. This bandwidth capacity can be expanded to 1.2 to 1.6 GHz in the existing plant and to 2 to 3 GHz with deployment of expanded bandwidth passives. Implementing Gbps bi-directional capacity over coax becomes possible in this scenario.

### Evolution to FTTP

The fiber push to the last active shrinks the distance between the fiber and the farthest customer. This distance stays below 1,000 m and most customers are within 500 m and drastically closer in densely populated areas. An opportunistic deployment of fiber to the premises becomes affordable, especially when provisioning for the future deployment took place during the plant construction. P2P dedicated links to businesses and high-bandwidth users and P2MP PON deployments from the node will allow for a new dimension added to the HFC network to further improve its competitiveness.

### Other Factors to Consider

In the environment of increased competition, other factors besides bandwidth and capacity are important. In a perfectly competitive environment, the variable cost of providing a unit of outcome becomes critical. While HFC deployments have an advantage in capital outlay per household, operational costs are also important parameters. As operators extend fiber deeper it both increases network reliability and lowers maintenance and other operational cost.

## ACKNOWLEDGEMENT

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