OPTICAL SEGMENTATION TECHNOLOGY ALTERNATIVES AND ARCHITECTURES

Phil Miguelez – Director, BAN Advanced Technology
Fred Slowik – Director, ANS Systems Marketing
Motorola Access Networks Solutions - 051808

Abstract

Fiber non-linearity presents serious challenges to fielding multi-wavelength optical systems capable of transporting full broadcast / narrowcast channel loads. Equipment vendors are rising to meet this challenge with new technologies that will allow MSO's to cost effectively segment nodes and harvest fiber for new services or future network segmentation.

In this paper we briefly review the key fiber optic challenges that are driving innovation and examine the different technology choices that are being offered today. We also look at a few implementation models of multi-wavelength on the HFC plant for a variety of different applications.

INTRODUCTION

Market Drivers:

Cable operators are faced with a wide range of opportunities for expansion into adjacent markets such as commercial access and cell tower backhaul. On top of this, competition and customer expectations are creating the need for ever increasing bandwidth capacity in the traditional CATV network. In order to meet the needs of both markets additional fiber or increased capacity of existing fiber is required. In most cases operators prefer to keep business services on a separate fiber network from residential video and data. Cable modems serve small offices well but larger businesses require GigE data rates and dedicated fiber.

Operators are also challenged to minimize CapEx spend and limit system down time. This is especially true in the current unforgiving economic environment. Pulling new fiber is not an option except in green fields and point to point business access situations where the revenue opportunities justify the expense. For all other applications a means to increase capacity using existing fiber is required. Multi-wavelength broadcast + digital transport is an ideal solution to meet this challenge.

Multi-wavelength transport allows node segmentation with minimal touching of the physical plant. More importantly, the increased BW capacity of fibers carrying multiple wavelengths allows surplus fiber to be harvested for other uses. These repurposed fibers can be used for business access or further network segmentation needs.

WDM solutions for digital transport are commonplace. CWDM and DWDM network architectures for baseband digital and QAM data delivery have been in place for 10 years or more. The major barrier for realizing these networks as part of the HFC downstream broadcast system has been the transport of analog video carriers. Early attempts to transport analog broadcast services over a CWDM network yielded poor results. Analog video is extremely susceptible to noise and distortion. Fiber induced distortions add directly to the native distortion of the source laser transmitter. Additionally, fiber and passive device nonlinearities create a host of potential impairments that must be avoided, minimized, or overcome.

Obstacles to Multi-Wavelength Transport:

When multiple wavelength signals propagate through optical fiber an array of impairments come into play, the most significant of these are Raman crosstalk, four wave mixing, dispersion, and cross phase modulation (XPM). The magnitude of each of these impairments is a function of the laser chirp, the optical launch power, the length of the fiber link, and the dispersion properties of the deployed fiber.

Additional impairments are also possible due to interactions with passive elements in the system such as optical mux and demux filter components.

Detailed descriptions of each of these optical nonlinearities have been presented in numerous articles, technical whitepapers and previous conference presentations on emerging multi-wavelength technology. This paper will provide a brief explanation for each of the critical distortion generators where appropriate to emphasize their impact to analog or digital QAM performance.

Broadcast + Narrowcast Multi-Wavelength Solutions:

Different techniques to mitigate the numerous fiber induced distortions listed above have driven each vendor to create unique, proprietary solutions. In order to take advantage of the wide availability of proven analog capable lasers and keep the complexity low, most vendors have elected to operate in the 1310 nm region. Some vendors have chosen to pursue ITU standard coarse wavelength spaced (CWDM) solutions. Other vendors have promoted dense wavelength spaced (DWDM) solutions. Both approaches permit some of the fiber nonlinearity issues to be minimized while making other optical impairments more difficult to correct.

All of the various solutions have a few common requirements. First among these is the necessity of having identical analog broadcast channel lineups on each wavelength. Analog carriers are the most susceptible to crosstalk distortion. If the signal modulation on each channel is identical, crosstalk susceptibility significantly reduced. Broadcast QAM will also benefit from this same effect. Narrowcast QAM by definition is unique to each wavelength. Narrowcast modulation channels will experience increased noise impairments due to crosstalk but the nature of digital modulation is more robust to these impairments.

Optical power levels for each wavelength should be roughly equal. Mixing high and low power lasers creates the potential for Raman scattering issues.

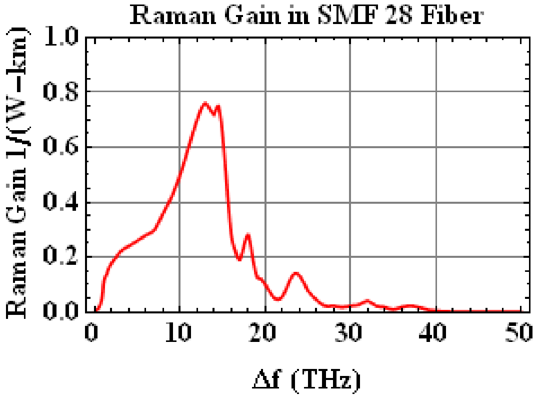
Another requirement in common is that the native laser distortion at each wavelength be as low as possible. Many of the fiber induced distortions will magnify the raw distortion of the laser transmitter. Each distortion parameter in a multi-wavelength system is a composite of the laser distortion plus the distortion generated within the fiber and passive elements as shown in the following example equation to calculate end of line (EOL) CSO performance.

$$\text{EOL (cso)} = 20 \log \left(10^{(\text{Laser CSO}/20)} + 10^{(\text{Fiber CSO}/20)} + 10^{(\text{Mux CSO}/20)} + 10^{(\text{Demux CSO}/20)}\right)$$

The following sections will discuss differences between DWDM and CWDM solutions for multiple wavelength transport of analog broadcast + narrowcast channel loading.

1310 DWDM Solution for Multi-Wavelength Transport:

Stimulated Raman Scattering (SRS) effects have always been the most difficult impairment to conquer. However, Raman gain is predictable based on the optical power, link length, and wavelength spacing. The plot below shows the Raman gain coefficient versus wavelength spacing in THz. Operating with close spaced wavelengths (left side of the plot) is an effective way to minimize SRS.



ITU standards do not exist for DWDM in the 1310 nm O-Band spectrum but translating the 200 GHz or 100 GHz channel spacing commonly used at 1550 nm wavelengths to 1310 nm is easily done.

While DWDM spacing helps to solve Raman crosstalk it enables another impairment, Four Wave Mixing (FWM). This impairment acts in an analogous manner as composite triple beat distortion. With equally spaced wavelengths the interaction of three wavelengths will create a beat that falls on the fourth wavelength. Custom wavelength selection avoiding equally spaced wavelengths is part of the solution to FWM. Distortion from Four Wave Mixing is most pronounced as the wavelengths used are operated near the zero dispersion point (ZDP) of the fiber. Additional crosstalk and CSO with as few as two DWDM wavelengths has been reported when the optical channels were operated in the zero dispersion region.

The selected wavelengths must be located away from the zero dispersion point of the fiber. The ZDP of SMF28 and SMF 28e fiber typically falls near 1310 nm but can vary from fiber lot to fiber lot over a range of +/- 10 nm. The newest version of fiber that Corning plans to introduce this year (SMF28e+) will shift the typical ZDP to 1317 nm. Balancing the choice of wavelength selection to avoid FWM and the ZDP of the deployed fiber is one of the reasons for the different proprietary schemes of the vendors supporting the DWDM approach.

Perhaps the most challenging issue facing DWDM multi-wavelength solutions is related to the optical passives. Mux and demux devices are constructed using thin film optical filters. The broadband response of these filters is usually quite flat but as the filter bandwidth becomes narrow as required for DWDM wavelength spacing the pass band ripple response can increase significantly. This higher ripple creates sloped or tilted regions in the bandpass response which interacts with laser chirp to generate additional CSO beat products. At tilts larger than a few tenths of a dB / nm the CSO generated in the filter will begin to dominate the end of line distortion performance depending on the chirp level of the laser used. To avoid the problem of passband ripple, mux and demux filters must be selected to very tight specifications.

1310 CWDM Solution for Multi-Wavelength Transport:

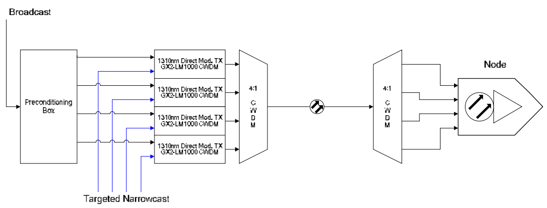
Maintaining ITU standard CWDM spacing simplifies a number of the challenges that face vendors of DWDM O-Band systems. Four Wave Mixing issues are eliminated since the phasing of the optical wavelengths are de-correlated by fiber dispersion. Optical passives with 20 nm channel spacing provide flat passband response with measured ripple slope of < 0.1 dB / nm. The filter bandwidth is much greater than the worst case wavelength variation of the cooled laser transmitter, so stability over environmental conditions is generally assured.

The major challenge to CWDM broadcast transport is Stimulated Raman Scattering. CWDM wavelengths are based on 20 nm spacing defined by ITU standards. At this spacing, Raman gain is a significant factor and peaks in systems with 3 to 4 sequential channels. CSO distortions generated in the RF and Optical domain by the laser are magnified by Raman gain interactions within the fiber and can dominate the overall system performance. High fiber dispersion such as occurs at 1550 nm would tend to de-correlate the modulated signals (walk off effect) and help reduce the magnitude of Raman crosstalk. Near 1310 nm dispersion is low so walk off is minimal. Optical launch power strongly contributes to the magnitude of the Raman induced CSO distortion. Therefore, limiting laser output levels will minimize the effects of Raman at the expense of link reach.

Adding wavelengths increases the optical power into the fiber and therefore increases the magnitude of Raman crosstalk proportionate to the additive optical level. Without using some external means of correction, multiple CWDM wavelengths with Broadcast + Narrowcast loading muxed onto a single fiber will produce unacceptable CSO distortion in optical links that exceed 12 to 15 Km.

Enhanced Coarse Wavelength Division Multiplexing (E-CWDM)

Enhanced CWDM is a patented technology developed by Motorola to mitigate Raman impairments in multi-wavelength systems. A unique method of conditioning the RF broadcast carriers minimizes Raman distortion along the fiber path. RF conditioning in conjunction with low chirp laser transmitters allows extended link reach of up to 30 km.


E-CWDM Block Diagram

As shown in the block diagram above, the broadcast input channels are conditioned and split to feed the individual CWDM lasers. Narrowcast channels are fed directly to each laser. No custom equipment is required at the node. This solution can be configured with separate forward and return path fibers or combined with a 1310 / 1550 WDM to provide a single fiber solution for upstream and down stream loading.

For short reach applications (<15km) RF conditioning is not a requirement. We have found in these cases that it is possible to reuse currently deployed 1310 transmitters as long as the output power is equal or padded to match the added CWDM lasers.

Multi-wavelength solutions are extremely cost effective compared to the capital expense of pulling new fiber. However, this technology does have limits. Fiber and passive component insertion loss reduces link reach compared to a single transmitter. Since many of the fiber distortions are optical level sensitive, cranking up the power is not effective. Distortion performance is a few dB lower than comparable single transmitter distortion particularly CSO which is the most vulnerable to degradation from Raman and dispersion. Even with these restrictions, multi-wavelength solutions can provide sufficient performance to meet the requirements of typical N+6 cascade architectures.

The next portion of this paper reviews the applications of multi-wavelength technology for Fiber Deep network migration strategies.

Multi-Wavelength Applications

The next wave of network migration for cable operators seems to be focusing upon creating smaller node serving areas in order to provide increased bandwidth capacity to and from fewer numbers of subscribers. Whether accomplished by creating "smaller virtual nodes" via adding physical node segmentation capabilities at existing node locations, or by deploying additional satellite nodes deeper into the network, one fact remains - there may not be sufficient fiber available to support this migration strategy.

Previous sections of this paper address some of the various multi-wavelength technologies that are becoming available to operators to help alleviate fiber constrains. Because node sizes, deployment depth and fiber counts can vary from operator to operator and system to system, this paper refers to node migration in terms of a size reduction factor as opposed to absolute house count per node. In this way, the reader can obtain an appreciation of available multi-wavelength options to meet their end goals. For example, an operator with existing node sizes of 1200 HP might desire a 4X reduction factor whereas existing node sizes of 500 HP may only desire a 2X reduction factor to meet the end goals.

Node Segmentation vs. Fiber Deep

Perhaps we should clarify that node segmentation and fiber deep architectures, both candidates for multi-wavelength solutions, have distinct differences and are not always synonymous.

Early in the evolution of HFC network deployment, cable operators had the choice of designing their coaxial plant emanating from optical nodes in either a balanced or unbalanced fashion. Balanced means that all homes serviced from that node were equally divided among all feeder legs from the node. Due to topology, this balancing often required adding express coaxial cables for segmentation purposes. Although this approach provides a smoother migration path for future node segmentation, cable operators were hesitant to invest in the added material and construction cost to balance their node serving areas. Consequently, many operators chose to opt for the less expensive unbalanced approach where the number of homes passed per feeder leg was random.

Ideally, if the original network design had followed the balanced approach, then virtual node segmentation could occur rather smoothly at existing node locations using segmentation capable nodes. Experience to date seems to indicate that only about 20% of existing nodes are sufficiently balanced to permit this ideal form of segmentation. The remaining 80% of existing nodes may be so unbalanced that some combination of segmentation capable nodes plus the addition of new satellite nodes or adding express coaxial cabling may be required. The latter approach does drive fiber deeper in certain areas,

Tables 1 & 2 illustrate a logical example of node segmentation for both balanced and unbalanced scenarios using a hypothetical 512 home passed node and migrating fiber all the way to the home. Note the unbalanced node creates the need for new fiber deployment during the initial migration process.

Table 1

Motorola HFC Network - Balanced Node Migration Path

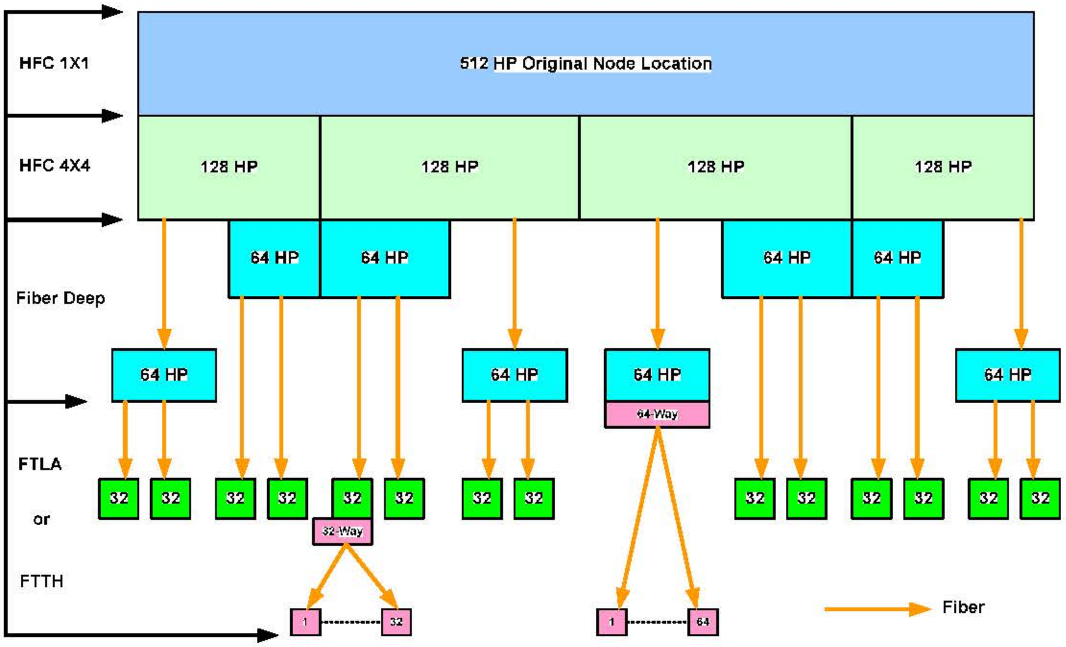
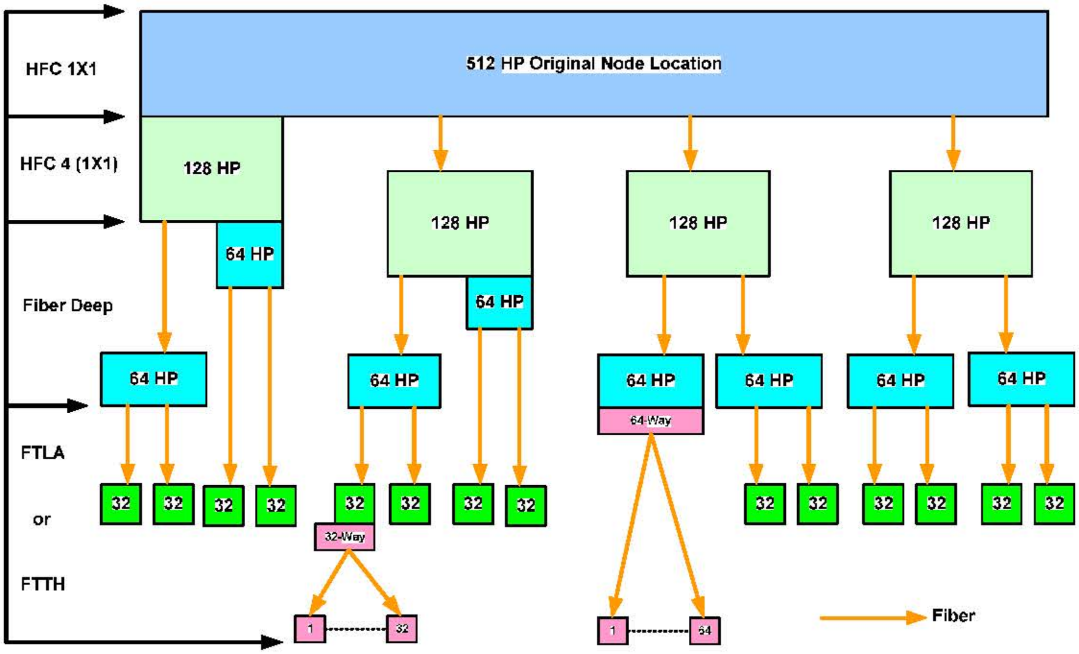


Table 2

Motorola HFC Network – Unbalanced Node Migration Path



Cascade Reduction

Although node segmentation and fiber deep architectures reduce the serving area size with respect to the number of homes/users per virtual node, the amplifier cascade length often remains unchanged. This, due to the fact that certain portions of the segmented node fed from the original node retain their existing footprint while cascade reductions usually take place in those areas where satellite nodes are added.

Figure 1 Existing Node

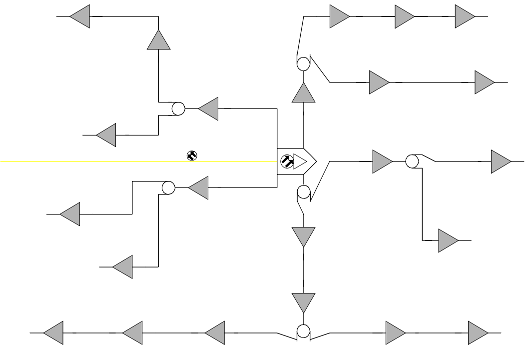
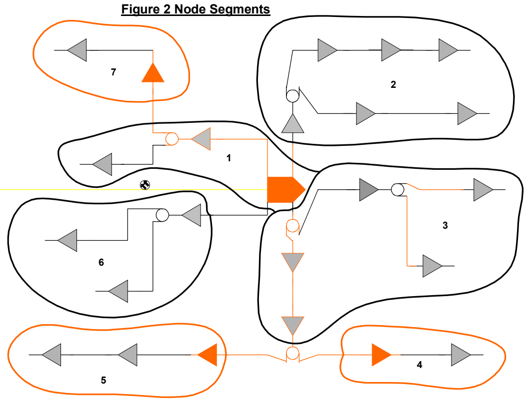


Figure 2 Node Segments



Intentional attempts to drive fiber deeper with the goal of strict cascade limitations often lead to very expensive migration solutions. Maybe a better way of looking at fiber deep would be to size the node to a desirable house count and ignore the cascade length. Pulling fiber to a Node + 0 architecture for example, without a lot of re-plumbing becomes tremendously expensive especially if one merely chooses to drop-in new nodes at all existing amplifier locations.

It is important to understand the cascade impact of fiber migration since different multi-wavelength technologies offer different performance characteristics at the node. Combined optical and RF performance becomes an important consideration in determining which technology will support end-of-line network performance goals. Depending upon RF amplifier cascades, one optical technology might mesh better with reduced amplifier cascades as opposed to another that might be better positioned to support longer amplifier cascades.

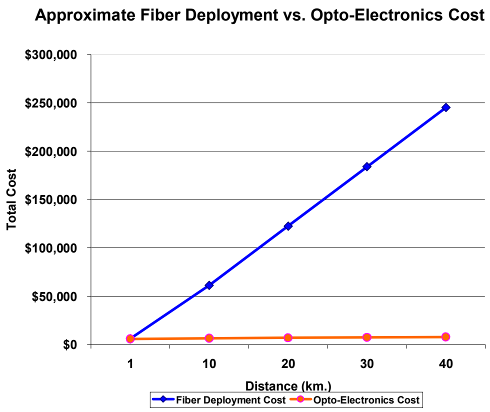
What About Adding Fiber?

If existing fiber counts were unlimited, network migration would be a much simpler task. Unfortunately, fiber counts are constrained in many systems, so operators need to understand new fiber deployment costs versus alternative options such as multi-wavelength technology. A very simple example illustrates.

Fiber Count	Material Per Foot	Aerial Labor per Foot	Aerial Make Ready Per Foot	Total Aerial Per Foot
6	$ 0.27	$ 0.60	$ 1.00	$ 1.87

Using this as an average aerial constructed price per foot, we can easily understand just how expensive installing new fiber can be ($1.87 X 5,280 = $9,873/mile). This cost is far more than the cost of the opto-electronic elements required at the headend / hub, and node location. Multiply this cost by the total distance required to reach an existing fiber starved node location and the cost can become prohibitive. This fiber installation cost does not consider more complex installations such as underground or areas where significant make-ready costs could arise.

The following graph illustrates fiber installation cost on a per km. basis versus the opto-electronic cost per virtual link for various multi-wavelength solutions.



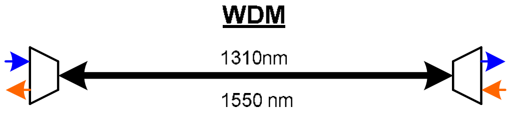
Depending upon the distance and fiber counts to existing nodes, and whether feeder legs are balanced as previously discussed, being able to expand bandwidth capacity via adding wavelengths on existing fiber to existing nodes is advantageous. Less significant are new fiber extensions to satellite nodes that may be required beyond existing node locations. Since these links are usually less than 2 km., the cost becomes much more tolerable, again, depending upon the extent of deployment.

What is the Right Solution?

It now becomes clear that alternative technology is needed to be able to cost effectively drive fiber deeper into the network. Depending upon the particular situation, several multi-wavelength solutions exist or are emerging that may co-exist in the same network. Three basic types of solutions are presented below. All of these options offer significant benefits. These are WDM, E-CWDM, and Broadcast/Narrowcast Overlay. Cost of these bi-directional solutions begin in the $5000/link range (including forward, reverse and nodes, excluding installation and new fiber if needed) and extend upwards based upon specific application needs.

WDM

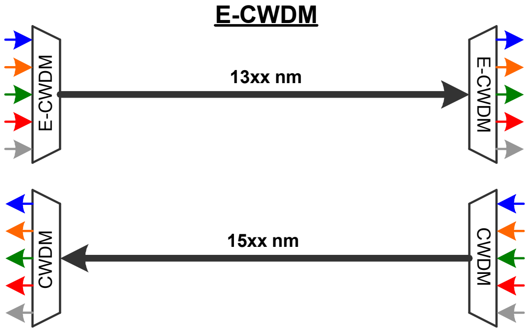
The least complex of the multi-wavelength solutions, this approach simply uses a 1310nm full band (54-1002MHz) downstream wavelength and a 1550nm upstream wavelength placed upon a single fiber. These wavelength directions can be reversed in some applications.



Node segmentation is accomplished by simply lighting up one fiber per wavelength pair. Assuming up to 6X migration is desired and sufficient fibers exist, this method is generally a low cost least complex means to achieve node area segmentation, and can achieve distances greater than 40 km. with excellent performance in the area of 51/-70/-66 dB CCN/CTB/CSO.

E-CWDM

Considered advantageous for fiber constrained applications, this approach, although a bit more complex, enables full band (54-1002MHz) downstream 13xx nm wavelengths upon a single fiber. Depending upon distance requirements, upstream wavelengths may also be deployed upon the same fiber or a second fiber may be required as illustrated in the example below.

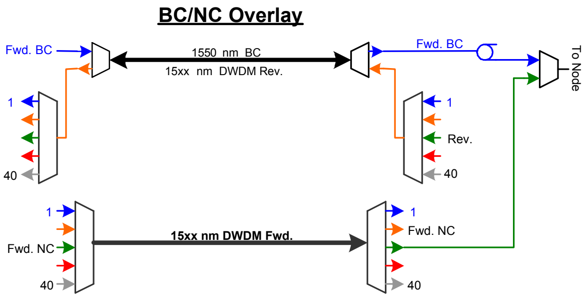


Based upon the number of wavelengths deployed upon a single fiber, this approach can cover distances of up to 30km, providing performance in the area of 50/-68/-60 dB CCN/CTB/CSO. This solution may also permit the ability to re-purpose existing fibers for other business applications.

BC/NC Overlay

A bit more complex than the two previous solutions, this solution offers advantages in networks requiring longer reach as optical amplification is possible. Generally, a two fiber solution, it consists of a single broadcast wavelength typically operating in the 54-550MHz pass band placed on one fiber which also can accommodate upstream
CWDM or DWDM wavelengths.

A second narrowcast fiber is used to transport up to 40 wavelengths typically used for QAM signals in the operating pass band of 550-1002MHz.



Distance, channel loading and performance requirements dictate whether a single or dual downstream optical receiver is required. This solution is also well suited for applications requiring optical path redundancy. Reach of up to 80+ km. are possible producing performance in the area of (49/51)/-66/-66 dB CCN/CTB/CSO.

Which Solution is Best?

Applications vary and so too does the answer to this question. A network analysis is generally required to determine the best fit and in certain instances, more that one solution may be required. Some generic guidelines however, may be helpful in determining where to begin.

A starting point would be to identify existing node sizes in the plant and determine the ultimate node size desired. This is determined by network operator bandwidth requirements based upon service offerings. Once this goal is established, dividing the existing node size by the new desired node size establishes a node reduction factor.

This factor, when considered with the fiber counts to the existing node, the distances required to be covered, and link performance goals, enables a high level selection of which multi-wavelength technologies are most applicable. In some circumstances it may be wiser to just utilize spare fibers if available or convert an existing two fiber solution to a 2X WDM solution (1 DS and 1 US wavelength per fiber).

Ongoing network analysis seems to indicate that the E-CWDM solution will become a dominant short to mid-range tool in the HFC network bandwidth expansion tool kit.

Once this analysis is accomplished, and a few options are selected, it becomes time to put pencil to paper and validate the chosen solution on the network design. At this time, additional decisions may be made to provision for additional future levels of migration should a staged approach over time be desired.

Conclusion

There are many factors to consider when deploying multi-wavelength solutions for node segmentation and fiber deep applications in order to increase network bandwidth.

This paper only presents a high level discussion of some of the technology and options available. Much more detailed analysis of which solution(s) make the most sense for a particular application is required to establish a rational migration strategy.

It is important to note that many operators approach the need to migrate their optical networks as an all or nothing proposition, basing their strategy and CAPEX requirements on an entire network optical migration. In reality, the migration process can and should take place in a phased approach addressing those areas of immediate or impending node congestion and deferring migration of those less endangered nodes to some point in the future if and when needed.

Numerous tools are evolving to expand HFC networks in order to provide increased bandwidth. The tools are growing and are of great interest to the cable industry.

Deployment of these various technologies and architectures can only help in the battle against the competitive forces that threaten the current market.