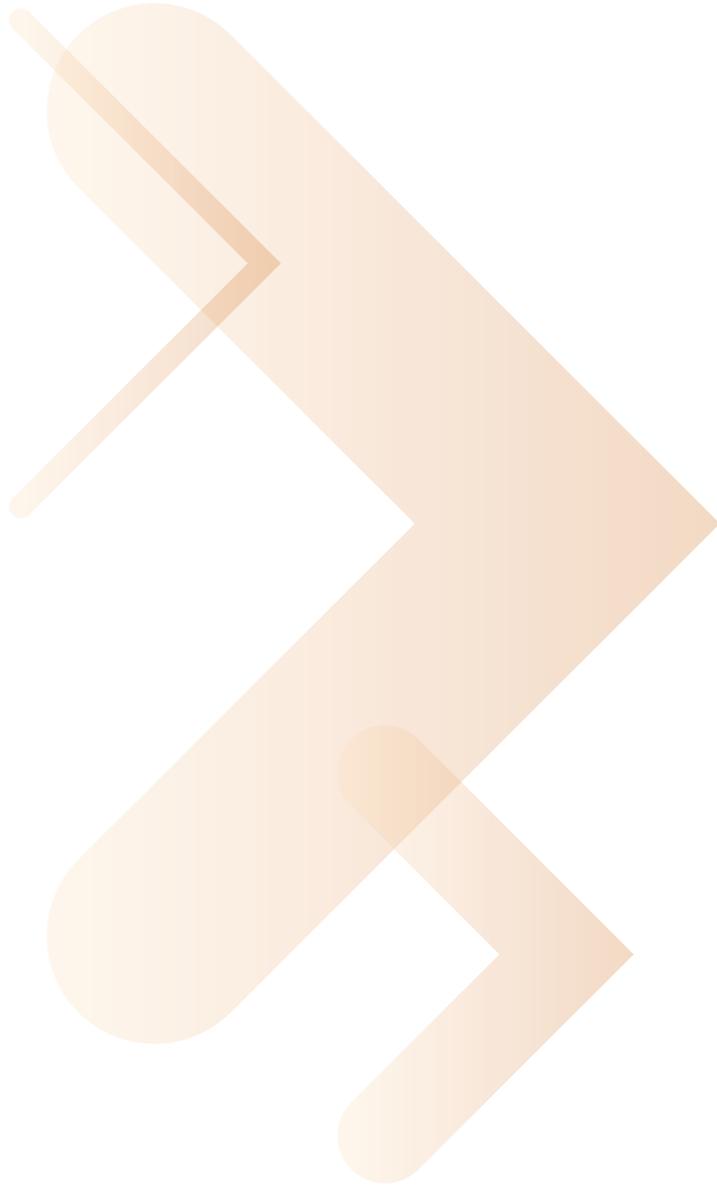




WDM/CWDM/DWDM: Segmentation Primer—Maximizing Capacity for Revenue





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Introduction

Cable operators need to satisfy the increasing demand from consumers for more services, such as video-on-demand, Internet, and voice. Segmentation, which divides node serving areas into smaller groups, is one of the primary tools that cable operators are employing to provide these additional services to their customers. At the same time, there are increasing revenue opportunities for cable operators to provide commercial services, such as cellular backhaul and business services. Segmentation and business service demands are both vying for the existing fiber in the access network. Since installing new fiber is an expensive proposition, cable operators are looking at solutions that maximize the capacity of the existing fiber.

Basic 1310nm transmitter segmentation has been used for many years to send multiple, unique optical signals, each on their own fiber to the optical node. But as segmentation and delivering business services becomes more rampant, Wavelength Division Multiplexing (WDM) optical solutions are becoming a valuable tool for cable operators.

Wavelength Division Multiplexing is a technique that sends multiple optical signals in the downstream and/or upstream over a single fiber. Using simple two-wavelength WDM can increase service capacity by two times over the same number of fibers. For several years, there have also been some limited solutions using more complex Dense Wavelength Division Multiplexing (DWDM) and Coarse Wavelength Division Multiplexing (CWDM) techniques that can carry four or more optical signals on the same fiber. Recently cable equipment manufactures have rolled out innovations using DWDM and CWDM that transport multiple broadcast optical signals over a single fiber, making node segmentation more cost-effective and operationally friendly.

There are advantages and disadvantages of the different solutions with respect to cost, operational friendliness, performance, link distance, and fiber utilization. The cable operator needs to be cognizant of the different approaches so the optimal solution is chosen. This paper will review each solution and the optimal conditions suited to their deployment.

Broadcast Versus Narrowcast Services

As a basis for this discussion, it is important to understand the different types of services that are delivered to customers over the Hybrid Fiber/Coax (HFC) network. Broadcast services are point-to-multi-point services, or services that all customers in the node serving area can utilize. Examples of broadcast services are analog video and digital video, which includes standard-definition and high-definition digital television content. In North American cable systems, analog broadcast signals typically start at channel 2 (55 MHz) and extend to channel 79 (553 MHz). Digital broadcast signals usually start after the analog channels at 553 MHz and, though the amount of digital broadcast varies system-by-system, the digital content will typically extend up to 650MHz or 750MHz.

Narrowcast services are point-to-point services, or services that are targeted at a single customer in the node serving area. All customers in the serving group will receive the narrowcast signals but only the authorized user will be able to utilize a specific service. Examples of narrowcast services are video on demand, Internet data and telephony. The frequency location of narrowcast downstream signals varies greatly by system, but for simplicity we will assume that narrowcast signals are above the broadcast digital signals and fill the band up to 1 GHz.

For the sake of this paper, return-path signals will also be considered narrowcast since they are unique signals from the subscribers to the headend. Through time and frequency multiplexing techniques, all of the return signals from the serving group are combined on the HFC network up to the headend. Examples of return-path signals are video on demand control signals, return Internet data, and return telephony traffic. In North American cable systems, return-path signals almost always occupy the frequency band from 5 MHz to 40 MHz.

Figure 1 shows a typical frequency plan.

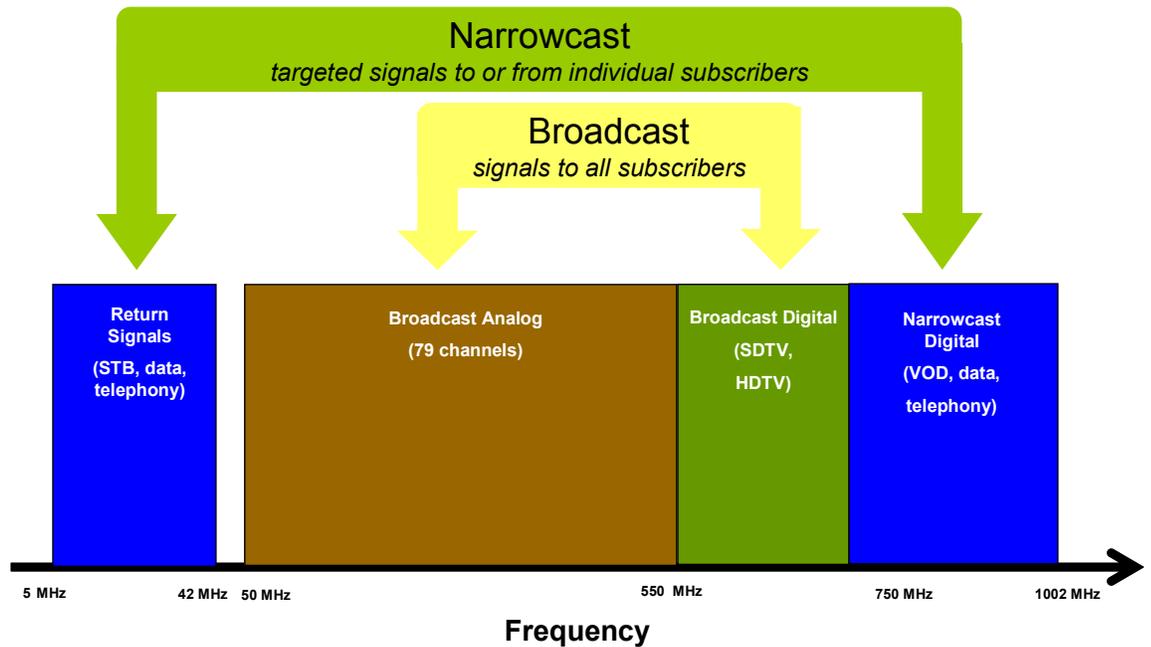


Figure 1 – Typical North American Frequency Plan

Hybrid Fiber/Coax Architecture

Figure 2 shows a diagram of a simple HFC architecture. Two fibers are utilized between the headend/hub and the optical node, one with an optical signal in the downstream and one with an optical signal in the upstream. The optical node is in a 1X1 configuration, which means the node receives just one set of downstream content (broadcast + narrowcast), and transmits one set of upstream, return-path signals.

The optical node shown has four RF ports which interface with the coaxial section of the network. In this example, this node covers 1000 homes passed (HP). If the node is perfectly balanced, then each RF port would serve 250 homes. In the 1X1 configuration, though, all four RF ports have the same downstream content and the upstream traffic from all four RF ports are combined onto the single upstream optical signal. This means that 1000 homes must share the downstream narrowcast bandwidth and the upstream return-path bandwidth.



OmniStar® GX2
Optical Broadband
Transmission Platform

OmniStar GX2 is a fiber optic transmission platform designed to deliver Ultra-Broadband services for cable operators over their Hybrid Fiber/Coax networks. It is a universal platform with a full complement of high-performance application modules that can accommodate any system architecture. The available modules include 1310nm broadcast transmitters, 1550nm broadcast transmitters, DWDM narrowcast transmitters, high-density return-path receivers, digital return transmitters and receivers, and several more. The four rack-unit chassis accommodates 16 Plug-n-Play application modules, minimizing headend space requirements.

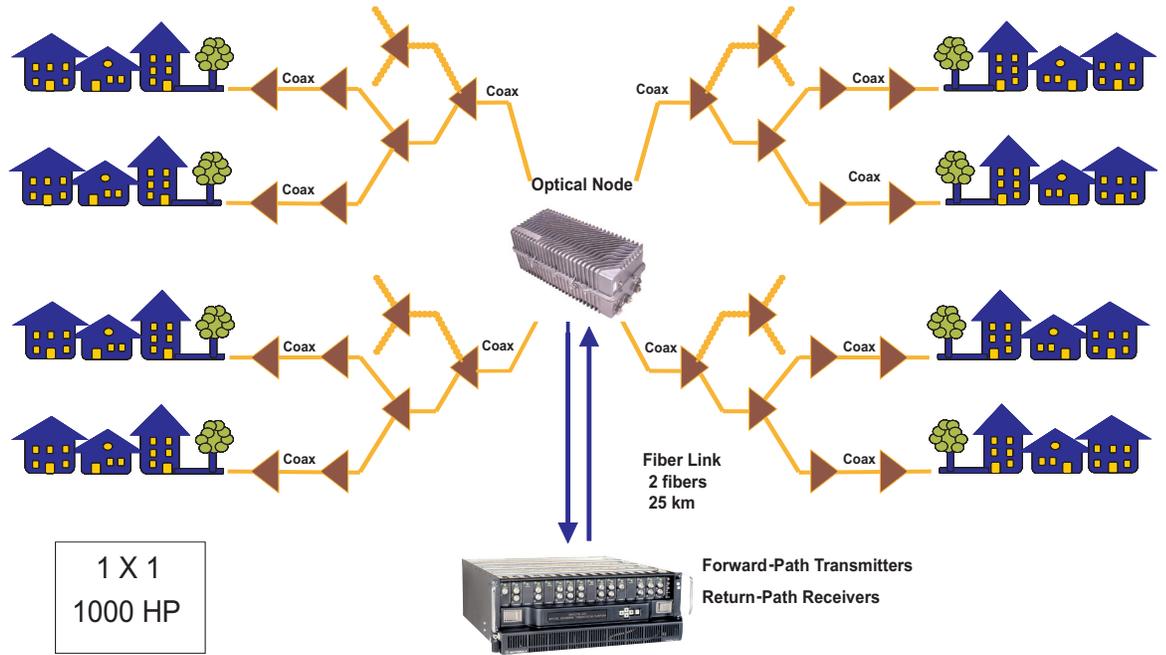


Figure 2 – Typical HFC network with 1X1 Node

Basic Node Segmentation

To generate more revenue from customers, cable operators need to offer more/better narrowcast services such as more VOD streams and higher Internet data rates to individual customers. To do this, more bandwidth per customer is required in both the upstream and downstream in the HFC network. A common tool to increase bandwidth per subscriber in HFC networks is called node segmentation. Node segmentation basically divides the node into sections to make the serving groups smaller, and thus, the bandwidth is shared by fewer customers. These smaller serving groups get their own unique set of narrowcast content and dedicated bandwidth for upstream traffic.

In node segmentation, the broadcast analog and broadcast digital content remains the same across all of the smaller serving groups—the narrowcast downstream content is unique and the upstream return-path bandwidth is dedicated to the serving group. Note that the unique narrowcast and return-path signals still occupy the same frequency ranges; they just have their own “pipe” from the headend to the smaller serving group. Figure 3 shows how these bandwidths are replicated four times which enables 4X4 node segmentation. This essentially increases the bandwidth for narrowcast services by four times.

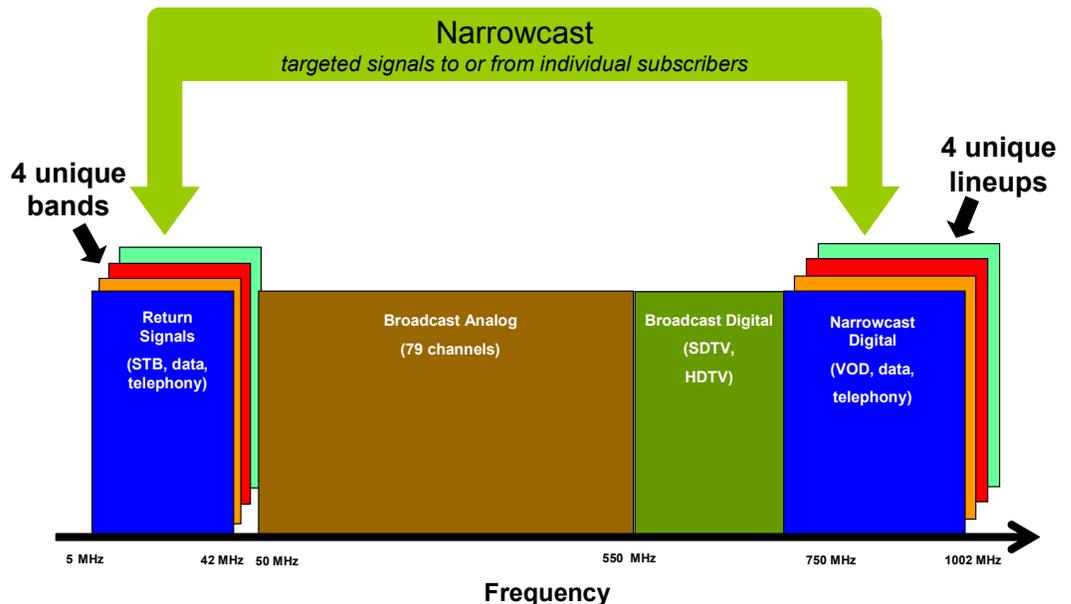


Figure 3 – Replicating Bandwidth for Narrowcast Content



SG4000

4x4 Optical Node Platform

Motorola's SG4000 1 GHz modular optical node features the latest technology to allow cable operators to support advanced fiber architectures. With provisions for up to nine optics modules in the lid, the SG4000 scales from its most basic 1x1 configuration to full 4x4 capability without any loss of initial investment and with minimal service interruptions. Independent RF modules in the base are the foundation for total segmentation and provide excellent port-to-port isolation. Unique configuration boards plug in to the lid router to direct the signal flow as the station expands to handle increased network demands. The SG4000 features CWDM or DWDM return-path transmitter modules to facilitate node segmentation with the optimum re-use of existing fibers.

In most cases, even though the broadcast content is the same for all the smaller serving groups, the content is copied and transported on multiple optical signals to the node along with the each unique narrowcast content. Even though this seems bandwidth inefficient, it is the most operationally friendly for the HFC network. Broadcast/DWDM Narrowcast overlay, discussed later in this paper, is a solution that only sends one copy of the broadcast content to the node, where it is split to serve the multiple serving areas.

Figure 4 shows a diagram of an optical node segmented four times in both the forward and return, otherwise known as 4X4 node segmentation.

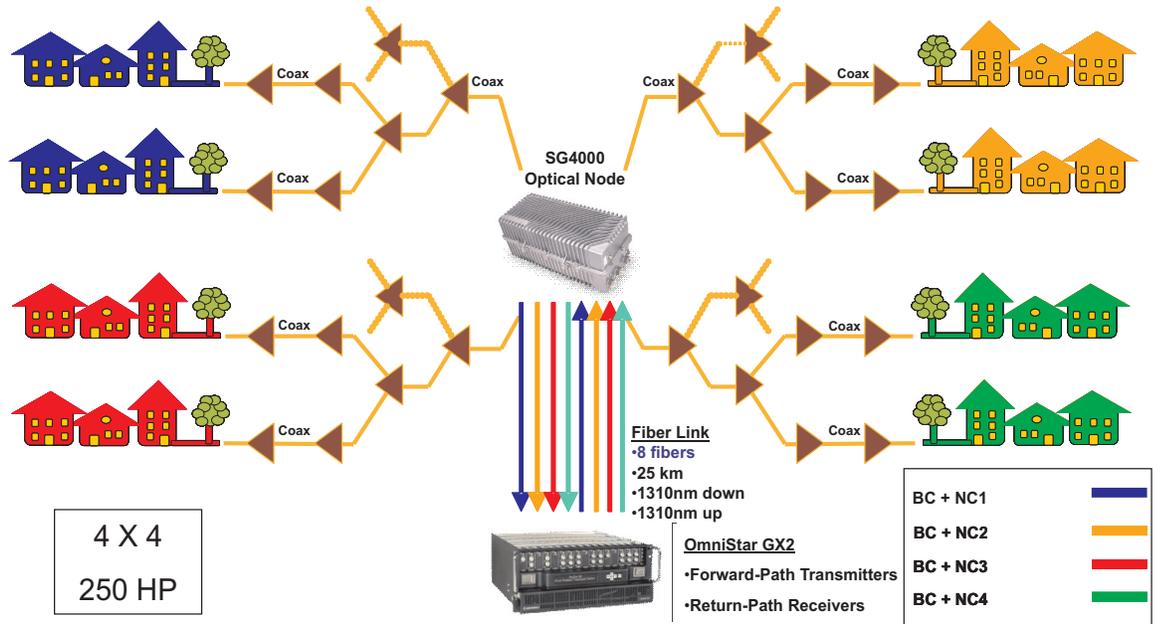


Figure 4 – HFC network with 4X4 Node Segmentation

There are eight fibers utilized between the headend/hub and the optical node: four with unique optical signals in the downstream and four with dedicated optical signals in the upstream. Each RF port has a dedicated 1310nm optical transmitter in the headend/hub and optical receiver in the node for its downstream (broadcast + unique narrowcast) content; and a dedicated 1310nm optical transmitter in the node and dedicated optical receiver in the headend/hub for upstream return-path traffic. Note that even though the broadcast content is exactly the same for all four segments, a copy of this content is transported on all four forward optical signals.

Value of Fiber

Using the basic technique for 4X4 node segmentation described in the previous section requires eight fibers. Most cable operators have limited fiber counts from the headend/hub to the node: as few as two fibers and usually no more than ten fibers. More often than not, cable operators do not have eight fibers between the headend/hub and node to segment the serving area four times. Even if eight fibers are available, there are emerging opportunities in commercial services, such as enterprise access and cellular backhaul, which can utilize those fibers for new revenue streams.

The cost to lay new fibers over 20km is typically \$150,000 minimum for aerial, and \$500,000 to \$2,000,000 minimum for underground. This is a large investment to increase cable services to customers and/or to address business services opportunities. It could also take many months to get township approvals and negotiate with utility companies to lay new fiber. Alternative techniques to segment nodes that better utilize existing fiber resources present a more compelling case for cable operators to pursue these revenue opportunities.

Wavelength Division Multiplexing

Wavelength Division Multiplexing (WDM) is an optical technique that combines multiple, unique optical signals at different wavelengths (colors) onto a single strand of fiber. At the receiving location, these optical signals are split back out, or demultiplexed, into separate fibers. Essentially, the bandwidth capacity of the fiber is multiplied by the number of wavelengths multiplexed onto the fiber. Figure 5 conceptually shows the WDM technique.

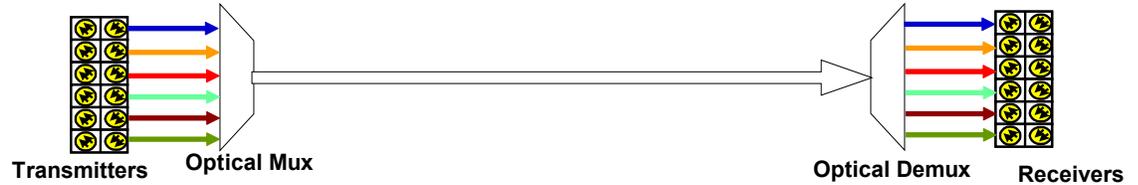


Figure 5 – Concept of Wavelength Division Multiplexing

There are three variations of WDM that are commonly used: Broad WDM, Coarse WDM, and Dense WDM. Each variation has different capabilities, costs, and operational friendliness.

As shown in Figure 6, broad WDM (often just called WDM) utilizes two wavelengths: one wavelength at 1310nm and one wavelength at 1550nm. Broad WDM is very simple to implement. Off-the-shelf optical transmitters without tight control of wavelengths can be used. These applications also utilize low-cost optical multiplexers and demultiplexers with low insertion loss.

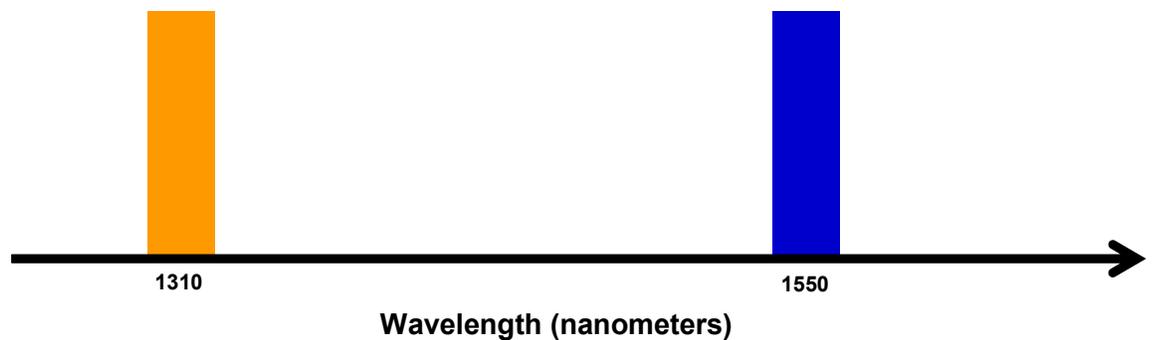


Figure 6 – Broad WDM Wavelengths

Coarse WDM (CWDM) utilizes multiple wavelengths spaced at 20nm, as shown in Figure 7. The International Telecommunication Union (ITU) in Reference [1] specifies 18 CWDM wavelengths from 1271nm to 1611nm. Transmitters, optical multiplexers, and demultiplexers are at defined wavelengths, but they do not need to be tightly controlled, which translates into lower equipment costs compared to Dense WDM.

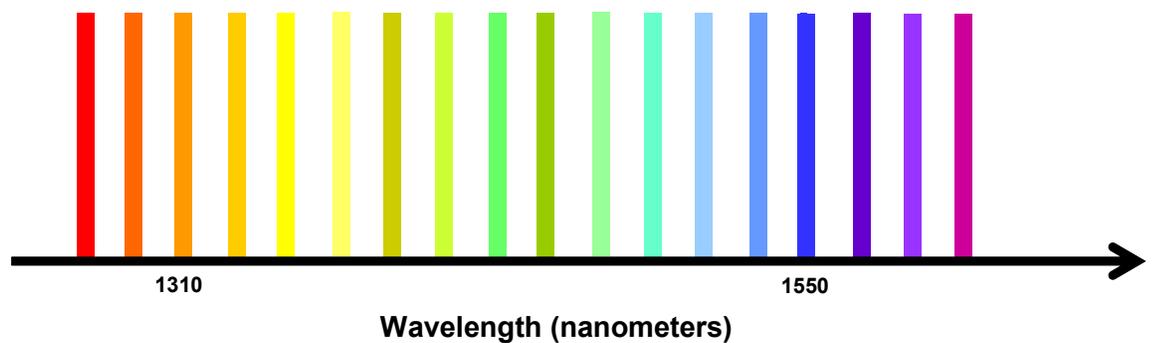


Figure 7 – Coarse WDM Wavelengths

Dense WDM (DWDM) utilizes many wavelengths spaced narrowly, and they are most commonly located in the C-band, the wavelength range from 1530nm to 1565nm shown in Figure 8. ITU in Reference [2] specifies the center of the DWDM wavelengths. Practical deployments of DWDM today are spaced at 100 GHz frequencies (or approximately 0.8nm spacing), which allow about 40 wavelengths in the C-band. DWDM requires that the optical transmitters, multiplexers and demultiplexers have very tight control over the wavelength under all operating temperature conditions. One key advantage of DWDM is that the gain region of Erbium-Doped Fiber Amplifiers (EDFAs) is also in the C-band, which enables all the wavelengths to be amplified to overcome loss over long spans of fiber and/or high passive losses (e.g. from splitting, multiplexing, etc.).

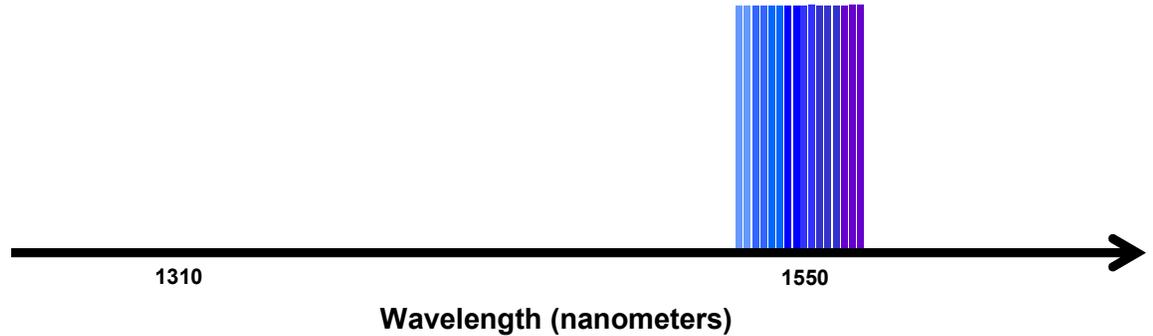


Figure 8 – Dense WDM Wavelengths

Figure 9 shows conceptually how a node can be fully segmented with just two fibers.

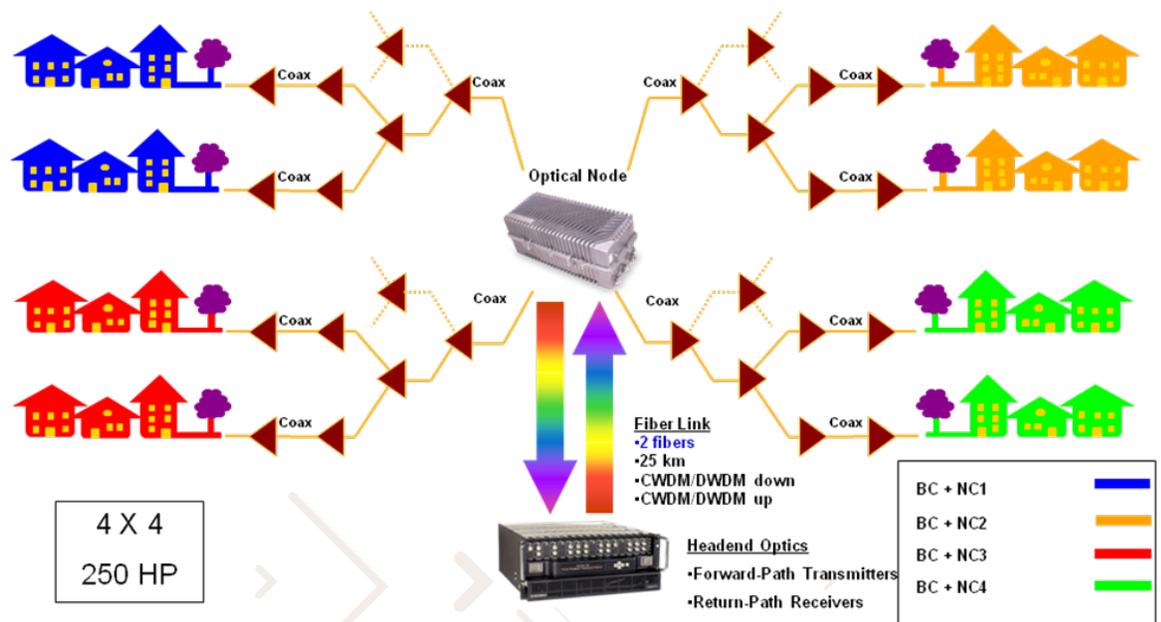


Figure 9 – Node Segmentation using WDM/CWDM/DWDM

Broad WDM for Node Segmentation

A simple way to segment the node from a 1X1 configuration to a 2X2 configuration over two fibers is to utilize Broad WDM, often called just WDM. The typical implementation is to have a 1310nm downstream optical signal and 1550nm upstream optical signal bi-directionally on each of the two fibers, as shown in Figure 10. Common, off-the-shelf broadcast transmitters and return transmitters can be utilized for this.

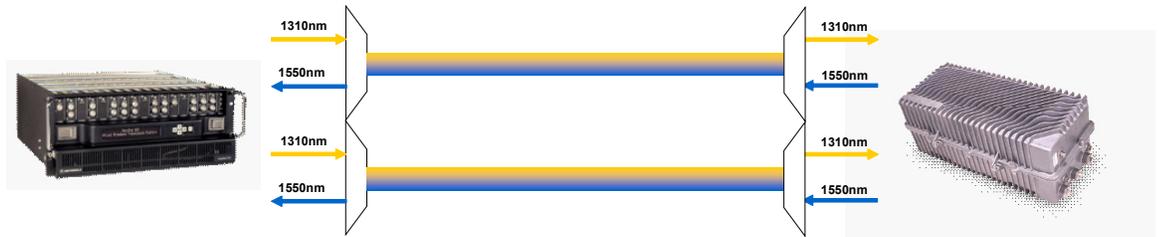


Figure 10 – 2X2 Node Segmentation with Broad WDM

The node can be migrated later to 4X4 segmentation in two different ways. The first way is to utilize two more fibers, for a total of four fibers, and implement Broad WDM on those also. A second way is to migrate to the CWDM/DWDM techniques discussed later in this paper, which would not require additional fibers to be used. So the initial capital investment on transmitters in the 2X2 configuration can be re-used; the cable operator, however, needs to carefully choose the initial transmitters with regard to wavelength selection and optical power. For example, instead of initially using 1550nm return transmitters with uncontrolled wavelengths, they should consider using 1551nm and 1571nm CWDM return transmitters. The initial equipment cost will be a little more, but significant capital investment could be saved later.

Coarse WDM for Node Segmentation

Up until recently, Coarse WDM methods have only been available for HFC networks in the return-path. (New CWDM methods for the forward-path will be discussed in a later section.) With regard to return-path, up to eight transmitters at different CWDM wavelengths can be multiplexed onto a single fiber. This can be useful if the return-path has significantly more bandwidth contention than the forward-path, so 2X4 node segmentation may be sufficient. Figure 11 shows 2X4 segmentation utilizing three fibers: two fibers for downstream and one fiber with CWDM in the return-path.



Figure 11 – 2X4 Node Segmentation with Coarse WDM in return

Dense WDM for Node Segmentation

DWDM offers much flexibility for node segmentation, but, at the same time, it is more costly and more operationally challenging than other methods. Theoretically, the node serving area can be segmented up to 40 times in both the forward-path and return-path over three fibers by using the 40 available wavelengths in the C-band. Since the optical signals are in the C-band, they can all be amplified by EDFAs so high insertion losses of optical passives can be overcome and/or theoretically achieve fiber link distances of 65 km or longer. Of course, it is very unlikely that a node serving area would ever need to be segmented 40 times and such long link distances to a node are rare. However, these capabilities could be valuable in some Fiber Deep networks, a specialized method to segment node serving areas that is becoming more prominent.

The method to segment nodes utilizing DWDM in the forward-path is called Broadcast/Narrowcast DWDM Overlay. The concept is shown in Figure 12. The Broadcast/Narrowcast DWDM Overlay utilizes two fibers in the downstream: one fiber with an optical signal with the broadcast content, and one fiber with multiple optical signals on DWDM wavelengths, each containing unique narrowcast content for a segment. At the node, the narrowcast DWDM wavelengths are separated onto their own fibers. The narrowcast content can then be overlaid with the broadcast content at the node either in the RF domain or the optical domain.

Motorola's Fiber Deep solutions enable cable operators to effectively segment node serving areas by pushing fiber closer to the homes while using existing fiber resources. DWDM and CWDM transmitters in both the OmniStar GX2 and SG4000 enable services to be increased by eight times and more. With optical amplifier and optical switch modules, the SG4000 can become an all-optical, collector node in a Fiber Deep architecture. With the **MBN100 1 GHz MiniBridger optical node** and the **BLN100 1 GHz optical node**, cable operators can convert existing Motorola RF Amplifiers in their plant to fiber deep nodes providing CapEx savings and minimal service interruptions.

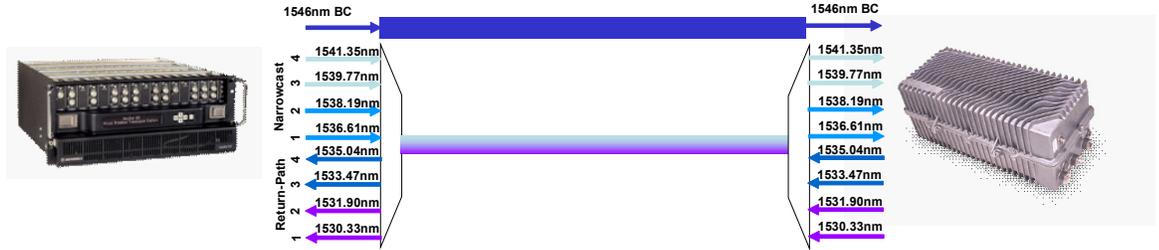


Figure 12 – 4X4 Node Segmentation with Dense WDM

Figure 13 shows a schematic of how this is done in the RF domain in the node. When combining in the RF domain, the broadcast wavelength and each narrowcast wavelength go to their own receivers. The broadcast signal is then split and combined with each narrowcast signal in the RF domain. This method can provide the best performance, as much as 3 dB better in distortions compared to combining in the optical domain, because out-of-band noise can be filtered in the RF domain before the signals are combined. To do this filtering, though, none of the frequencies of the narrowcast can be dispersed through the frequency band of the broadcast. Combining in the RF domain is attractive; unfortunately, most nodes do not have this capability.

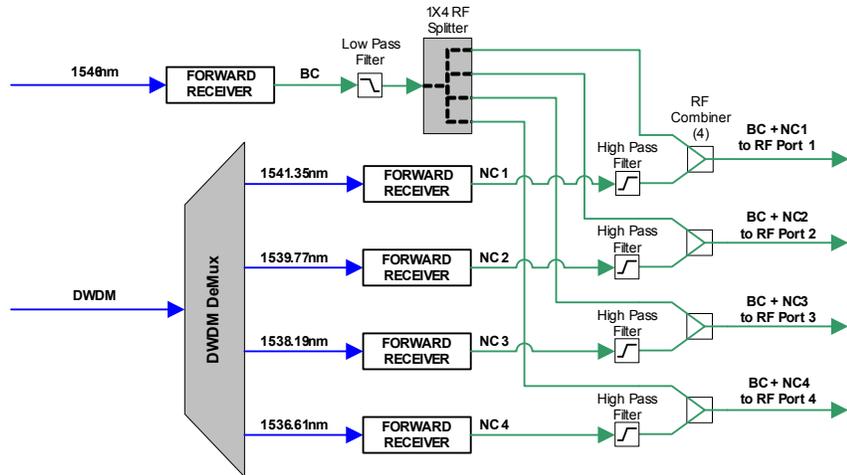


Figure 13 – Schematic of BC/NC RF overlay in node

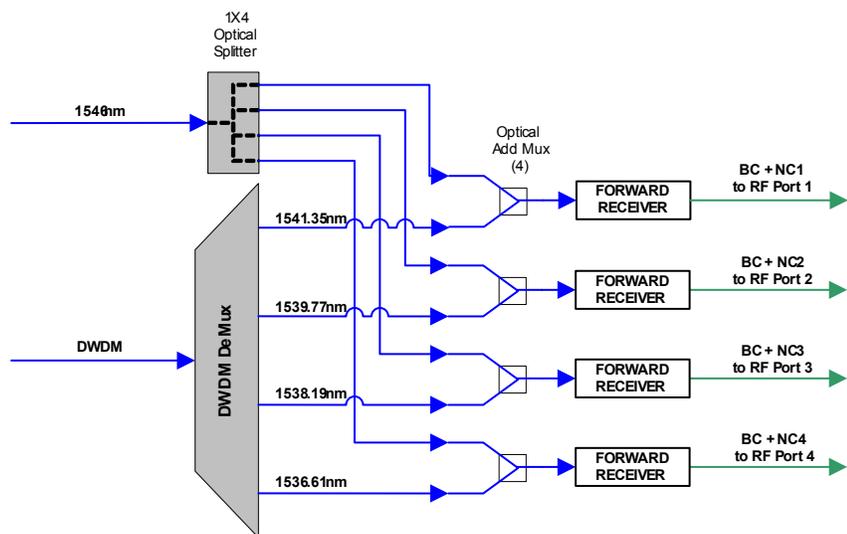


Figure 14 – Schematic of BC/NC optical overlay in node

As an alternative, the broadcast and narrowcast content can be combined in the optical domain. Figure 14 shows a schematic of how this is done in the node. This requires that the optical signal with the broadcast content be split the same number of ways as there are narrowcast wavelengths. Each narrowcast wavelength is optically combined with the broadcast wavelength, and then each broadcast + narrowcast pair goes to a receiver. This method requires carefully adjusting that the optical levels during installation so the digital signals will be offset from the analog signals at the appropriate level in the RF domain. If the ratio of broadcast to narrowcast content changes later, then the optical levels may need to be adjusted. This makes installation and maintenance of this architecture challenging.

In the upstream, each node segment has a dedicated DWDM wavelength for return-path content. Depending on the network layout, these wavelengths can actually be multiplexed onto the same fiber as the narrowcast wavelengths so a node area can be segmented multiple times over two fibers. This is shown in Figure 12.

With regard to cost, the Broadcast/Narrowcast DWDM Overlay method requires a high-performance 1550nm broadcast transmitter, multiple narrowcast transmitters with tight control on the DWDM wavelengths, and usually one or more EDFAs to amplify the signals to overcome passive losses and fiber link loss.

New Multi-wavelength Downstream Full-band Solutions

Until recently, the Broadcast/Narrowcast DWDM Overlay method was the only way to segment nodes in the forward-path multiple times over a minimal number of fibers. Due to the cost and operational challenges, this is not attractive for most 4X4 node segmentation. A more optimal solution for cable operators would be full-band transmitters at multiple wavelengths, each carrying the analog broadcast services, digital broadcast services and digital narrowcast services. Early attempts at using full-band downstream transmitters in CWDM or DWDM architectures yielded poor performance. The reason is that analog video is extremely susceptible to noise and distortion, and there are additional impairments when multiple wavelength signals propagate through optical fiber. As detailed in the *Optical Segmentation Technology Alternatives and Architectures* whitepaper (Reference 3), the most significant impairments 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. Additionally, nonlinearities in the fiber and optical multiplexers create a host of potential impairments that can degrade the analog performance.

As cable operators have more need to increase targeted services and WDM device capabilities have improved, equipment vendors have made innovations so that nodes can be segmented with multi-wavelength, full-band transmitter solutions that are more cost-effective and operationally friendly. Different techniques to mitigate the numerous fiber-induced distortions 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 O-band, which is the wavelength range from 1260nm to 1380nm. Some vendors have chosen to pursue ITU standard coarse wavelength spaced (CWDM) solutions, while other vendors have promoted dense wavelength spaced (DWDM-like) solutions. Each approach minimizes some of the fiber nonlinearity issues while making other optical impairments more significant.

These downstream solutions can be coupled with CWDM return-path solutions to provide symmetric node segmentation. They can also be coupled with CWDM solutions in the C-band on the same fiber to transport baseband digital optical signals, such as Gigabit Ethernet, for commercial services.

Figure 15 shows conceptually how a node can be segmented four ways in the forward-path and return-path over two fibers with these solutions.

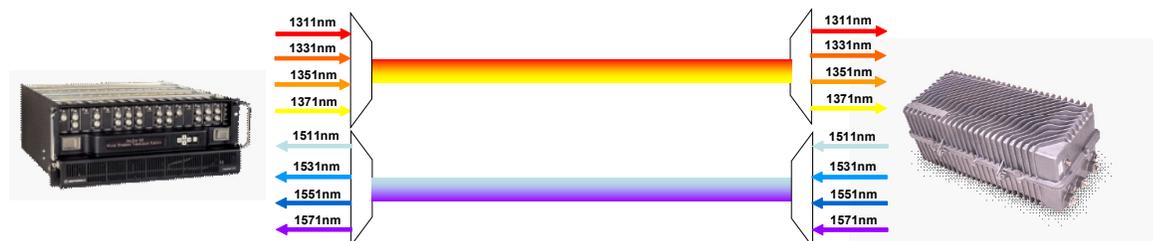


Figure 15 – 4X4 Node Segmentation with Multi-Wavelength Downstream

Motorola's Enhanced CWDM Solution

Motorola's E-CWDM technology increases downstream service delivery capacity over cable networks by transmitting multiple CWDM optical signals over a single fiber optic connection, enabling operators to segment serving areas into three, four, or five discrete areas. With each optical signal carrying a full 1 GHz loading of broadcast and narrowcast content, over distances up to 25 kilometers between the hub and optical node, operators can cost effectively meet the need for additional service capacity for HDTV, VoIP, VOD, and high-speed DOCSIS services. Part of Motorola's proven portfolio of Ultra-Broadband bandwidth expansion solutions, E-CWDM is both economical and simple to deploy, with inherent system reliability that can endure harsh outside plant environments and changes in optical characteristics of components over time.

The DWDM-like downstream solutions operate at wavelengths that are narrowly, but unevenly spaced in the O-band. These wavelengths are custom and vary between vendors. The narrow wavelength spacing reduces Raman crosstalk, and the uneven spacing reduces some of the Four-wave Mixing impairments. To further reduce Four-wave Mixing, the wavelengths are selected away from the zero dispersion point (ZDP) of the fiber. The ZDP of a majority of 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 (SMF28e+) will shift the typical ZDP to 1317 nm. For optimal performance, different wavelength plans may be needed depending on the dispersion of the deployed fiber. The most challenging aspect of these DWDM-like solutions is the requirement for tightly controlled optical multiplexers and demultiplexers with pass bands that are very flat and have very low ripple to minimize CSO beat products; these requirements significantly increase the level of test screening needed to verify performance, which lowers yield and increases cost.

The CWDM downstream solutions also operate in the O-band, but at ITU standard CWDM wavelengths. These wavelengths have been used for many years in high-volume baseband digital applications, such as Gigabit Ethernet optical transport, so the components are well-understood and well-characterized. When used for analog transport in a CWDM solution, optical passives multiplexers and demultiplexers do not need to be tightly controlled like the DWDM-like solutions because 20 nm channel spacing provides flat passband response. Four-wave Mixing issues are eliminated in CWDM applications since the phasing of the optical wavelengths are de-correlated by fiber dispersion. The major challenge to CWDM broadcast transport is Stimulated Raman Scattering because there is more Raman gain between wavelengths when they are spaced further apart. Without any mitigation techniques, this Stimulated Raman Scattering limits the fiber distances from 12km to 15km.

Motorola's Enhanced CWDM (E-CWDM) solution, shown in Figure 16, utilizes a patented technology 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 with CWDM. This extends the link distance up to 30 km so most nodes can be reached using CWDM. This extended reach coupled with the benefits of CWDM components makes this an attractive multi-wavelength downstream solution.

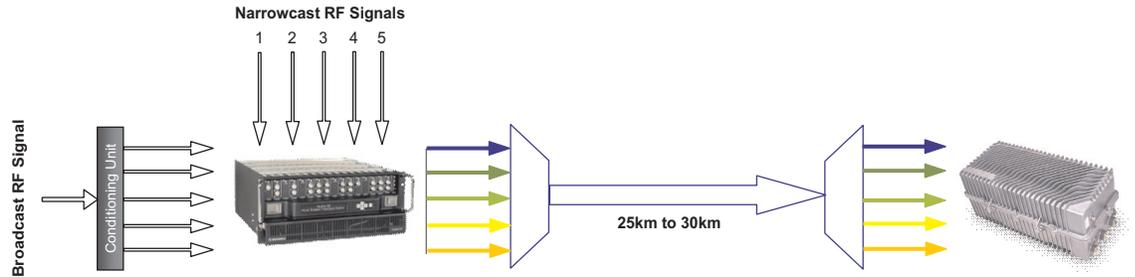


Figure 16 – E-CWDM with Mitigation Techniques

Table 1 outlines the technical comparisons between DWDM-like and CWDM solutions.

Table 1 – Technical Comparisons for DWDM-like and CWDM Multi-wavelength Downstream Full-band Solutions

	DWDM-like	CWDM
Wavelength selection	Uneven, narrowly spaced	Standard ITU wavelengths
Raman crosstalk	Reduced	Significant without mitigation techniques
Four-wave Mixing	Minimal with selective wavelength spacing	Not applicable
Dependence on the Dispersion of deployed fiber	High dependence	Low dependence
Number of wavelengths	2–8 (advertised)	2–5
Maximum link distance	20 km to 30 km	12 km to 15 km with no mitigation; 25 km to 30 km with mitigation
Optical multiplexers and demultiplexers	Custom wavelengths; challenging vendor specifications	Utilizes mature components at standard ITU wavelengths

When evaluating the different multi-wavelength downstream solutions to segment nodes, these items should also be considered:

- Link distances from the hub to the node
- Number of fibers available between hub and node
- Amount of segmentation required now and in the future: 2, 4, 8, or more
- Is the number of subscribers off each RF port of the node “balanced” or “unbalanced”? If “unbalanced”, segmentation utilizing Fiber Deep should be considered.
- Required performance at the RF ports on the node
- Baseline the performances of the solutions with the same amount of broadcast analog + digital content and narrowcast digital content. The performance will vary depending on how much of the content is broadcast versus narrowcast.
- Dispersion characteristics of the fibers deployed in your network and the dependence of the solutions on them
- Operational friendliness

Summary

Node segmentation provides a good tool for cable operators to increase targeted services, such as VOD, Internet data, and telephony. In many cases, cable operators have limited fibers and/or they could reclaim fibers for emerging opportunities such as commercial services. WDM/CWDM/DWDM techniques offer better utilization of the existing fiber resources. Simple WDM techniques can double the fiber capacity, and CWDM/DWDM techniques can increase the capacity multiple times. Recently, equipment vendors have developed new solutions for multi-wavelength downstream broadcast transport that are more cost-effective and more operationally friendly than what was previously available. Cable operators need to evaluate their requirements and select the best solutions that fit them.

Table 2 shows a comparison between the different WDM/CWDM/DWDM solutions for node segmentation.

Table 2 – Comparisons Between WDM/CWDM/DWDM Solutions for Node Segmentation

	WDM	CWDM	DWDM	Multi-wavelength full-band downstream
Effective increase in fiber capacity	2X	4X to 8X (in return only)	16X (practically)	2X to 8X
Fiber distances, maximum	40 km	60km (in return only)	80 km	12 km to 30 km
Cost	Low	Medium	High	Medium
Operational friendliness	High	High	Low	Medium

References

1. ITU-T Recommendation G.694.2, *Spectral grids for WDM applications: CWDM wavelength grid*
2. ITU-T Recommendation G.694.1, *Spectral grids for WDM applications: DWDM frequency grid*
3. *Optical Segmentation Technology Alternatives and Architectures* (P. Miguez and F. Slowik)
NCTA Cable Show white paper, Motorola P/N 556508-001



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