



New Technologies for Fiber Efficient HFC Architectures

White Paper

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INTRODUCTION

Service providers are actively rolling out improved narrowcast services such as higher speed Internet and HD VOD. These new services require increased dedicated bandwidth per subscriber, and must be provisioned through network segmentation of existing nodes and/ or by augmenting the network with new nodes. With abundant fiber, this presents few problems. However, in many cases, fiber plant which once appeared sufficient to meet future needs has now been exhausted. In this scenario, the service provider can either deploy new fiber or utilize the fiber-sharing technology of wavelength division multiplexing (WDM). WDM has been deployed extensively through the broadcast and narrowcast architecture in both the forward and the return path for many years, and is well-understood.

This paper describes the recent advances in forward path WDM including O-band DWDM and full-band 1550 C-Band DWDM, and their relationships to the more traditional broadcast and narrowcast architecture.

SIMPLIFIED HFC NETWORK

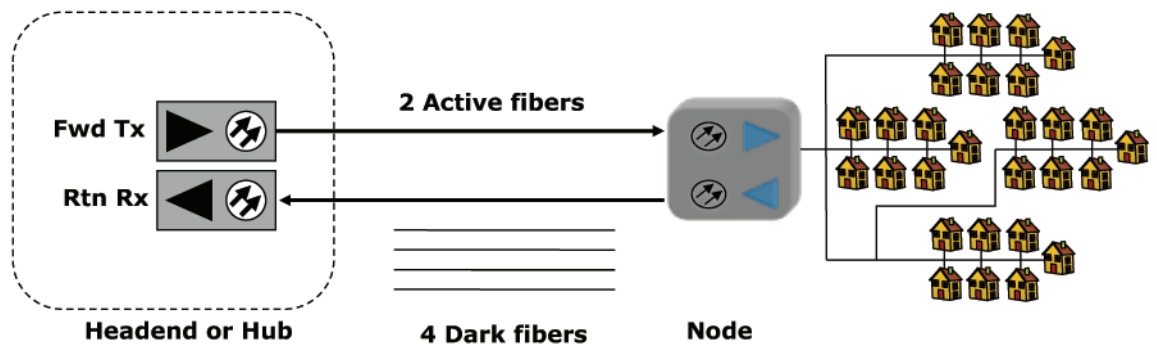


Figure 1. Typical HFC network at deployment

Figure 1 shows a portion of a typical HFC network at initial deployment. Broadcast and narrowcast services are combined in RF into a full band and transported over a single transmitter and single fiber to a node serving 2,000 subscribers. The return signal is also transported back to the headend or hub on a single fiber. In the same fiber bundle, four additional fibers were dedicated for future services and left dark. At some later point in time, a decision was made to segment the serving group into 1000 homes passed. For that segmentation two additional fibers were lit, one for the forward path and the second for the return path, as shown in Figure 2.

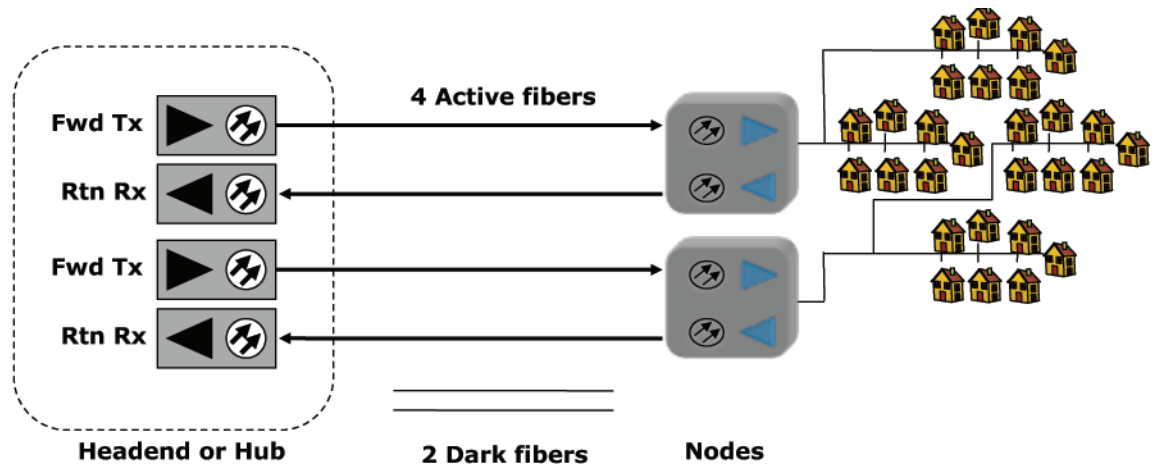


Figure 2. Segmentation to 1000 homes passed per node

Later, a commercial services group sells Ethernet and phone services to a business. The last two dark fibers are consumed for those services.

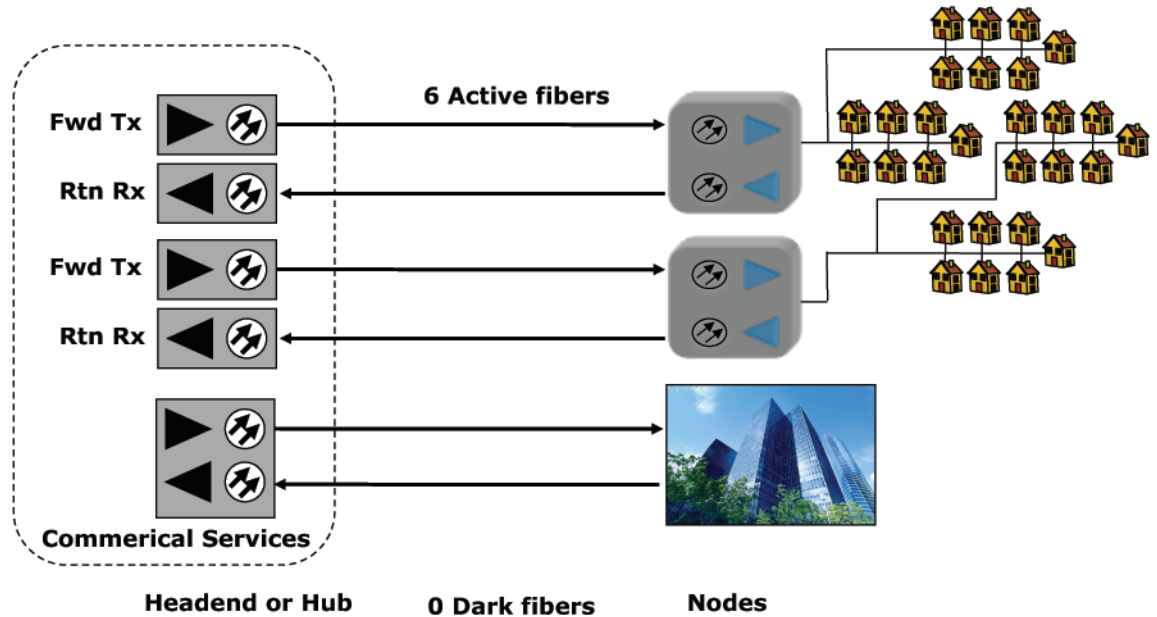


Figure 3. Last 2 available fibers taken for commercial services

Lastly, due to competitive pressure, the decision is made to further segment the network to 250 homes passed per node. At this point, there are no fibers left for expansion. Additional fiber must be deployed or new technologies explored. WDM is a well-understood technology for combining multiple light streams on a single fiber, and WDM has been used for many years in both the forward and return path through broadcast and narrowcast architecture. Due to performance impairments caused by optical fiber and laser transmitter interaction, however, careful attention must be paid to system design. With these factors in mind, lowest equipment cost and highest performance occurs with a single wavelength on each fiber. If dark fibers are available in the network, using those fibers to segment is the least expensive option. If the fibers are not available, then any of the WDM solutions described in this white paper will be more cost-effective than deploying new fibers.

CATV TRANSMITTER DEVELOPMENT

In an optical transmission system, the optical fiber and optical transmitter interact to cause system impairments. These interactions and the search for mitigation measures have driven the development of optical transmission for CATV applications.

The extremely low loss of optical fiber was one of the features that made fiber so attractive as a transmission medium. Standard optical fiber has two low attenuation regions around the wavelengths regions of 1310 nm (O-Band) and 1550 nm (C-Band), with the 1550 nm region having slightly lower loss. Additionally, the 1550 nm region offers the use of optical amplifiers to further compensate for fiber and other passive losses.

A second important parameter of optical fiber is chromatic dispersion. Chromatic dispersion is the variation of group velocity with wavelength. This parameter is zero around 1310 nm and increases as the wavelength increases. With modulation, a transmitter's wavelength will vary slightly (chirp). The distortion that occurs due to the interaction between chromatic dispersion and chirp manifests itself as CSO degradation. In modern CATV systems, mitigating the CSO chirp-dispersion degradation has driven the development of transmitter technologies.

In the late 1980s and early 1990s, modern hybrid-fiber coax (HFC) systems based on single mode optical fiber and 1310 nm transmission for CATV were developed. Around that time, advances in 1310 nm DFB laser technology allowed for the introduction of low-cost directly modulated DFB laser transmitters. Due to the performance achieved with low-chirp, low-noise, low-cost lasers operating near the zero dispersion point, this technology has since been the workhorse transmitter for CATV system. Transmitters built with this technology can currently achieve 51 dB CNR, -64 dBc CSO, and -69 dBc CTB with a 45 km reach.

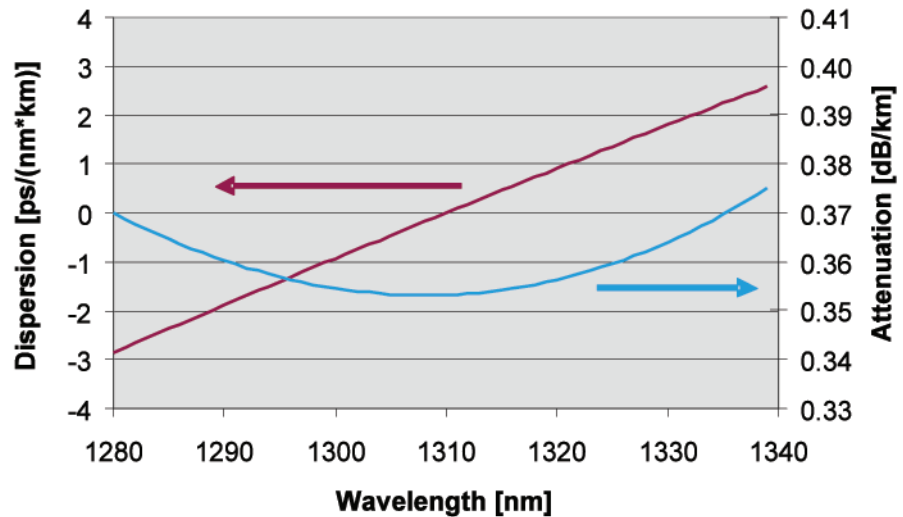


Figure 4. Optical Loss and Chromatic Dispersion in the O-Band

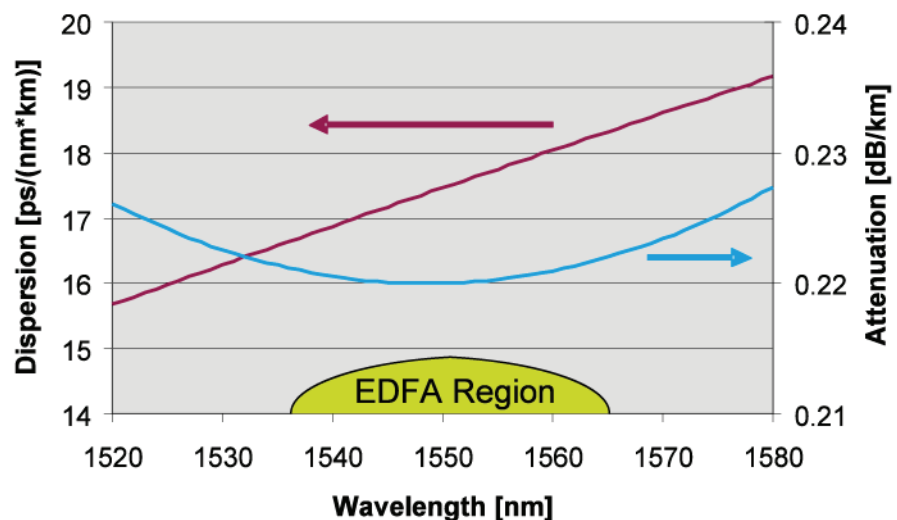


Figure 5. Optical Loss and Chromatic Dispersion in the C-Band

Another early technology was the high-power externally modulated 1310 nm laser. This development took advantage of low dispersion in the 1310 nm region, the low chirp of an external modulator and the high power of an external cavity laser. These choices, coupled with linearization of the external modulator, allowed for CNR, C/CSO, and C/CTB distortion specifications acceptable for use in CATV systems.

While 45 km reach is sufficient for the majority of links, some require longer reach. To increase the reach, 1550 nm products were introduced to take advantage of the lower loss and the availability of Erbium optical amplifiers (EDFA) in the 1550 nm region. However, due to high dispersion in the 1550 nm region, these transmitters require the use of external modulators. With the use of optical amplification and SBS suppression techniques, reaches of 100 km with 51 dB CNR, -62 dBc CSO, and -65 dBc CTB are possible.

In late 1990s, VOD, high speed internet, and other digital narrowcast services were growing in popularity. Supporting the transition from a broadcast network to a broadcast and narrowcast network required the segmentation of existing service groups, without the deployment of new fiber. This led to the development and deployment of WDM technologies in the CATV forward path. The first architecture deployed was the broadcast and narrowcast architecture. Recently, further innovations in WDM for the forward path have been announced: O-Band (between 1260 nm and 1360 nm) DWDM transmitters, and full-band C-Band (between 1530 nm and 1565 nm) DWDM directly modulated transmitters. The remainder of the paper will compare and contrast these three key technologies for fiber-efficient HFC architectures.

1550 BROADCAST AND NARROWCAST

In the broadcast and narrowcast architecture, the broadcast (BC) transmitter carries the analog and digital (QAM) traffic intended for all users while the narrowcast (NC) transmitter carries the digital (QAM) information intended for a subset of users. This architecture can be implemented with either optical combining and one optical receiver or RF combining of the outputs of two optical receivers.

The simplest, highest-performance architecture uses two receivers. A solution to the segmentation example described previously is shown for the forward path in Figure 6. For this example, the broadcast and narrowcast signals are transported from the headend or hub to the node via a dedicated fiber for each. At a splice enclosure, the broadcast signal is split four ways and sent to an optical receiver in the node. The narrowcast wavelengths are de-multiplexed and sent to a separate optical receiver in the node. The broadcast RF signals occupy one portion of the RF spectrum while the narrowcast signals occupy a different portion of the RF spectrum. The RF outputs of the two optical receivers are filtered, to remove out-of-band noise and distortion, and combined. In this manner, all four nodes are served using only two fibers in forward path and the goal of 250 homes passed per node is achieved.

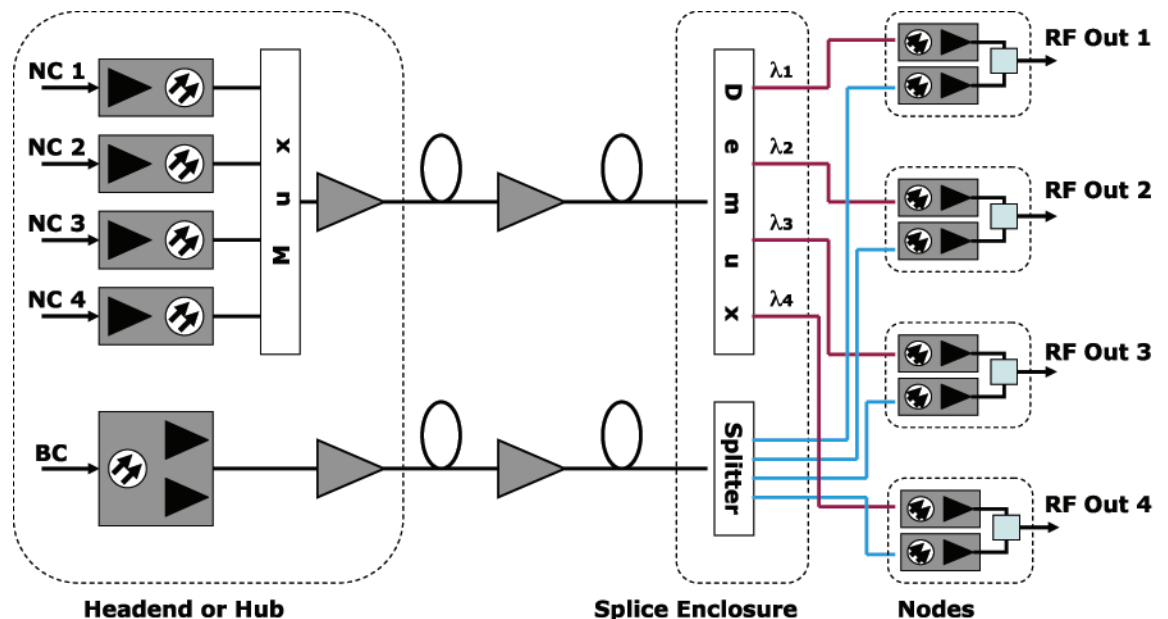


Figure 6. Broadcast and Narrowcast segmentation solution

For maximum performance, the broadcast and narrowcast transmitters both operate in the 1550 nm band. The 1550 nm band is chosen for the availability of Erbium optical amplifiers to overcome optical fiber and passive filter and splitter loss. However, at 1550 nm, the chromatic dispersion of the fiber is large. To minimize the degradation, the broadcast transmitter makes use of an external modulator. This is economical because the cost of the broadcast transmitter is shared among many more users than the cost of each narrowcast transmitter.

For the narrowcast transmitters, directly modulated DFB lasers are used. When loaded with QAM signals, the chirp-dispersion interaction from the multiple QAM channels becomes noise-like and can fall in the broadcast frequency range as shown in Figure 7.

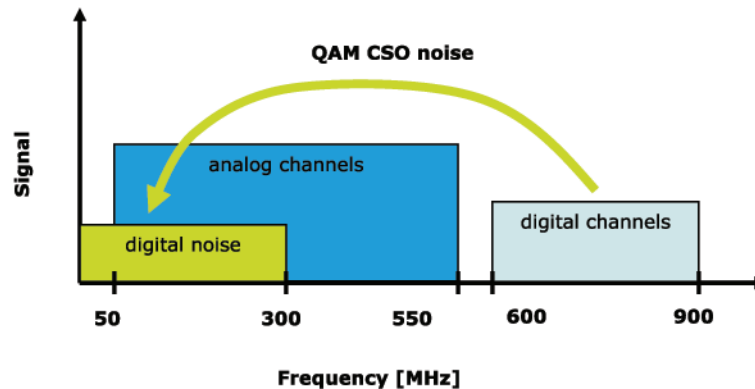


Figure 7. Noise caused by QAM chirp-dispersion interaction

In early versions of architecture that utilized optical combining of the broadcast and narrowcast signals with a single receiver, the narrowcast channel bandwidth was limited to less than 50 MHz, so that the QAM CSO noise products would not degrade the analog signals. In mid-2002, electronic chirp compensation was utilized to eliminate the problem of chirp-dispersion-induced noise products, enabling the use of up to 300 MHz bandwidth on each narrowcast transmitter. The magnitude of this compensation is such that a transmission distance of 70 km is now possible.

Even so, with the single receiver architecture, the CNR of both the broadcast and narrowcast signals degrades due to two light sources impinging on a single receiver. The additional sources of noise include shot noise, RIN laser noise, and fiber generated noise. However, this additional degradation is manageable with careful selection of the RF modulation depths and optical received powers.

For the dual-receiver architecture, the broadcast and narrowcast links can be optimized independently and any additional noise products can be eliminated by the use of a high quality RF filter after each receiver.

Using this solution to our segmentation problem, the following performance parameters can be achieved with a 70 km transmission distance and channel loading of 80 broadcast signals and 50 narrowcast signals.

Broadcast CNR	> 50 dB
Broadcast CSO	< -63 dBc
Broadcast CTB	< -65 dBc
Narrowcast BER	< 10^{-6} uncorrected

In all, up to 40 wavelengths on the 1550 nm ITU grid around are available. Fiber count can be saved by multiplexing all 40 wavelengths onto one fiber if required.

O-BAND DWDM

With the recent introduction of O-Band DWDM technology, a simpler solution for fiber efficient architectures in the forward path now exists. In the O-Band, directly modulated DFBs have been deployed extensively as the workhorse transmitters for CATV systems. This is due to their simple operation and robust performance, based on operation close to the zero dispersion point at 1310 nm. However, adding multiple wavelengths in the 1310 nm band presents a host of non-linear optical fiber challenges, such as four-wave mixing (FWM), cross phase modulation (XPM), and stimulated Raman scattering (SRS). Steps can be taken to minimize or balance these effects but they serve to limit number of wavelengths, system reach, and performance.

In optical fiber, the refractive index varies with instantaneous optical power. In multi-wavelength systems, this leads to crosstalk impairments between wavelengths such as XPM and FWM.

XPM is a function of separation between the wavelengths. XPM impacts the higher RF frequencies and manifests itself as CSO degradation. To mitigate XPM, the channels must have adequate channel separation.

FWM is a third order effect which leads to the creation of new optical signals which can fall into the channel band of the desired signals. FWM increases when close to the zero dispersion point and manifests itself as CNR degradation from the new channels or CSO degradation from a secondary mixing effect. In standard single mode fiber, the dispersion zero point is specified nominally at 1310 nm but can vary from 1302 nm to 1322 nm. However, the channels must not be so far away from the zero dispersion point that chirp-dispersion CSO dominates. Similar to an uneven channel spacing in the RF domain, an uneven channel spacing in the optical domain and controlling the launch power can also be used to mitigate this effect.

SRS transfers energy from short wavelengths to longer wavelengths and manifests as CSO degradation at low RF frequencies. SRS is a function of launch power and wavelength spacing. Unlike FWM, SRS increases with an increase in channel spacing. Minimizing the launch power and the channel spacing are mitigation effects for SRS.

Figure 8 illustrates how, for an eight-wavelength system, these interactions between the optical fiber and transmitter serve to box in the system designer.

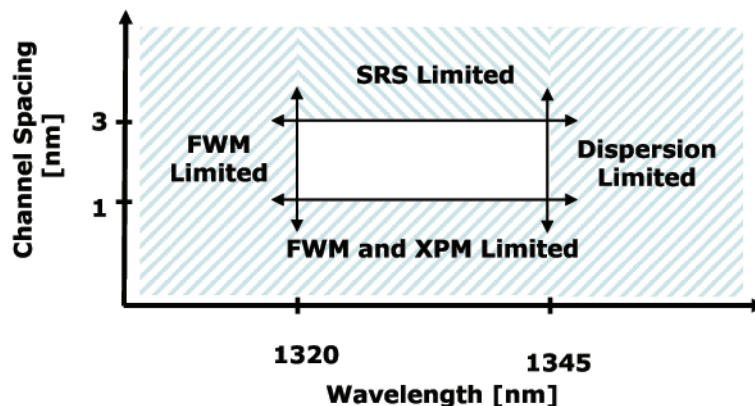


Figure 8. Non-linear fiber effects box in the system designer

However, even with these limitations, Figure 9 shows a simple solution to the segmentation example described previously using O-Band technology for the forward path.

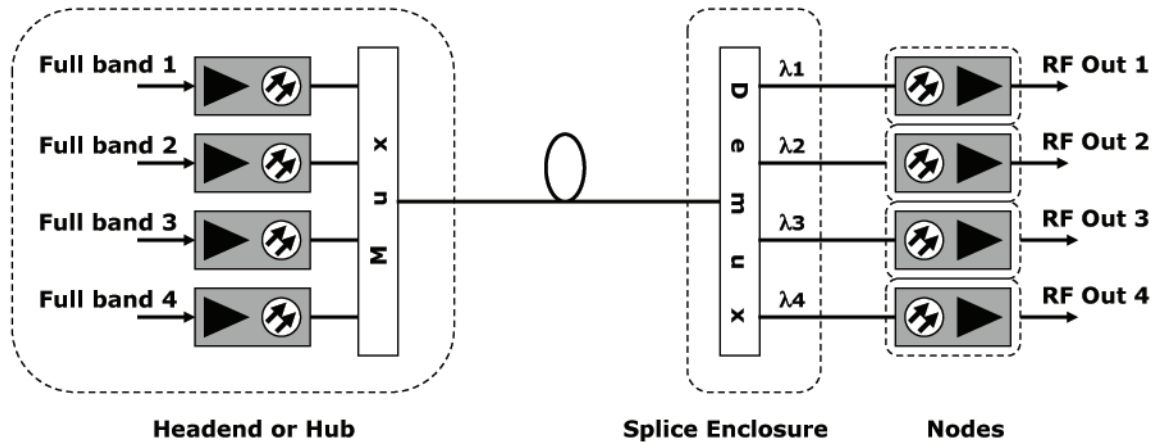


Figure 9. O-Band Segmentation Solution

In this case, the transmitters are full-band in that each one carries both broadcast and narrowcast traffic. Setup and operation are much simpler than for the broadcast and narrowcast architecture. Using the O-Band solution to our segmentation problem, the following performance parameters can be achieved for a 20 km transmission distance with traditional analog and digital channel loading up to 1 GHz.

Broadcast CNR	> 51 dB
Broadcast CSO	< -62 dBc
Broadcast CTB	< -68 dBc
QAM BER	< 10 ⁻⁶ uncorrected

For other wavelength counts, similar performance can be achieved for different transmission distances. For a common optical channel plan, system reach is limited by SRS and chirp-dispersion as wavelength span increases with the number of wavelengths, as shown in Table I.

Wavelengths	System Reach
8	10 km
6	15 km
4	20 km
2	30 km

Table I

C-BAND DWDM

Many links in a typical network can be served with O-Band DWDM. However, there are some that require longer reach. To improve on the reach of the O-Band DWDM solution while using a cost-competitive technology, designers have looked to take advantage of the C-Band. The C-Band offers lower intrinsic fiber loss, plus the use of EDFAs to compensate for both fiber and passive loss.

Direct modulated 1550 nm DFB lasers currently have slightly lower chirp than those at 1310 nm, approximately 100 MHz/mA compared to 150 MHz/mA. However, fiber chromatic dispersion at 1550 nm is much greater than in the O-Band, approximately 17 ps/nm compared to maximum 5 ps/nm. Although the low chirp of the 1550 nm transmitters helps combat the effects of dispersion somewhat, further reducing the chirp will cause a decrease in the CNR due to interferometric intensity noise from double Rayleigh backscattering. While the combination of chirp and dispersion would normally make the link unusable due to CSO degradation, the technology used for dispersion compensation in the QAM narrowcast transmitters can be extended for use in the 1550 nm full-band transmitter.

As a benefit, the non-linear effects that constrained the O-Band system are less severe for the C-Band system. The high chromatic dispersion at 1550 nm mitigates FWM and SRS in the C-Band multichannel system. FWM and SRS depend on phase alignment between the co-propagating lightwaves, and high chromatic dispersion destroys the phase alignment and reduces the impacts of FWM and SRS. Lower FWM means the channel spacing can be decreased, which again contributes to a reduction in SRS.

With this in mind, Figure 10 shows the forward path solution to the segmentation problem using C-Band DWDM technology.

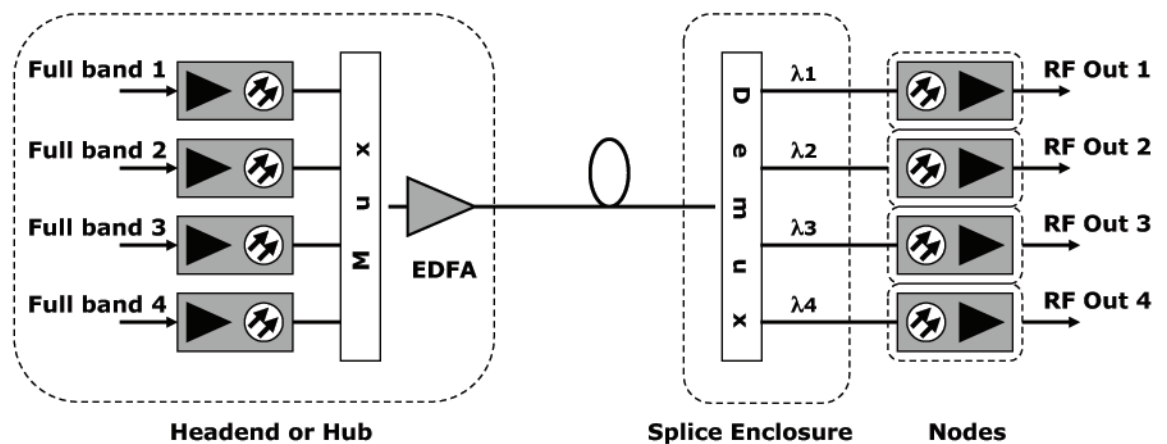


Figure 10. C-Band segmentation solution

As in the O-Band case, the transmitters are full-band with each one carrying both broadcast and narrowcast traffic. Setup and operation are similar to the O-Band solution, but much longer link distances are possible. An added benefit is that unlike in the case of the O-Band technology, the system reach is less sensitive to the number of optical channels and a 40km reach can be achieved with an eight channel system. Using the C-Band solution to our segmentation problem, the following performance parameters can be achieved for a 40km transmission distance.

Broadcast CNR	> 48.4 dB
Broadcast CSO	< -58 dBc
Broadcast CTB	< -65 dBc
QAM BER	< 10 ⁻⁶ uncorrected

CONCLUSION

If dark fibers are available in the network, using those fibers to segment is the least expensive option. If the fibers are not available, then any of the WDM solutions will be more cost-effective than deploying new fibers. Table II shows the pros and cons of each WDM approach. Figure 11 and Table III show the relative performance of each solution. O-Band and C-Band full-band transmitters offer a similar cost point and simplicity when compared to the broadcast and narrowcast architecture. C-Band DWDM offers longer reach by making use of optical fiber amplifiers than the O-Band with slightly reduced performance metrics. The broadcast and narrowcast architecture is more complicated for planning, operation, and segmentation but offers a solution with more wavelengths and longer reach, which is not possible with the O-Band or C-Band technologies.

Architecture	Pros	Cons
O-Band DWDM	<ul style="list-style-type: none"> Operational simplicity Cost-effective 	<ul style="list-style-type: none"> Limited system reach (especially for higher number of wavelengths)
C-Band DWDM	<ul style="list-style-type: none"> Better system reach independent of the number of wavelengths Operational simplicity Cost-effective 	
Broadcast and Narrowcast	<ul style="list-style-type: none"> Highest fiber efficiency Longest system reach 	<ul style="list-style-type: none"> Operational complexity Narrowcast bandwidth limited to contiguous 300MHz

Table II

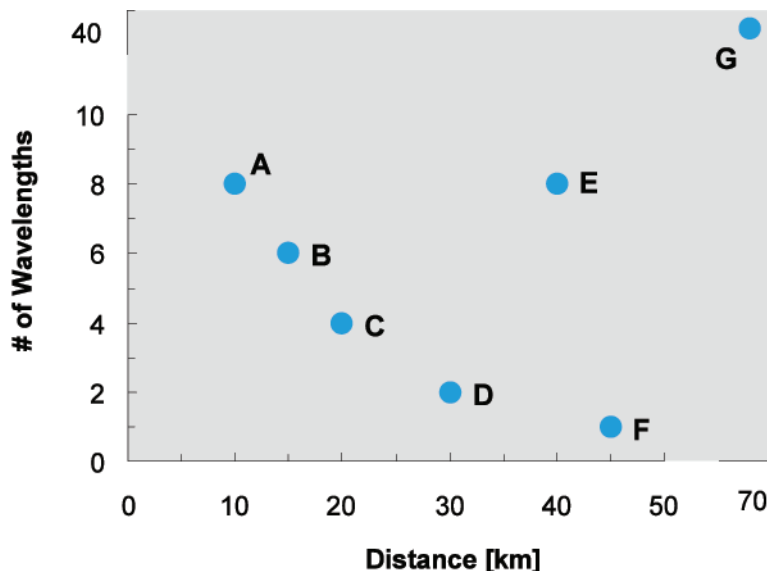


Figure 11. Technology map

ID	Description	Wavelengths	Reach	CSO	CTB	CNR
A	O-Band direct modulation	8	10km	-62 dBc	-68 dBc	51 dB
B	O-Band direct modulation	6	15km	-62 dBc	-68 dBc	51 dB
C	O-Band direct modulation	4	20km	-62 dBc	-68 dBc	51 dB
D	O-Band direct modulation	2	30km	-62 dBc	-68 dBc	51 dB
E	C-Band direct modulation	8	40km	-58 dBc	-65 dBc	48.4dB
F	1310 nm single wavelength	1	45km	-64 dBc	-69 dBc	51 dB
G	1550 nm BC/NC	40	70km	-63 dBc	-65 dBc	50 dB

Table III

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