MULTI-WAVELENGTH ACCESS NETWORKS: A PRACTICAL GUIDE TO IMPLEMENTATION

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Abstract

Continued growth in residential data, voice and video traffic is a success story that has driven MSOs to increase throughput capability in all parts of their networks. When increasing throughput capacity, different parts of the end-to-end network require different approaches. In the access (or "distribution") part of the network there have been advances in optical technology that lend themselves to being a rapidly deployable, robust, cost effective solution. Multi-Wavelength Access Networks are an additional tool in the cable operator's toolbox that will allow MSOs to increase throughput capacity or provide additional services on their existing infrastructure at significantly less cost than new fiber construction.

This paper will lay out a practical guide to implementation of multi-wavelength access networks. It will first present a model that explains the various benefits and trade-offs of implementing Multi-Wavelength Access Networks. The paper will then document all the optical impairments that accrue within access networks, and conclude with recommendations for the practical implementation of multi-wavelength systems.

BUSINESS MODEL FOR IMPLEMENTING MULTI-WAVELENGTH ACCESS NETWORKS

One of the driving forces for the use of multi-wavelength optics in the access network is the requirement to increase throughput capacity. Optoelectronics equipment, installed over the past 15 years, employed a design in which one fiber carried the forward path and a second fiber was used for the return path. Some cable operators built out networks using fiber sheaths containing four or six strands of glass to each optical node, while other cable operators used as few as two or occasionally more than six. In the cases where six fibers inside a sheath are going to a specific area of the system, 3 optical nodes could be served. If a fourth node was needed to serve increased data traffic in that area, another pair of fibers would be required. A typical solution is to install additional fiber to serve that area. The costs for constructing fiber add up on a per-foot or per-mile basis. The process of obtaining construction permits and working during bad weather conditions can add delays to construction projects and the attending service disruptions may also have additional negative consequences.

However, the development of multi-wavelength optical technology presents the opportunity to make increased use of existing fiber and delay the need for building out additional fiber. Additional forward and return paths can be added to the fiber already in place. Construction delays along busy highways and streets or in back easements with difficult access can be postponed. The use of multi-wavelength technology allows for additional throughput capacity to be turned up quickly.

A comparison of the relative costs of multi-wavelength optics versus construction provides a compelling justification. Each mile of aerial fiber construction costs in the range of $12,000-$16,000 (depending on a handful of factors). Constructing 10 miles of aerial fiber would therefore cost $120,000 or more. Underground fiber construction can cost up to twice as much per mile as aerial construction. On the other hand, the total cost of multi-wavelength optical equipment for both ends of the fiber run is less than the cost of constructing two miles of new fiber. Chart 1 shows the relationship between the costs of construction versus multi-wavelength implementation. This is a powerful financial incentive for the use of multi-wavelength optics.

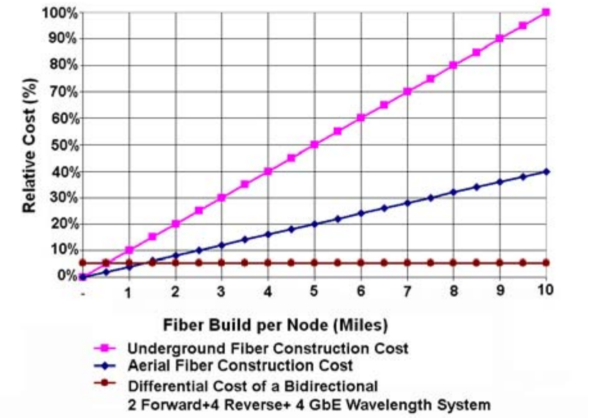


Chart 1 – Multi-wavelength Access networks are much more cost-effective than construction

	Existing 1310 design	**Multi-wavelength design**
Construction of additional fiber	If fiber exhausted must build additional fiber (overlash aerial or trench in u/g)	Only required if extending fiber a short distance to serve additional node(s)
Time required for implementation	Requires weeks to design, plan, obtain any required permits, and construct fiber	Can be installed in under a week or even in one night
Costs	Approx $12k/mile aerial or $30k/mile u/g	Cumulative differential cost for additional wavelengths is much less than 10% of fiber construction cost

Table 1 – Multi-wavelength Access networks can be implemented more quickly than construction

Continued growth in residential services drives the need to continue increasing throughput capacity. The commercial services segment is a market in which cable operators have staked out a solid business. Businesses represent a market with strong growth potential for cable operators. Cable operators have a range of options for providing service to small, medium, and large businesses. A few of these options include:

- a direct fiber feed into the business
- cable modem business class service
- wireless DOCSIS

A widely preferred approach is to use fiber for serving businesses. Although other options such as wireless DOCSIS can be used as a temporary solution to quickly establish service by reaching across obstacles (railroad tracks, large parking lots, rivers), fiber has long been established as a reliable solution.

Most networks were built with spare fiber capacity in the access part of the network. As fiber is used to connect new business customers, the spare capacity in the fiber sheaths is reduced. Multi-wavelength technology is an alternative path to providing additional services on the networks without incurring the cost of new fiber construction.

THE FIBER SPECTRUM

The CWDM wavelength plan is detailed in ITU Recommendation G.695, which was ratified in January 2005. The plan provides for 18 wavelengths spaced 20 nm apart over a range from 1271 to 1611 nm. Typically the 1371 and 1391 nm wavelengths are the designated water peak wavelengths of deployed optical fibers (Figure 1 provides insertion loss for a 20 km fiber link for fiber with and without the water peak).

Cable operators can choose to reserve the 1531 and 1551 nm bands for possible deployment of services utilizing the DWDM spectrum. Long haul 1550nm optics, EDFA, and QAM overlay architectures utilize this portion of the optical spectrum. The wide CWDM channel spacing allows the use of lower cost uncooled DFB laser technology for reverse path transmitters.

Additionally, CWDM channel spacing enables the use of cost effective, environmentally hardened optical passives for field deployment. These passives can typically be obtained off-the-shelf from suppliers and do not require unique specification considerations. The CWDM specifications for active devices promote GbE SFPs, reverse path analog transmitters and forward transmitters. The CWDM spec therefore provides for a significant increase in fiber capacity and promotes a level of plug and play capability.

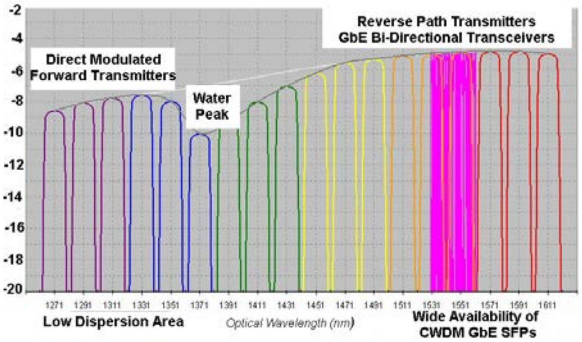


Figure 1 – Some wavelengths are more suitable for specific services than others.

From Figure 1, it is also seen that the familiar DWDM wavelengths are in the 1525 to 1560 nm region and are covered by the spectrum of the 1531 to 1551 nm CWDM bands.

OPTICAL IMPAIRMENTS WITHIN ACCESS NETWORKS

Although distances involved in access networks are quite modest - around 20 km as compared to long haul transport networks of around 500 to 1000 km - there still are numerous optical impairments that could cause measurable degradation of the RF spectrum. The ability to identify all such impairments and manage their impact on the RF spectrum is central to making multi-wavelength access systems work.

Optical impairments are artifacts in fiber networks and the fiber itself that impacts how well the RF spectrum is carried in the network. There are two broad classes of impairment: linear and non-linear. It is generally the case that non-linear impairments are dependent on optical intensity whereas linear impairments are not. The two classes of impairments can be further divided into single and multiple wavelength non-linearities for the optical non-linear impairments, and fiber linear effects and optical passive effects for the optical linear impairments.

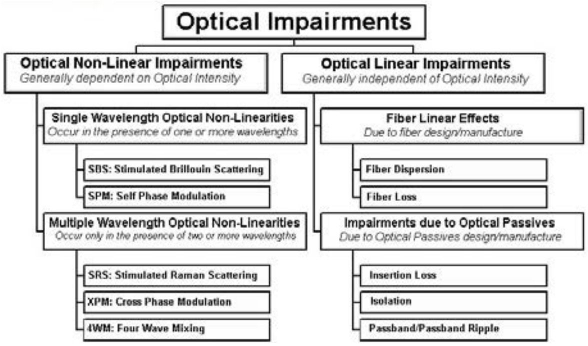


Figure 2 – Identifying Optical Impairments

Linear impairments, like dispersion and passband ripple, impact RF spectrum figures of merit, such as CSO and CTB. Most often, linear impairments are the performance manifestations of optical passives/fiber design and manufacture. Careful attention to (and verification of) product specifications can limit the effects of this class of impairment.

Single-wavelength optical non-linearities include the well known Stimulated Brillouin Scattering (SBS) and the lesser known Self-Phase Modulation (SPM). The SBS is often compensated for by manipulating the optical spectrum and/or limiting optical launch power in the network.

Multiple wavelength non-linear impairments, such as Stimulated Raman Scattering (SRS) and Cross Phase Modulation (XPM) induce crosstalk between two or more wavelengths. Crosstalk could be between wavelengths carrying similar services, such as two wavelengths carrying signals in the reverse direction; two wavelengths carrying GbE; or two wavelengths carrying forward signals. In these cases, the RF spectra coincide and the crosstalk results in a direct impact on the RF performance.

Crosstalk may also crop up between wavelengths carrying dissimilar services, such as a forward wavelength and a reverse wavelength, or a forward wavelength and a GbE wavelength. In these cases, if the frequency spectra overlap, there could be a direct impact on the RF performance. For example, since the GbE and forward RF spectra overlap, GbE signals (such as spurious spikes when the GbE is unloaded) could bleed through from the GbE RF spectrum into the forward spectrum due to fiber non-linearities, causing measurable performance degradation.

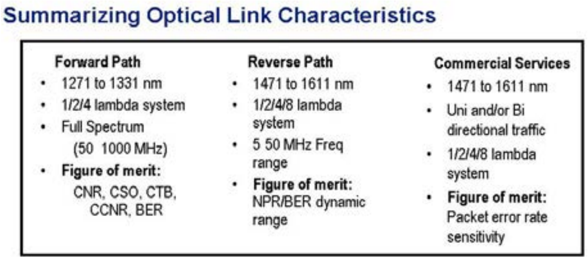
For access network design, SRS and 4 Wave Mixing (4WM) are the dominant non-linearities. Both of these are sensitive to polarization and become progressively worse with higher launch power. Both these phenomena depend upon the wavelength spacing and fiber dispersion as well. While SRS becomes worse with increasing spacing up to approximately 100 nm and then decreases becoming essentially extinct after about 200 nm, the 4WM potentially flares up as the wavelength spacing decreases and one of the signal wavelengths approaches the fiber dispersion zero point.

Typical CWDM multi-wavelength systems employ two forward wavelengths spaced 20 nm apart. Here, the SRS is the dominant non-linearity and the system reach is limited by the total power launched into the optical network. It is possible to reduce the SRS effects by reducing the wavelength spacing below the standard 20 nm used in CWDM and thereby increase the power launched into the network and/or increase the number of forward wavelengths. However, this approach can also substantially increase the 4WM potential when additional variables such as dispersion are introduced in the system, sometimes leading to a less robust system. A nonstandard wavelength spacing plan could also increase the system cost due to lower volumes.

The ability to adequately model and test all aspects of fiber impairments with particular emphasis on the number of wavelengths, polarization and fiber dispersion, along with the earlier mentioned variables such as maximum power launch, wavelength spacing and optimally selected optical filters, is critical to promoting a robust cost-effective solution that also satisfies capacity needs.

DESIGN TRADE-OFFS

The analog realm features familiar RF trade-offs, such as the fact that CNR can be traded off to achieve better CSO and CTB and vice-versa. Similarly, multiple wavelength access networks will have trade-offs to make sure that each wavelength passes through the network without impacting the other wavelengths on that network.



Summarizing Optical Link Characteristics

Forward Path
- 1271 to 1331 nm
- 1/2/4 lambda system
- Full Spectrum (50 1000 MHz)
- **Figure of merit:** CNR, CSO, CTB, CCNR, BER

Reverse Path
- 1471 to 1611 nm
- 1/2/4/8 lambda system
- 5 50 MHz Freq range
- **Figure of merit:** NPR/BER dynamic range

Commercial Services
- 1471 to 1611 nm
- Uni and/or Bi directional traffic
- 1/2/4/8 lambda system
- **Figure of merit:** Packet error rate sensitivity

Figure 3 – Multi-wavelength network system performance requires adequate single wavelength performance and limited optical interference

To employ these trade-offs effectively, the inherent optical linear and non-linear impairments should be studied to identify and quantify their impact on the overall system.

A good deployment strategy would include comprehensive testing and analysis of all optical parameters of the system so that design rules for field deployment can be devised. These rules may govern the locations of optical wavelengths such that the overall optical crosstalk is minimized.

Another rule would consider appropriate intermixing of wavelengths of diverse RF spectra to ensure that the optical level of the composite signal being launched into the fiber remains below specified limits.

Another useful strategy consists of identifying and investing in optical passives that support the selected wavelengths and have adequate isolation and loss specifications. These will often be unique to a specific application. For optimal economic efficiency, it is good practice to set a standard usage plan for wavelengths in order to drive higher volumes of identical optical passive configurations.

Since the launched power of a multi-wavelength system is limited by optical non-linearities, the fiber reach of a multi-wavelength network can still be enhanced by supporting lower optical node receive power. It is often the case that adding a node results in a shorter RF cascade with inherently less CNR degradation, so lower optical receive power can be used without degrading the end-of-line performance. For this reason, segmentable nodes, placed deeper into the network, are particularly well suited for multi-wavelength access networks.

WAVELENGTH PLAN

The service disruptions that plague new fiber construction can be minimized for multi-wavelength access networks if a wavelength plan is considered in advance of the design. This plan should ideally proceed sequentially from an examination of fiber link lengths and fibers available for deployment (fiber link description) to the services intended for each fiber (deployment package description) and further into future plans for services and fiber usage. Important aspects of future use planning include consideration for 10 GbE usage, preservation of the DWDM band and the desire for route redundancy.

RECOMMENDATIONS FOR PRACTICAL IMPLEMENTATION

The following well tested design examples present architectures ranging from simple to complex that progressively allow higher and more effective utilization of installed optical fiber. The fiber utility table at the bottom center of the figures will keep a running tally of the number of wavelengths used in each fiber. Although the architectures are presented in the context of the CWDM standard, similar architectures can be conceived for DWDM or other multiple wavelength allocation plans.

The classic architecture in Figure 4 is essentially characterized by a fiber pair from the hub or the headend terminated into a node. Each fiber then carries only one wavelength, generally at 1310 nm.

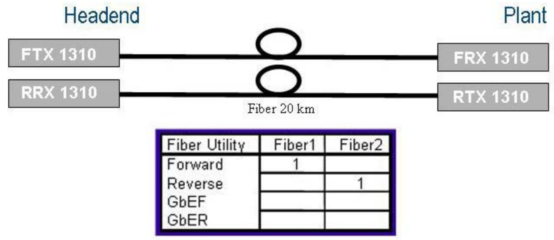


Figure 4 – Basic Architecture

Figure 5 illustrates a very cost effective way of increasing fiber utility and providing reverse segmentation capability.

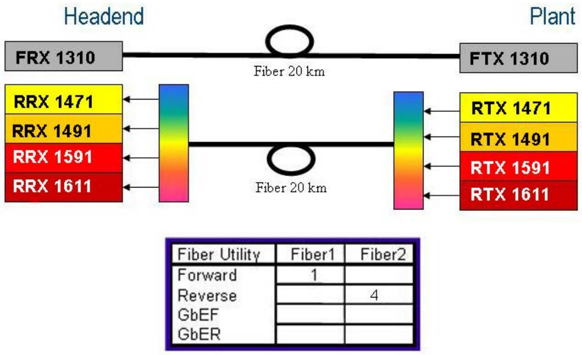


Figure 5 – CWDM in the Reverse

Figure 6 represents an improvement over the previous architecture in that the node can now be segmented in the forward *and* reverse path. This architecture enables the operator to have specific fibers designated for forward or reverse purposes and is least disruptive in providing service augmentation. Please note however that the two wavelengths should have the same analog broadcast signals, but could have different QAM 256 narrowcast signals.

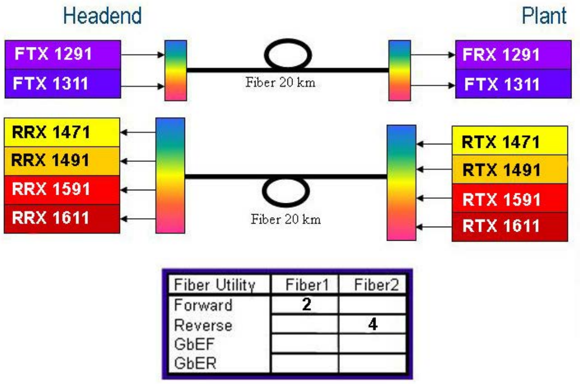


Figure 6 – CWDM in the Forward and Reverse

Figure 7 carries the previous architecture further. Here the operator may add the Gigabit Ethernet (GbE) traffic to the previously analog/QAM HFC plant.

This architecture maintains the forward and reverse designations on the available fibers and is minimally invasive. Higher utilization of the fiber is possible when the two fibers are collapsed into one. That strategy is the subject of the next architecture.

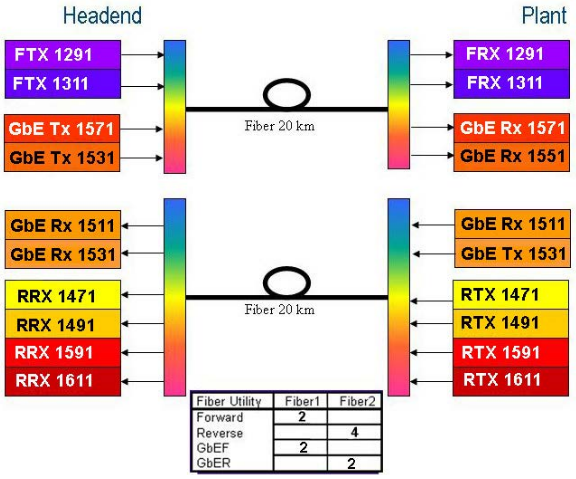
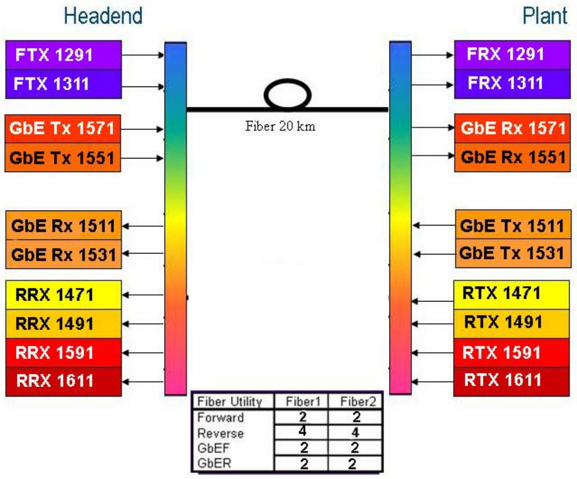


Figure 7 – GbE in the Forward and Reverse Fibers

Figure 8 shows the three different services propagated on a single fiber. An architecture of this type provides the most effective usage of the optical fiber. A single fiber is therefore able to provide 2-way segmentation of the forward narrowcast QAM 256 signals, 4-way segmentation of the reverse signals and 2 bi-directional GbE business service links.



Fiber Utility	Fiber1	Fiber2
Forward	2	2
Reverse	4	4
GbEF	2	2
GbER	2	2

Figure 8 – Typical CWDM Capacity per Fiber

As indicated earlier, the RF input to each forward transmitter is independent; however, the analog broadcast content of the two transmitters should be the same. The QAM 256 narrowcast content for each of the transmitters can differ. The actual capacity of the optical fiber is much higher than represented here however. The higher capacity is obtained by employing additional wavelengths that are carefully chosen to be compatible with the system needs after considering the optical impairment mechanisms discussed earlier.

CONCLUSION

Multi-wavelength systems in the metro, long haul and transport arena have been designed for many years now in the form of Multi-Wavelength optical networks. Multi-wavelength systems are increasingly being considered for use in the access (distribution) part of the network. The technology behind multi-wavelength access networks has been evolving over the past year to offer significant new capability.

Traffic continues to grow in cable operator networks. In some metro areas the rate of growth has been astonishing. Development of multi-wavelength optics technology has progressed to the point where it offers a very attractive alternative to construction of additional fiber for increasing throughput capacity. This provides an opportunity for operators to save large amounts of capital by taking advantage of multi-wavelength optics.

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