Considerations for Optical Dense Wave Division Multiplexing in Digital and Analog CATV Network Applications

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The use of optical dense wave division multiplexing (DWDM) is well established in high speed, digital networks in both telephony and CATV networks. However, DWDM has not been deployed in broadband linear systems for CATV distribution to date. This paper explores the potential applications and benefits of DWDM in large scale CATV networks. A comparison is made between the economics, technical merits and technical obstacles of employing DWDM in digital backbones and deployment of DWDM in broadband linear distribution systems. Current technical limitations in broadband linear systems transmission are defined and explained (for example Raman and SBS effects), and empirical data is presented. The paper concludes with predictions on future functionality and economics of DWDM in both broadband linear and digital CATV network applications.

INTRODUCTION

The year 1998 finds the demand for transmission information capacity continuing to accelerate. Some carriers report a doubling of capacity requirements every five months. This puts a tremendous demand for new fibers on the physical fiber optic plant. In wide area fiber networks, the cost of the physical fiber plant represents a major portion of network costs. Some networks have exhausted their installed fiber capacity. Therefore, a tremendous need exists to reduce the cost of adding transmission without the need for investment in additional fiber cable installation, in order to provide new capacity and additional revenue generating services cost effectively.

Dense wave division multiplexing (DWDM) refers to the process by which multiple independent optical signals differing only by their respective optical wavelength (i.e. "color") can be transmitted simultaneously through a single optical fiber. DWDM technology effectively multiplies the transmission capacity of a fiber by the number of simultaneous wavelengths that can be effectively transmitted through that fiber. (Holobinko, NCTA Technical Papers 1997)

The deployment of DWDM technology for high speed digital optical transmission is now widely established in both long distance telecommunications and cable television regional interconnect applications. The total market for these systems is widely estimated to be $500 Million to $1 Billion in 1998. In the cable television industry, deployment of four and eight simultaneous wavelengths has been made by ADC Telecommunications, Inc. with the DV6000 2.4 Gb/s system, representing a total capacity of up to 20 Gb/s on a single fiber for transmission of video, data and voice services. Other systems designed primarily for long distance telecommunications carriers have demonstrated up to eighty (80) simultaneous optical wavelengths over a single fiber (Lucent Technologies, January 26, 1998).

Figure 1 illustrates a typical cable television regional interconnect network architecture. A digital fiber optic transmission backbone connects the primary hubs and the master headend. A combination of digital fiber transmission and broadband linear fiber transmission connects the primary hub and secondary hubs, while broadband linear transmission is used exclusively to connect the secondary hub with the nodes.

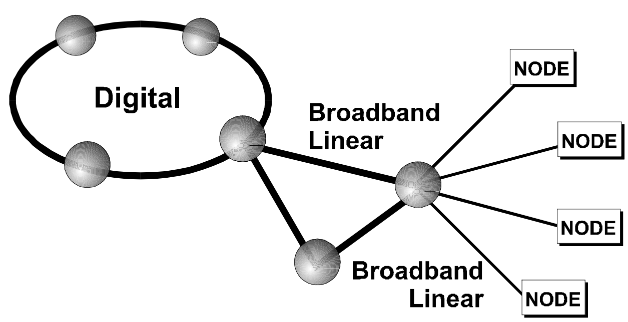


Figure 1

- DWDM is an enabling technology that has the potential of greatly affecting CATV networks. For example:
- What is the potential impact of DWDM technology on this network architecture?
- Can broadband linear transmission capacity be accomplished using DWDM?

- What will be the role, if any, for pure digital transmission, if DWDM using broadband linear techniques can be accomplished over long distances?
- What if any, are the network implications as fiber reaches further into the network and node sizes become significantly smaller?

One possible application for broadband linear DWDM transmission is in the forward path from the primary hub to the node. If one fiber is used for all broadcast services, a second fiber can be used to carry a number of narrowcast channels to the secondary hub, and even to individual nodes served from the secondary hub. This is represented in figures 2 and 3.

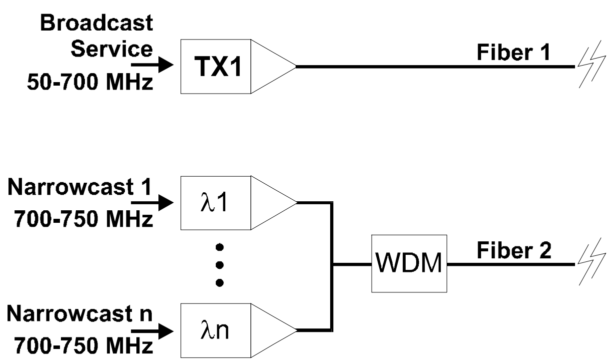


Figure 2.

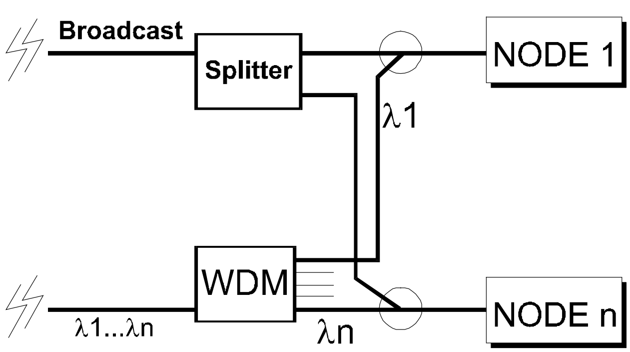


Figure 3.

In CATV systems comprised of a broadcast architecture with a narrow cast overlay, WDM can employed in the implementation of the narrow cast portion of the system. In these systems, ADC has assumed that the narrow cast optical signal consists of a linear transport scheme consisting of QAM modulated carriers. Multiple narrowcast signals can then be combined to comprise a WDM stream. This might lead one to assume that the system performance and limitations can be modeled as a purely digital system. However, because the QAM signals must be combined and coexist with the broadcast AM-VSB signals in the optical domain, the interaction of the QAM noise and distortions must be treated much the same as an analog problem in so far as these artifacts spill over into the AM-VSB bandwidth. Therefore the usual suspects in both linear and nonlinear signal degradation must be considered. These include: Stimulated Brillouin Scattering (SBS); Self Phase Modulation (SPM); and dispersion related CSO and CTB. In addition there are a few optical domain mixing processes such as Four Photon Mixing (FPM) and Stimulated Raman Scattering (SRS) which must also be considered.

Stimulated Brillouin Scattering (SBS)

In a system such as the one being considered here there need not be any special considerations for SBS. In particular, the AM-VSB and QAM optical signals can be considered separately since the wavelengths are to be intentionally different. In the QAM WDM link the energies are spread over discrete but separate wavelengths thus insuring safe SBS operation since no one optical carrier will rise above any SBS threshold particularly, in the usual first defense, phase or frequency dithering, is employed.

Self Phase Modulation (SPM)

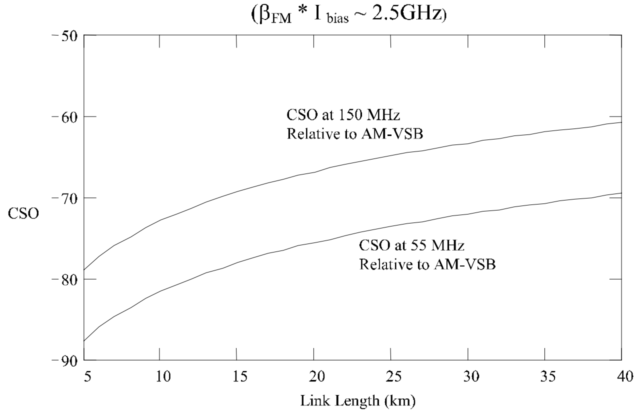
It is the opinion of the authors that there need not be any special consideration given to controlling SPM in this implementation other than that given to any other analog link.

Dispersion

In optical links, dispersion can result in significant CSO performance degradation in propagation over fiber. This effect will dictate the modulation mode for both AM-VSB and QAM carrying optical signals. In the case of the AM-VSB broadband optical link, dispersion will dictate external modulation because of the required link CSO performance. In most instances, AM-VSB requires external modulation because it is difficult to achieve the <-65 dB CSO with commonly used fiber (Corning SMF-28) with D~17ps-nm/km at 1550nm.

For the QAM signals, the situation is not quite as clear. In this case, the CSO specifications are not so stringent so as to prohibit the use of direct modulation on dispersive fiber. Figure 4 shows an estimate of the upper and lower CSO for a set of 10 carriers situated above 550 MHz. Note that the worst case is at 150 MHz. Since the dispersive effect is greater at high frequencies, the spill over into the lower frequency, AM-VSB signals is somewhat less than the worst case CSO for the QAM, which occurs at the highest frequency. Also in this

Figure 4 - CSO Due to Dispersion with Direct Modulation
(β_{FM} * I_{bias} ~ 2.5GHz)



figure, we estimate the CSO contribution from the QAM at 550 MHz relative to the AM-VSB carrier situated there. This assumes that the QAM carrier levels are -6dB relative to the AM carriers and the OMI for the QAM carriers is about 10%. Since the CSO in a QAM modulated system takes the form of a broadband signal spread over the whole channel bandwidth, one could argue it behaves much like additive noise to the AM-VSB signals. Therefore, if the added CSO "noise" can be tolerated, direct modulation of low chirp lasers on the ITU grid can be used for the QAM WDM narrow cast overlay and meet the overall network performance objectives.

Four Photon Mixing (FPM)

In WDM systems, FPM can result in significant signal degradation through an optical mixing process. This effect allows mixing in the optical domain to occur thus giving rise to third order optical products. This mixing process mimics the RF analogy in that the worst case for nonlinearities is where the optical carriers are evenly spaced. One strategy for the minimization of this effect is strategic placement of the wavelengths in the WDM system on the ITU grid. An additional remedy may be implementation of polarization diversity, which has also been reported to achieve a high degree of suppression of FPM.

Perhaps the most important factor governing the efficiency of this process is dispersion. The FPM process relies upon a phase matching condition and thus is spoiled by any chromatic dispersion present in the fiber. Therefore, we do not believe that FPM will be a major contributing factor to system performance. Measurements need to be performed to confirm this and assess the impact of this FPM on the WDM QAM link.

Stimulated Raman Scattering (SRS)

SRS has been a consideration of WDM system design for two reasons. The first is the inherent gain tilt caused by the Raman gain process. This is reasonably easily mitigated by tilting the signals at the primary hub to compensate for the SRS induced effects. The second and more troubling is a process which is somewhat like the optical analog of cross modulation. Because the Raman gain process relies upon at least two wavelengths being present and one providing the energy for the amplification of its companion, variations in the amplitude of the pump wavelength will result in gain variations and thus cross mod. Based on the magnitude of the carriers and their composition, ADC does not anticipate at this point that SRS will impose any severe limitation on the WDM link being considered here.

Effects of Other Components

Direct modulation of the QAM carriers promises to be the most economic solution to forward path narrowcast WDM transmission. If direct modulation is employed in the WDM QAM link, any component which has an optical frequency dependent transfer function will impart odd or even order distortions depending on its symmetry. In the case of this link, there are two potential contributors: the EDFA and the WDM muxes and demuxes. The EDFA gain profile can be minimized, to some degree, by gain flattening. However, the WDM mux/demux problem is not as simple. The optical filters in a DWDM will always possess some tilt or curvature particularly when the number of WDM channels becomes dense enough to require very sharp skirts for adjacent channel rejection. This can result in both CSO and CTB depending on the exact filter shape and the placement of the center wavelength of the laser within the filter response. This effect is potentially the most difficult to deal with and may prohibit immediate deployment of a full complement of sixteen ITU wavelengths because of the narrowness of each channel filter.

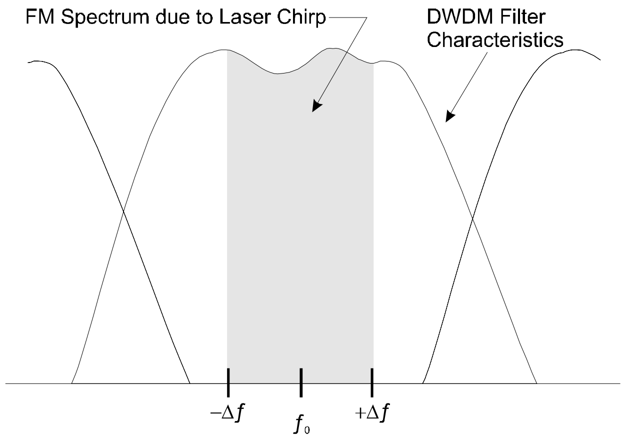


Figure 5.

The in-band figure to the optical filters in the DWDM demux will result in non-linear distortion.

Broadband Linear DWDM Component Economics

Figure 6 illustrates the three major elements which dominate the costs in a broadband linear DWDM network: Narrowcast optical transmitters are used to transmit different sets of channels down the same fiber at different optical wavelengths; DWDM passive optical multiplexers and demultiplexers for combining and separating optical wavelengths on a given fiber with a minimum loss of optical power; and gain flattened optical amplifiers which are used to amplify the entire optical spectrum on the fiber to compensate for losses of signal strength due to fiber attenuation, splitting losses, etc.

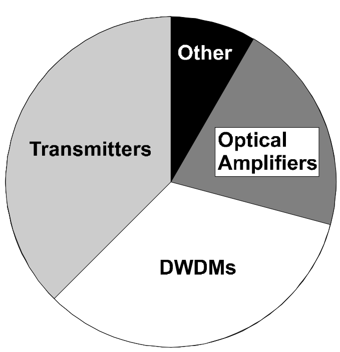


Figure 6

DWDM System Component Costs

Currently, the price of a narrowcast transmitter is roughly twice the cost of an 860 MHz broadband transmitter with ten times the output power. DWDM multiplexers and demultiplexers tend to be priced similarly to narrowband transmitters. Optical amplifiers are approximately three times the cost of the other components, but based on rapidly increasing volumes, the price of optical amplifiers is rapidly decreasing. If optical amplifier prices can be reduced by at least 50% from current levels, it will become practical to use standard optical couplers replacing DWDM multiplexers in many applications. At this point, the cost of lost power due to optical coupling will be less than the power savings minus the cost of the dense wave division multiplexor. This will reduce the overall cost of the WDM network, and also simplify physical configuration of the network. Fewer DWDMs also means less considerations of optical filter roll-off and impact to CSO and CTB.

Other Forward Path Limitations

As the number of narrowcast channels grow, expansion of the narrowcast spectrum beyond ten channels and to twenty, thirty or even forty channels will place significant demands on the narrowcast network. This paper focused on relatively low narrowcast channel counts. Further research needs to be conducted on means of controlling SRS and other optical phenomena as the number of narrowcast channels grow. The potential expansion of some domestic CATV networks to 860 MHz represents the anticipation that more narrowcast channels may be anticipated in the future.

Broadband Linear DWDM versus Digital Transmission in the Primary Ring

As optical amplifiers become more powerful and offer improved noise performance, and 1550 based broadband optical transmitters become more linear, the question is raised as to the viability of eliminating digital in the backbone altogether.

Broadband linear DWDM relies on the fact that the broadcast channels going to the nodes will be identical. From the secondary hub this can be the case. But from the primary hub a number of factors may dictate that the channel content at each secondary hub is different. These factors include but are not limited to the following:

- Revenue generation from narrowcast advertising
- Channel line up variations due to local must carry rules
- Imbedded VBI information in revenue generating services
- Local origination programming
- Data oriented services for SOHO and residential delivery

As the number of custom channels expands and channel configurations vary, combining optical narrowcast signal streams to create specific, differentiable broadband channel line-ups becomes technically difficult and expensive. The addition of more than two optical signals together results in noise floor penalties, and thus lower delivered signal quality. Simultaneously, new data applications call for expanding the data capacity to the primary hubs. (See Figure 7).

Based on these same factors, in regional networks the migration of broadband linear transmission back toward the primary headend is highly dubious based on both economics and technical considerations.

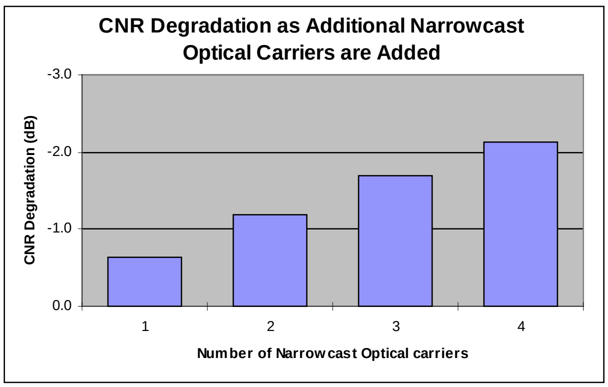


Figure 7.

Digital DWDM in the Primary Ring

The greatest potential for upside revenue in CATV networks today arguably is in non-traditional, i.e. non-entertainment based services. Some examples of these include

- E-Mail
- Internet Access
- High Speed Data
- Web Site Service
- Corporate VLANs
- Cable Telephony

The ability to provide new services to existing customers and to expand the customer base to include small office/home office (SOHO) and even larger corporate customers represents both new revenue opportunities and new network challenges. Given this scenario, CATV networks will soon find themselves in the same situation as other network providers: namely, digital traffic will grow exponentially and begin to consume enormous amounts of network capacity.

In this environment, the ability to expand network capacity incrementally, and gracefully is paramount. For example, if doubling of network capacity every six months is required, replacement of routers and transmission path equipment is unacceptable both in terms of cost and network service disruption. Many classic data networks are built on a distributed routing architecture as shown in Figure 8. This architecture is highly susceptible to this problem.

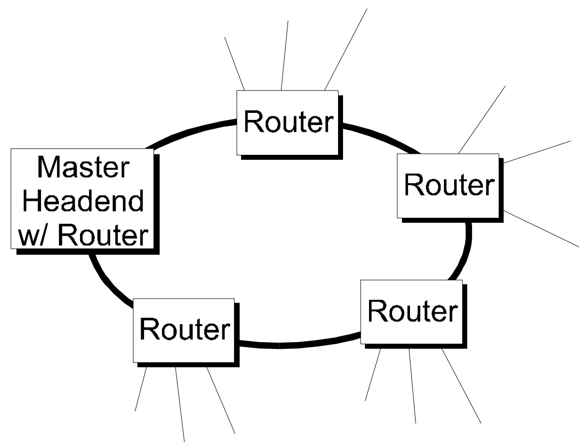


Figure 8.

Ring Network with Distributed Routers at Every Hub

An alternative architecture is to provide centralized routing with distributed switches that have some intelligence to provide data “sniffing”, e.g. the ability to recognize multicast addresses, as shown in Figure 9. The advantages of this configuration are:

- Ability to segment the network into multiple parallel rings via WDM without replacing any individual switches;
- Through centralized routing, more balanced loading and greater ease in upgrade than with distributed routers.

In this scenario, data rates can be upgraded with minimum disruption to the network. Any equipment changeout is virtually limited to the master site where the network router is located. The use of DWDM and distributed switching with centralized routing provides a network solution for handling video, data and voice in an environment in which traffic is growing at high rates.

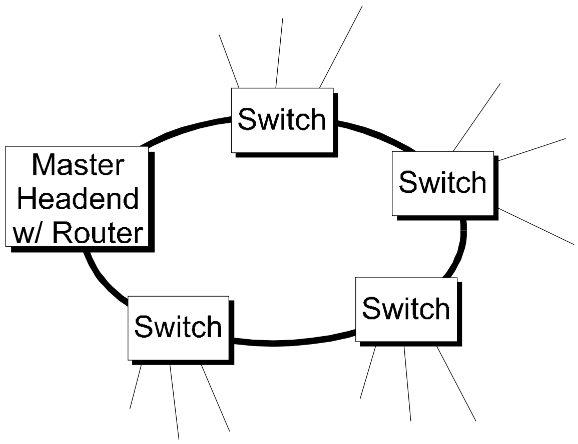


Figure 9.

Ring Network with Centralized Router and Distributed Switches at each Hub

Return Path Considerations

Given elimination of main service equipment at the secondary hubs, the return path information must be transported not only from the nodes back to the secondary hub, but on to the primary hub as well. In CATV networks, return path information takes the form of RF carriers of different bandwidths and modulation schemes, simultaneously occupying a total bandwidth of approximately 40 MHz. Dedicating one fiber per node to transport return path information to the primary hub would be cost prohibitive based on the transmission distances and number of nodes involved. Correspondingly, although DWDM addresses the fiber count issue, it is not practical based on the current cost of the DWDM devices. (The return path in essence would cost as much as the forward path fully loaded with narrowcast services.) Today, RF spectrum block conversion is an alternative for addressing this issue, albeit not an ideal one, since each step of frequency upconversion and downconversion introduces undesirable artifacts such as noise, group delay, etc.

A Look Towards the Subscriber

As optical amplifiers and other broadband linear DWDM components become more cost effective, the cost of bringing fiber closer to the customer will become a reality. Given that delivered VSB/AM quality to the residential tap is typically 49 - 50 dB CNR with -54 dBc distortions, an optical node which serves eight to thirty two homes passively can perform with very low signal level and relatively high distortions, since there are no other active devices such as amplifiers between the node and subscriber. At the point where no active devices exist between the optic node and subscriber, a look at return path methods will be required. Firstly, the number of return paths is inversely proportional to the number of homes served per node. For example, for a system with fifty homes per node, there are ten times the number of return paths as a system with five hundred homes per node.

CATV networks use an RF return path based on traditional architectures in which there are multiple active broadband devices required between the hub and the subscriber. As a result, for every return path signal on the network, format conversion is required at both the customer origination and the receive point, in the form of RF modulation and RF demodulation equipment. Yet, in contrast to the forward path where most channels are still analog video, virtually all information in the return path is digital.

As the node moves closer to the subscriber, there will be a time where a reevaluation of the use of RF carriers for transport of return path is necessary. If signals in the return can be sent to the node digitally, then multiplexed at the node, very low cost optics can be used to transport large amounts of data back to the hub, with no additional loss of signal quality, and a reduction in problems associated with RF interference. Given appropriate digital encoding techniques, the current 5-42 MHz return path represents an opportunity for a very high speed digital return path or shared digital and analog return path from the subscriber back to the headend.

CONCLUSIONS

DWDM is an enabling technology that allows digital backbones to expand capacity gracefully in response to exponential growth in new traffic types. Within the distribution system, DWDM represents a potential means to reduce the cost of delivering narrowcast services to secondary hubs and nodes, where the number of narrowcast services is limited to a few channels. As optics migrate closer to the subscriber, additional complexities in the return path may challenge current thinking on the accepted transmission technology of the return path.

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