DWDM: MATCHING TECHNOLOGY ADVANCEMENTS WITH BUSINESS REQUIREMENTS

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Abstract

Dense Wavelength Division Multiplexing (DWDM) technology has been used in digital communications systems for several years, but its use in analog CATV networks is only recent. Although the components for DWDM technology exist, their use in CATV systems is quite different from that of digital systems, and the requirements are quite often complicated and conflicting.

In general, factors such as number of optical hubs, required bandwidth capacity, transport distances, required RF level differential between the broadcast and narrowcast inputs, choice of return transmission scheme determine the shape and transparency of the envisioned network

Proper analysis of the above parameters determines the number of optical wavelengths needed, level of transparency of the optical hub, the choice of a proper multiplexing scheme for the return transmission system, and the number of nodes that may be combined on each return DWDM transmitter.

These choices are, in turn, ultimately limited by fiber effects such as Stimulated Raman Scattering (SRS) cross-talk, fiber dispersion, EDFA noise and gain-tilt, and available passive and active component specifications, like DWDM laser chirp.

This paper will examine the state of the art in DWDM technology from a system architectural point of view. The goal of the paper is to explain several competing architectures within the framework of DWDM technology in an effort to insure a cost effective and optimally functional network design.

INTRODUCTION

We start with the question "How much fiber is enough?" A Network Manager recently explained to me that his company started a particular network about 3 years back with 12 fibers connecting a ring of hubs with the main headend. The next year, the demand was for 24 fibers, and this year, the demand is for 48! "Nobody can tell me why we need 48 this time around, but it looks like 48 is the magic number this year" he said. Although this may be an extreme case, the truth is most MSOs today realize that headend fiber counts are limited as compared to potential demand. By the time they allocate fiber for broadcast, telephony and internet access using standard equipment, most MSOs struggle trying to determine how much additional fiber is needed for broadcast and interactive services.

DWDM offers a way out. In this technology, several wavelengths of light in the 1550 nm low-loss wavelength window are multiplexed into one optical fiber, thereby increasing its capacity many times over. Although this technology has been used by digital systems for many years; it has only recently been introduced in the analog CATV realm. Yet in less than a year, DWDM has found many passionate proponents. However, as with any other technology, operators and designers face the challenge of determining when DWDM makes sense and when it does not.

DWDM SYSTEM ISSUES

This paper will provide a quick summary to give substance to the discussions that follow. The term "*RF channel*" is used to designate regular sub-carrier multiplexed systems (such as 77 NTSC channels etc). This is to prevent confusion with "*wavelength channel*" that describes multiple optical wavelengths multiplexed using the DWDM technology over one fiber.

Fiber Dispersion

Fiber dispersion along with laser chirp generates CSO and CTB in multi RF channel optical transmission systems. The dispersive effect is dependent on the number of *RF channels* over single wavelength, RF frequency of operation, fiber link length and the laser chirp. Higher chirp lasers over longer distances of fiber have worse CSO and CTB and so on.

Figure 1 shows a DWDM transmitter's performance with a 50 km fiber link and an equivalent passive link without fiber. In each case, the receiver input power is maintained constant. It is seen that CSO (located between 50 to 200 MHz) is enhanced due to fiber dispersion, and although not clearly visible in this graph, there is CTB degradation as well.

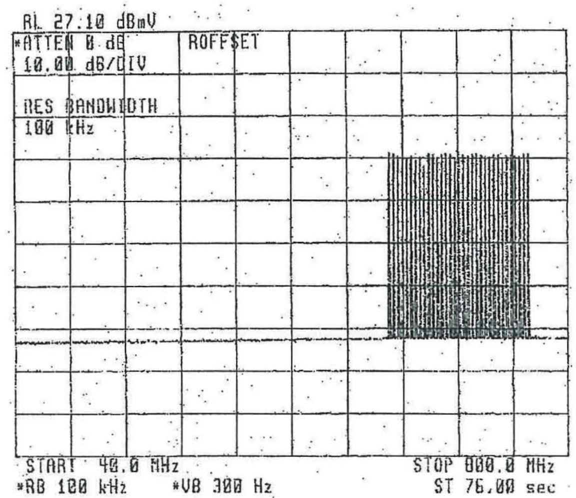

Figure 1a

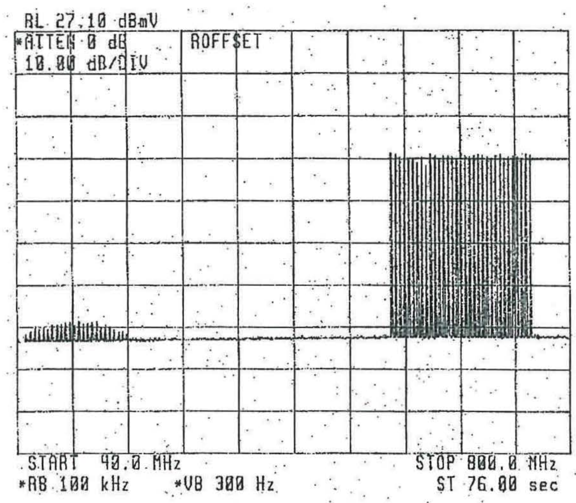

Figure 1b

Figure 1. RF spectrum on DWDM transmitter with passive attenuation (Fig. 1a) and over 50 km of fiber (Fig. 1b)

In long fiber link systems, fiber dispersion is one of the most severe limiting factors. Several compensation techniques exist that reduce this effect. The most obvious is the externally modulated transmitter which because of its almost non-existent chirp generates very little fiber induced CSO and CTB. Other ways include dispersion compensating fiber (DCF) and fiber Bragg gratings. All of these technologies are lossy and expensive. Proper *RF channel* allocation to eliminate in band

CSO (which happens in overlay systems since the narrowcast signals are from 550-750 MHz), combined with patent pending techniques to compensate for fiber dispersion using electronic means offer the least expensive solution today.

Fiber Non-Linearities

In addition to fiber dispersion, several fiber non-linearities exist due to the small core size. The most prominent that concerns us is Stimulated Raman Scattering (SRS) cross talk. SRS cross talk in fiber links appears in multi wavelengths systems where the longer *wavelength channels* get amplified at the expense of *shorter wavelength channels*. It depends upon RF frequency, fiber link, EDFA spacing and output power and polarization.

Figure 2a shows equipment set-up to investigate the effect of polarization effect on SRS. The dark well defined line maximizing at –13.70 dBmV is the SRS crosstalk when the system polarization is set-up to maximize SRS. Next, with the whole system entirely intact, the polarization paddles are moved 50 dB! Polarization effect (which occurs with fiber movement) on SRS is so strong that it could completely mask SRS effect in a potentially SRS limited system. Any experimental set-up will generally severely underestimate SRS cross-talk if proper care is not taken to account for the worst-case polarization states. This holds particularly true for more than 2 wavelengths DWDM systems.

Accordingly, the only technically acceptable way to characterize SRS in DWDM systems is by design and calculations confirmed by testing worst case SRS scenarios. SRS is measured in a two-wavelength system and the SRS effect is prorated for multiple wavelengths and for different EDFA fiber links. Since polarization state of the optical link cannot be predicted beforehand – it may be influenced by the climate inside and outside the plant that is dynamically changing - the design must be effected for the worst case SRS effect. The SRS effect changes rapidly with RF frequency. The severe RF frequency dependence of SRS may be understood as an

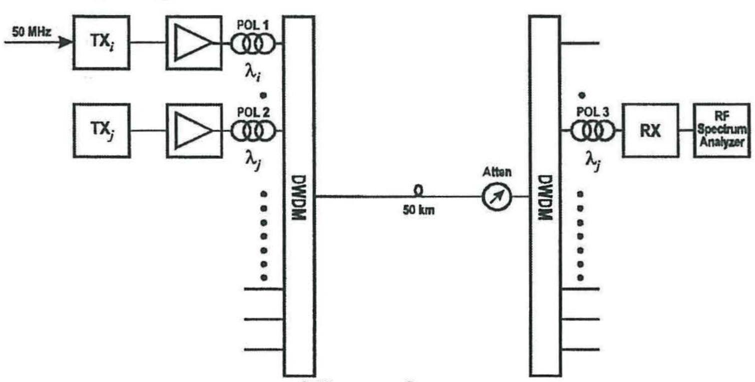

Figure 2a

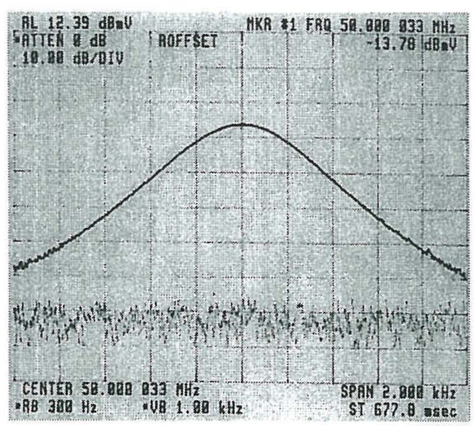

Figure 2b

Figure 2. Setup to measure fiber induced SRS effect. Notice three polarization controllers (Fig. 2a). Polarization effect on SRS. It is possible to completely mask the effect of SRS by changing polarization

wavelength 1550 nm transmission still apply here, and proper design must be incorporated to limit this. Four Wave Mixing (4WM), so called because two optical wavelengths interact in the fiber and create two additional wavelengths around themselves is much below the SRS effect in most multi-wavelength systems, due to the high fiber dispersion.

It is clear that fiber dispersion is a necessary evil. Were it not for fiber dispersion, SRS and 4WM effects would dominate and severely limit the system performance. However, dispersion induces distortions in the RF domain, which could limit system performance anyway. The techniques to limit dispersive effects while still gaining the needed benefits is a balancing act.

Because of the above discussion decisions regarding the use of different fiber types such as DSF (dispersion shifted fiber) that has zero dispersion at 1550 nm, must be evaluated carefully. Since the core size of DSF is smaller than the regular SMF 28 fiber, the resulting fiber non-linearity is larger to begin with. When combined with the lack of adequate dispersion however, SRS and 4WM are significantly enhanced. Other fibers such as the NZDF (non-zero dispersion shifted fiber) that has small amount of dispersion around 1550 nm primarily to reduce 4WM may not adequately reduce the SRS effect. Fibers such as the LEAF (larger core size) do reduce non-linearities, and the AllWave fiber eliminates the water peak at 1400 nm. These may be employed for future purposes. One of the elegant options however is to accept the dispersion for reducing the non-linearity and to compensate for the resulting distortions.

EDFA Gain-flatness

Traditional EDFAs do not have a "flat" gain bandwidth with respect to wavelength. This means that a "flat" multi wavelength input would not result in a flat output. Large wavelength tilts are undesirable not only due to SRS considerations, but also because system design in complex DWDM networks is considerably complicated as receiver input powers cannot be calculated and guaranteed accurately.

Presented in Figure 3 is a measured graph of a 20-wavelength channel DWDM system through two EDFAs and 105 km of fiber. It is seen that the system has a peak to peak flatness of about 7 dB EDFA gain equalization in such cases must be attempted

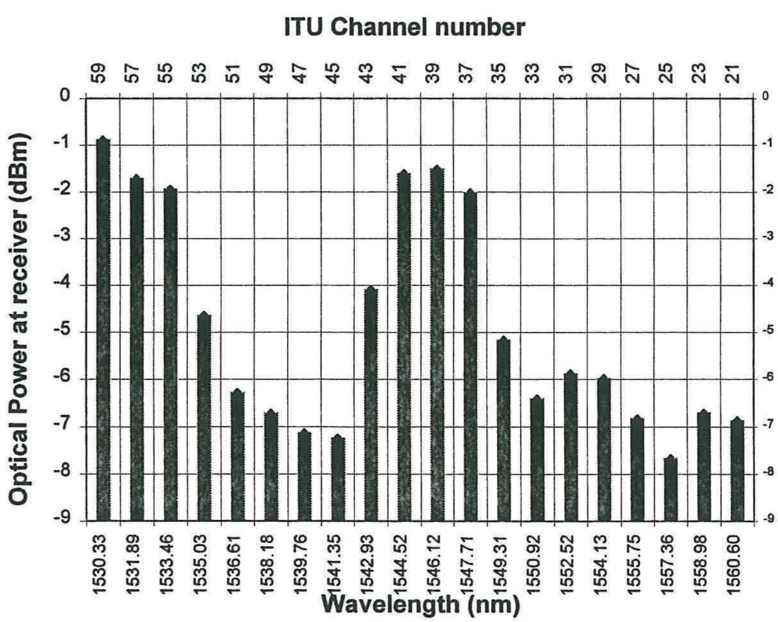

Figure 3. Measured EDFA gain tilt through two EDFA and 105 km of fiber for a 20 channel DWDM system

where the input wavelengths are pre-emphasized to achieve the required output flatness. Sophisticated computer programs are used to estimate the pre-emphasis as the gain-flatness for EDFAs dynamically changes with the optical input power. In a typical system employing several wavelengths, it is almost always necessary to pre-emphasize at least a few wavelengths.

Internally Gain-flattened EDFAs for particular input levels are very popular for long haul digital interconnect (2.5 GB/s) operations. These EDFAs could be restrictive to CATV system designers as in most cases, amplifier spacing in CATV networks is dictated by varying hub locations where maintaining precise optical input levels may not be possible.

Other Effects

Since the fiber core guides the shorter wavelengths better than the longer wavelengths, minimum optimum fiber bend radius for 1550 nm fiber management is much larger than it is for 1310 nm systems. Accordingly, proper fiber routing inside the node where space is limited is extremely important. This is particularly important for DWDM system where a precise RF level differential must be maintained and trouble shooting is complicated.

DWDM transmitter Loading, SNR and Clip Margin

Loading of DWDM transmitter is of the form of QAM64 or QAM256 signals. It is generally assumed that each RF QAM channel is spaced 6 MHz wide (with 5 MHz of noise bandwidth) and 8 such QAM Channels fit in a 50 MHz bandwidth or 32 such channels fit in a 200 MHz bandwidth. Generally broadcast transmission is from 50 to 550 MHz, and the RF plant in the US is usually 750 MHz. Therefore, 550 to 750 MHz loading represents the maximum possible loading in most typical cases.

Digital signal performance is represented by the signal to noise ration (SNR) as opposed to the CNR. In this paper, all data for narrowcast transmission is presented assuming a 5 MHz noise bandwidth.

A Word about Clip Margins

The CNR that we commonly understand for analog networks is the ratio of the "average carrier power" to the "average cumulative noise" within the video bandwidth. This concept works very well for analog video signal transmission over the optical links. However, QAM64 and QAM256 signals are usually described as a constellation where there is considerable variation between their peak powers and their average powers. This is particularly severe when a "large number" of *RF channels* (such as 32 QAM channels in the 200 MHz loading) modulate the laser.

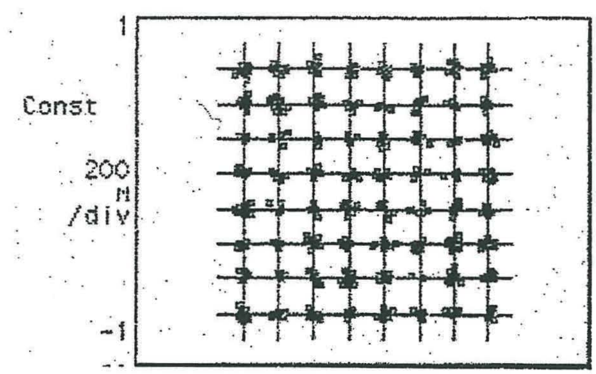

Figure 3a. QAM64 Constellation diagram illustrating peak and average power

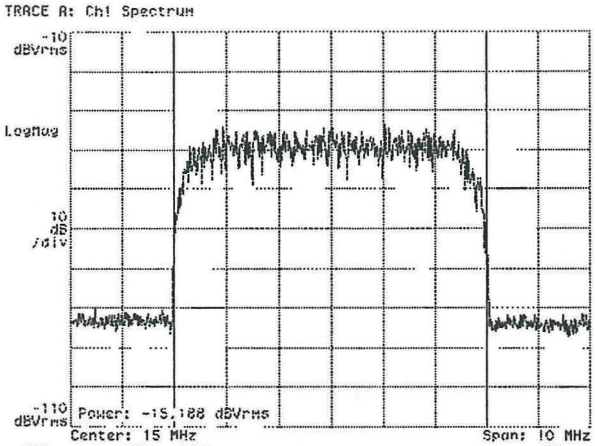

Figure 3b. The average power normally seen on an RF power meter or the vector signal analyzer

While the combined average video carrier power does not clip the laser, their peak powers clip lasers several times. In analog video transmission, these clip time periods are small and do not affect the picture quality significantly because the eye averages out minor glitches in the picture. However for digital systems, when the laser is in even very modest clipping, (the laser light is essentially off), bit errors result. Empirically it is found that for a "large number" of QAM channels modulating the laser, the total RF input to the laser must be run 2 to 3 dB below the normally understood value of clipping. This is designated as the *clip margin*. All discussion to follow includes a 3 dB clip margin for the narrowcast transmission, and the graphs to be presented must be understood in this context.

DEVICE PERFORMANCE

DWDM transmitters must be maintained at very closely held optical frequencies set by the ITU channel numbers. DWDM performance is dependent on three factors

Temperature performance

Temperature performance over specified temperature range usually 0C to 40C and long term stability and drift of the DWDM laser and its temperature control circuitry. Such control circuitry is crucial and must be tested and verified.

Transmitter Performance

The yield for higher chirp devices (>300 MHz/mA Chirp parameter for 10 mW) is larger, and such devices are less expensive. However as noted above, higher chirp devices in collaboration with fiber dispersion generate large amounts of fiber CSO and CTB thus limiting their application, unless something can be done to compensate for dispersion.

Passives Selection

Passive DWDM components are usually thin film based or grating based or AWG design based. Their insertion loss, temperature performance and passband flatness is of interest for DWDM performance.

In the current state of the art, we have transported 20 optical wavelengths, over more than 100 km, with thirty-two QAM256 channels per wavelength, after taking into account all fiber non-linearities and dispersive effects over standard single mode fiber. This represents a 200 GHz spacing on the ITU raster, and is essentially limited by the gain bandwidth of the EDFAs. With some effort, this spacing may be reduced to 100 GHz, thereby increasing total capacity to a 40 wavelength DWDM system.

DWDM IMPLEMENTATION

Single Receiver architecture

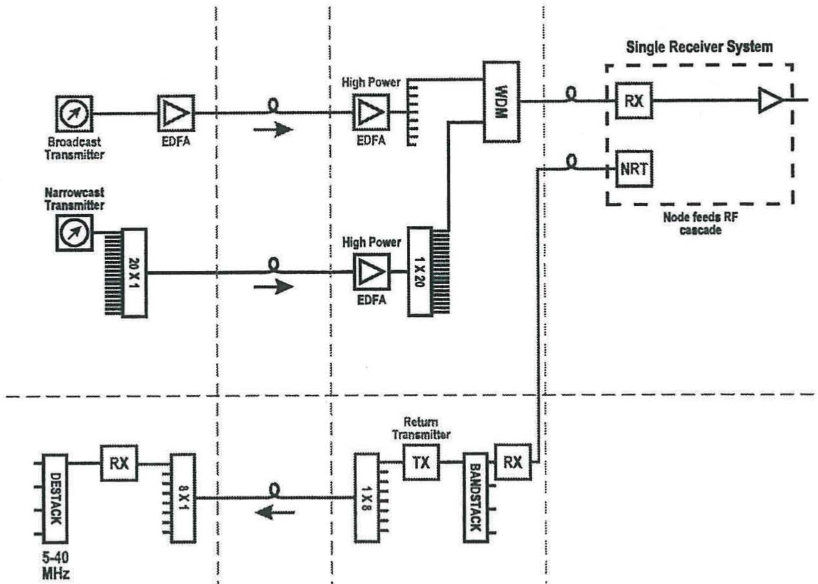

Figure 4. A single receiver system with narrowcast and broadcast optical signals combined on one single receiver at the node

As is seen in the above diagram, the each receiver receives the cumulative input of the broadcast and narrowcast input. The receiver now has an aggregate noise from both the transmission media including the shot noise, laser RIN, EDFA noise and fiber

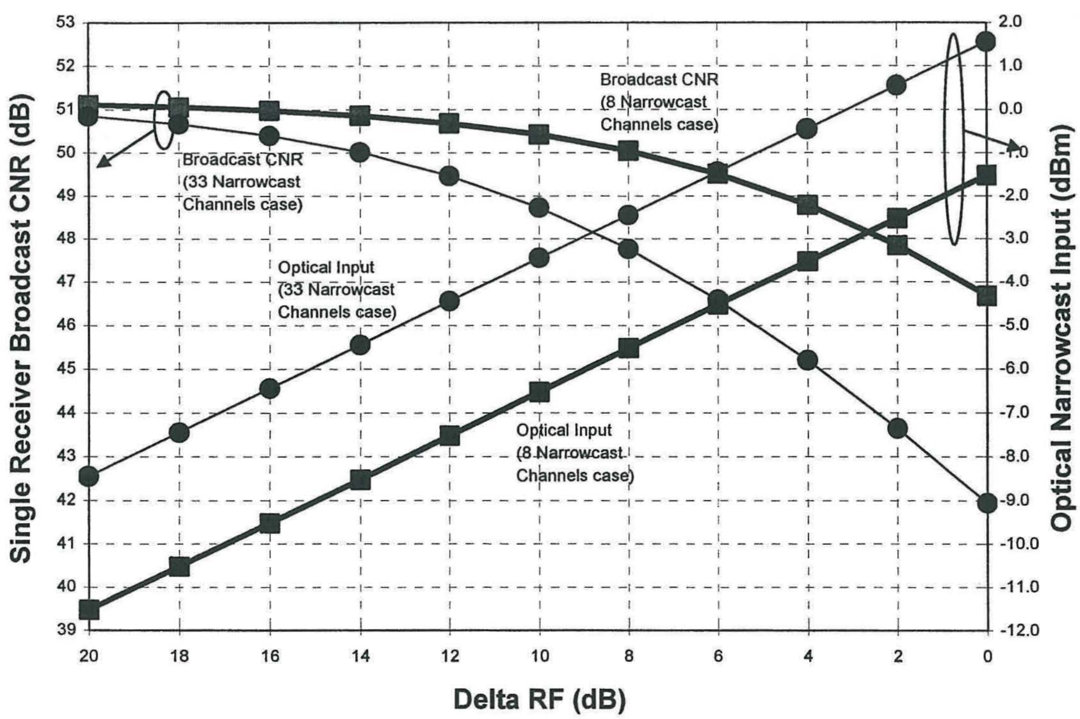

Figure 5. CNR penalty in the single receiver system. Notice that the CNR penalty increases as the narrowcast optical input increases, Analog input = 3 dBm (optical), total fiber link =65 km (45 km long haul+15 km distribution)

noise for the broadcast along with similar terms for narrowcast. These are then combined with thermal noise of the receiver

Such noise sources can be quantified quite accurately and the resulting CNR can be evaluated very accurately. Usually, the operator specifies a certain RF Level differential between the broadcast and the narrowcast. Since the number of channels for transmission and the RF drive level for a particular system is fixed, one ends up having to maintain a constant ratio of optical power differential to obtain the required RF delta

Figure 5 is a graph of performance in a single receiver system. It is seen quite clearly that in the above architecture higher optical input from the narrowcast input results in a large CNR penalty for the broadcast. From the graph, one can see that precise optical levels for both broadcast and narrowcast must be maintained not only to generate the specified CNR and SNR, but also to maintain the specified RF Delta. This is a non-trivial problem especially given the varying gain tilts of the EDFAs. In general, optical attenuators must be used for each node to satisfy the various power requirements. For higher number of channels (for example 32 channels from 550 to 750 MHz), the CNR penalty is quite severe. In the graph presented in figure 5, it is seen that even with a +3 dBm input to the receiver from the broadcast receiver, the final broadcast CNR is only 49.5 dB. To maintain a 6 dB RF Delta, the narrowcast optical input must be –1.5 dBm. Such high optical levels for narrowcast and broadcast require receivers that can handle high optical power. The end result is also an inefficient use of system optical power budget.

From Figure 1, it is seen that fiber induced CSO and CTB distortions are prevalent in systems having even modest fiber link (50 km). These distortions which are generated by narrowcast QAM signals are spread over the lower RF band from 50 to 200 MHz and could really limit the CNR of channels located at those places even further.

For all of the above reasons, single receiver systems can generally be used effectively when the number of narrowcast channels are quite limited (for example 8) and when the required RF level differential is quite high (for example 10 dB).

Return System: A typical return system is shown in Figure 4. Since the loading on the return transmitter is limited (in the US from 5 to 42 MHz), many return links from the node to the hub may be "stacked" together over one DWDM transmitter for purposes of transportation back to the headend.

Figure 4 shows a typical case where 4 such return streams are multiplexed. DWDM transmitters used for return systems could potentially be identical to the forward transmitter if a proper block conversion scheme were chosen.

If the return transmission scheme was QPSK (as it is the most prevalent), both the transmitter capacity and fiber capacity could be increased significantly. For higher modulation formats such as QAM16 and OFDM signals over long links, return system design is complicated and challenging and sometimes could be the limiting factor.

Alternatively an A/D scheme may be effected within the node to digitally sample the return band and transmit the bits over available node return transmitter. Multiple links of this type could be aggregated at the hub for transportation to the headend.

Dual Receiver Architecture

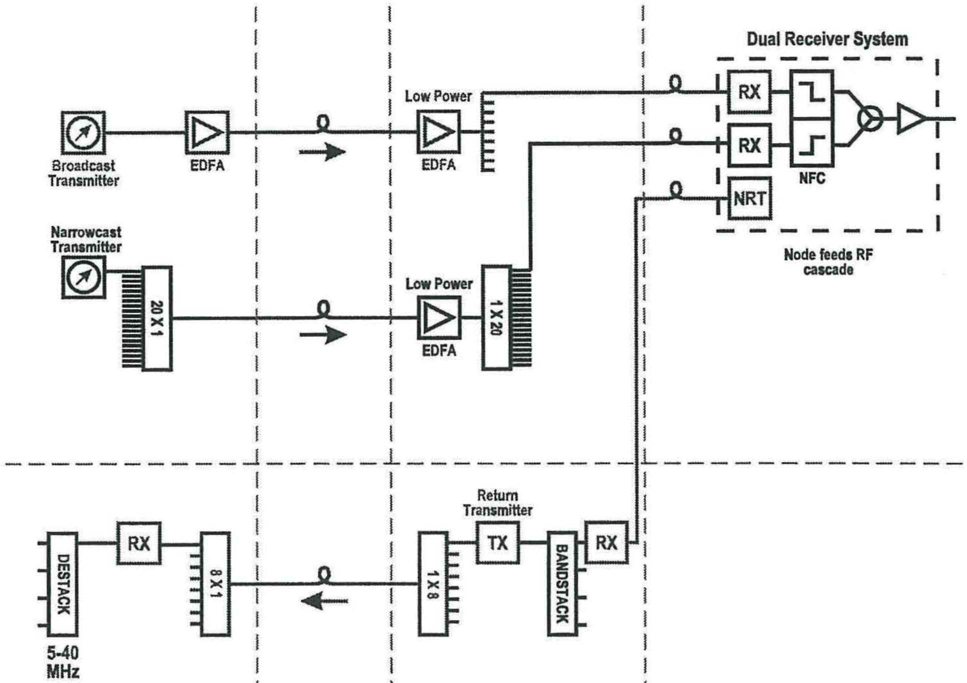

Figure 6. Dual receiver system, and NFC (network forward combiner) within the node combines broadcast and narrowcast signals

In the dual receiver system, the transmission is achieved by using two receivers in the node (one for broadcast and one for narrowcast) and a network forward combiner (NFC). Here, the RF level differential can be de-coupled from optical levels, which is a significant simplification.

Since appropriate filtering and amplification/attenuation can be done *after* the receivers, broadcast CNR and narrowcast SNR are reasonably independent of each other. Lower optical input power may be applied to the individual receivers and there is no conglomeration of noise normally seen in single receiver systems.

The component NFC is similar to a forward diplex filter and must be designed to have a crossover at the frequency band of interest such that minimum impact occurs over the entire broadcast and narrowcast band. Also, because of the NFC, CSO distortions shown in Figure 1 do not affect CNR of the broadcast link in this architecture thus enabling longer fiber links.

Figure 7 is a graph, showing performance for a 32-channel dual receiver system the same link as the single receiver case. It is seen that a 6 dB RF level differential is maintained with 0 dBm into the broadcast receiver and –10 dBm into a narrowcast receiver, where the CNR and SNR are similar to those attained by the single receiver solution. A quick comparison illustrates that there is a 3-dB reduction of optical budget for the broadcast an 8.5-dB reduction in the narrowcast power budget. This is a very persuasive argument for the dual receiver concept since it results in EDFA cost reductions.

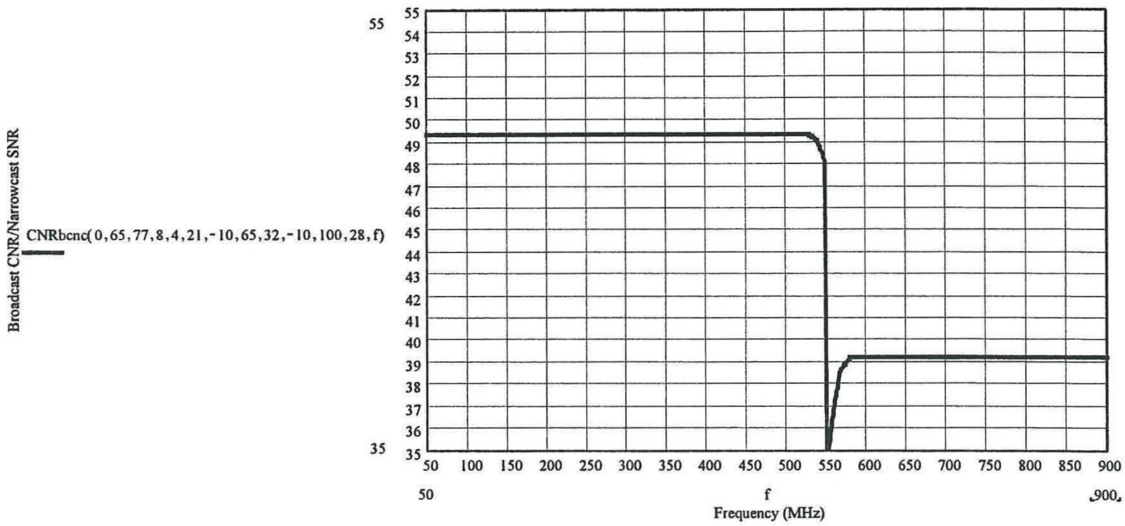

Figure 7. Graph illustrating the CNR in a dual receiver system. The shape at the crossover frequency is due to the shape of the NFC

The main limitation of this dual receiver concept is that the fiber counts and node configuration must change from its present structure. Appropriate space in the node platform must also be accommodated. In many cases, the cost advantage of lower system power budget is offset by the added cost of the additional node receiver and the NFC.

Digital convergence over the next several years is another issue that must be carefully evaluated. In this situation, the amount of broadcast analog frequency content may steadily decrease until it becomes necessary to change the NFC within the node. If the serving area were very large, it would be inconvenient to change the NFC within the node several years down the line.

The dual receiver concept conserves system budget and enables easier implementation of the DWDM architecture, particularly when the number of narrowcast channels are large (for example 32 QAM Channels) and the required RF level differential is small (6 dB). In these cases, in addition to ease of implementation, significant cost reductions are possible.

Ultimately decisions like digital convergence, size of the serving area, fiber counts, temperature performance of the node and space constraints along with performance considerations would determine when the dual receiver concept is applied.

Dual Hop Architecture

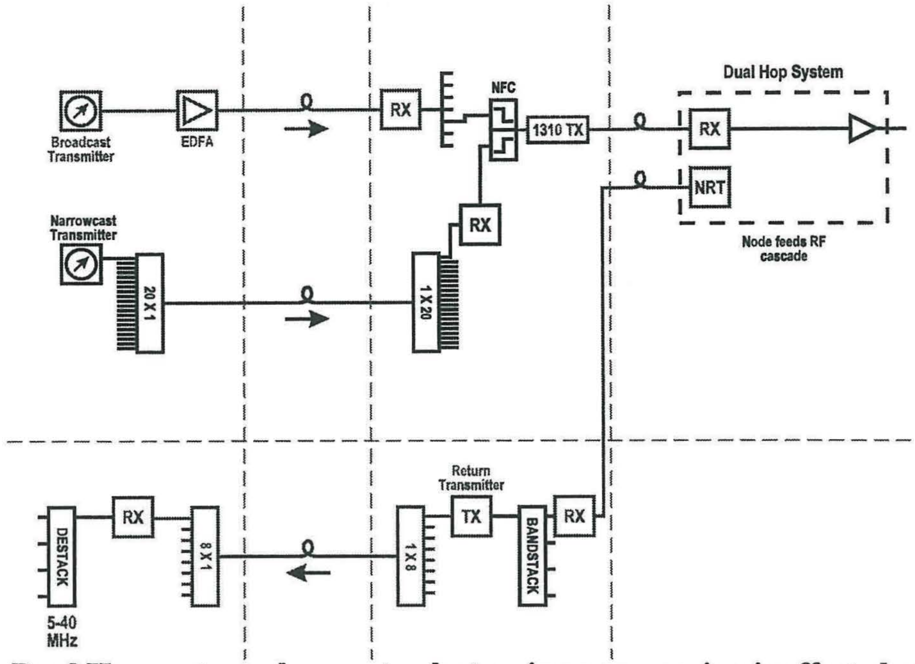

Figure 8. Dual Hop system where opto-electronic re-conversion is effected at the hub.

Here, a 1550 nm broadcast and 1550 nm narrowcast are propagated over fiber as normally envisioned. However, at the Hub, the receivers convert both the broadcast and narrowcast to RF and appropriate broadcast and narrowcast levels are connected to one single 1310 nm transmitter. These are then sent by conventional means over optical fiber to the node.

Analyzing a dual hop system for broadcast transmission is similar to any other dual hop operation with the exception that a *clip margin* must now be applied to the 1310 nm distribution transmitter. This is to protect digital QAM transmission over the same laser. Narrowcast transmission may be analyzed in a similar fashion.

Figure 9 shows the end of line results for a dual hop system. The thick lines show the EOL as a function of the distribution broadcast link CNR. However, a 1 to 3-dB *clip margin* may need to be applied to the 1310 nm transmitter resulting in lower EOL specification than that given in the graph. Note however that the distribution CNR may be maintained even with the clip margin for example by increasing the optical level to the receiver.

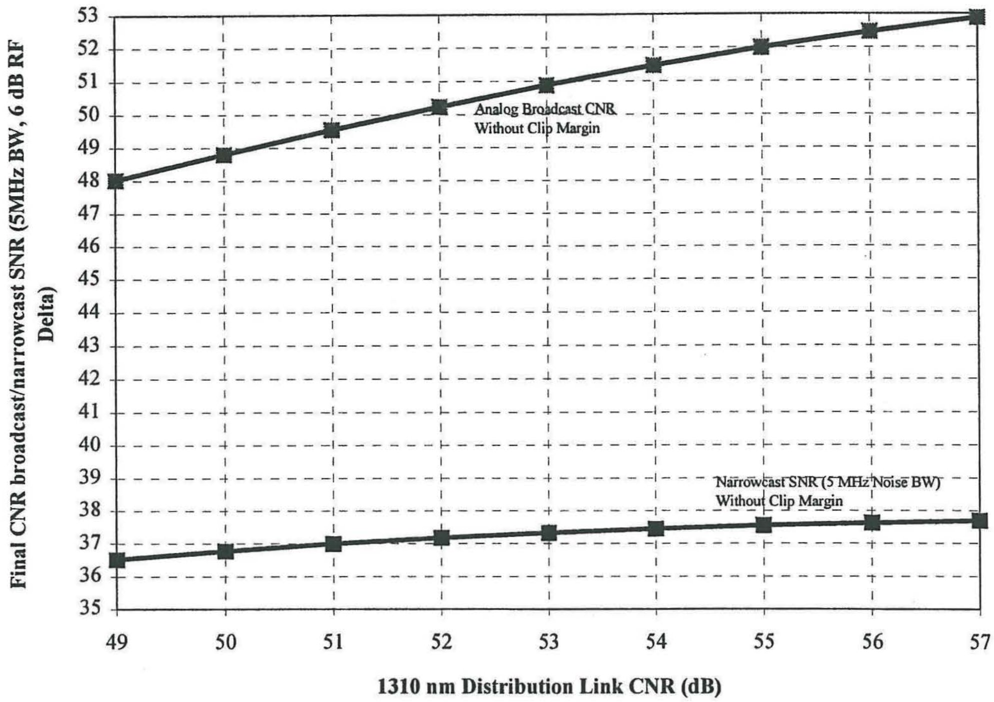

Figure 9. Final dual hop broadcast transmission depends on the CNR of the long haul link and the distribution link CNR and the Clip margin The broadcast long haul CNR is assumed to be 55 dB, and the narrowcast SNR in a 5 MHz bandwidth is 38 dB. The graph shows a calculated final CNR and SNR value as a function of the CNR of the distribution link CNR, without *Clip Margin.*

The dual hop operation is very resilient against various digital convergence paradigms. If it were necessary to change the digital and analog balance, it would all be done at the hub location as opposed to the node in the dual receiver case. True local ad insertion not normally possible in the single and dual receiver models are possible in this scheme. The dual hop operation is equally applicable for cases with small and large number of channels and for small and large RF level differentials.

Cost wise, the system has even fewer EDFAs than both the single and dual receiver systems. However, one extra receiver and one extra 1310-nm transmitter, would potentially offset the cost advantages. Fiber counts from the hub to the node are conserved while additional space and equipment is needed at the hub.

Among operators with an established 1310 nm base, this concept has found a lot of favor. The advantage of the dual hop system is that the node is unaffected, thus making laying of the cable plant a completely transparent operation. Since 1310 nm is a mature technology currently experiencing cost reduction exercises the distribution plant for DWDM requirements may be built with little extra investment.

CONCLUSIONS

Operators are concerned about capacity constraints and of over building. Over built systems represent an opportunity cost that presumably could have been spent on other lucrative options. Even so, DWDM represents the best way to invest in a system, since it enables the subscribers to use advanced services while deferring the costs of expensive hub builds to the future when such services actually take-off and are able to produce money on their own. In other words, DWDM potentially represents a "faster to revenue" way while still maintaining all options for the future.

All three architectures presented here have their own unique applications in the DWDM universe. Another significant advantage of DWDM technologies is the "transparent" hub, and the associated cost savings that it brings with respect to the real estate and manpower. In all cases, the capacity of the long haul fiber is considerably enhanced.

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