EFFECTS OF CROSSTALK ON BI-DIRECTIONAL AND HYBRID QAM/DIGITAL DWDM SYSTEMS

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Abstract

The increased demand for fiber links in metro market networks has made it necessary for AT&T Broadband to build bi-directional DWDM networks in several locations. Furthermore, the collocation of primary and secondary hub ring routes and the need to address third-party requests for baseband digital capacity have required, at times, the transporting of both analog, or quasi-analog signals such as N-QAM (subcarrier multiplexed signals) and baseband digital signals (SONET, Ethernet or ATM) on different wavelengths within the same fiber. In both cases, the effects of crosstalk generated by DWDM passive components and nonlinear fiber effects had to be analyzed carefully in order to prevent severe degradation of the signal. It became important to specify design rules (relative optical power levels) in DWDM networks and DWDM component performance for proper operation of such networks.

This paper reports on the results of the laboratory testing conducted at AT&T Broadband to determine the acceptable levels of crosstalk, and to specify system guidelines to ensure that crosstalk effects remain within tolerable limits. The paper also summarizes basic specification parameters for DWDM passive components for uni-directional and bi-directional links with analog, quasi-analog and digital baseband signals.

INTRODUCTION

Initially, the metro market systems were supporting video signal transportation from one or a few locations into a number of locations for local distribution. These systems were configured in a ring or a point-to-multipoint topology. Although the optical fiber cable placed for this purpose contained some spare fibers, the fiber count was limited to lower costs, and many of these fibers were used for video signals since DWDM technology had not yet matured.

Later, a number of new services, including local ad signal distribution and insertion, high-speed Internet access, digital telephony, VOD and iTV, competed for the limited fiber capacity in the cable intended primarily for video signal distribution. Additional capacity was also needed to support internal telephony traffic between centralized customer care centers, and from the facilities and the network status monitoring systems to national and regional network operating centers (NOCs). Many of these new services and applications required ring architectures for increased reliability. In many cases, the ring closures were achieved with fibers leased from other operators and the fiber count in these leased runs was limited.

In addition to these internal needs, third party telecommunications service providers and affiliates who secured agreements with the metro cable operators requested capacity in the same cable routes. Sometimes, the locations they served or their offices were located in proximity to analog fiber links. Moreover, the desire to serve as a CLEC increased the requirements for digital bandwidth, and often along the analog transport fiber routes. Finally, in some areas, analog and digital transport routes used in different segments of the metro network were co-routed. Some of these are depicted in Figure 1.

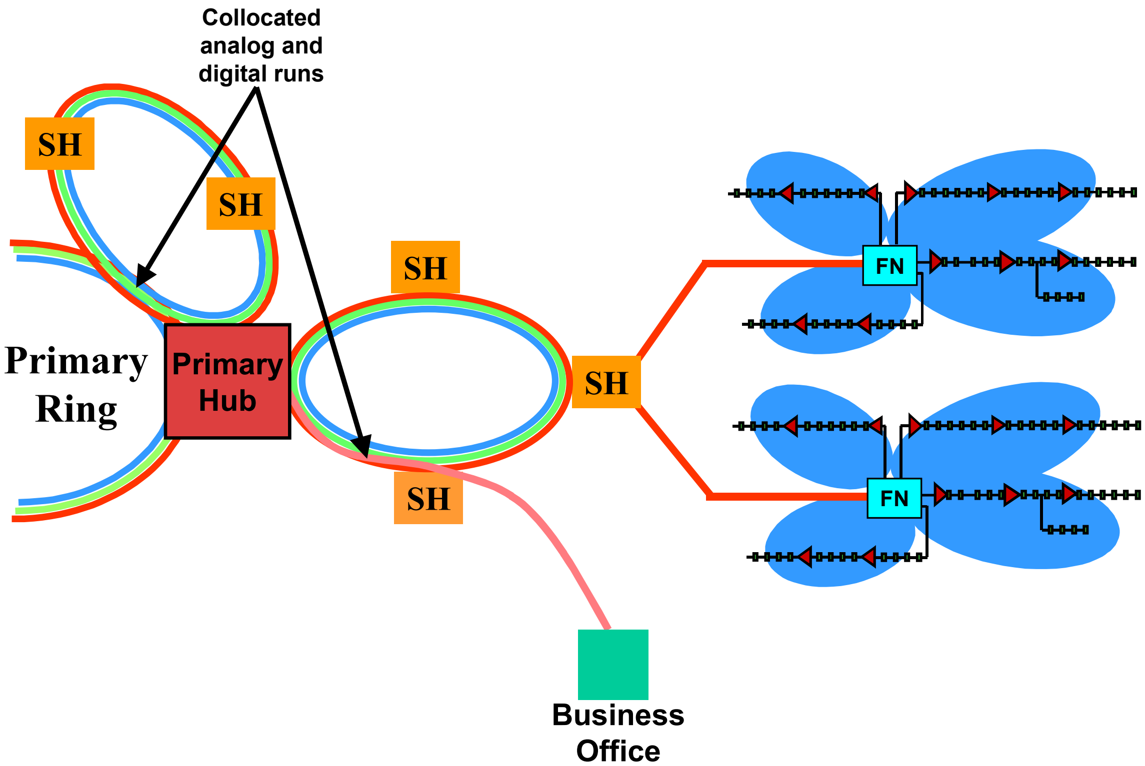

Figure 1: Optical Fiber Network in Metro Markets

These situations made it necessary to use DWDM systems in both primary and secondary hub rings, especially in areas where fiber was scarce or leased. In extreme cases, bi-directional DWDM systems had to be deployed. In a few cases, analog and quasi-analog signals had to be routed over the fiber with baseband digital signals. This situation prompted AT&T Broadband to test, analyze and design DWDM systems that allow for different transport systems on an optical fiber in uni-directional and bi-directional configurations.

The major problems with DWDM links are related to the crosstalk between the wavelengths used. Although multi-wavelength systems existed before the testing commenced, these systems usually were deployed for uniform transport platforms (for example, all wavelengths supporting SONET transports) and were often integrated with these platforms. In many instances, they were quite expensive due to conservative specifications. The results of the testing and analysis conducted by AT&T Broadband led to a reasonable set of specifications on components from independent sources thus lowering their cost. This approach also resulted in a set of design rules for DWDM systems, dependent on the types of signals in different wavelengths as well as on the direction of the signal flows. The separation of DWDM systems from the transport systems allowed for moving the legacy systems to multi-wavelength fibers and to recover fibers in some runs.

SOURCES OF CROSSTALK IN DWDM OPTICAL LINKS

Linear Mechanisms

The major linear source of crosstalk in DWDM systems is related to less than perfect isolation of the DWDM de-multiplexer. In bi-directional systems, the directivity (i.e., crosstalk from one channel to another) of the DWDM multiplexer is also a critical parameter.

Nonlinear and Hybrid Mechanisms

Nonlinear fiber effects must also be considered if analog signals are transported over a DWDM system. If the optical power coupled in to the fiber exceeds 5 dBm per channel, then Stimulated Raman Scattering (SRS)-induced crosstalk may become a significant[1] contributor to the crosstalk between wavelengths. At these power levels, the worst-case total electrical SRS-induced crosstalk is in the low −50 dB range for the case of a 16-channel DWDM system transporting quasi-analog signals at frequencies above 550 MHz. But, considering that SRS-induced crosstalk is approximately inversely proportional to the RF frequency squared, it could increase to the low −30 dB range (relative to the digital signal levels) at 55.25 MHz (analog channel 2). This is unacceptably high unless the digital signal levels are constrained to be well below that of analog signals.

Other fiber nonlinearities should also be considered. For example, Cross Phase Modulation (XPM) in the fiber results in optical frequency modulation of one signal by the other channels. This occurs because the optical power of one channel modulates the refractive index of the fiber, thereby inducing a phase modulation of all other channels. This nonlinear mechanism combined with a linear mechanism of conversion from phase to intensity modulation results in crosstalk. The XPM is converted to intensity modulation as a result of the non-zero transmission slope of the DWDM filters. This hybrid nonlinear/linear mechanism can be a significant source of crosstalk since a transmission slope of 0.1 dB/GHz represents a 2.3% optical modulation index (OMI) per 1 GHz of frequency modulation.[2] Typical transmission slopes of demultiplexers are in the 0.02 - 0.11 dB/GHz range within their 1 dB passband.

Another source of crosstalk to consider arises from a combination of XPM and polarization dependent loss (PDL). XPM is known to cause polarization modulation of one signal due to the combined power in the other channels. This polarization modulation is converted to intensity modulation (and hence crosstalk) if the demultiplexer (or receiver) exhibits PDL. The optical crosstalk can increase by 10 dB as the PDL increases from 0.1 dB to 0.5 dB over a frequency range of 50 - 800 MHz.[2]

EFFECTS OF DIGITAL CROSSTALK ON ANALOG SYSTEMS

A controlled level of either OC-12 or OC-48 signal was optically combined with a 750 MHz analog signal (550 MHz of broadcast and 200 MHz of narrowcast) and transported over 12 km of singlemode fiber to an optical node. The wavelengths of the analog signal and the digital signal were close together in the 1550 nm window; therefore, there were no correction factors applied for differences in the responsivity of the receiver. The worst case degradation occurred at lower RF frequencies. A graph of the analog CNR (ch. 2) as a function of OC-12 and OC-48 interfering optical signal level (crosstalk) is presented in Figure 2.

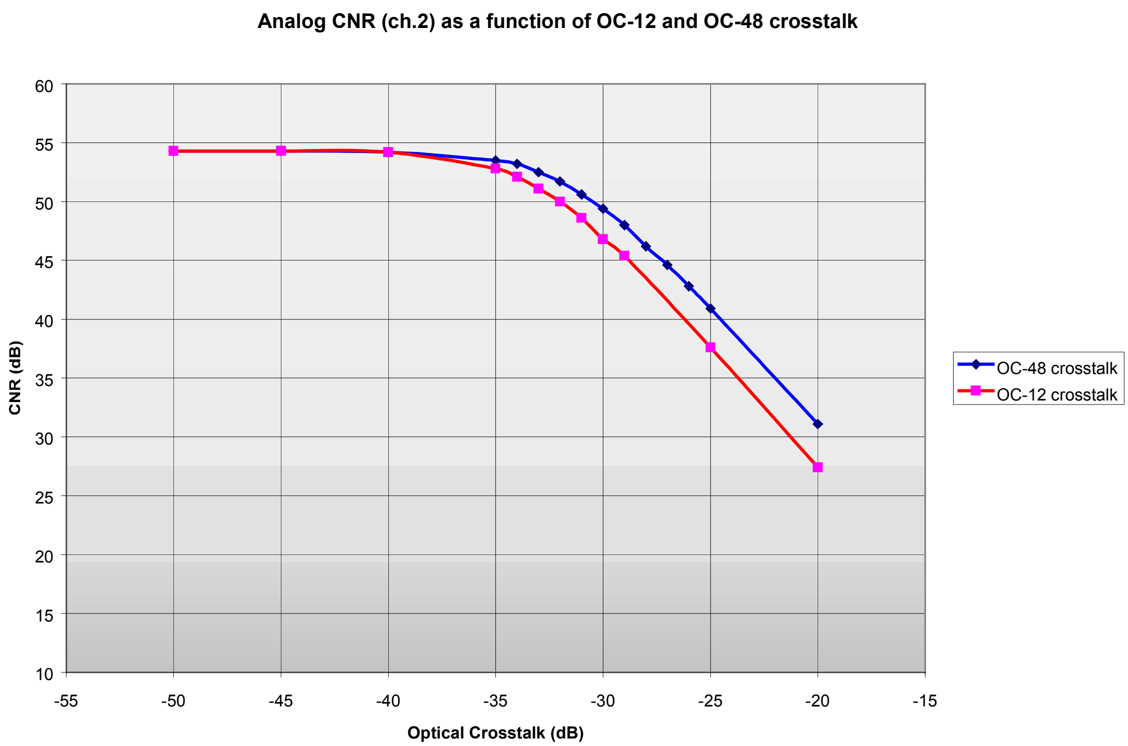

Figure 2: Analog CNR Degradation Resulting from Digital Crosstalk

At high levels of optical crosstalk, the slope of this graph is −2, indicating that the crosstalk behaves like a simple noise floor. The noise floor is not flat but has a shape given by the spectrum of the digital signal, namely a "sinc" function with the first notch at 622 MHz (for OC-12 signal) or 2.488 GHz (for OC-48 signal). This explains the greater degradation of CNR at lower frequencies and greater degradation caused by OC-12 signal crosstalk. For the same optical power, the spectral density of the OC-12 signal is higher at low frequencies than the spectral density of the OC-48 signal.

The equivalent CNR of the noise floor resulting from digital crosstalk is given by relationship (1).

$$CNR_{eq} \equiv -10 \bullet \log\left(10^{-\frac{CNR_{meas}}{10}} - 10^{-5.435}\right) \qquad (1)$$

The equivalent CNR values caused by the OC-12 and OC-48 crosstalk are shown in Figure 3.

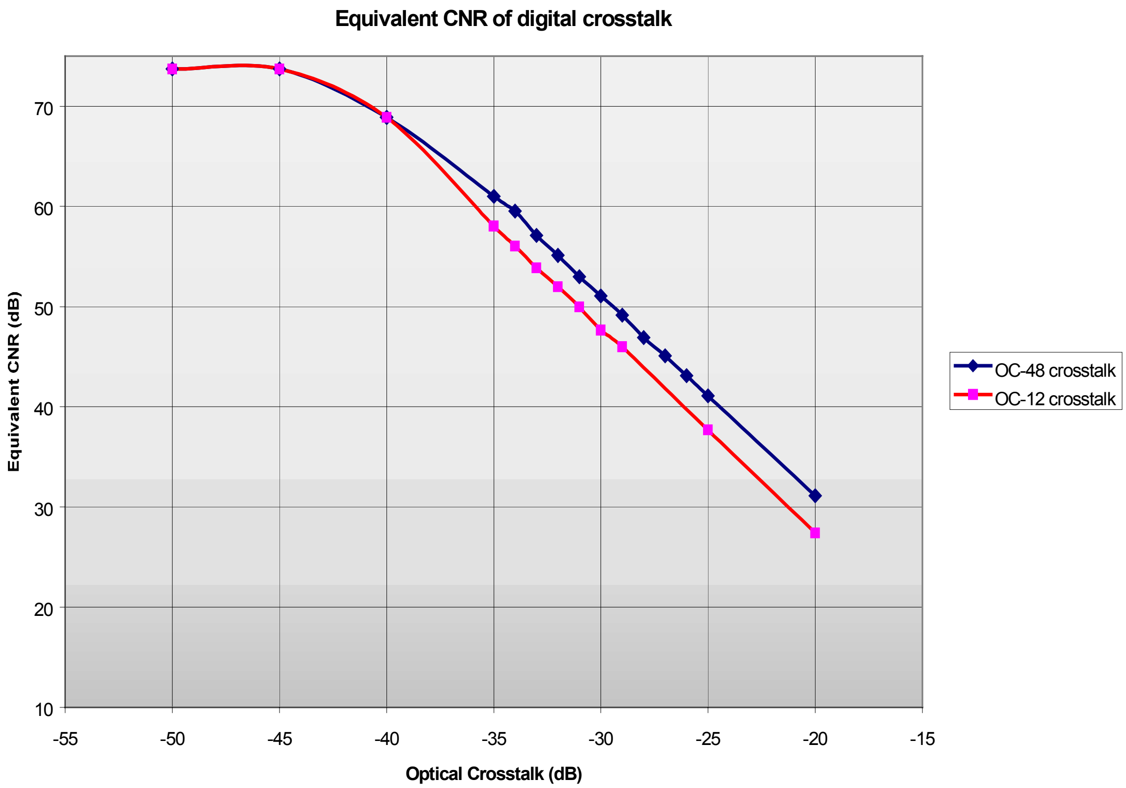

Figure 3: Equivalent CNR Caused by OC-12 and OC-48 Crosstalk Levels

As expected, the equivalent CNR of the OC-12 crosstalk is worse (i.e., lower) than for OC-48 crosstalk. An equivalent CNR figure caused by crosstalk should be higher than 60 dB to ensure that the digital crosstalk has negligible impact on analog performance. Figure 3 indicates that this level of crosstalk can be achieved if the optical crosstalk is lower than –37 dBc. This does not translate into a requirement of 37 dB optical isolation for the DWDM demultiplexer since the digital signals are typically much lower than the analog signals at the demultiplexer input. Typical analog optical power levels at the output of the demultiplexer are 0 to 5 dBm, while digital optical levels are lower than –15 dBm in order to avoid saturating the APD receivers. At the worst, it can be assumed that the optical levels of the digital channels are at least 10 dB below the analog channels prior to the DWDM demultiplexer. If an EDFA is used at the multiplexer, then optical pads may be required in the digital path (prior to the multiplexer) in order to ensure that the optical delta is not less than 10 dB. Consequently, the required –37 dBc of total digital crosstalk can be obtained using a demultiplexer with a total isolation (i.e., isolation from all wavelengths occupied by digital signals) specification of 27 dB. DWDM demultiplexers with adjacent-channel isolation of 35 dB are available and provide the required total isolation. There are no special requirements for the DWDM multiplexer in this application.

EFFECT OF ANALOG CROSSTALK ON DIGITAL (OC-12 AND OC-48) SYSTEMS

A controlled level of 750 MHz analog signal was optically combined with an OC-48 signal and transported over 50 km of singlemode fiber to an OC-48 APD receiver. The BER characteristics for the OC-48 system under different test conditions are presented in Figure 4.

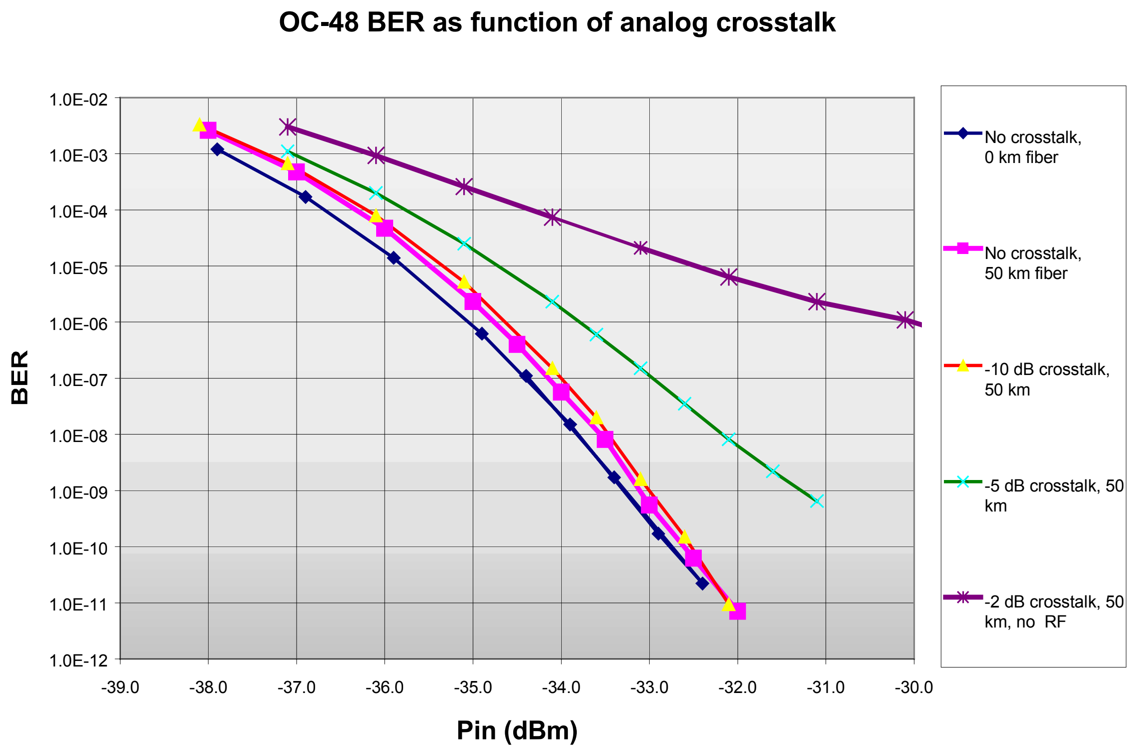

Figure 4: OC-48 BER Characteristics for Different Analog Crosstalk Levels

The leftmost BER characteristic is the baseline characteristic for the case where there is no analog crosstalk and the transmitter and receiver are connected with a 6 m fiber patchcord. To its immediate right is the characteristic for the case where there is no analog crosstalk but there is 50 km of singlemode fiber between the transmitter and receiver. The horizontal displacement of 0.3 dB represents the power penalty resulting from chromatic dispersion. This power penalty would be expected if the spectral width of the laser was 0.13 nm (FWHM).

The next three BER characteristics illustrate the increasing degradation of the digital signal for analog crosstalk levels corresponding to −10 dBc, −5 dBc and −2 dBc, respectively. The degradation becomes significant when the analog crosstalk exceeds −5 dBc. To verify whether this degradation is caused by the crosstalk or by the shot noise generated in the receiver due to the high optical level of the crosstalk signal, BER characteristics for analog crosstalk of −2 dBc were measured with and without RF modulation of the analog source. The results of these tests are plotted in Figure 5.

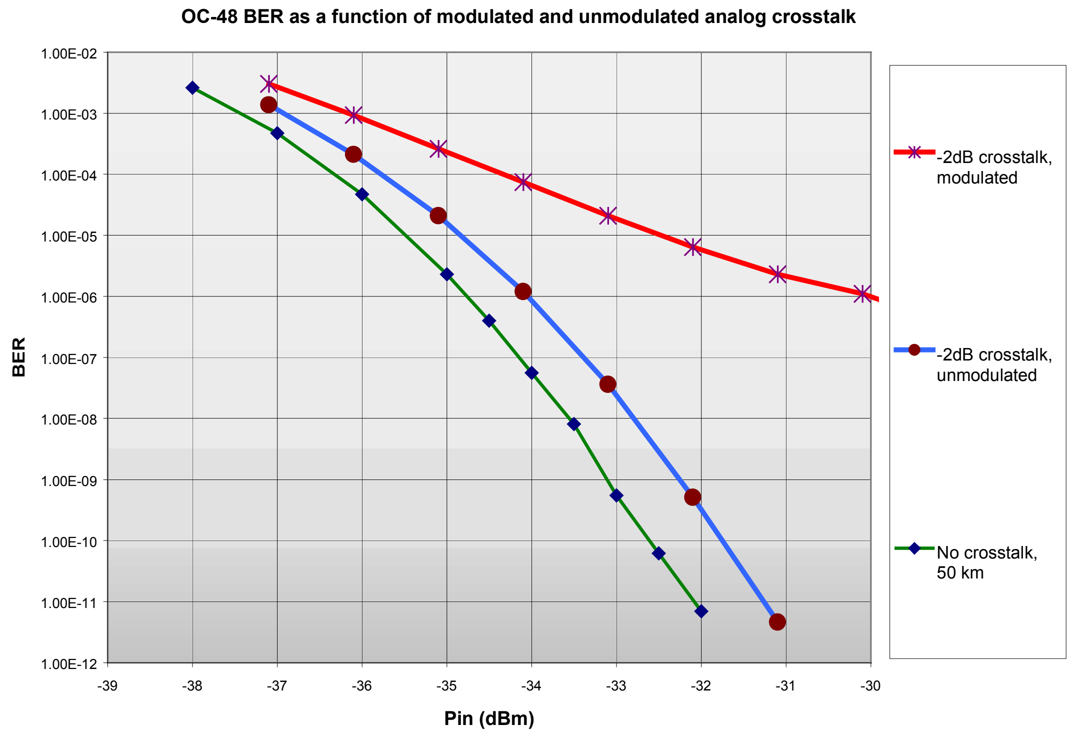

Figure 5: Comparison of BER Degradation Caused by Shot Noise and by RF Interference

The two BER characteristics on the far right correspond to the same average optical crosstalk of –2 dBc; however, in one case the crosstalk signal is modulated while in the other case it is not. The BER characteristic when no crosstalk is present is also included for comparison. Examining the BER characteristic for the case where the optical crosstalk is unmodulated shows that a crosstalk level of –2 dBc is high enough for the shot noise generated by this light level to cause a power penalty of almost 1 dB. However, this is insignificant in comparison to the degradation resulting from the overlap of the digital and analog spectra in the case when the crosstalk light is modulated.

Similar tests with an OC-12 signal showed slightly lower BER degradation resulting from analog crosstalk. This is understandable since there is less overlap between the analog and digital spectra in this case. Therefore, only the OC-48 results were considered in determining DWDM component requirements.

Based on the test results presented in Figure 4, the acceptable total analog crosstalk should be less than –10 dBc. At this level of crosstalk, the digital power penalty is lower than 0.1 dB. While digital systems can tolerate much higher levels of crosstalk than analog systems (–10 dBc versus –37 dBc respectively), they actually pose a greater design challenge. This is due to the fact that the analog receiver sensitivities are much worse than the digital receiver sensitivities (typically 0 dBm and –30 dBm, respectively). Typically, the analog channel is at 0 dBm and the digital signal is at –30 dBm at the output of a demultiplexer. In order to meet the requirement for the total analog crosstalk to be lower than –10 dBc, a DWDM demultiplexer with 40 dB of total isolation from all wavelengths with analog load is required. Such a requirement will result in a substantial premium for these passives. Alternatively, the channels adjacent to the digital channels could be left empty. Either alternative would incur a cost penalty.

In systems with higher levels of digital signals (a more typical situation), it is possible to use demultiplexers with an isolation of 30 dB and still obtain a total analog crosstalk lower than –10 dBc by using optical attenuators in the digital paths prior to the multiplexer. The objective is to maintain the optical delta between adjacent digital and analog channels of no higher than 20 dB just prior to the demultiplexer. An optical delta lower than 20 dB and a demultiplexer with total isolation of 30 dB will ensure that the total analog crosstalk is lower than –10 dBc. As previously, there are no special requirements for the DWDM multiplexer.

EFFECTS OF DIGITAL CROSSTALK IN UNI-DIRECTIONAL AND BI-DIRECTIONAL SONET SYSTEMS

The digital systems could tolerate analog crosstalk as high as –10 dBc while suffering a power penalty lower than 0.2 dB. However, they are more sensitive to digital crosstalk. The reason is that, to avoid laser clipping, the optical modulation index (OMI) of subcarrier multiplexed analog systems are much lower than OMI of digital systems. For example, the composite OMI for an analog system is typically 30% (peak) while the OMI for SONET systems is about 90% (corresponding to an extinction ratio of approximately –10 log (5%) = 13 dB). This ratio of three between the OMIs should theoretically translate into a 5 dB increase in crosstalk sensitivity.

A controlled amount of OC-12 signal was optically combined with an OC-48 signal and transported over 50 km of singlemode fiber to an OC-48 receiver. As in the previous section, BER characteristics were measured for different levels of crosstalk. In contrast to the previous experiments, however, it was not the relative optical crosstalk in dB that was maintained constant for each BER characteristic, but the absolute level of the crosstalk, in dBm. This was done to test a hypothesis that the BER degradation depended on the absolute level of the crosstalk in dBm rather than on the relative optical crosstalk in dBc.

The BER characteristics for crosstalk levels between –60 dBm and –35 dBm are presented in Figure 6. No evidence of the existence of some critical absolute value of crosstalk above which the BER degrades suddenly was discovered. The crosstalk of –45 dBm at the signal level of –30 dBm results in power penalty of less than 0.1 dB. That is, a relative crosstalk of –15 dBc results in a power penalty lower than 0.1 dB for a receiver input level of –30 dBm. At higher input optical levels, the relative crosstalk levels that can be tolerated are higher. This can be ascertained by noting that the horizontal shifts of the BER characteristics are lower than 5 dB if the crosstalk is increased from –45 dBm to –40 dBm or from –40 dBm to –35 dBm. The –15 dBc threshold is used as an acceptable level of digital crosstalk. This is 5 dB lower than the acceptable level of analog crosstalk and agrees with the prediction based on the fact that the OMI for digital system is approximately 5 dB higher than the OMI for analog systems.

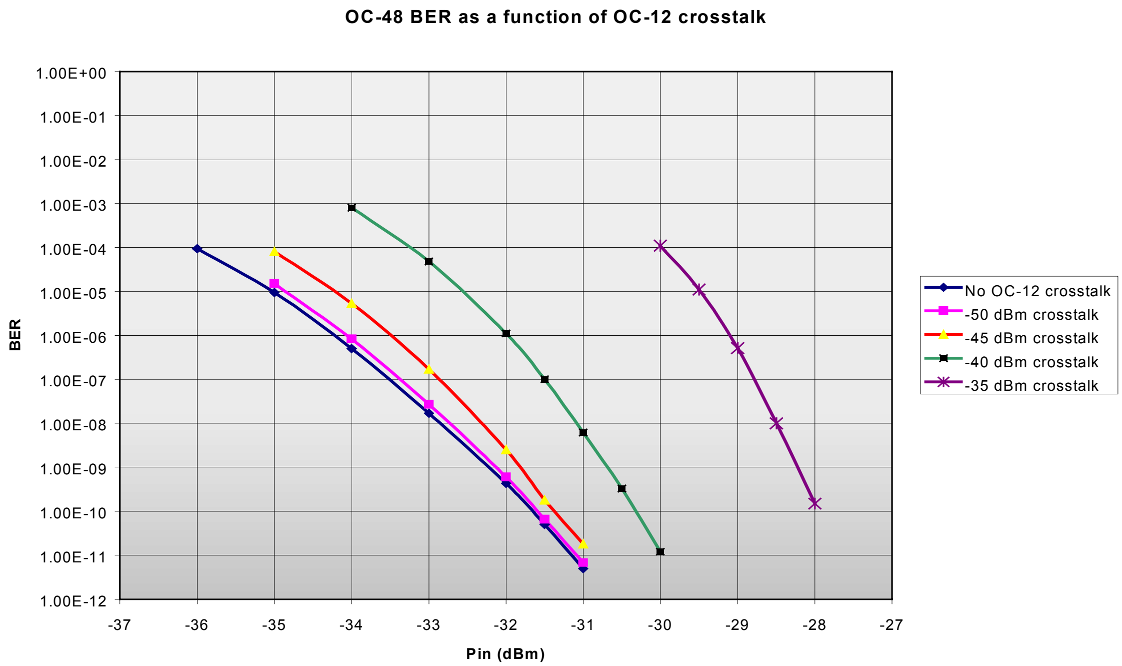

Figure 6: OC-48 BER Characteristics for Different levels of OC-12 Crosstalk

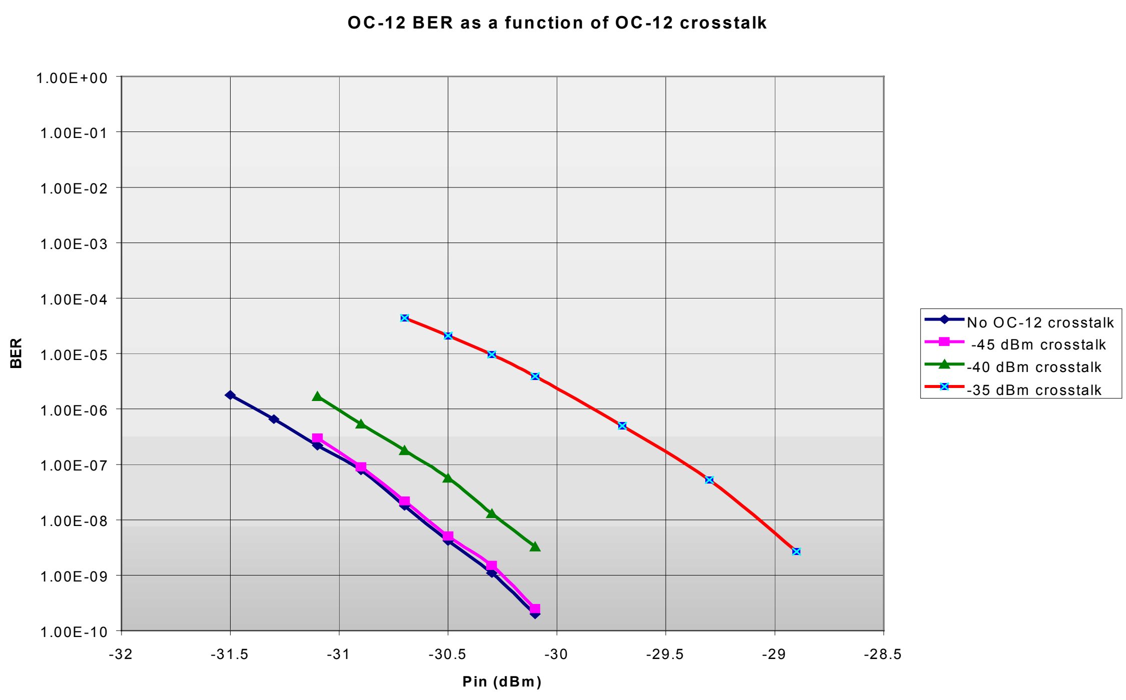

Figure 7: OC-12 BER Characteristics for Different Levels of OC-12 Crosstalk

These tests were repeated to verify the effect of OC-12 crosstalk on another, independently clocked OC-12 system. The results are presented in Figure 7.

The results indicate that a crosstalk of −15 dBc is still sufficiently low to ensure a power penalty lower than 0.1 dB, even when the crosstalk is from a source with the same SONET rate as the signal. The −15 dBc crosstalk requirement has implications for both the directivity and isolation of DWDM passives in bi-directional SONET systems. A bi-directional system has both transmitters and receivers attached to the DWDM mux/demux at the two ends of the system; thus the mux and demux must have identical specifications. This is in contrast to a uni-directional system where only the demux specifications are of concern in relation to crosstalk penalty and the directivity of the multiplexers is the same as the optical return loss (ORL) requirement of 50 dB. The –15 dBc crosstalk requirement also has implications for the isolation required of DWDM demultiplexers in uni-directional SONET systems.

The allowed amount of coupled light from a strong transmitter back to a port where a receiver is detecting a low light signal can exceed the –15 dBc crosstalk requirement. Assuming the worst case scenario of a +10 dBm transmitter and a receiver with a –30 dBm input signal, the directivity of the mux/demux has to be at least 55 dB to keep the crosstalk from the transmitter to the receiver below –15 dBc. This is only slightly higher than the 50 dB directivity of standard (inexpensive) demultiplexers.

The isolation requirements for the DWDM demux depend on the range of received power levels. Since the optical attenuation is approximately equal for all of the wavelengths and the range of transmit powers are fairly well standardized, it can be assumed that the difference between the strongest and weakest received signal is no higher than 15 dB. Consequently, a total isolation specification of 30 dB is the minimum required to ensure that crosstalk at the receive end is lower than –15 dBc. In order to provide a safety margin, and allow for more stringent requirements for future OC-192 systems, a minimal demultiplexer isolation of 35 dB for both bi-directional and uni-directional applications is recommended.

OC-192 CROSSTALK REQUIREMENTS

For the same optical power, the spectral density of an OC-192 signal is lower (at low frequencies) than the spectral densities of either an OC-48 or OC-12 signal. Consequently, the effect of OC-192 crosstalk on analog systems will be less severe than OC-48 or OC-12 crosstalk. It was shown previously that analog crosstalk affected OC-48 systems more than OC-12 systems. This was explained by the fact that the Nyquist filter in an OC-48 receiver allows more analog crosstalk to pass through than an OC-12 receiver. However, this trend does not continue to OC-192 systems. Since the analog bandwidth is at most 860 MHz and both the OC-48 and OC-192 filters have cutoff frequencies well above this, the effect of analog crosstalk on OC-192 systems should be similar to that on OC-48 systems. Based on previous results indicating that the effects of digital crosstalk on the BER is explained by treating the crosstalk as a noise floor, it is also expected that OC-192 crosstalk of –15 dB or less will have a negligible affect on other digital systems.

It is expected, therefore, that DWDM mux/demux requirements will be unchanged for OC-192 systems. The results of OC-192 experiments to verify these predictions will be presented at the NCTA conference.

SUMMARY OF DWDM MULTIPLEXER/DEMULTIPLEXER REQUIREMENTS

In uni-directional DWDM systems transporting both analog and digital signals, the DWDM mux should have directivity higher than 50 dB and the DWDM demux should have total isolation higher than 30 dB. The optical delta between the analog and digital signals in these systems must be maintained higher than 10 dB (to prevent degradation of the analog signals due to digital crosstalk) but lower than 20 dB (to prevent degradation of the digital signals due to analog crosstalk). This can be achieved by inserting optical attenuators in the path of the digital signals at the mux end, and at the demux end if necessary to bring the received signals within the dynamic range of the receivers.

In uni-directional and bi-directional DWDM systems transporting OC-12 and OC-48 signals, the DWDM demux (and mux in bi-directional systems) should have total isolation higher than 35 dB. Moreover, in bi-directional DWDM systems transporting OC-12 and OC-48 signals, the mux/demux should have a minimum directivity of 55 dB and a minimal total isolation of 35 dB. The maximum transmitted power in the bi-directional systems should be lower than +10 dBm and the maximum spread of received signals in both bi-directional and uni-directional systems should be lower than 15 dB.

In order to avoid problems arising from XPM and PDL, it is also recommended that the maximal transmission slope of a de-multiplexer be lower than 0.1 dB/GHz within the passband, and that the PDL be lower than 0.5 dB.

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[2] M. R. Philips and D. M. Ott, "Crosstalk in cable-TV WDM systems", Integrated Communications Design Magazine, pp32-36, September, 2000.