Hybrid Wavelength-Division-Multiplexing Systems for High-Capacity Digital and Analog Video Trunking Applications

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***Abstract*— A five-channel hybrid wavelength-division-multiplexing (WDM) system with one AM-VSB channel and four 2.5-Gb/s channels was demonstrated for video trunking and distribution applications. Two erbium-doped fiber amplifiers (EDFA's) with saturated output power of +13 dBm were used for a standard single mode fiber span of 100 km. Error-free transmission for the digital channels and a carrier-to-noise ratio (CNR) higher than 50 dB for the AM-VSB channel could be achieved simultaneously.**

***Index Terms*— Hybrid wavelength-division multiplexing (WDM), video trunking.**

I. Introduction

HIGH-DENSITY wavelength-division multiplexing (WDM) can fully utilize the optical fiber bandwidth and increase the capacity of the fiber link. Most WDM systems distribute homogeneous traffic, for example, all channels transmit OC-48 (2.5 Gb/s) signal or OC-192 (10 Gb/s) signal. Ideally, a WDM optical channel is transparent to signal format, data rate, and transmission protocol. In practice, different signal formats require different sensitivity for a given quality of service, for example, around 0 dBm for AM-VSB subcarrier multiplexing (SCM) signal and about −30 dBm for an OC-48 signal. The implementation of hybrid WDM systems with different signal formats is still a challenge, especially for long-distance applications using optical amplifiers. In the trunking and distribution of cable-TV signals, although the signal can be always digitized with or without video compression and transmitted by baseband digital scheme, it is advantageous to distribute the traditional analog AM-VSB or digital quadrature amplitude modulator (QAM) signal in the fiber backbone such that no complicated signal conversion is required in the cable head-end. Hybrid WDM system with heterogeneous traffic is a natural choice to distribute both analog SCM signals and baseband digital signals simultaneously.

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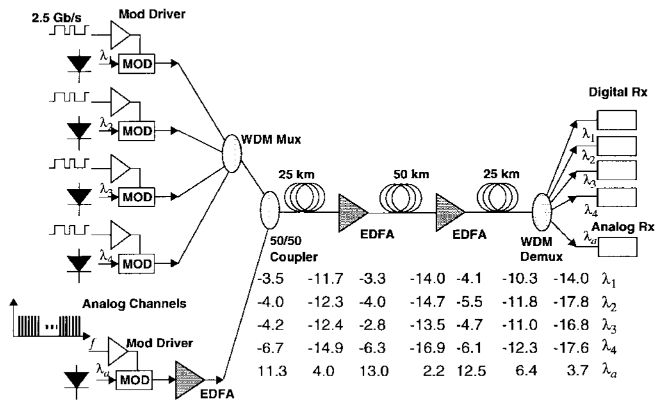


Fig. 1. Experimental setup for the five-channel hybrid WDM system for a fiber span of 100 km.

Hybrid WDM systems have been studied previously [1]–[5] with FM-TV and OC-12 [1], AM-VSB and PCM-video [2], AM-TV and 622-Mb/s B-ISDN signal [3] (WDM in 1310 nm and 1550 nm), QAM-SCM and OC-48/192 [4]. This work demonstrates a hybrid WDM system with four digital 2.5-Gb/s channels and one AM-VSB SCM channel for a fiber span of 100 km. The digital channel can transmit PCM video, SONET traffic, ATM cells, etc.

This hybrid system will be very useful for both cable-TV and telecommunication industries in combined digital and analog trunking [6]. The same technology can also be employed to upgrade existing 1550-nm AM-VSB trunking lines for additional high-capacity digital transport. Due to its flexibility and upgradability, the hybrid WDM systems can serve both hybrid fiber/coaxial (HFC) and fiber-to-the-curb (FTTC) broad-band access networks. If the system is currently deployed to support HFC system, it may upgrade to support other future broadband local access architectures.

II. Experiments

Fig. 1 shows the experimental setup of the hybrid WDM system for a span of 100 km. Both WDM multiplexer and demultiplexer (MUX) are multilayer interference-filter-based devices having 1.6 nm (or 200 GHz) of channel spacing, the

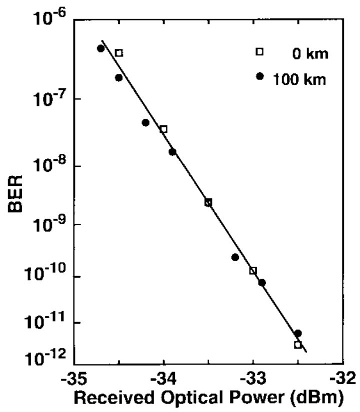
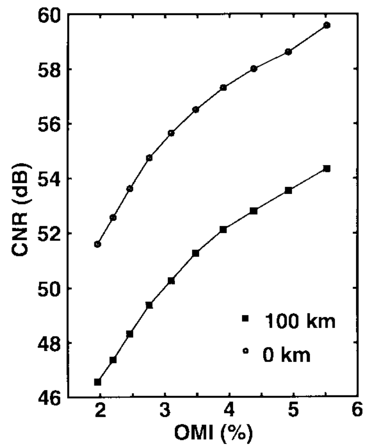


Fig. 2. Performance of the 2.5-Gb/s digital channel for the 100-km hybrid WDM link.

same as the ITU draft standard. The power loss of each channel at the WDM MUX is less than 6.0 dB with a variation of about 3 dB. The four externally modulated OC-48 2.5-Gb/s optical channels are from λ_1 to λ_4 with wavelengths of 1546.1, 1547.9, 1549.4, and 1550.9 nm, respectively. Although the analog channel is demultiplexed by a WDM MUX because its wavelength $\lambda_a = \lambda_9 = 1558.9$ nm is located at the passband of the ninth port, the analog channel is combined with other channels using a 50/50 coupler for smaller loss. The fifth to eighth ports are empty for future upgrades and crosstalk reduction. The analog channel is located far away from the digital channels to reduce crosstalk from the high-power analog channel.

The combined WDM signal is sent through 25 km of fiber, followed by an EDFA with output power of 13.4 dBm, another 50 km of fiber, an addition EDFA with an output power of 12.8 dBm, and a final 25 km of fiber. All fiber links use standard single-mode fiber. The power levels after the 50/50 coupler for each channel are −3.5 (λ_1), −4.0 (λ_2), −4.2 (λ_3), −6.7 (λ_4), and 11.3 dBm (λ_a). Note that the power levels of the digital channels are much smaller than the analog channel so that the digital channels have only a small effect on the EDFA gains. The power levels at each location is also shown in Fig. 1. At the receiver end, the optical powers at the demultiplexer output are −14.0 (λ_1), −17.8 (λ_2), −16.8 (λ_3), −17.6 (λ_4), and 3.7 dBm (λ_a). The total optical power after the 50/50 coupler is about 11.8 dBm, the total input to the first EDFA is about 4.4 dBm, and that to the second EDFA is about 2.5 dBm. While the high input value is required to achieve a high CNR for the AM channel [6], it limits the gains of the two EDFA's to 9 and 10.3 dB, respectively. With those low gains, the transmission distance is limited to about 100 km [6].

Figs. 2 and 3 show the performance of digital and analog channels for the 100-km WDM link. Back-to-back performance is also shown for comparison. For the digital channels, received signal levels of −33.4 dBm are needed for a bit-error rate (BER) of 10^{-9} with no penalty due to 100 km of transmission. The crosstalk level from adjacent digital channels and analog channel is also measured with an optical spectrum analyzer. Because the crosstalk level is less than −30 dB, no penalty is observed due to crosstalk from either digital or analog channel. Further measurements using a digital transmitter equipped with a tunable laser show that the digital channel can be brought closer to the analog channel with no crosstalk induced penalty as long as the wavelength separation is larger than 400 GHz. The 400-GHz separation is independent of input signal power at EDFA and number of EDFA stages, but depends on the optical power difference of the analog and digital channels.



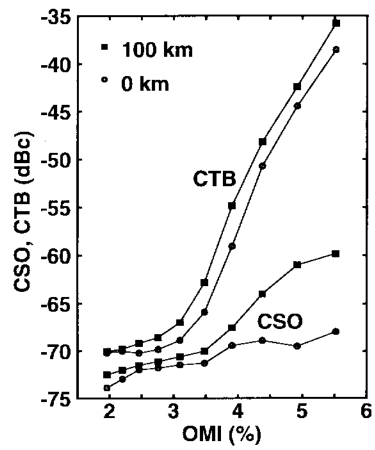


Fig. 3. CNR, CSO, and CTB as function of the optical modulation index of the analog channel for the 100-km hybrid WDM link.

The analog channel has 80 AM-VSB channels simulated by tones generated by a matrix generator. For the AM channel, at an optical modulation index (OMI) of 3.1%, a CNR larger than 50 dB can be obtained at the end of the WDM link with both CSO and CTB less than −65 dBc. The 100 km of transmission induces a penalty of about 5 dB on the CNR of the analog channel, mostly due to noise from the cascaded EDFA's. Both CTB and CSO are measured in the middle channel with the highest triple-beat counts. Because CSO does not limit the system performance, although the middle channel does not have the highest second-order counts, we measure CSO there for convenience. Fig. 3 shows that the transmission system induces both CTB and CSO penalty. While the CTB penalty is about 3 dB at all OMI levels, the CSO penalty increases with OMI because the original CSO in the transmitter is very small, a small extra distortion from fiber dispersion provides large degradation in CSO. No crosstalk penalty is observed due to digital channels.

III. Conclusion

We have demonstrated a hybrid WDM system for both analog and digital trunking and distribution applications over a fiber span of 100 km. Signal levels of -33 dBm give a BER of 10^{-9} for the digital channels and an optical modulation index of 3.1% provides more than 50 dB CNR for the AM-VSB channel. It is found that the 100 km of transmission induces no penalty for the four WDM digital channels and about 5-dB penalty on the CNR of the AM-VSB channel.

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