Multiwavelength Analog Video Transport Network

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Abstract

We report an experimental 8-channel dense wavelength division multiplexed 1550-nm analog video transmission using directly modulated lasers over 40 km of standard fiber, through two cascaded Erbium-Doped Fiber Amplifiers with adequate carrier-to-noise and distortion performance. Multiwavelength analog video transport networks provide an end-to-end transparent information pipe with increased service penetration.

I. INTRODUCTION

Progress in 1550-nm linear fiber optic technology is continuing to move forward rapidly. Long-distance fiber transmission of broadcast channels, narrowcast (i.e., targeted) services and high-speed data are possible by increasing the channel capacity and power budget. The use of dense wavelength division multiplexing (DWDM) technology combined with Erbium-Doped Fiber Amplifiers (EDFAs) provides a simple and powerful method of increasing channel capacity in Hybrid Fiber/Coax (HFC) networks [1]. The installation of a DWDM CATV system may initially require higher capital cost. However, service upgrading will be significantly cheaper as more wavelengths are added to increase service penetration [2].

In designing a transparent DWDM analog transport network many system parameters must be considered carefully. These include transmitter source characteristics, multiplex and demultiplex optical filter requirements, fiber effects, optical amplifier performance, and optical receiver design. The fundamental issue is the accumulation of capacity limiting impairments in the optical transparent network [3]. This paper reports an experimental demonstration of eight wavelength division multiplexed 1550-nm analog lightwave system and investigates linear and nonlinear amplifier, fiber, and demultiplex optical filter effects.

II. TRADITIONAL CATV OPTICAL NETWORKS

A. Broadcast 1550-nm network:

Figure 1a shows a high-power 1550-nm CATV network. 1550-nm externally modulated transmitters combined with optical amplifiers provide 750 MHz bandwidth of broadcast services. Although the high-power 1550-nm network provides low cost broadcast services, the network is limited in that it can not deliver targeted services. Therefore, the one service it provides is shared among optical nodes (8-16 typically) with thousands of homes passed.

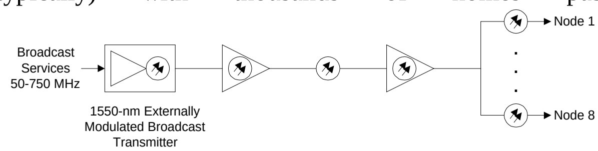

Figure 1a Schematic of a broadcast 1550-nm CATV network.

B. Scalable 1310-nm or 1550-nm network:

Figure 1b shows a scalable CATV network. The headend is composed of several directly modulated 1310-nm or externally modulated 1550-nm transmitters each carrying dedicated 750 MHz bandwidth of broadcast and targeted services on dedicated fibers. The scalable network offers future targeted service capacity expansion [4]. However, targeted service penetration is only possible by increasing dedicated fibers that run from the headend to the optical nodes.

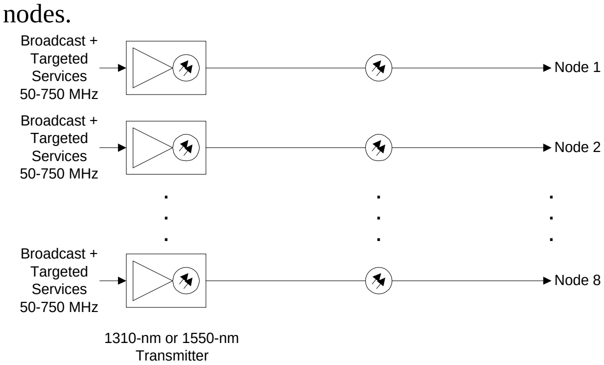

Figure 1b Schematic of a scalable 1310-nm or 1550-nm CATV network.

C. Broadcast 1550-nm and narrowcast 1310-nm overlay network:

Figure 1c shows the 1550-nm broadcast, 1310-nm narrowcast overlay CATV network. These networks place SONET interconnect equipment, service-enabling digital terminals, modulators, optoelectronic converters and 1310-nm narrowcast transmitters in a large multi-cabinet hub [5]. Low-power 1310-nm DFB laser transmitters carry targeted services in the 550-750 MHz frequency range to optical nodes. The targeted services on a 1310-nm optical carrier are overlaid on the same fiber as the broadcast services on a 1550-nm optical carrier through a WDM or coupler. Such a CATV optical network is opaque in the sense that services cannot be targeted to a particular node by routing from the headend.

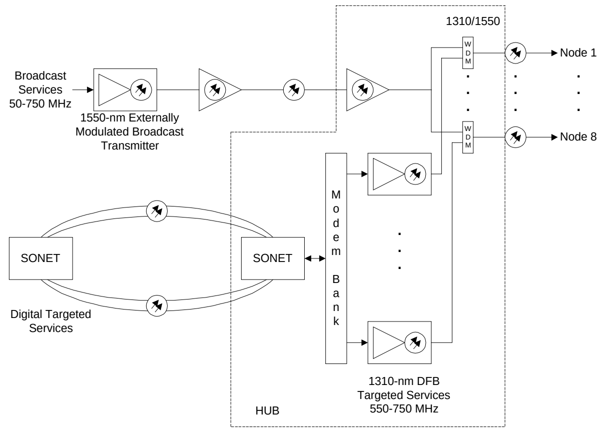

Figure 1c Broadcast 1550-nm and narrowcast 1310-nm overlay network.

III. DWDM 1550-nm CATV OPTICAL NETWORK

Figure 2 shows the DWDM CATV optical network. The headend consists of a 1550-nm broadcast transmitter transporting broadcast services through the first optical fiber and with two erbium-doped fiber amplifier cascades to the hub. A second optical fiber link combines eight narrowcast optical signal beams operating at wavelengths which follow the International Telecommunication Union (ITU) wavelength standard [6]. The combined optical beam passes through two EDFA cascades before entering to the hub. The network is flexible such that each narrowcast transmitter is capable of accepting a unique service. For capacity expansion with unique services additional transmitters operating at a different ITU wavelengths can be deployed. At the hub, the narrowcast signals are demultiplexed such that each unique service is combined with the broadcast signal and transmitted to their respective nodes.

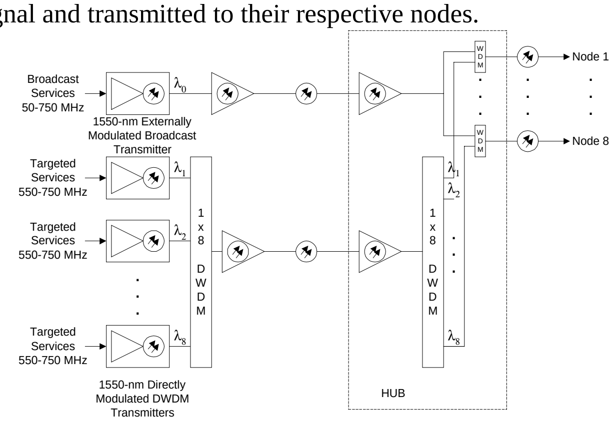

Figure 2. DWDM CATV optical transport network.

The use of DWDM technology enables electro-optical processing for targeted services to be routed from the headend rather than at the hub, as is the case shown in Fig. 1c. This network flexibility provides transparency through a much smaller hub site [5]. DWDM CATV architecture offers a cost effective solution compared to installing additional optical fiber. With DWDM system installed, the secondary hub may initially service tens of thousands of homes passed with one wavelength targeting about ten thousand homes. As service penetration is increased by adding more wavelengths, one wavelength could service much smaller home segments.

IV. TECHNICAL ISSUES

Several system parameters require consideration in designing 1550-nm DWDM CATV optical transport networks. These design and technical issues are related to transmitter source characteristics, optical amplifier performance, fiber effects, and multiplex-demultiplex optical filter performance. Amplifiers can degrade CNR by noise accumulation due to cascaded EDFAs with low input power per optical carrier and degrade distortion due to amplifier gain-slope. Fiber effects can cause distortion, crosstalk, and CNR performance degradation. Fiber effects are stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), Self phase modulation (SPM), cross-phase modulation (XPM), and chromatic dispersion (CD). Multiplex-demultiplex optical filters can also degrade performance due to crosstalk generated by adjacent channel isolation and distortion induced by non-uniform passband flatness.

A. 1550-nm transmitter source design:

Broadcast transmitter

In the design of 1550-nm analog broadcast systems, the choice of source must be an externally modulated transmitter. A 1550-nm externally modulated transmitter is attractive and offers several advantages such as very low chirp, and high power with the ability to be amplified further by optical amplifiers to service remote locations.

DWDM narrowcast transmitters

However, the CW DFB laser source, external intensity modulator, and associated electronics and RF circuitry that constitute the transmitter are altogether too expensive to be used as narrowcast transmitters. Two alternatives to an externally modulated transmitter are directly modulated DFB laser and electro-absorption modulated DFB laser (EAML) source. Current EAML sources are moderately expensive, have low output power and have very nonlinear light-electrical transfer characteristics. Directly modulated DFB laser sources are lower cost, have high output power, and have linear light-current transfer characteristics.

However, the magnitude of the laser chirp of directly modulated DFB lasers may limit the number of subcarriers to be used by each narrowcast optical channel. The operating center wavelengths of the DFB sources follow the ITU wavelength standard.

When two optical signal beams share a receiver at the node, mixing takes place. The mixing of the two optical signal beams is unavoidable and generates optical beat interference noise. To minimize optical beat interference noise between broadcast and narrowcast optical channels at the node, channel separation must be more than about 2-nm. However, actual required minimum separation depends on the optical line shape of the two optical channels.

A. Optical Amplifier effects:

Noise

If more than one optical beam is passed through the amplifier the intensity noise increases as a function of the number of optical channels M. The accumulated amplifier RIN per optical channel in an amplified DWDM analog transport system is proportional to $M \cdot F$ where F is the noise figure of the amplifier cascades in a single optical channel system. Here we have assumed that the optical power delivered by the multiple optical signal beams to each amplifier input is equal to the optical power delivered by a single optical signal beam in a single channel system. With DWDM CATV systems, to reduce the impact of noise cascades per channel we must increase the total power to the input of the amplifier.

Gain flattening

The gain of the EDFA across the waveband 1530- to 1560-nm is not flat. The need for improved flatness across the whole wavelength window is to ensure that all narrowcast optical channels are equally amplified, separated, and sent to their respective nodes. To flatten the EDFA gain profile sophisticated filter technologies are used [7]. With these enabling filter technologies it is possible to achieve a 1 dB peak-to-peak flatness over the narrowcast waveband 1540- to 1560-nm.

Gain-slope

Amplifier gain-slope coupled with laser chirp, $\Delta\lambda_{chirp}$ causes composite second-order intermodulation distortion (CSO). The amplifier gain-slope induced distortion is flat, i.e., not dependent on modulating frequencies, and is proportional to $\Delta g \cdot \Delta\lambda_{chirp}$ where Δg is overall gain-slope of the amplifier cascade. To keep distortions to an acceptable level, the magnitude of total gain-slope should be less than 0.2 dB/nm when the chirp is less than 0.0017 nm.

B. Fiber effects:

Laser phase noise to intensity conversion

As the optical signal beam travels through the fiber, fiber chromatic dispersion converts laser phase noise to intensity noise. The intensity noise is proportional to $\Delta\nu \cdot L^2 \cdot f^2$ where $\Delta\nu$ is the laser linewidth.

Stimulated Brillouin scattering

SBS is a nonlinear fiber effect that limits the amount of optical power per channel that can be launched into the fiber. In standard fiber, for narrow linewidth sources the SBS threshold at 1550-nm is 6 dBm. SBS scatters light into the backward direction and reduces received power as well as increases noise in the forward direction, thereby degrading the received CNR. The SBS launch power threshold can be increased by 10 dB (i.e., 16 dBm fiber launch power) by spreading the optical spectrum. However, to reduce fiber nonlinear effects such as SRS and XPM to an acceptable level, the launch power per optical channel in analog DWDM systems should be maintained to be less than 10 dBm.

Stimulated Raman scattering

SRS is a phenomenon similar to SBS. SRS in optical fiber is a nonlinear process that depletes the lower wavelength optical channels and amplifies the higher wavelength optical channels. In analog DWDM systems, each optical channel is intensity modulated by subcarriers. The intensity of the optical channel with the lowest wavelength modulates the intensity of optical channels at higher wavelengths. Therefore, SRS leads to crosstalk (XT) between optical channels. The magnitude of XT depends on launched power per channel, polarization of each optical signal beam, channel spacing, number of optical channels, chromatic dispersion, and fiber length. Fiber chromatic dispersion reduces the magnitude of crosstalk due to walk-off where the group velocity of adjacent channels are slightly different. For fiber distances greater than 20 km SRS crosstalk is almost fiber length independent. To reduce SRS crosstalk, the launched power per optical channel should be kept to less than 10 dBm.

Self- and cross-phase modulation

SPM is caused by the change in the optical index of refraction with intensity. The intensity dependent nonlinear index causes phase shift of the signal which is dependent on the launch power and fiber distance. XPM is similar to SPM where intensity of one optical beam modulates the phase of the other optical beam. The phase shifts combined with fiber CD causes frequency shift which introduces a relative delay as the intensity of the optical beam is modulated. The intensity modulated signal is distorted as it travels through the fiber. The distortion increase with modulating frequency.

XPM generated second-order distortion is proportional to $(2M-1)\cdot L^2\cdot f^4$ where M is the number of optical channels, L is the length of fiber and f is the frequency of modulation. Phase modulation (generated by SPM or XPM) occurs mostly within the first 20 km and becomes less dependent on fiber length at longer lengths. Frequency deviation (generated by SPM or XPM and CD interaction) increases as a function of fiber length. When amplifiers are cascaded, after each amplifier the power of the optical signal beam is at its highest before launched into the fiber. In amplifier-fiber cascades, to reduce distortion, XPM and SPM must be kept to a minimum by launching low powers into the fiber.

Chromatic dispersion

When fiber chromatic dispersion is combined with laser chirp, frequency deviation is converted to intensity modulation. The product of the induced intensity modulation and the original intensity modulation generates distortion. The intensity modulated optical signal is distorted as it travels through the fiber, and the distortion increases with fiber length and modulation frequency. Chirp-dispersion induced second-order distortion is proportional to $\Delta\lambda^2_{chirp}\cdot L^2\cdot f^2$ where $\Delta\lambda_{chirp}$ is the laser chirp, L is the length of fiber and f is the frequency of modulation. To eliminate CSO distortion products falling within the broadcast band, narrowcast channels can be arranged to occupy frequency bands such that CSO distortion products fall out-off band (OOB). Other methods are also being considered to reduce CSO and CTB distortion generated by laser chirp combined with fiber CD.

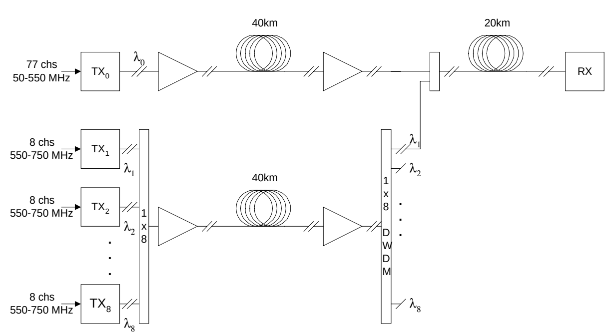

Figure 3. Experimental set-up of a DWDM 1550-nm analog lightwave transmission system.

V. EXPERIMENTAL DWDM SYSTEM

Figure 3 illustrates the experimental DWDM system configuration. The system consists of a broadcast transmitter operating at 1544.54-nm with an output power of 7 dBm and a RIN of less than -164 dB/Hz. The broadcast transmitter is modulated by 77 NTSC channels. The eight narrowcast transmitters operate at 200 GHz spacing, with the lowest wavelength laser operating at 1549.32-nm. The narrowcast transmitters are modulated by 8 channels spaced consecutively above the broadcast channels. The output signal power of each narrowcast transmitters is adjusted to 10 dBm. The transmitters have relatively low RIN of less than -160 dB/Hz and linewidth of about 2 MHz. The eight narrowcast optical carriers are modulated by eight analog channels. Figure 4. shows the optical spectrum of the DWDM narrowcast channels after being combined at the headend. The wavelength of the broadcast channel is about 5-nm below the lowest wavelength narrowcast channel. Broadcast and narrowcast optical channels are transmitted through separate dedicated fibers of 40 km length (see Fig. 3). At the end of the 40 km narrowcast fiber link a dielectric filter type demultiplexer is used to separate the eight wavelengths at the hub. One of the narrowcast wavelengths is combined with the broadcast wavelength and launched through 20 km of standard fiber. The broadcast and narrowcast optical channels are then mixed on a single optical receiver.

TABLE I

Measured CNR and Distortion Performance of Broadcast and Narrowcast (1550.92-nm) Optical Channels mixed on a Single Receiver.

Frequency	Broadcast Band			Narrowcast Band		
(MHz)	CNR	CTB	CSO	CNR	CTB	XT
61.25	51.2	66.8	66.1			
211.25	51.9	68.4	67.4			
319.25	51.3	67.0	68.9			
445.25	51.3	66.7	67.0			
547.25	52.0	57.2	66.5			
553.25				41.4	50.2	
577.25				40.8	47.2	
595.25				41.6	46.5	55*

* XT is measured at 598 MHz.

Table I shows a summary of the experimental results. The received optical power for the broadcast and narrowcast optical signals were 2.0 and -8.0 dBm, respectively. The RF level difference was about 10 dB. The SRS and optical filter induced XT is measured to be about -55.0 dBc at 1550.92-nm. Polarization controllers were used on four narrowcast transmitters to measure worst case XT numbers. We have observed that the narrowcast OOB CTB distortion degrades the broadcast channel CTB performance at frequencies 545.25 and 547.25 MHz. Conversely, the broadcast OOB CTB distortion degrades the narrowcast CTB performance at frequencies 553.25 to 595.25 MHz. Narrowcast OOB CSO distortion products were below 54 MHz.

VI. CONCLUSIONS

These architecture feasibility tests demonstrated the enhanced narrowcast capability that DWDM can add to the more conventional 1550-nm broadcast network. Excellent 77 channel analog AM-VSB transmission performance from the head end, through the hub, to the node was observed. The carrier-to-noise ratio and distortion performance of the narrowcast channels permit transmission of at least 8 digitally modulated RF subcarriers to carry targeted forward path services such as cable telephony and cable modem. The transparency of the DWDM approach allows the targeting of a service to a particular node only, it does not require routing activities at the head end and none at the hub site.

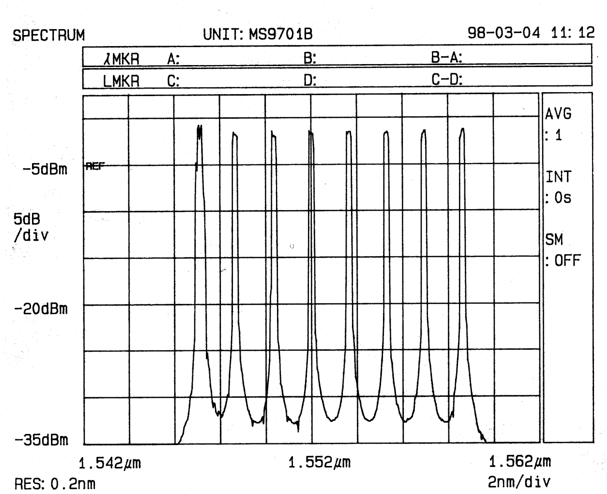

Figure 4. Spectrum of eight wavelength division multiplexed narrowcast optical signal beams.

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