AM Lightwave Technology

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The rapid evolution of lightwave transmission systems, from the early 45-megabit-per-second FT-3 to the present 2.4-gigabit-per-second FT-2000, took place during a period in which telephone networks have added only digital capacity. As a result, the primary applications for lightwave transmission technology, and the infrastructure required to support it, have been almost entirely digital. The applicability of available lightwave technology to CATV systems is not obvious. In this paper, we compare broadband analog systems to available digital technology, focusing on critical parameters for each application. We report on the significant improvements in electronic and media components that are part of a working AM broadband system, and on the architectural flexibilities that result from having broadband analog as well as high-speed digital facilities available for future lightwave system architectures.

Introduction

Fiber-optic cable, an ideal medium for long-haul digital transmission, has made the digital network of the 1980s possible. The most recent step in this digital evolution, the mass deployment of single-mode cable and the availability of distributed feedback (DFB) lasers, has opened a new application: broadband analog networks. (See Panel 1 for definitions of abbreviations, acronyms, and terms.) The most widely deployed analog networks today are operated for cable television (CATV) systems. From a small start in 1988, today's AM lightwave applications in CATV are the foundation of next-generation broadband distribution networks. The rapid evolution of lightwave transmission technology used for telephony and data transmission is stimulated by two significant factors: large demand and well-established, cost-effective interfaces. The availability of advanced information age services creates the demand for increased caller volumes and more sophisticated business and consumer data transmission. As network capabilities increase and costs continue to drop in real dollars, customer interest in new applications and services "creates" the need for expanded facilities.

For transmission technologists, the impact of interface efficiency is subtle and often overlooked. Human hearing is still an analog process, and the most common customer interface—the telephone—is analog as well. Analog signals are converted to digital signals by low-cost, high-performance analog to digital (A/D) and digital to analog (D/A) coder/decoder (CODEC) devices. Early CODEC applications required several large circuit packs. They were also difficult to manufacture and practical only for use in central offices. Over the years, advances in silicon integrated circuit technology have significantly improved the performance and availability of CODECs. In many cases, CODECs are function cells that designers of application-specific integrated circuits (ASICs) can select from design libraries, just as they would select memory or complex digital logic functions. End-to-end digital connectivity is more flexible in network routing and switching, since the degradations that are inherent in cascaded analog connections are eliminated. This flexibility has stimulated the development of many new telecommunications services that consumers now demand from their service providers.

There are well over 90 million television sets in North American, and about 15 million are being added each year. Currently, at least 55 percent of these receive their primary signal from coaxial cable broadband networks, known originally as community antenna television (CATV), and currently as cable TV. The demand for new video services continually challenges suppliers of transmission technology to expand the bandwidth and performance of these coaxial networks. The components and subsystems of these coaxial systems can operate at up to 1 gigahertz (GHz); however, the practical limit for domestic U. S. networks is between 550 and 600 megahertz (MHz), limited by the need for long amplifier cascades. (Long amplifier cascades are long [distance] strings of amplifiers.)

Single-mode fiber-optic cable, now the dominant medium for high-capacity transmission in the AT&T network, has characteristics important to the broadband industry, which include low cost, robust cable designs, extremely low signal loss, and high bandwidth.

However, digital applications have spurred the development of fiber technology. At present, no simple, economical interface exists for delivering entertainment video over digital networks. To meet this need, AT&T has developed Laser Link, an analog electro-optical interface technology. (Laser Link, developed by AT&T Bell Laboratories, is a trademark of Anixter Cable TV.) AM fiber has opened significant new market opportunities for broadband service to the home.

Broadband Systems Architecture

Current systems architecture is the key to understanding the applications of AM fiber-optic technology.

The Source Signal. In the U. S. today, video is delivered to home television sets using an analog-encoding system known as NTSC, developed by the National Television System Committee and finalized in 1953. The committee succeeded in upgrading the previous black-and-white transmission standard to make color broadcasts compatible with the existing black-and-white sets, while allowing for the inevitable changes that would come. The composite signal spectrum, shown in Figure 1, includes the luminance (brightness), or picture signal, the chroma (color) signal on a separate subcarrier, and a monaural audio channel added as a frequency-modulated (FM) subcarrier.

Delivery Systems Architecture. Broadcasters first delivered video using over-the-air transmission from high-power transmitting stations by frequency shifting the analog signal spectrum of Figure 1 into a channel, or band of spectrum, assigned by the Federal Communications Commission (FCC). Initially, thirteen 6-MHz channels were allocated in the VHF frequency band between 54 and 216 MHz. Later, as the need for more channels developed, the FCC allocated them in the UHF frequency band between 470 and 806 MHz. For both VHF and UHF channels, the analog signal is delivered using vestigial sideband (VSB) modulation, which provides the optimum balance between transmission efficiency and cost of implementation in the consumers' television sets.

Back to Basics—AM Transmission Technology

The signals transported on AM broadband links are fundamentally different from those encountered in classical digital telephony. As component and system providers, research organizations in AT&T Microelectronics, AT&T Network Systems, AT&T Network Cable
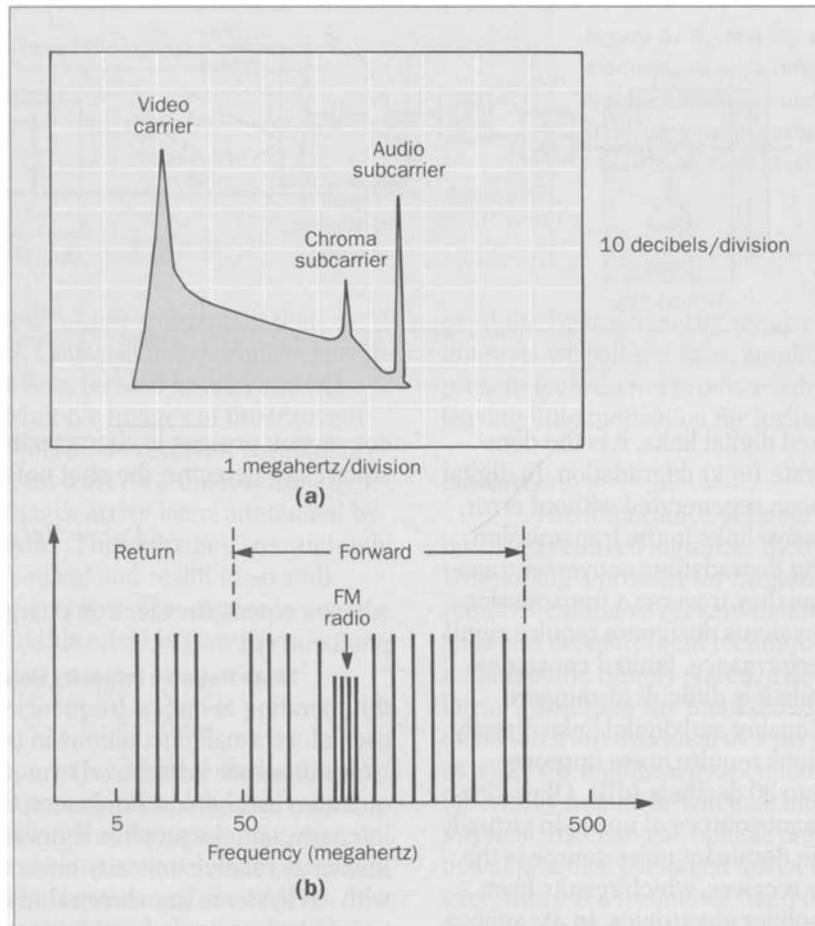
Figure 1. (a) Analog spectrum for television transmission. This is what the tuner expects from the antenna [broadcast (off-air) or cable]. (b) Typical broadband frequency plan for CATV system. Each "carrier" line represents a video carrier, as in Figure 1a. This interface between multiple television channels on cable and the television set is very economical.

Systems, and AT&T Bell Laboratories have invested heavily in developing both a theoretical[1] and working[2] understanding of the critical parameters that affect performance as viewed by the end user. Not surprisingly, several parameters that are of only secondary importance in traditionally baseband digital applications are of prime importance in the design of AM links.

Figure 2 shows a simplified model of the significant parameters that determine performance in AM systems.

Noise and Distortion in Analog Systems

The CATV network designer treats the fiber-optic link as an amplifier whose output is separated from its input by several kilometers of fiber. For system designs, the AM link becomes one "amplifier" in a cascade, or serial connection, of many amplifiers. While many

parameters are important, noise figure (NF) and linearity are dominant.

Network engineering of concatenated analog facilities is part of the heritage of telephony that has been nearly lost to the digital transmission revolution in both copper and fiber media. The L-carrier coaxial system, developed by AT&T, was a widely used analog transmission system that, in the past few years, has been made obsolete by digital fiber-optic technology. Some transmission engineers may remember it; Reference 3 offers some background.

Noise

The addition of noise to a transmitted signal, commonly referred to as reducing the signal-to-noise (S/N) ratio, is often the performance parameter that determines the design of both analog and digital

Figure 2. A typical fiber and coaxial cable architecture. Compatible signaling on the fiber results in an economical fiber-cable interface close to the subscriber.
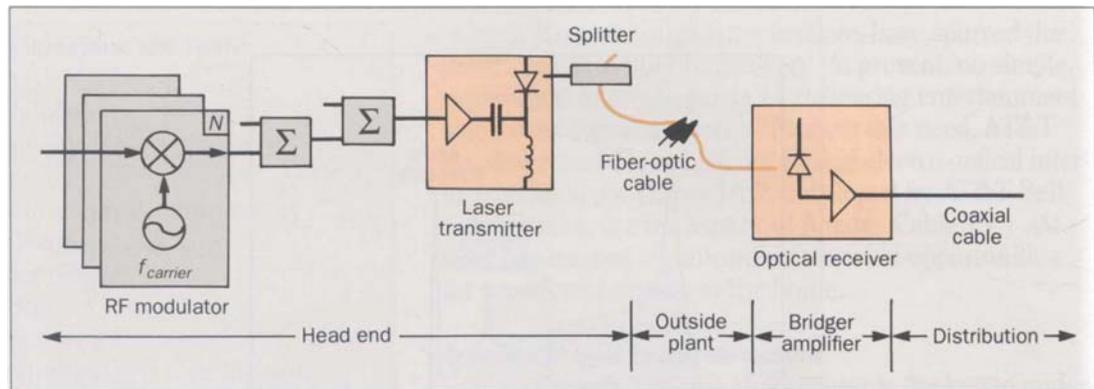
facilities. For well-designed digital links, it is the dominant source of bit error rate (BER) degradation. In digital systems, after a bit has been regenerated without error, it propagates over successive links in the transmission path without accumulating degradation; conversely, analog signals gather noise as they traverse a transmission facility. To compensate, systems designers require significantly higher per-link performance, limited concatenation lengths, or both. While it is difficult to compare required performance in analog and digital links directly, in general, CATV applications require noise improvements on the order of 20 to 30 decibels (dB). Of particular interest are the dominant sources of noise. In virtually all digital applications, the dominant noise source is the noise performance of the receiver, which results from thermal effects in the amplifier electronics. In AM applications, significant noise sources are:

- Shot noise
- Laser intensity noise
- Interferometric noise
- Front-end noise.

In the discussions that follow, we will see that shot noise and laser intensity noise, caused both by the laser device itself and the interaction between the laser's optical spectrum and the transmission media, dominate the noise performance in AM applications. These contributors are seldom significant in typical digital system applications.

Shot Noise. Quantum, or shot, noise in the receiver stems from the quantum mechanical process of photon (light) absorption and conversion to electron or current flow in the detector diode. It resembles quantization noise in analog-to-digital conversion systems, in that the light-to-current conversion occurs in discrete steps, determined by the amount of photon energy the conversion system receives. Energy lost in this discrete

conversion process is characterized as noise. In an ideal square law detector, the shot noise is given by:

$$<I>^2 = 2eI_p \frac{A^2}{Hz} \qquad (1)$$

where e equals the electron charge and I_p is the detected photocurrent.

Laser Relative Intensity Noise. A laser is an oscillator operating at optical frequencies. As with electronic oscillators, small fluctuations in the amplitude of the oscillator output are introduced by non-ideal fabrication and by quantum mechanics. For lasers, the amplitude is termed intensity, and the amplitude noise of a real-world device is known as relative intensity noise (RIN). Our experience with AM systems has shown that only carefully manufactured DFB lasers can meet system noise objectives. For comparison, both Fabry-Perot (FP) structure multimode lasers and DFBs, used in popular 100- to 600-megabit-per-second digital applications, typically operate with RIN performance of –110 to –120 dB/Hz. The minimum RIN useful in AM applications is three to four orders of magnitude lower, –150 dB/Hz, or lower. Most lasers currently used in AM applications exhibit performance lower than –155 dB/Hz, with RIN as a secondary contributor. Consistently achieving low levels of RIN requires optimum chip design, fabrication, and packaging processes. Optical power reflected back to the laser device can be a significant contribution to such noise and must be kept at least 55 dB below the laser output level. Since the return loss from a normal fiber is about –30 dB, the output of the laser device requires an optical isolator.

Interferometric Noise. Reflections in optical components such as splices and couplers, caused by index of refraction differences between materials and imperfect surfaces, and even the intrinsic Rayleigh backscatter in
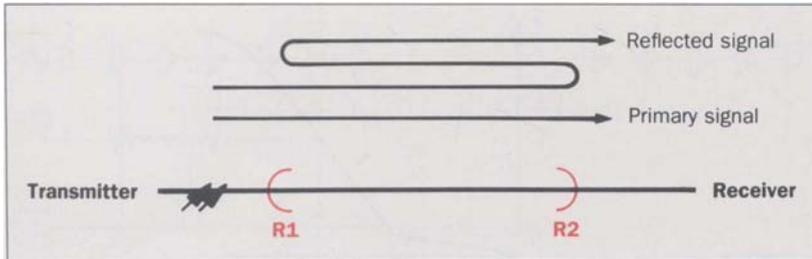
Figure 3. R_1 and R_2 are reflections. They can be discrete, as with reflections caused by connectors or splices, or distributed, as in fiber physics (Rayleigh backscatter). The latter defines a "floor," or asymptotic level of performance.

the fiber itself, introduce a system impairment that appears at the receiver as Gaussian noise. Figure 3 gives a graphical view of this effect, termed interferometric intensity noise (IIN).[4,5] Multiple images of the transmitted signal arrive at the photodiode receiver, combining with the primary image that traversed the low-loss fiber. The multiple reflected images arrive later, attenuated by the concatenated reflections. These images are randomly correlated with the main signal and result in an additional noise source at the receiver. The carrier-to-noise ratio (CNR) resulting from this effect is given by:

$$CNR = \frac{\sqrt{2}\,\pi}{8}\ \frac{m^2}{R_1 R_2}\ \frac{B_{1/2}}{N_{BW}} \qquad (2)$$

In Equation 2, R_1 and R_2 are the effective forward and back reflectances in the transmission path, as shown in Figure 3. $B_{1/2}$ is the half-width of the optical spectrum and N_{BW} is the noise bandwidth of the channel, by which convention for NTSC video measurements is 4 MHz. Acknowledging the potential degradations caused by reflections in AM and high-speed digital systems, several vendors of optical components have made components available with return loss values far lower than –40 dB, which makes their contribution to CNR degradation caused by this phenomenon insignificant. Rayleigh backscatter, however, is unavoidable and asymptotically approaches –30 dB as a function of fiber loss. Its contribution, via Equation 2, will be combined with other contributions in the discussion on controlling parameters.

Front-End Noise. Typically, receiver noise performance for AM and digital lightwave systems is given in terms of an equivalent input noise current at the input to an "ideal" amplifier. The noise current and signal current are then added to form the total input current. The performance of these amplifier devices, which must be flat and linear from 10 to 600+ MHz, typically is 8 to 15 pA/$\sqrt{(Hz)}^{1/2}$. Although high-performance transimpedance designs with less than 4 pA/$\sqrt{(Hz)}^{1/2}$ are available for digital applications, these amplifiers generally fail to

meet the typical linearity requirements for AM applications. As we will see later, amplifiers performing at the present level do not produce a dominant noise source, leaving little motivation for further improvement.

Linearity

The importance of linearity in active circuits has been reduced significantly by the digital revolution. Developing a product for broadband AM applications requires extensive reexamination of the important criteria and measurement techniques, both for design and manufacture. Simply stated, a device or subsystem is linear if doubling the input *exactly* doubles the output. A deviation from this ideal of 1 percent would be measured as a –20 dB nonlinearity. Semiconductor lasers are inherently nonlinear when all interactions among the physical, mechanical, optical, and electrical characteristics of practical packaged devices are considered. However, there is a frequency band of interest for CATV applications in which state-of-the-art DFB lasers can meet extremely stringent cost and performance criteria. Looked at broadly, laser devices have several inherent nonlinearities. The applications described in this paper fall in a region of operation where the nonlinearities can be avoided or changed. Considered this way, typical CATV applications require linearity of about –70 to –90 dB. While developing the Laser Link system, we found three dominant contributors to system nonlinearity:

- Device (laser, detector) nonlinearity caused by device imperfections, leakage paths, and non-ohmic interconnections
- Fundamental limits on modulation depth, owing to device constraints
- Complex interactions among optical reflections, nonideal (real-world) waveguide phenomena (subject to fabrication perturbations and installation effects), and nonideal device behavior, which affect time-domain characteristics of the transmission channel, and, in turn, result in nonlinear performance.

Figure 4. A composite view of system non-linearity caused by device nonlinearity and limits on modulation depth.
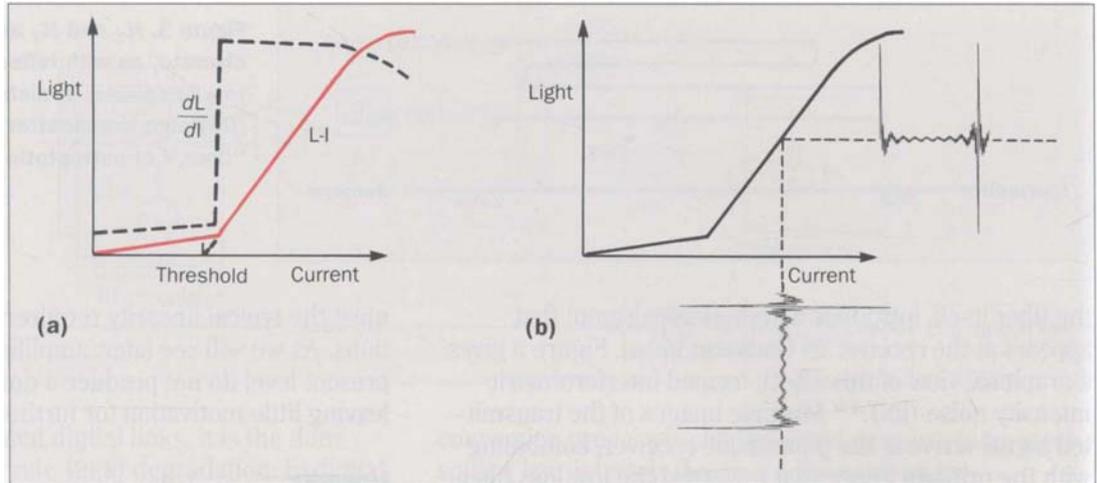

(a)

(b)

Figure 5. A Laser Link AM trunk system showing the parameters that affect performance.

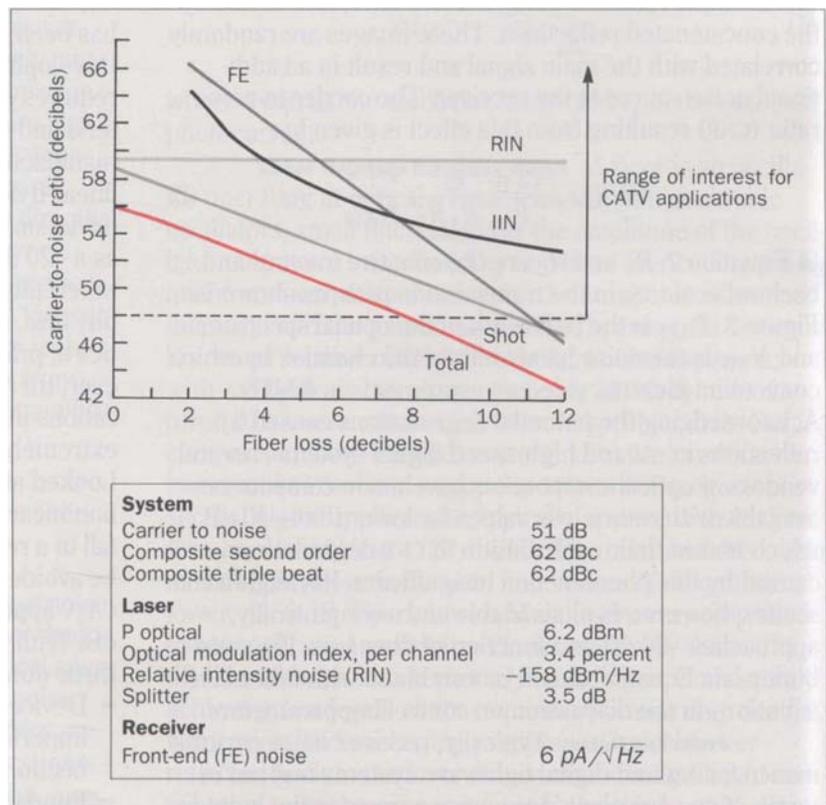| System	
Carrier to noise	51 dB
Composite second order	62 dBc
Composite triple beat	62 dBc
Laser	
P optical	6.2 dBm
Optical modulation index, per channel	3.4 percent
Relative intensity noise (RIN)	−158 dBm/Hz
Splitter	3.5 dB
Receiver	
Front-end (FE) noise	6 pA/√Hz

Figure 4 presents a composite view of the first two contributors. A typical curve of semiconductor laser light versus current (L-I) depicts the "transducer performance." The slope, or first derivative (dL/dI) of the L-I curve, must be constant to maintain the linearity of the device. While L-I curve linearity is useful to evaluate devices initially for analog performance, it is impossible to guarantee from measurement and observation of the L-I characteristic whether it is adequate. To achieve adequate measurement accuracy, we tested all steps in the manufacturing process that replicate system conditions. We have substantially improved the linearity of DFB
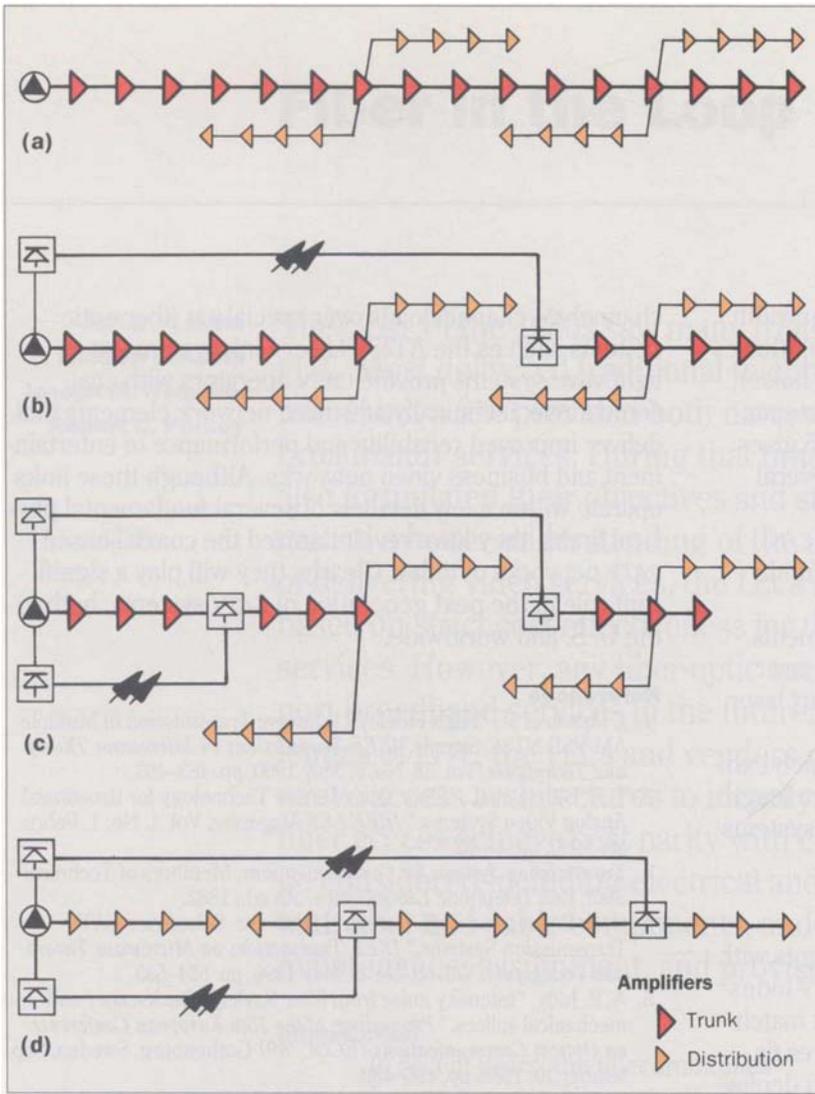
devices manufactured by AT&T Microelectronics and have set performance standards for the AM industry by combining device design and fabrication techniques and a patented[6] biasing technique. Careful consideration[7] of the fundamental limits on modulating threshold-limited devices, as depicted in Figure 4b, was critical to an understanding of the inherent capabilities of the devices and their potential in AM applications. This work, later verified by laboratory evaluation, places limits on the achievable index of modulation (amplitude) of individual carriers in a multichannel system load. The best achievable performance for typical CATV applications is given by:

$$NLD = \frac{1}{\sqrt{2}\,\pi} \frac{-\mu^3}{1 + 6\mu^2} \exp\left[-\frac{1}{2\mu^2}\right] \qquad (3)$$

where μ, the RMS modulation depth, is given by:

$$\mu \equiv m\sqrt{N/2} \qquad (4)$$

Here, N is the number of channels and m is the optical modulation index per channel. A value of modulation

index about 2 dB below the theoretical limit is normally used for system modeling and comparative performance calculations to account for the other processes in the overall system.

Controlling Parameters

Figure 5 shows a composite view of the parameters that determine carrier-to-noise performance. This chart was generated for a typical device that operates 2 dB below the theoretical limit for index of modulation. It demonstrates how, together, these several parameters determine the overall Laser Link system performance as a function of optical loss between the transmitter and the receiver.

The total CNR curve in Figure 5 is given by:

$$CNR = \frac{Carrier}{Noise}$$

$$= \frac{m^2 I_p^2/2}{N_{BW}\left[2eI_p + I_p^2 * RIN + N_{FE} + \frac{4I_p^2}{\sqrt{2}\,\pi}\,\frac{R_1 R_2}{B_{1/2}}\right]} \qquad (5)$$

where, in the denominator, N_{BW} is the noise bandwidth for the channel (4 MHz for NTSC) and in the parentheses the noise contributions for shot noise, RIN (laser noise), front-end noise, and IIN (interferometric noise), respectively, are summed. The numerator of Equation 5 gives the signal or carrier signal level. We can draw several conclusions from Figure 5:

- The dominant contributor to carrier-to-noise (C/N) degradation in these systems is shot noise, a fundamental limitation that cannot be overcome.
- Generally, IIN, which is generated from laser-media interaction, degrades performance more than laser device RIN, which is produced by state-of-the-art laser devices.
- Unlike the performance of digital systems, which exhibits a significant roll-off once the critical design length has been reached, the performance of analog systems degrades slowly.

Deployment

Since 1988, when the first field experiments with AM broadband systems were completed, the CATV industry has developed new system architectures that match the technology to their evolving networks. Figures 6a through 6d show the progression of fiber system deployment in these networks, starting conservatively with cascade reduction applications and evolving rapidly to the current deployment strategy known as "fiber to the bridger," or fiber trunk and feeder (FTF). FTF and similar architectures, such as the one shown in Figure 6d, can transform traditional tree and branch systems to star architectures serving between 500 and 2000 individual subscribers. These focused networks create an opportunity for services that are tailored to specific serving areas, such as foreign language channels, special interest movies, and, at the limit, virtual dedicated channels to each subscriber as the serving area size is reduced.

Today, FTF or similar architectures are the preferred replacement for virtually all CATV systems that are upgraded or rebuilt. Even though AM lightwave technology offers higher bandwidth, reduced amplifier cascades, and the flexibility to accommodate new services, its cost is competitive with that of coaxial cables.

Summary

We have looked at the significant parameters and key contributors to performance in transmitting multi-channel AM channel loads over special AM fiber-optic systems such as the AT&T Laser Link system. AM lightwave systems provide CATV operators with cost-competitive, technically advanced network elements that deliver improved reliability and performance to entertainment and business video networks. Although these links operate within a few decibels of several fundamental physical limits, they have revolutionized the coaxial-based CATV networks of today. Clearly, they will play a significant role in the next generation of CATV systems, both in the U. S. and worldwide.

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