AN OPTICAL LINK FOR CATV

by

R. T. Daly and M. G. Cohen

ABSTRACT

This paper studies the technical feasibility of using a free space cascade of optical (laser) links for CATV service. By employing available Weather Bureau visibility statistics for New York City, the effects of optical path attenuation on link reliability are determined. Based upon these results, a link is proposed which will provide 99.9% reliability with a 42db signal-to-noise ratio for transmission of 25 TV channels plus the FM band. Repeater spacings, required optical powers, detailed configurations, modulation techniques and costs are discussed.

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I. TECHNICAL DISCUSSION

The performance requirements and construction of link elements (transmitter and receiver) will be developed in this section based upon the following assumptions:

(a) The cascaded link elements are identical and are spaced by 80 meters. (80 meters is about the distance between East-West streets in Manhattan, New York City.)

(b) The cascade of links must achieve an overall reliability with respect to weather conditions of 99.9%. That is, for 0.1% of the time the carrier-to-noise ratio at the output terminal of the cascade may be below the minimum design value.

(c) Weather statistics correspond to those of New York City.

The cascade consists of K equally spaced outdoor intervals as shown in Figure 1. Atmospheric transmission path losses are uniform over the entire length of the cascade and correspond to 33 db/1000 ft. This value of optical path transmission is exceeded (on the average) in New York City 99.9% of the time.

As shown, the input to the link is a high-level, noise-free signal. At each stage in the cascade, the carrier-to-random noise power ratio, c/n, (measured at the output of each receiver) decreases, since each square-law photodetector load and associated preamplifier contributes additive white noise which can be treated as thermal noise at the effective noise temperature of the preamplifier. With a noise-free and high-level input signal at the head end of the cascade, the input to the second transmitter has a finite value $(c/n)_0$. At the output of the Kth receiver the carrier-to-noise ratio $(c/n)_K$ will be $1/K\,(c/n)_0$. Expressed in db, $(c/n)_0 = (c/n)_K + 10 \log K$. For a cascade one mile long consisting of 20 intervals, $10 \log K = 13$ db, so $(c/n)_0 = 55$ db is required for $(c/n)_K = 42$ db. This level must be maintained under the assumed optical path transmission conditions.

Before proceeding with a discussion of the equipment configuration, it is necessary to consider the significance of atmospheric transmission. The relation $T_a(R) = \frac{R^2}{R_c^{\,2}}$, where $T_a(R)$ = one way path transmission and R and R_c, the range and clear ($T_a = 1$) range respectively, establishes the fade margin required for the system. Statistical visibility data gathered at several U.S. cities for air traffic control planning permits the evaluation of the frequency and duration of the optical path fading[1]. Data given for New York (taken at JFK International Airport) show that over an 80 meter path, a fade of 17 db (referenced to a point in the receiver following the square law optical detector) is exceeded only 0.1% of the time. Thus, with this fade margin, each element of the cascade is within performance specification

99.9% of the time. Additionally, the data support predictions that fading over the cascade is correlated, i.e., the overall cascade availability is the same as that for any element.

With this information, the value R_c can immediately be established by noting that

$$20 \log T_a(R) = 40 \log (R/R_c) = -17\,\text{db}$$

so that for $R = 80$ meters, $R_c = 210$ meters.

At the present state of technology, and for the signal bandwidth to be accommodated in this service, the optical transmitter must consist of a cw laser source in the wavelength range between about $1\mu m$ (near infrared) and $0.4\mu m$ (visible blue) and an external modulator capable of handling the signal bandwidth.

For the cascade element separation ($\approx$ 80 meters), the relatively high carrier-to-noise ratios required in this service and in the interest of cost, direct square-law optical detection is the practical choice. Depending upon the wavelength region selected, i.e., the laser transmitter choice, two more or less different detector devices can be considered. For those wavelengths corresponding roughly to the visible spectrum ($0.7\mu m$ to $0.4\mu m$) the combination of photocathode and electron multiplier (photomultiplier tube) is available. Alternatively, the use of solid state photodiodes for the near IR portion of the spectrum ($1\mu m$ to $0.6\mu m$) offers good performance. The lower cost, accurate linearity and excellent performance of available silicon PIN diodes as IR detectors strongly recommends their use, even though link performance may be degraded by a few db.

For a system consisting of a cw laser, optical modulator, solid state (diode) detector, optics and electronic circuits, the schematic diagram would be as shown in Figure 2.

It can be shown that the "clear" range, R_c, of a single transmitter-receiver link element, is given by

$$R_c{}^2 = \frac{R^2}{T_a(R)} = \left(\frac{m^2}{(c/n)_0}\right)^{1/2} \left(\frac{\eta_o P_L A_R}{2\Omega_T}\right) \left(\frac{S^2}{8 k T_e C_T B B_o}\right)^{1/2} \tag{1}$$

where (1) applies in the case of a system limited by detector/preamplifier thermal noise.

The parameters in Eq. (1) are defined as follows:

$T_a(R)$ = one way atmospheric path transmission

R_c meters = maximum range separation at which performance level will be met with zero atmospheric path attenuation ($T_a(R) = 1$)

R (meters) = maximum range for $T_a(R) < 1$

m = peak modulation of optical carrier for any single channel signal

$(c/n)_0$ = electrical carrier-to-random noise power ratio referred to maximum rms channel carrier

η_o = system optical efficiency, i.e., lens and filter losses

P_L watts = cw laser power generated

A_R (meters^2) = clear aperture of receiver

Ω_T (steradians) = effective solid angle of projected transmitter beam. $4\pi/\Omega_T$ would be termed "antenna gain" in microwave terms

B (Hz) = overall link bandwidth

B_o (Hz) = bandwidth of a single individual TV channel

S (amperes/watt) = responsivity of the optical detector element

k (joules/°K) = Boltzmann's constant

T_e (°K) = effective noise temperature of receiver preamplifier, i.e., $T_e = F \times (290)$ °K where F is the preamplifier noise factor

C_T (farads) = total capacity shunting the optical detector element

A good approximation to the details of the link can be gained by solving Eq. (1) using some typical values. For the moment we assume that a total of N independent but frequency-contiguous TV channels are to be carried and that the total depth of modulation is adjusted such that $m = (4N)^{-1/2}$* Other parameter values are as follows:

$(c/n)_0$ = 3.2×10^5 (55 db in the receiver circuits for a 20 element cascade)

η_o = 0.7

A_R = 1.3×10^{-2} m^2 (5" dia. optics)

Ω_T = 1.5×10^{-6} ster (2×10^{-3} rad. linear angle or 0.12°)

B_o = 4×10^6 Hz

B = $3/2\, NB_o$

S = 0.4 amperes/watt (for silicon PIN diode at $\lambda = 0.63\,\mu m$)

k = 1.38×10^{-23} joules/°K

T_e = 600°K (3 db noise figure)

C_T = 5×10^{-12} farads

R_c = 210 m

Eq. (1) can be solved, using these values, to give

$$\frac{P_L}{N} = 110 \times 10^{-6} \text{ watts/channel}$$

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* The choice of this value for m results from a detailed calculation of the modulation scheme and will be published separately.

The value selected for S, above, anticipated that the laser wavelength was 0.63μm radiation from a helium-neon gas laser. Small helium-neon lasers are readily obtainable with power outputs of 3 milliwatts, sufficient to transmit over 25 TV channels.

A value S = 0.2 amperes/watt is appropriate for wavelength λ = 1.06μm corresponding to a YAG laser. Eq. (1) would give, in this case, $P_L/N = 220 \times 10^{-6}$ watts/channel. Small YAG lasers have been built with outputs exceeding 500 milliwatts, which is one hundred times the required level for 25 TV channels.

Because the modulation/demodulation process generates beats among the modulated VHF channel carriers, it is not possible to cleanly transmit more than one octave on a "single" optical carrier. However, using the two orthogonal linear polarization states of a laser beam, two optical carriers can be created. These carriers may be separately modulated and then recombined for transmission. At the receiver, each beam produces its own photocurrents since no demodulated signal can arise from interaction of the orthogonal polarizations. Polarization beamsplitters and recombiners are not the most economical method of providing dual channel operation. It may be possible to employ acousto-optic modulators which act upon only one polarization with two crossed modulators positioned along the beam. Each modulator channel is imposed upon an orthogonal polarization component, with the transmission and demodulation proceeding as described previously.

Using the dual channel technique, substantially all of the presently desired CATV spectrum can be accommodated. Thus, 54 to 108MHz feeding the first modulator covers channels 2 through 6 plus the FM channels, while 120 to 240MHz feeding the second modulator provides coverage of channels 7 through 13 plus the non-standard midband and high-band channels A through M, resulting in transmission of a total of 25 TV channels plus the FM band.

II. SAFETY AND ECONOMICS

While there is general agreement as to the potential eye hazard created by intense laser beams in the spectral region from 1.5μm to 0.35μm wavelength, there is, as yet, no solid data as to the flux density levels which can safely be tolerated. At least two issued specifications[2][3] cite as a safe level 5×10^{-5} watts/cm^2 at $\lambda = 0.63\mu m$ (helium-neon laser) and 1.5×10^{-4} watts/cm^2 at $\lambda = 1.06\mu m$ (YAG laser). From a 5" diameter objective, therefore, about 7 milliwatts from a helium-neon laser and 20mw from a YAG laser will provide this flux level near the transmitter. However, these published values are generally regarded as highly conservative, perhaps by as much as 1000 times, and workers in the laboratory frequently receive higher exposures without apparent effect.

It has been reported that the cost of material and installation for one mile of underground CATV cable in New York City usually ranges between $10,000 and $20,000 and in some special cases, as high as $40,000. Assuming the optical link to be fully equivalent to cable in function and performance, in order to be cost-competitive with cable, each repeater unit must sell for a maximum of $1,000 (including installation) since 20 repeaters would cost $20,000. At a higher selling price, the optical link would appear to find application only in special cases, for example, where its capability for quick installation with high recovery value on an abandoned route was important.

An estimate of the component and assembly costs for the types of equipment discussed in Section I shows that the helium-neon system with 25 channel capacity is just possible at $1,000/repeater if production volume were high. The YAG system, on the other hand, would be difficult to produce for under $2,500 - again, if volume were high.

III. RECOMMENDATIONS

The significantly lower cost of a helium-neon laser (about $100, in quantity) compared with a YAG laser (about $1,500 in quantity), is the major contributor to the difference in system cost. The helium-neon system would be an immediate choice on the basis of cost alone, but as the results show, a 3 milliwatt helium-neon laser provides little margin over the nominally required 2.6 milliwatts. Unfortunately, fundamental limitations exist in obtaining higher usable output from this laser unless the cost is significantly increased.

The YAG laser, on the other hand, while its cost is nearly $1,500/unit greater, provides a very significant margin. Thus, compared to a nominally required 5 milliwatts, the YAG can provide, easily, 500 milliwatts. This power excess can be advantageously used in several ways:

(a) Increased weather immunity - a reliability of 99.99% can be obtained with a 10-fold increase in power.

(b) Wider transmitted beam for more tolerance in mounting and aiming is obtained by increasing the projected beam to 3 milliradians.

(c) Greater tolerance to lens dirt, which reduces to a transmission to 70% instead of 90%, costs another factor of 1.8.

With these advantages, a total laser power of 180 milliwatts is required, still leaving a margin for component degradation. In view of these considerations, it is recommended that any system design which aims toward 25 channels utilize the YAG laser. For one or a few channels, however, the helium-neon laser remains the clear choice.

REFERENCES

[1] B. G. King, W. C. G. Ortel and H. J. Schulte, Intl. Comm. Symposium, San Francisco, 1970.

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[2] A Guide For Uniform Hygiene Codes or Regulations for Laser Installations, The American Conference of Government Industrial Hygienists (1968).

[3] Policies and Practices for Personnel Using Laser Devices, Bell Telephone Laboratories

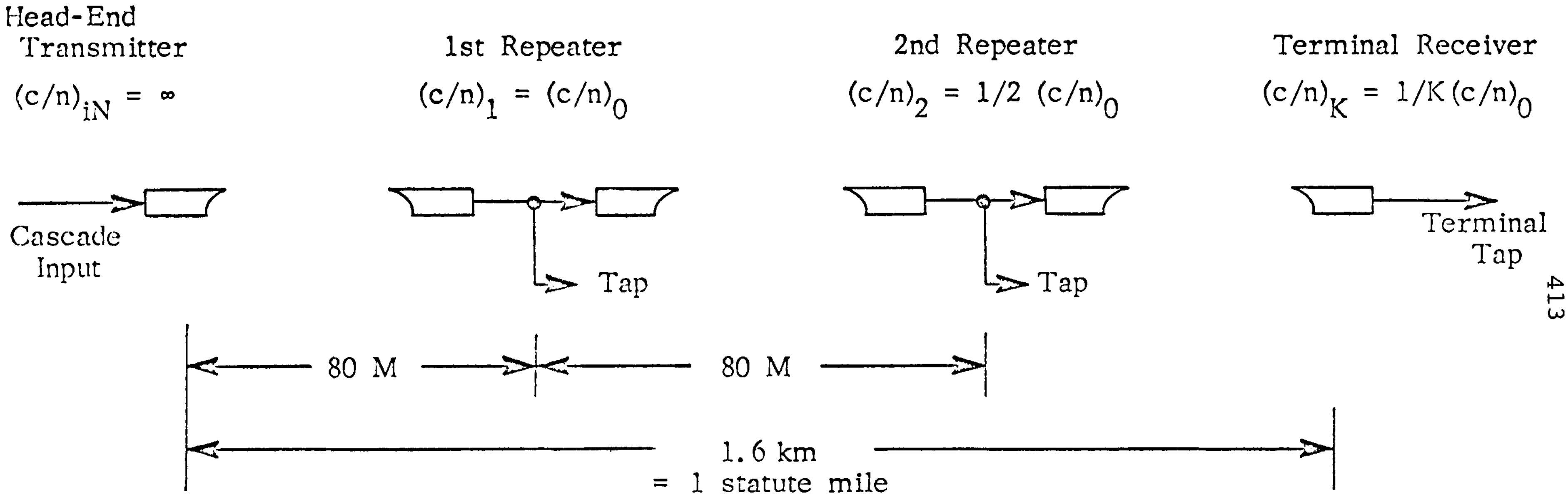

FIGURE 1. ONE MILE CASCADE OF K OPTICAL LINKS

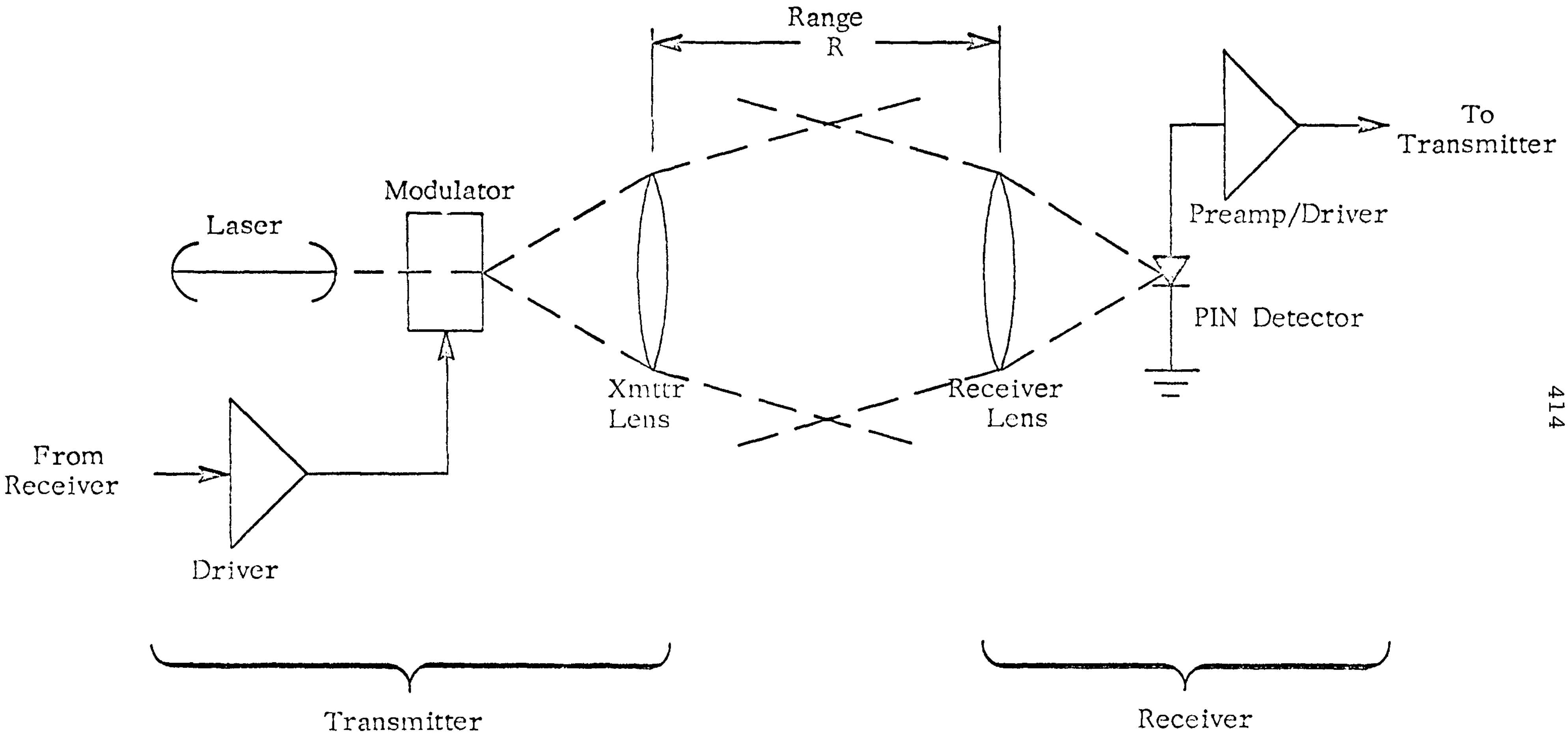

FIGURE 2. SCHEMATIC FOR ONE CASCADE LINK ELEMENT FOR CATV