

Fiber-Optic CATV/Telephone/Data Network

This novel fibre optic system could replace coaxial cable and space transmission of television, telephone and data to the home — while providing an enormous commercial market for MMIC's.

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In December, 1989, the first experiment using fiber optic CATV/telephone/data network with five actual subscribers, will begin trial service in Cerritos, a city about 20 miles south east of Los Angeles, California. The five subscribers are located within a radius of 5 Km from the central office of the network.

The system will broadcast sixteen common CATV channels and four video-on-demand channels. In addition, the same fibre optic link will accommodate two-way transmission of telephone, data and one video channel.

This is the first substantial application of microwave transmission for homes. Successful demonstration of this system may open a massive consumer market for microwave components, providing further impetus to accelerate the development of monolithic microwave integrated circuit (MMIC) components and subsystems.

This paper describes the microwave portion used in the downstream transmission, from central office to subscriber homes, including subscriber receiving equipment. In this system, microwave subcarrier multiplexing techniques are used to transmit, via an optical fiber, twenty digitized video channels at a

data rate of 107 megabits per second (Mb/s) per channel, plus a voice/data channel at a data rate of 2.144 Mb/s.

The upstream transmission, from the subscriber home to the central office, consists of one digitized video channel at a data rate of 107 Mb/s and a telephone/data channel at a data rate of 2.144 Mb/s. The upstream video transmission enables subscribers to send video information to other subscribers. The data channel provides data for home terminals, on-screen program information, as well as network control by the central office.

Each subscriber station is equipped with a high frequency PIN diode photodetector followed by five double conversion microwave receivers.

The twenty-one microwave subcarriers are multiplexed together to intensity modulate a high speed 1300 nanometer (nm) wavelength, single mode laser, one dedicated to each subscriber, for downstream transmission. Each subscriber station is equipped with a high frequency PIN diode photodetector followed by five double conversion microwave receivers, each followed by a coherent demodulator.

Comparison Between Time Division Multiplexing (TDM) and Subcarrier Multiplexing (SCM)

Both TDM and SCM have been used in multi-channel fiber optic transmissions. The following three key points illustrate the comparison between these two methods as applied to fiber optic transmission.

1) Mixed use of different modulation format: Since TDM is an all digital system, analog signals cannot be used, unless they are first converted to digital format. However, in a microwave SCM system different modulation formats, digital and analog, can be mixed and transmitted by the same fiber as long as the required bandwidth does not exceed the channel bandwidth provided.

2) Ease in adding or deleting channels: In a TDM system, the clock frequency, i.e. the frequency at which bits are transmitted, in the multiplexer is equal to the final output data rate. Adding a new channel increases the total output data rate. Thus it requires a new clock frequency and a new frame sync code (the specification for how many bits in the stream correspond to a set of video pictures) data and telephone blocks of information.

If a channel is deleted, it must be replaced by a

dummy data stream to maintain the same frame format. Accordingly, the remaining channels in a TDM system do not benefit in carrier to noise ratio (C/N) due to a reduction in the number of television, data or telephone channels transmitted.

With microwave SCM, channels can be added or removed independently without such a system impact. When a channel is removed, the power given up by the removed channel is redistributed equally among the remaining channels, resulting in a proportionate C/N improvement. This is effected simply by adjusting to the optimum value the total RF power fed to the laser.

3) Cost and availability: To use TDM, multi-gigabit signal processing components are required. At the present time, such components are in the development stage. On the other hand, all of the essential multi-octave microwave components, such as amplifiers, mixers, and circulators, required for SCM applications to cover the entire 2 to 8 GHz band are fully developed and are available on a production basis. Furthermore, increased application of SCM for home video delivery will open the mass consumer market for MMIC components, helping to bring down the cost of these components for all applications through the continuing advances in MMIC technology.

Selection of a modulation method

Subcarrier multiplexing in fiber optic transmission is the same as frequency multiplexing used in microwave radios. The only distinction lies in the wave propagating medium. With conventional microwave radio transmission, the medium is either free space or cable. These media suffer from bandwidth limitations due to spectrum allocations for free space and moding and frequency dependent loss effects in cable. Also, unequal propagation times for differing frequencies (frequency dispersion) limit bandwidth in these conventional media. Furthermore, insertion loss effects are considerable in free space due to spacial spreading of the radiated wave and in cable due to the considerable losses over long paths. To mitigate some of these effects, various modulation methods were developed, such as m-ary-SK and m-ary-QAM.

In a fiber optic system, the carrier wave propagates in a glass fiber and the microwave (subcarrier) is carried by this coherent laser produced optical carrier. The fiber has tremendous inherent bandwidth, hundreds of GHz with little frequency dispersion.

In practice, the available bandwidth for micro-

wave SCM transmission on fibers is limited to 10 GHz due to laser bandwidth limitations. Nonetheless, with a 10 GHz available bandwidth, there is no need to use bandwidth-efficient high level modulation methods; simple modulation methods can be used. The two simplest digital modulation methods are frequency-shift-keyed(FSK) and biphas-shift-keyed(BPSK). The fiber has a total loss of about 1 dB per kilometer, several orders of magnitude less than cable or free space.

Several authors [1,2] have described lightwave distribution networks using FSK microwave subcarriers. In their system, FSK modulation is achieved by applying the digital data stream directly onto to the control terminal of a microwave voltage controlled oscillator (VCO).

BPSK modulation is usually achieved by an external modulator, consisting of 3 dB hybrids and switching PIN diodes. For instance, a double balanced mixer can be used as a BPSK modulator when the data stream is connected to the IF port and the modulated output is taken from the signal port.

In the system under discussion, BPSK modulation is used for three reasons:

1) For the same error rate performance, BPSK requires an electrical energy per bit over noise density ratio, E_b/N_0 , 3 dB less than that required by coherent orthogonal FSK.

2) External BPSK modulator can operate at data rates of several hundred Mb/s, whereas direct FSK modulation of VCO is limited to a data rate of about 50 Mb/s due to the low pass filter effect of the tuning varactor[1].

3) FSK modulation requires an individual VCO for each subcarrier. Due to poor frequency stability, VCOs are unsuitable for use in an operational system requiring stable channel frequencies unless external frequency stabilization methods are used.

BPSK modulation is achieved with external modulators, giving the designer freedom to choose the best method of generating all the subcarrier frequencies. In the present system, all subcarrier frequencies are obtained from the harmonics of a temperature compensated crystal controlled oscillator.

End-to-End Link Calculations

In fiber optic transmission, besides the thermal noise of the microwave receiver, there are three additional noise terms. On the transmitter side, there is the noise term due to the fluctuations of laser output power, defined as relative intensity noise (RIN). On the receiver side, there are the quantum noise and the dark-current noise of the

photodetector. At received optical power less than -10 dBm, the total noise due to the photodetector is much smaller than the thermal noise of the microwave receiver, and is usually neglected.

For a given E_b/N_0 , the receiver thermal noise determines the maximum transmission distance, whereas RIN determines the maximum number of channels that can be transmitted.

The signal to noise ratio E_b/N_0 is shown as a function of the received optical power, P_r , in Figure 1. Both calculated and the measured values are shown at 5.9 GHz for different laser intensity noise, RIN, and modulation depth per channel, m , of 0.05 and data rate, f_b , of 107 Mb/s. The laser used for the measurements has a RIN about -132 dBc/Hz. Measured values of photodetector responsivity and receiver noise figure are used in the calculations. Laser RIN is seen to cause saturation of E_b/N_0 at high values of P_r , setting an upper bound on the achievable value of E_b/N_0 for a fixed modulation depth.

Bit error rate decreases with an increase in E_b/N_0 , but when E_b/N_0 is at saturation, regardless of how much the received optical power is increased, there is no corresponding decrease in bit error rates (BER). In conventional microwave transmission, a decrease in BER always follows an increase in received power. Therefore, laser RIN plays a vital role in fiber optic transmission. It determines the minimum modulation depth needed to obtain a required value of E_b/N_0 .

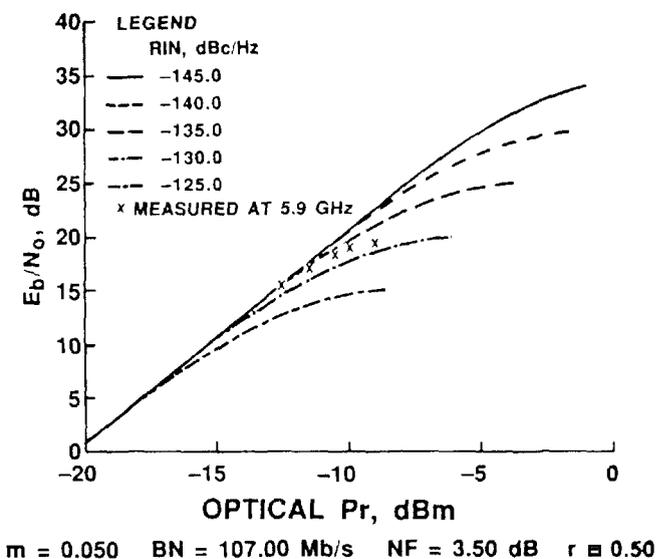


Figure 1. Signal to noise ratio, E_b/N_0 , as a function of received optical power, P_r , for various values of laser intensity noise, RIN. For these data laser modulation/channel, $m = 0.05$; data rate, $f_b = 107$ Mb/s; laser intensity noise, RIN, = -132 dBc/Hz, receiver noise figure, NF, is 3.5 dB; and photodetector responsivity is 0.5.

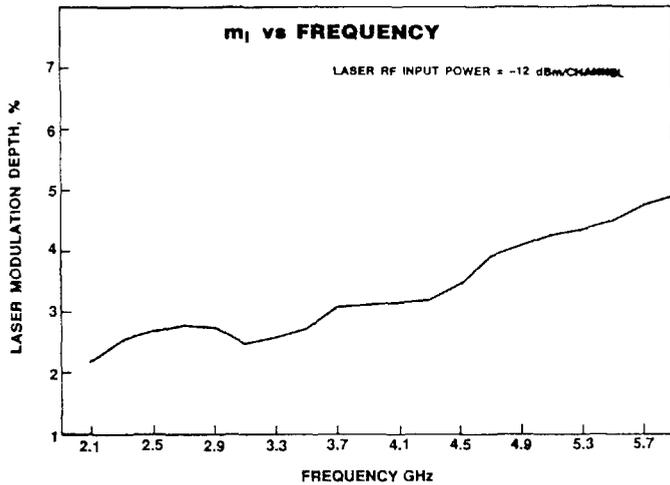


Figure 2. The measured frequency response of the laser used in this system when a constant, -12 dBm modulating power is applied.

The measured RF frequency response of a typical laser used in this system is shown in Figure 2. The modulation depths are measured with the RF modulation power fixed at -12 dBm. The response peaks toward the high frequency end due to laser relaxation resonance.

Central office downstream transmission system

A major portion of the components used in the central office downstream transmitter consists of

multiplexing and demultiplexing. There are basically three different methods of multiplexing and demultiplexing:

- use of multiplexing filters,
- use of circulator-filter combinations, and
- use of power combiner/divider and filter combinations.

The first method has the least amount of insertion loss, but is very difficult to design for narrow band contiguous channels and very expensive to manufacture. The second method is commonly used in microwave radios. Besides the loss of the filter, it adds a loss equal to the loss of the total circulator paths traversed by each respective channel. The third method incurs an additional loss due to the power divider. Both the second and third methods are used in this system's configuration. The third method usually requires an amplifier due to the loss through the power divider. The particular method used in each application is determined by cost considerations.

Central office microwave mux/demux system

A simplified block diagram of the central office downstream transmission equipment is shown in Figure 3. Subsystem B generates sixteen BPSK modulated common microwave channels, equally distributed among five subscribers. Subsystem A

DOWNSTREAM TRANSMISSION

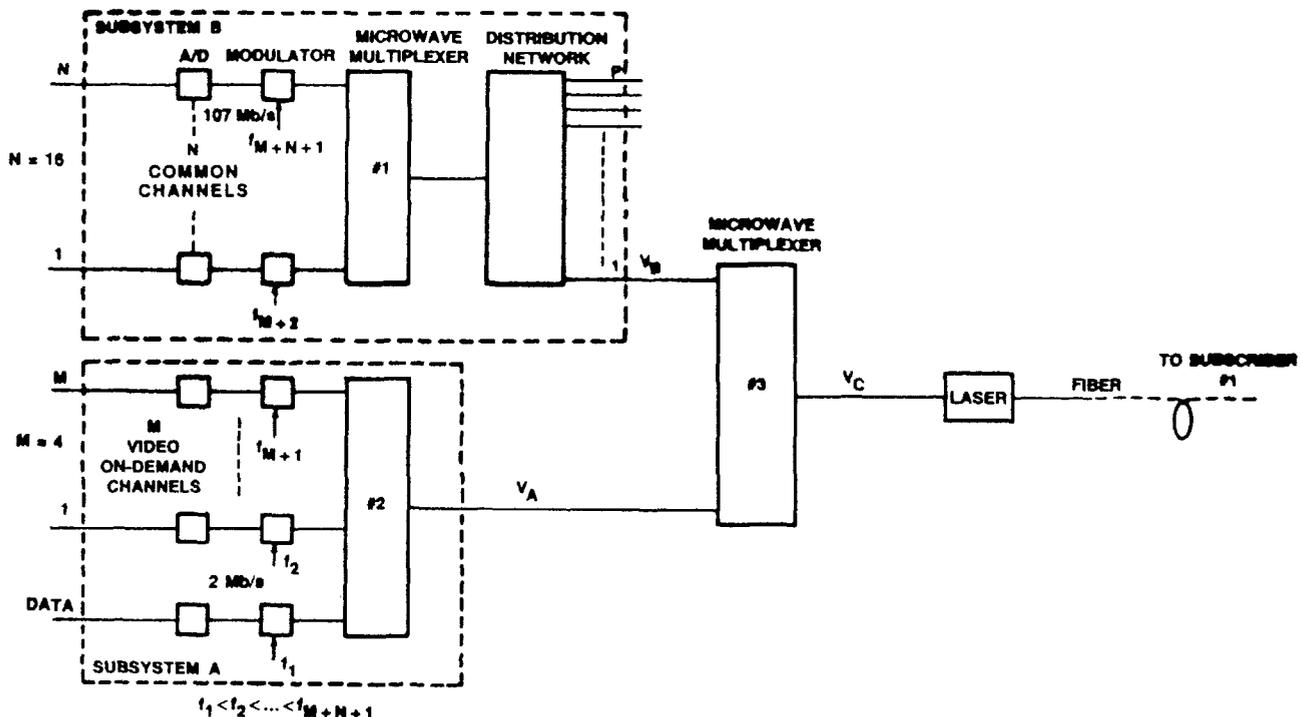


Figure 3. Simplified block diagram of the central office transmitter.

generates four video-on-demand and one data/voice BPSK modulated microwave channels.

There is one Subsystem A for each subscriber. The output from subsystem A and one of the distributed output from subsystem B are combined in power combiner #3 for output to laser modulation port.

The higher frequency limit of the particular laser used in this system is about 6 GHz. The subcarrier frequencies cover the frequency range from 1.9 GHz to 5.9 GHz, with a 200 MHz spacing between subcarriers. Since the signal frequencies cover more than an octave, odd frequencies are used such that second order intermodulation products fall at the center between adjacent channel, outside of the bandwidth of the receiver IF filter.

The use of odd frequencies made it necessary to use a 100-MHz crystal controlled oscillator. The oscillator has a frequency stability of 1 part per million from -30 to +70 deg C. Figure 4 illustrates how the twenty-one subcarriers are generated. The twenty-one carriers are divided into five groups as shown. The circulator-filter method is used for demultiplexing and multiplexing. Narrow band filters, with a bandwidth of 40 MHz, are used. Filters are identified by a three digit code. The first digit indicates type of filter. "5" indicates a narrow band carrier filter with a bandwidth of 40 MHz, and "4" indicates a channel filter with a bandwidth of 125 MHz. The second and third digits indicate frequency. For example, 519 identifies a narrow band source filter with a center frequency of 1.9 GHz.

A redundant crystal oscillator-harmonic generator was provided in the subcarrier generation unit. In case of failure, the spare unit can be switched in to maintain service continuity. A photo of the subsystem is shown in Figure 5.

Similar frequency groups are used in the BPSK modulator section to produce the final twenty-one modulated channels according to the simplified block diagram shown in Figure 2. Figure 6 shows the modulation unit for the sixteen common channels; Figure 7 shows the modulation unit for the video-on-demand channels for five subscribers; and Figure 8 shows the final power combiners and laser drivers for five subscribers.

Subscriber receiver

The receivers used in the subscriber terminal are double-conversion microwave receivers with a coherent demodulator for data recovery. In order to keep all local oscillator (LO) frequencies outside of the signal channels, a relatively high heterodyne intermediate frequency (IF) of 6.5 GHz is used. To

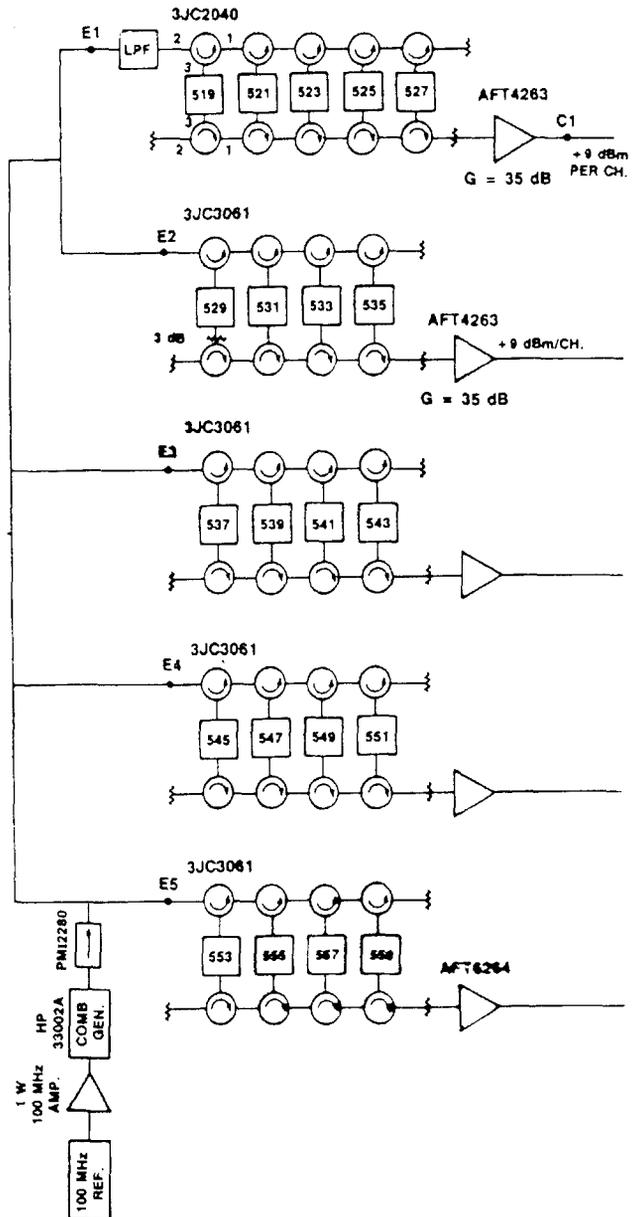


Figure 4. Subcarrier generation block diagram.

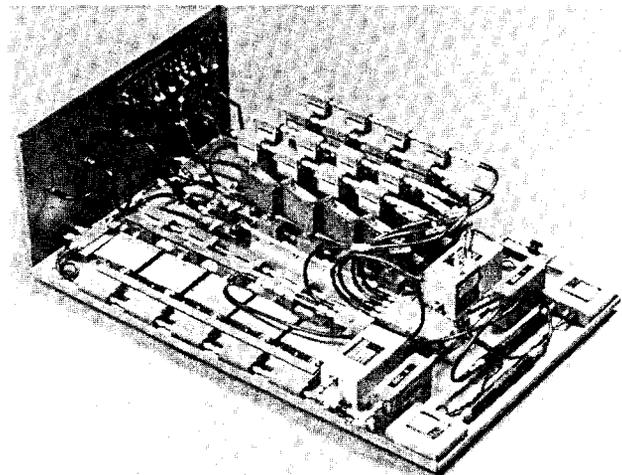


Figure 5. The subcarrier generation unit.

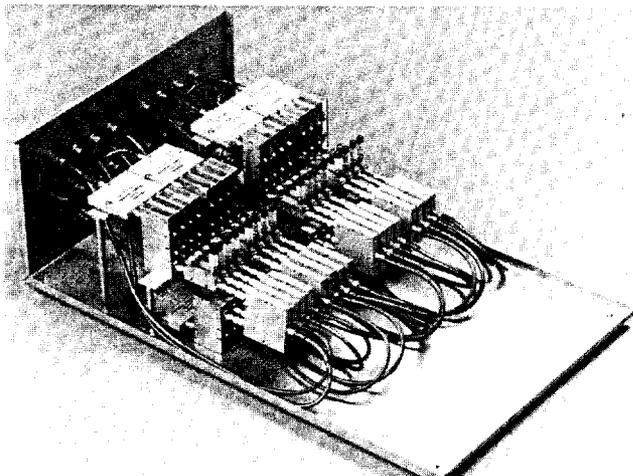


Figure 6. Common channel modulation unit, sixteen channels.

tune the twenty video channels, the required first LO frequency covers the frequency range from 8.6 GHz to 12.4 GHz in 200 MHz steps. Instead of using a tunable VCO to select these frequencies, a tunable YIG filter is used to select these frequencies from the harmonics generated by a temperature compensated 200-MHz crystal oscillator. The second LO is chosen to be 8.2 GHz to give a second IF of 1.7 GHz. The second LO is also obtained from the harmonics of the same crystal oscillator. Such an arrangement assures precise IF frequency control and avoids some of the difficulties in carrier recovery caused by the drift of VCO frequencies with temperature.

A block diagram of subscriber receiver is shown in Figure 9, and Figure 10 shows the generation and distribution of LO signals among the four receivers.

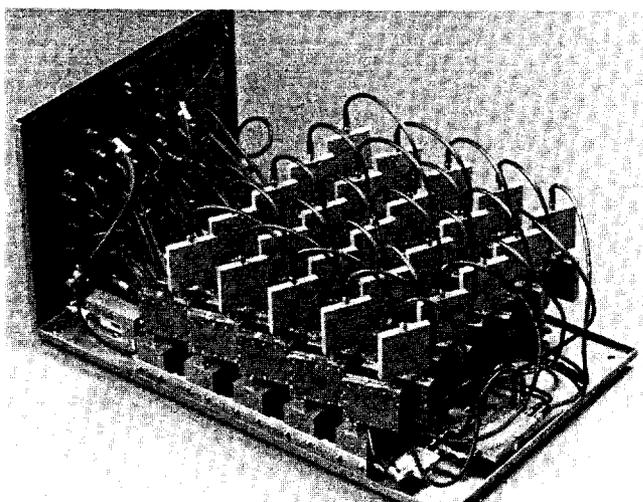


Figure 7. Video-on-demand modulation unit for five subscribers.

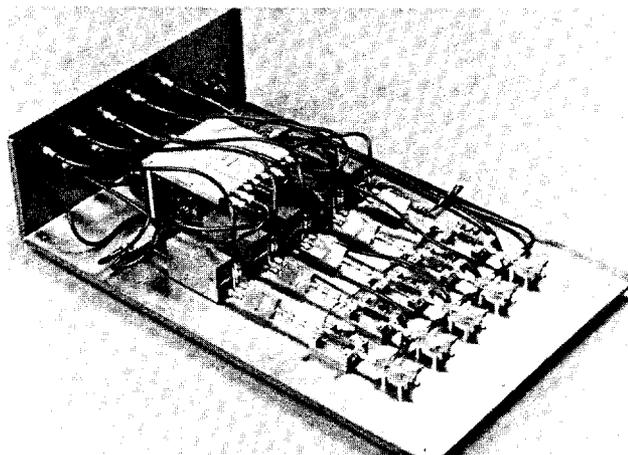


Figure 8. Laser driver for five subscribers.

Figure 11 is a photograph of subscriber receiver terminal.

Bit Error Rate (BER) measurements

Detailed measurements of BER versus received optical power at a data rate of 107 Mb/s were made at 5.9 GHz at different laser modulation depths per channel, with all twenty channels present. The results are shown in Figure 12. At received optical power of -12 dBm and a modulation depth of 5%, an E_b/N_0 of 15.5 dB was measured as shown in Figure 1, and a BER of 1 in a billion was measured as shown in Figure 12. Theoretically, an E_b/N_0 of 12.6 dB is required to achieved this BER. Hence, some overall degradation was observed.

A BER floor for $m_i = 2.14\%$ can be seen in the data of Figure 12, due to E_b/N_0 saturation as pointed out earlier. At higher values of m_i , the BER floor was beyond convenient measurement range. Similar results were obtained for the other nineteen channels.

Summary These experiments with an operational wideband lightwave video distribution system using digital BPSK microwave subcarriers show that for a BER of one part per billion and a laser with 1 mw output power, operating with an intensity modulation depth of 5%, an overall link loss of 12 dB can be accommodated. Since fiber path loss is on the order of 1 dB per kilometer, an operational system with path lengths of over 10 kilometers, 6 miles, is practical.

Appendix

When the dominating noise in the receiver is thermal, the minimum optical power required at

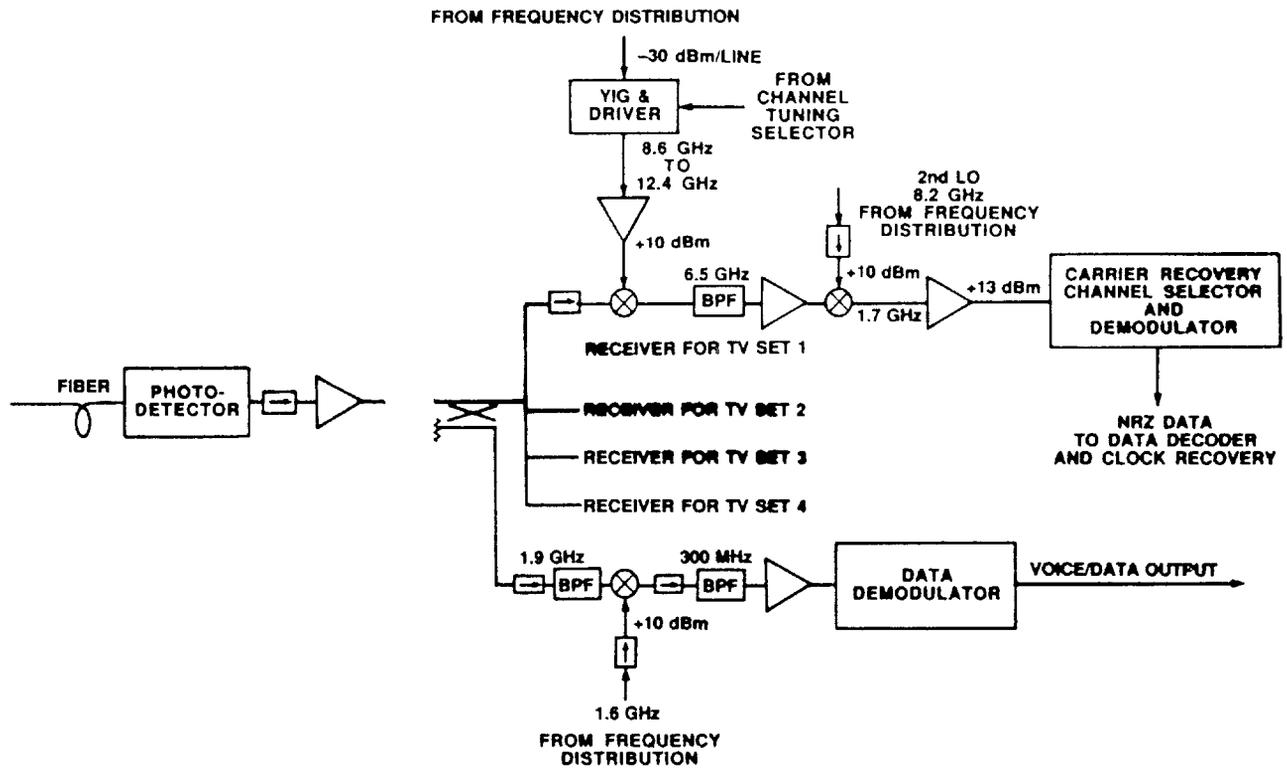


Figure 9. Subscriber receiver block diagram.

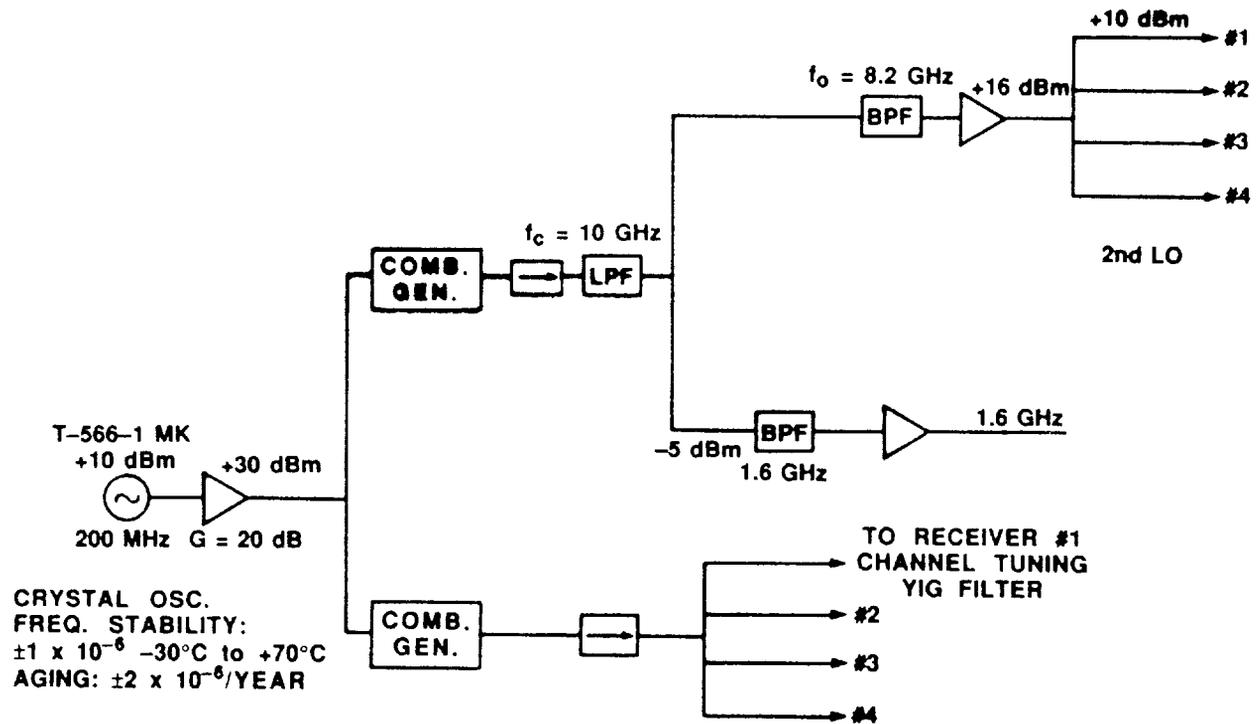


Figure 10. Receiver local oscillator block diagram.

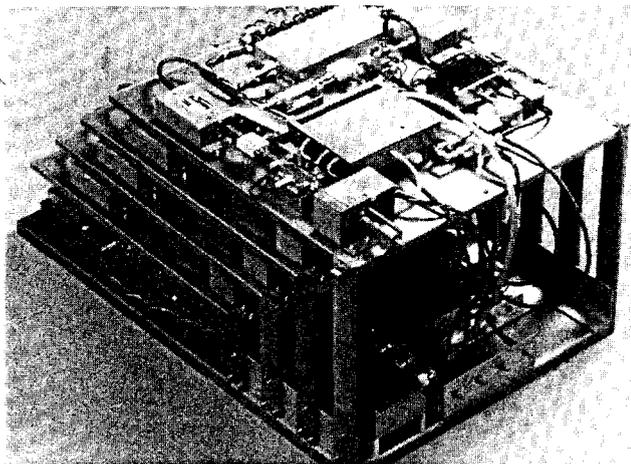


Figure 11. Photograph of a subscriber receiver.

the optical receiver is given by the following equation [3,4]:

$$P_r = \frac{\sqrt{\left[\frac{2f_b k T_{e2}}{R_r} \right]}}{r m_i \sqrt{\left[\frac{1}{S_t} - \frac{2(RIN)f_b}{m_i^2} \right]}}$$

where

- P_r = received optical power,
- r = detector responsivity,
- m_i = laser intensity modulation depth per channel,
- RIN = laser intensity noise,
- f_b = data rate,
- k = Boltzmann's constant,
- T_{e2} = receiver noise temperature,
- R_r = 50 Ω
- S_t = required E_b/N_o .

The modulation depth of the laser can be calculated according to the equation:

$$m_i = (0.2/I_{dc})\sqrt{P_m}$$

where I_{dc} is the measured dc current of the photodetector and P_m is the received microwave power from the photodetector.

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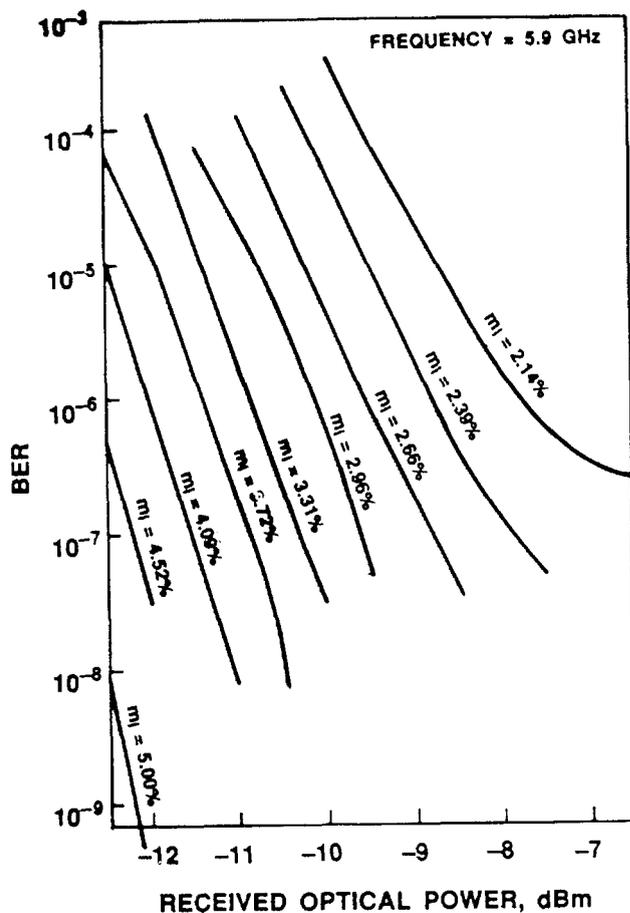


Figure 12. Measured bit error rate, BER, as a function of received power.

5. D. D. Tang, Portions of this paper were presented at the 1989 IEEE MTT-S Symposium in a paper entitled "Multi-gigabit fiber-optic video distribution network using BPSK microwave Subcarriers."

Douglas D. Tang received the B. Sc. Degree in Electrical Engineering from the National Taiwan University in 1954, the M.A.Sc. Degree in Electrical Engineering from the university of Toronto in 1959, and the Ph.D. Degree from Northeastern University in 1969.

He is currently a Principal Member of Technical Staff, GTE Laboratories. Since joining GTE Lab, he designed the microwave system used in the Tampa Triad 19 GHz and 29 GHz downlink propagation experiments using COMSTAR satellite beacons. During the life of the experiments, he also served as Project Manager overseeing operation and data reduction.

His current interests are in the application of microwave techniques to wideband fiber-optic communications. Prior to joining GTE Lab, he was with Lincoln Laboratories in charge of LO subsystem design for LES 8/9 satellites. Before joining Lincoln Laboratories, he worked on the design of microwave components and microwave antennas with AEL, Canadian Marconi Company, and Lindsay Antenna & Specialty Products.

