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MULTI-GIGABIT FIBER-OPTIC VIDEO DISTRIBUTION NETWORK USING BPSK MICROWAVE SUBCARRIERS

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Abstract

This paper describes the design and performance of a field deployable fiber optic video distribution system using bi-phase-shift-keyed (BPSK) microwave subcarrier multiplexing (SCM) techniques to provide each subscriber with twenty 107 Mb/s digitized video signals and one 2.04 Mb/s voice/data signal, giving a total transport capacity of 2.144 Gb/s. The microwave subcarrier frequency covers the range from 1.9 GHz to 5.9 GHz. The 21 microwave subcarriers are multiplexed together to intensity modulate a high speed 1.3 μm single-mode laser dedicated to each subscriber. Each subscriber station is equipped with a high frequency PIN diode detector followed by microwave receivers. A bit-error rate of 10^{-9} is achieved at a laser modulation depth of 5% and a received optical power of -12 dBm.

1. Introduction

This paper describes the design and performance of a field deployable fiber optic video distribution system using bi-phase-shift-keyed (BPSK) microwave subcarrier multiplexing (SCM) techniques to provide each subscriber with twenty 107 Mb/s digitized video signals. As shown in the block diagram of Figure 1, the twenty video channels sent to each subscriber consist of 16 broadcast channels and 4 video-on-demand channels carried on individual microwave subcarriers spaced at 200 MHz intervals from 2.1 GHz to 5.9 GHz. Each subscriber is also provided with a 2.04 Mb/s BPSK voice/data channel at a subcarrier frequency of 1.9 GHz. The 21 microwave subcarriers are multiplexed together to intensity-modulate a high speed 1.3 μm single mode laser dedicated to each subscriber, giving a total transport capacity of 2.144 Gb/s per subscriber. Each subscriber station is equipped with a high frequency PIN diode detector followed by five double conversion microwave receivers, each followed by a coherent demodulator. Four of these receivers are used for simultaneous reception of four video channels and the fifth receiver is for the reception of the voice/data channel.

The performance goal is to use a laser intensity modulation depth of 5% per channel and a received optical power of -12 dBm to achieve bit error rate of 10^{-9}

Subcarrier multiplexing in fiber optic transmission is the same as frequency division multiplexing used in microwave radios. The difference lies in the wave propagation medium, and the enormous difference in bandwidth. In conventional microwave radios, the medium is free space with the antenna as a transducer. Due to limited spectrum assignments, the bandwidth available for microwave radio application is very limited, and one is forced to use more complex bandwidth-efficient modulation methods such as high level QAM or PSK. In the fiber optic case, the medium is a dedicated optical fiber with laser as a transducer. The available bandwidth is the entire RF bandwidth of the laser, in the order of 10 GHz, and a data transmission bandwidth of several GHz can be achieved with simple BPSK or FSK modulation method.

Several authors[1,2] have described lightwave distribution networks using FSK microwave subcarriers. In their system, FSK modulation was done by applying the digital data stream directly onto the control terminals of a microwave VCO.

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

- For the same error rate performance, BPSK requires an electrical E_b/N_0 3 dB less than that required by coherent orthogonal FSK.
- External BPSK modulator can operate at data

rates of several hundred Mb/s, whereas direct FSK modulation of VCO is limited to about 50 Mb/s due to the low pass effect of the tuning varactor[1].

- FSK modulation requires an individual VCO for each subcarrier. Without external stabilization, a VCO has very poor frequency stability, making it unsuitable for use in operational systems requiring stable channel frequencies.

BPSK modulation is done with an external modulator, giving the designer freedom to choose the best method of generating all the subcarrier frequencies. In the present system, all the subcarriers are generated by a novel frequency synthesis technique using a 100-MHz temperature-compensated crystal-controlled oscillator to drive a comb generator. Narrow band microwave filters are used to extract the required subcarriers from the harmonics produced by the comb generator. The system has a frequency stability of ± 6 KHz at 6 GHz over an operational temperature range of -30°C to 70°C. Compared to the use of twenty-one VCOs for carrier generation, the comb generator frequency synthesizer technique results in greatly improved temperature stability. Still better stability, if required, can be achieved by using oven-stabilized crystal-controlled oscillator.

2. Comparison between TDM and SCM

Both time divison multiplexing (TDM) and frequency division multiplexing (FDM) have been used in multi-channel fiber optic transmission. The following is a brief comparision between these two methods.

A. Flexibility

- *Mixed use of different modulation formats*:

  Since TDM is an all digital system, analog signal can not be used. In a microwave SCM, different modulation formats, digital and analog, can be mixed and transmitted by the same fiber. Though only BPSK digital modulation format was tested, other digital modulation formats, such as QPSK, FSK, or QAM could be tested in the link, provided they occupy the same bandwidth.

- *Ease in adding or deleting channels*:

  In a TDM system, the clock frequency in the multiplexer is equal to the final output data rate. Adding a new channel increases the total output data rate. Thus it will require a new clock frequency and a new frame sync code. When a channel is deleted, it is replaced by a dummy data stream, to maintain the same output data rate. Thus the remaining channels do not gain any benefit in C/N due to a reduction on transmitted number of channels.

  With microwave SCM, channels can be added independently without disturbing the system. When a channel is removed, the power given up by the removed channel is distributed equally among the remaining channels, resulting in improved performance.

B. Cost and Availablility

To use TDM, multi-gigabit signal processing components are required. At the present time, such components are still in development stage. On the other hand, all essential multi-octave microwave components, such as amplifiers, mixers, and circulators, required for SCM application 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 and coupled with the maturing of MMIC technology, these components will be available in large production quantities at much lower costs.

3. End-to-End Link Calculations

In fiber optic transmission, besides receiver thermal noise, there is an additional noise term due to the fluctuation of laser output power, defined as relative intensity noise (RIN).

For a given carrier-to-noise ratio, the receiver thermal noise determines the maximum transmission distance, whereas RIN determines the maximum number of channels that can be transmitted.

When the dominating noise in the receiver is thermal, the minimum optical power required at the optical receiver is given by the following equation:[3,4]

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

where

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

Figure 2 shows both calculated and measured values of E_b/N_o as a function of P_r at different RIN values for $m_i = 0.05$ at a data rate of 107 Mb/s. Measured values of PIN diode responsivity and receiver noise figure are used in the calculations. Laser RIN is seen to cause saturation of E_b/N_o at high P_r, setting an upper bound on the realizable value of E_b/N_o for a fixed modulation depth. The value of RIN therefore determines the minimum modualtion depth needed to obtain a required value of E_b/N_o. Measurements in Figure 2 indicates that the laser used for this demonstration has a RIN between -130 and -135 dBc/Hz at 5.9 GHz.

4. Measurements of Laser Frequency Response

The channel frequencies cover the range from 1.9 GHz to 5.9 GHz in 200 MHz steps, with Ch 1 at 1.9 GHz and Ch 21 at 5.9 GHz. In order to maintain the same transmission quality, the frequency response of the laser rf modulation port needs to be measured. The microwave power from a photodetector is given by:

$$P_m = 0.5(rm_iP_r)^2R_r$$

where

P_m = RF power from the photodetector.

From the above equation, the laser modulation depth, m_i, can be written as

$$m_i = \sqrt{(P_m)}/(5rP_r)$$
$$= \sqrt{(P_m)}/(5I_{dc})$$

where

I_{dc} = photodetector dc current.

Hence the laser modulation depth can be measured by measuring the dc current of and the received microwave power from the photodetector. Figure 3 shows the measured laser modulation depth versus frequency, with rf drive power fixed at -12 dBm per channel. The response peaks toward the high frequency end due the laser relaxation resonance. m_i increases from 2.1% at 2.1 GHz to 4.9% at 5.9 GHz, representing a 7 dB increase in received rf power. The measured receiver gain decreases approximately linearly from 80 dB at 2.1 GHz to about 75 dB at 5.9 GHz, as shown in Figure 4. By maintaining equal rf drive power per channel, as shown in Figure 5, nearly flat overall frequency response is obtained due to the compensating effect of laser and receiver frequency responses.

5. BER Measurements

The link was first tested with microwave transmitter and receiver connected without the optical link. Measurements of BER versus E_b/N_o were made for all 20 channels. At a BER of 10^{-9}, the required E_b/N_o varies between 14.1 dB and 14.6 dB. Compared with the theoretical limit of 12.6 dB, the degradation is between 1.5 and 2.0 dB. Clock recovery circuit accounts for 0.5 dB of this degradation, the rest is largely due to adjacent channel interference and intersymbol interference. 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 6. At a received optical power of -12 dBm and a modulation depth of 5%, an E_b/N_o of 15.5 dB was measured as shown in Figure 2 and a BER of 10^{-9} was measured as shown in Figure 6. Therefore, an overall degradation of 2.9 dB was observed. By comparing Figure 2 and Figure 6 with the theoretical values of BER versus E_b/N_o for BPSK transmission, it can be shown that the fiber link introduces an additional penalty of less than 0.5 dB in optical power relative to the receiver sensitivity calculated from microwave back-to-back measurements.

Figure 6 also shows a BER floor for $m_i = 2.14\%$, due to E_b/N_o saturation as pointed out earlier. At higher values of m_i, the BER floor is beyond convenient measurement range. Similar results were obtained for the other nineteen channels.

In system testing, rf power is much easier to measure than laser modulation depth. Figure 7 shows the measured minimum rf power required to achieve a BER of 10^{-9} with 5 km of fiber and with -12 dBm of received optical power.

6. Conclusion

An operational wideband lightwave video distribution system using digital BPSK microwave subcarriers has been demonstrated. For a BER of 10^{-9} and a laser with 1 mw output power, operating at an intensity modulation depth of 5%, an overall link loss of 12 dB can be accommodated.

7. Acknowledgment

The author wisher to thank P.Baum and D.Voutour for supplying both the laser transmitters and PIN diodes used in the system, He also wishes to thank R.Cole for assembly and testing.

8. References

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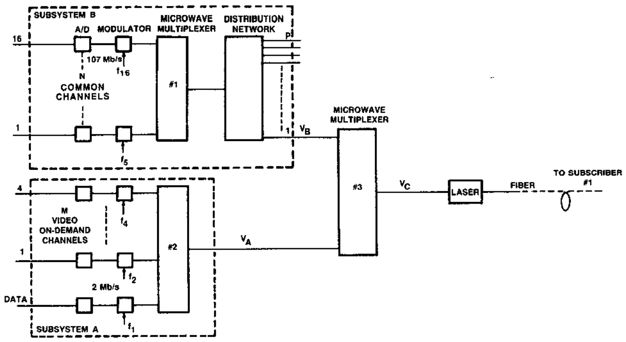

Figure 1. Simplified block diagram of Central Office transmitter.

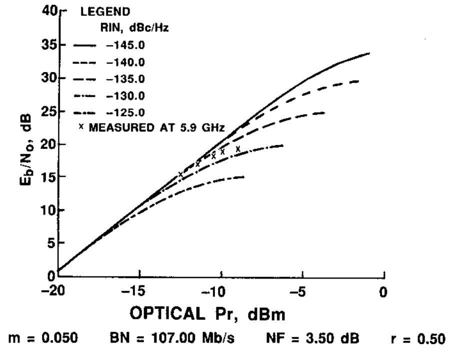

Figure 2. E_b/N_o vs P_r at different values of RIN.

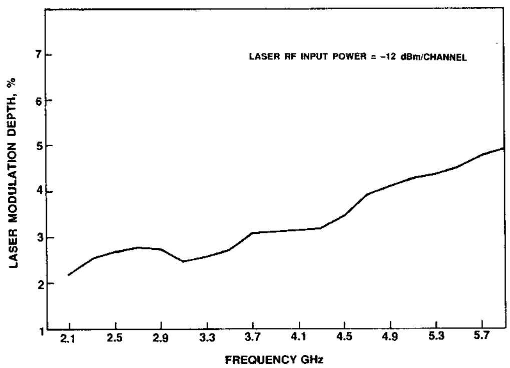

Figure 3. m_i vs frequency with laser RF drive fixed at −12 dBm.

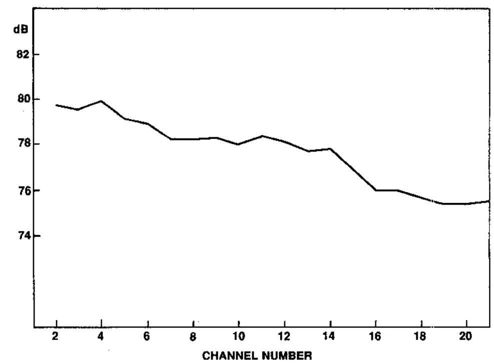

Figure 4. Receiver gain vs channel number.

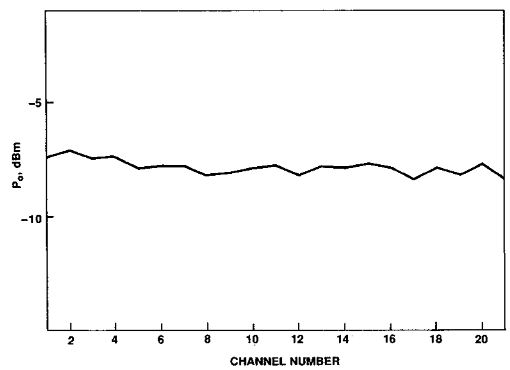

Figure 5. Available RF power vs channel number.

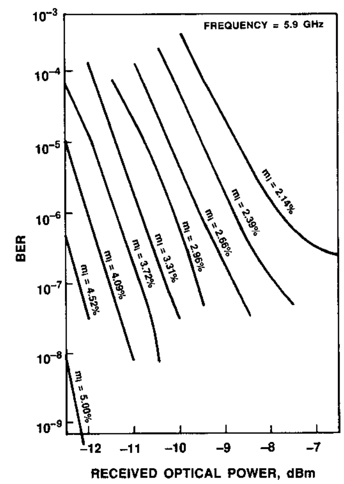

Figure 6. Measured BER vs received optical power.

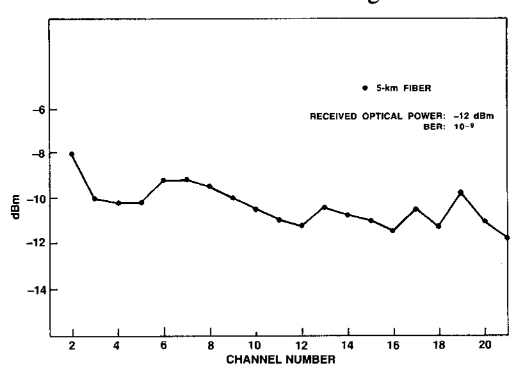

Figure 7. Minimum laser RF drive vs channel number.