# AN FSK/FDM MULTIPLEXED FIBER OPTICS SYSTEM FOR MULTICHANNEL ASYNCHRONOUS DIGITAL DATA TRANSMISSION

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**Summary**. In this paper the use of frequency division multiplexing to reduce the cost of fiber-optic digital data interconnects is investigated. An analysis is performed to determine the level of multiplexing achievable for a typical optical cable link and the cost of the multiplexed link is compared to that of all-parallel transmission for link distances of 0.5, 1.0 and 2.0 km and data rates of 100 kb/s and 1 Mb/s. The results of this work show that for the present and the near-term future, at least, multiplexing offers substantial cost savings over all-parallel transmission.

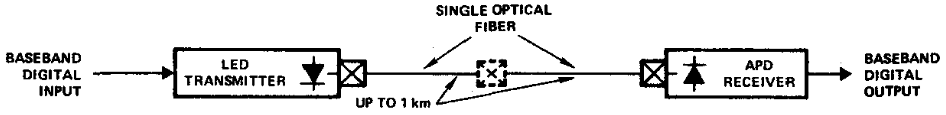
**Introduction**. The amount and complexity of computing equipment colocated within a facility is on the increase, creating a need for more complex interconnecting networks between and within buildings. These interconnects often consist of multiple, full-duplex asynchronous digital channels interconnecting computers and peripherals at data rates from a few hundred bits per second to over 6 Mb/s.

Fiber optics components are being used more and more today to perform these interconnects, since they offer a wideband, EMI/EMP link that is cost competitive. These components can be used in an all-parallel fashion, where each data channel has a dedicated fiber optics transmitter/receiver pair, and a single fiber channel of the cable. However, fiber optics components also exist that have sufficient bandwidth and transmission fidelity to allow multiplexing techniques to be incorporated. Time division multiplexing (TDM) approaches can be used, but the resulting hardware complexity is often excessive. This is particularly true when the input channels change in bit rate and format as the facility computing capability increases.

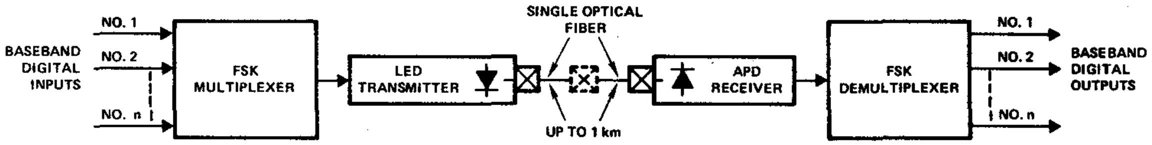
Frequency division multiplexing (FDM) of these channels using digital modulated subcarriers is not only feasible, but can offer significant cost savings over an all parallel approach. This paper presents the trade between these two approaches for various link distances and link cost assumptions.

The FDM plan is determined by the number and bit rate range of the channels to be interconnected. Other key parameters are link distance, allowable crosstalk, and the transparency of the electro-optical components. A model of the transmission channel is included in the next section, and will be used to analyze link performance under a set of assumed distances, number of channels, and channel rates. This analysis will be used to determine under what conditions the use of FDM techniques offers cost advantages over the all-parallel approach.

**Transmission System Models**. Two alternative approaches to the transmission of asynchronous digital data via optical fiber cable are shown in Figure 1 . Figure 1a depicts the all-parallel approach, in which a single optical fiber path and an optical transmitter-receiver set are dedicated to each of the data channels. Such links in the data rate and distance ranges of concern in this paper (0.1-1 Mb/s and 0.5-2.0 km, respectively) are quite practical today. For this reason, no discussion of the performance of all-parallel or dedicated links will 66 included here.



(A) ALL-PARALLEL APPROACH (ONE CHANNEL SHOWN)



(B) FSK/FDM APPROACH

☒ = SINGLE-FIBER CONNECTOR

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**Figure 1 . Two Approaches to Asynchronous Digital Data Transmission Using Optical Cable Components**

The number of optical fibers and optical transmitter-receiver sets required for the transmission of a number of data channels may be reduced through the use of multiplexing. The economy of this approach, of course, depends on the relative costs of the multiplexer-demultiplexer hardware, the electro-optical components and cable, and on the degree of multiplexing which can be achieved. For asynchronous data signals, frequency division multiplexing (FDM) is an attractive choice. Figure 1b shows an FDM system which uses frequency shift keying (FSK) to modulate the baseband data signals onto subcarriers. The composite subcarrier signal is used to intensity modulate the LED transmitter. At the receive terminal the composite signal from the APD receiver is separated into the individual subcarriers which, in turn, are demodulated to provide the baseband digital outputs.

FSK is a subcarrier transmission technique which can be readily implemented using voltage-controlled oscillator (VCO) modulators and limiter-discriminator demodulators. When properly implemented, this noncoherent FSK technique offers near-optimum performance (i.e., coherent detection and matched filtering) and is conservative of bandwidth[1,2,3]. In restricted bandwidth, the performance of noncoherent FSK approaches and can even surpass that of coherently detected phase shift keying (PSK). A further advantage of noncoherent FSK is the elimination of the need to extract a carrier reference, an important consideration in burst data systems. The remainder of this section deals with the degree of multiplexing which can be achieved using noncoherent FSK and currently practical optical cable transmission components.

Two factors limit the amount of multiplexing which can be accomplished with an optical cable link. The first of these is the modulation bandwidth of the optical transmission link, including the optical transmitter, the cable and the optical receiver. Second is the energy contrast ratio ($E_b/N_o$) which can be delivered to each channel of the multiplexer. Table 1 summarizes the pertinent characteristics of the optical transmission link which will be examined. These characteristics are representative of currently available components.

An estimate of the modulation frequency response for the total optical link has been computed for three link distances, 0.5, 1.0 and 2.0 km. The results of this computation are shown in Figure 2. An examination of the power spectrum for FSK with NRZ data[4] shows that n channels of rate R can be accommodated in a total bandwidth given by

$$B = 2.5\ (n-1)\ R+R \tag{1}$$

with better than 30 dB channel-to-channel isolation. This result assumes peak-to-peak frequency deviations of 0.7R and predetection filter bandwidths of 1.0R for each channel. These parameters are known to be near-optimum in terms of bit error rate (BER) Performance. Four-pole Bessel (linear phase) predetection filters are assumed. Using Equation (1) the modulation frequency responses of Figure 2, and not allowing any subcarrier signals below 2 MHz, leads to the bandwidth limits on the number of 100 kb/s and 1 Mb/s FSK/FDM channels which can be supported by the optical links. These limits are tabulated in Table 2. Again, this is the limit imposed by available optical channel modulation bandwidth and does not include the effects of noise and receiver sensitivity.

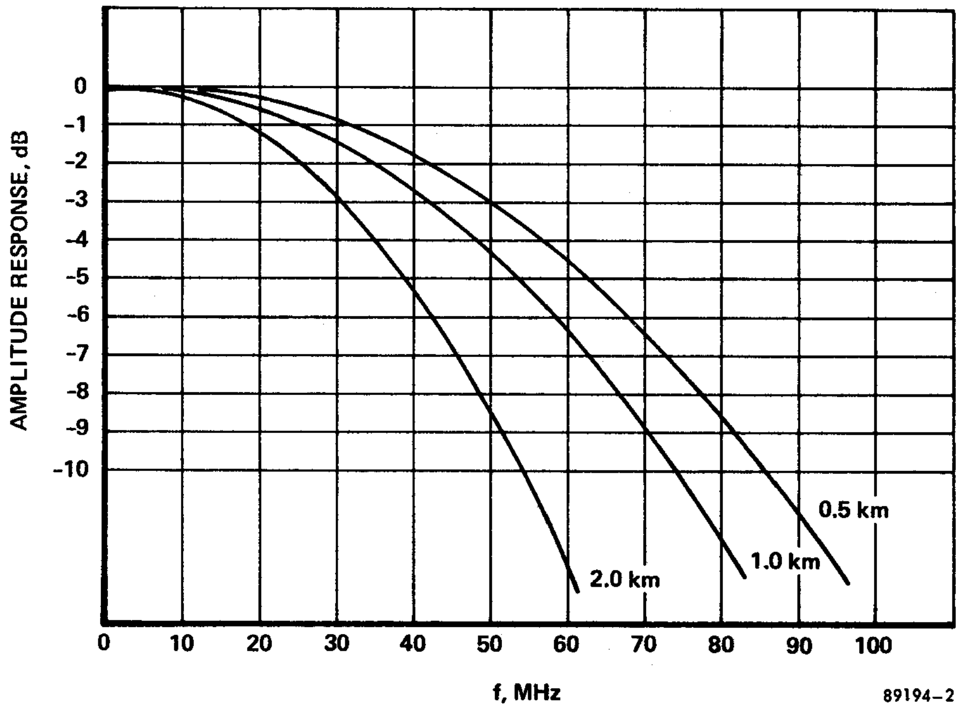

Figure 2. Modulation Frequency Response
of the Optical Cable Link

## Table 1. Optical Link Characteristics

| | |
|---|---|
| 1. TRANSMITTER: | HIGH RADIANCE LED WITH SINGLE, LOW-LOSS FIBER STUB ATTACHED, TERMINATED IN SINGLE-FIBER CONNECTOR<br>OPTICAL POWER OUTPUT -100,µW AVERAGE OUT OF FIBER STUB<br>MODULATION BANDWIDTH - 70 MHz (3 dB), SINGLE-POLE CHARACTERISTIC |
| 2. OPTICAL CABLE: | TEN-FIBER STRUCTURE USING LOW-LOSS GRADED-INDEX FIBERS<br>ATTENUATION - 10 db/km<br>MODULATION BANDWIDTH - 200 MHz-km WITH LASER SOURCE 70 MHz-km WITH LED SOURCE |
| 3. OPTICAL CONNECTORS: | SINGLE-FIBER COMPATIBLE<br>INSERTION LOSS - 2 dB (GRADED-INDEX FIBER) |

| | |
|---|---|
| 4. RECEIVER: | APO WITH SINGLE, LOW-LOSS FIBER STUB ATTACHED, TERMINATED IN SINGLE FIBER CONNECTOR; LOW-NOISE AMPLIFIER<br>UNITY GAIN RESPONSIVITY - 0.5 A/W<br>AVALANCHE GAIN - 80<br>EXCESS GAIN NOISE FACTOR - 3.7<br>MODULATION BANDWIDTH - 70 MHz (3 dB), 2-POLE CHARACTERISTIC<br>FIBER STUB/APD TERMINATION LOSS - 2 dB |

## Table 2. Optical Link Bandwidth Limit on the Number of FSK/FDM Channels Per Fiber

| LINK DISTANCE (km) | n (100 kb/s) | n (1 Mb/s) |
|---|---|---|
| 0.5 | 192 | 19 |
| 1.0 | 164 | 17 |
| 2.0 | 116 | 12 |

where

$M$ = intensity modulation index of the subcarrier
$r$ = unity gain responsivity of the APD
$G$ = avalanche gain
$P$ = average optical carrier power incident on the detector
$q$ = charge on an electron
$F_d$ = excess gain noise factor of the APD
$R$ = channel bit rate

With a well-designed APD receiver, the noise performance is substantially quantum noise limited. Thus, the $E_b/N_o$ which can be delivered to each demultiplexer channel is approximately[5]

$$\frac{E_b}{N_o} = \frac{(1/2)M^2 r^2 G^2 P^2}{2qrG^2 F_d PR} = \frac{(1/4)M^2 rP}{qF_d R} \qquad (2)$$

If the amplitude distribution of the composite FSK/FDM signal is taken to be Gaussian (a good approximation for more than about 10 subcarrier signals), then it may be shown that by choosing

$$M = \frac{0.35}{\sqrt{n}} \tag{3}$$

80% intensity modulation is exceeded only 0.14% of the time and that the rms intensity modulation is only 25%. At this drive level, a well-designed LED transmitter should exhibit distortion better than 35 dB down from the signal. This result assumes that all n channels are active 100% of the time. In a practical system, such is likely not the case and improved performance could be obtained through the use of AGC (with proper attention paid to the composite signal crest factor) to adjust to varying levels of channel activity. However, the approach described by Equation (3) is simple and conservative and will be used for the purposes of this paper. Substituting Equation (3) into Equation (2) yields

$$\frac{E_b}{N_o} = \frac{0.03rP}{qnF_dR} \tag{4}$$

For the optimized noncoherent FSK system, a $10^{-9}$ BER can be achieved with $E_b/N_o$ = 16 dB[1,2,3]. If we add to that 3 dB for "practical implementation" and 6 dB for link margin, the required $E_b/N_o$ = 25 dB.

The data in Table 1 may be used to compute the average optical power incident on the photodetector for each distance of interest. These values are given in Table 3. In the case of the 2.0 km link, a third, in-line, optical connector is assumed.

**Table 3. Average Optical Carrier Power Incident on the Photodetector**

| L (km) | P (µW) |
|---|---|
| 0.5 | 7.9 |
| 1.0 | 2.5 |
| 2.0 | 0.16 |

Now the energy contrast ratio limit on the number of FSK/FDM channels per fiber can be computed using Tables 1 and 3 and Equation (4). The results appear in Table 4. The limits shown in Table 4 are those due to source power, link attenuation and receiver performance alone and do not account for the bandwidth of the optical channel.

### Table 4. Optical Link Energy Contrast Ratio Limit on the Number of FSK/FDM Channels Per Fiber

| L (km) | n (100 kb/s) | n (1 Mb/s) |
|---|---|---|
| 0.5 | 6,300 | 630 |
| 1.0 | 2,000 | 200 |
| 2.0 | 128 | 12 |

A comparison of Tables 2 and 4 indicates that in all cases except the 1 Mb/s, 2.0 km case, the degree of multiplexing achievable is limited by available optical link bandwidth rather than by link noise performance. This, of course, suggests the possibility of equalizing the optical link frequency response at the expense of a noise penalty. This possibility will not be explored here, however. The remainder of this paper will investigate the economy of the level of multiplexing predicted in Table 2.

**Cost Comparisons of All-Parallel and FSK/FDM Approaches**. Table 2 of the previous section has established the level of multiplexing that can be achieved for the example links of interest in this paper. In this section, the relative costs of the all-parallel and FSK/FDM approaches are compared. The criterion for comparison is the cost per simplex channel as established by the cost of the optical transmitters and receivers, the cable, connectors and FSK hardware. Equipment common to both approaches such as racks and power supplies are not included in the cost. Of course, in the FSK/FDM case, the cost of the optical and electro-optical hardware is shared by more than one simplex channel. Installation costs are not considered.

Projected equipment and optical cable costs for the next 3 years are shown in Table 5. Note the assumed reductions in electro-optical components as the technology matures over the next 5 years. No reduction in FSK/FDM hardware is projected and the figures of Table 5 do not reflect any increases due to inflation, etc.

### Table 5. Hardware Cost Projections

|  | 1976 | 1977 | 1978 |
|---|---|---|---|
| TRANSMITTER/RECEIVER SET | $2,000 | $1,500 | $1,000 |
| CABLE (10 FIBER CHANNELS) | $27/m | $13.50/m | $6.25/m |
| CONNECTORS | $200 | $100 | $75 |
| FSK/FDM SIMPLEX CHANNEL | $2,000 | $2,000 | $2,000 |

Since the cost of the jacket, etc., must be included in the cable cost, an existing 10-fiber cable structure was chosen for the cost projection, rather than a simple rule such as 50¢/fiber foot. Cable installation is not included in the cost data.

The cost per simplex channel for the all-parallel approach has been computed for the three link distances using the cost assumptions of Table 5. The results of this computation are shown in Table 6. Table 7 summarizes the cost per simplex channel as a function of link distance and data rate for the levels of multiplexing predicted in Table 2.

**Table 6. Cost Per Simplex Channel - All Parallel**

| L(km) | 1976 | 1977 | 1978 |
|---|---|---|---|
| 0.5 | $3,750 | $2,375 | $1,463 |
| 1.0 | $5,100 | $3,050 | $1,775 |
| 2.0 | $8,000 | $4,500 | $2,475 |

**Table 7. Cost Per Simplex Channel - FDM**

| | 1976 | | 1977 | | 1978 | |
|---|---|---|---|---|---|---|
| L (km) | 100 kb/s | 1 Mb/s | 100 kb/s | 1 Mb/s | 100 kb/s | 1 Mb/s |
| 0.5 | $2,019 | $2,197 | $2,012 | $2,125 | $2,008 | $2,077 |
| 1.0 | $2,031 | $2,300 | $2,018 | $2,179 | $2,010 | $2,104 |
| 2.0 | $2,068 | $2,667 | $2,039 | $2,375 | $2,021 | $2,206 |

Observe that the cost saving offered by the FDM/FSK approach is significant at today's prices, especially for the longer link distances. In 1977 the cost advantages of multiplexing are still substantial. However, by 1978 the cost advantage for multiplexing a 2.0 km link is small, and in fact for shorter distances the all-parallel approach appears to be the most economical one if the fiber optics equipment costs decrease as assumed. The assumed cost reductions for the fiber optics components are perhaps optimistic, especially with regard to the cable. Furthermore, the projected cost figures for 1978 are at best speculative since it may not be realistic to assume the use of today's existing components for a system to be implemented 3 years from now.

**Conclusions**. The use of frequency division multiplexing to reduce the cost of multichannel digital data interconnects using optical fiber cables has been investigated. A theoretical analysis was performed to determine the degree of multiplexing achievable on a typical fiber-optic link. A cost comparison of all-parallel data transmission and FSK/FDM transmission was carried out based on projected costs of fiber-optic components and FSK/FDM hardware for the next 3 years. This study shows that for today and for the near-term future, multiplexing offers significant cost savings over the all-parallel approach. However, the results of this work predict that all-parallel transmission will be more economical by 1978 if the costs of fiber optics components, particularly cables, decrease as assumed. This conclusion should be regarded as tentative only, though, because of the uncertainties involved in predicting component costs and, indeed, even what technology will be available 3 years in the future.

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