Fibernet: Multimode Optical Fibers for Local Computer Networks

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(Invited Paper)

***Abstract*—Local computer networks which communicate over copper conductors have been developed both to promote resource sharing and provide increased performance. Such networks typically operate at bandwidth·length ($Bw{\circ}L$) products up to a few MHz∘km. In this paper we consider the use of fiber optics in such networks, and give a status report on a star-configured fiber optic network experiment called Fibernet which operates at a $Bw{\circ}L$ product of ~100 MHz∘km at a data rate of 150 Mbits/s and which in its final phases will connect up to 19 stations. We compare the merits and problems of linear, ring and several star configurations, and of active versus passive networks. The packet communication protocol is discussed and network efficiency is calculated as a function of the packet length, channel capacity and network propagation time. We describe the system performance of the present Fibernet experiment, which uses a 19-port transmissive star coupler, GaAlAs injection lasers and avalanche photodiodes, and incorporates bi-phase data encoding. Power distribution inhomogeneities, observed in the output of the transmissive star coupler's mixer rod, are explained geometric-optically.**

INTRODUCTION

It is not very controversial these days to claim that fiber optic communication technology is a major advance with great promise [1,2,3,4,5]. There are many who would agree that all of the essential components of this technology are at hand, with no major conceptual breakthroughs required. But there are those who ask, if the technology has promise and is at hand, why optical fibers have not yet found wide application[5]? One answer is that there are no standards, no repertoire of widely available, interchangeable, and interconnectable fiber optic components with which to configure serviceable systems. The technology exists to produce such a repertoire of components, but, without standards, neither the producing nor using industries can develop enough volume to achieve promised economies. Another answer is that pre-optical communication technology is still rather effective in serving yesterday's applications, and in many areas of communication only marginal gains, if any, are to be found by straightforwardly replacing existing copper with new silica. The enormous promise of optical fiber communications will largely be realized in new applications, one of which is local computer networks.

LOCAL COMPUTER NETWORKS

As computers have become smaller and more numerous, the reasons for interconnecting them have grown more than in proportion. Remote computer networks like the Arpanet have been developed to promote resource sharing; for example the sharing of expensive specialized processors, software, and data bases[6,7,8]. Multiprocessor computer configurations like the Illiac IV have been developed to get the increased performance of multiple computers working simultaneously on the same problem for either improved thruput or reliability[9]. Local computer networks like Ethernet[10] have been developed for reasons resembling those of both remote computer networks and multiprocessors. The experimental Ethernet, in particular, connects up to 256 communicating computers at 3 megabits per second (Mbits/s) through up to 1 km of coaxial cable. This paper is a status report on an experimental fiber optical local computer network, called Fibernet, which in its final phases will connect up to 19 stations at 150 Mbits/s through up to 1/2 km of optical fiber.

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CONFIGURATION

The emerging and evolving requirements of local computer networking were well met by Ethernet in 1976 as it carried 3 Mbits/s among 256 stations through 1 km of repeaterless coaxial cable. Straightforward substitution of fiber optic components for Ethernet electronics would result in what might be called an optical Ethernet, a bidirectional passively teed network, as in Figure 1. Such a configuration can in principle support much higher data rates over greater distances; that is, operate at a much higher bandwidth-length product ($Bw{\cdot}L$). However, two problems exist with such a substitution. First, the insertion loss of tee connections and associated connectors and splices must be very low, no more than a few tenths of a dB per station for useful numbers of terminals to be possible[11,12]. When Fibernet was begun, insertion splice and connector losses were sufficiently high to make the permissible number of stations unattractively low. Recently, Kawasaki and Hill[13] have described a tapered, fused fiber tap with insertion losses of 0.1 to 0.2 dB; so this impediment to linear teed networks may no longer exist. The second problem in making a linear, bidirectional teed network is that reflections at connectors, splices and tees should be sufficiently low to permit each station to monitor, while transmitting, for other interfering signals on the data bus without such an interfering signal being masked by the station's own reflected signal. Kawasaki and co-workers[14] demonstrated point-to-point bidirectional communication over a single fiber, using the tees described earlier and avoiding the use of connectors or other components in the line at which reflections could occur. In spite of

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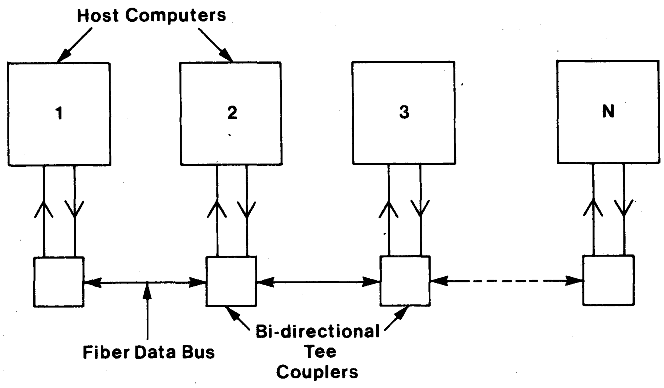

Figure 1. Optical Ethernet: linear, single-fiber bidirectional passively teed network.

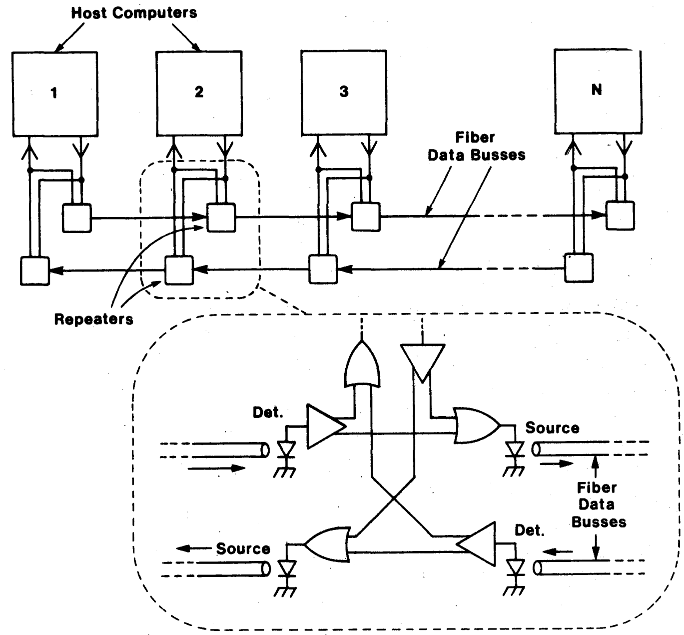

Figure 2. Linear, double-fiber unidirectional repeatered tee network.

this achievement, however, it is not clear that bidirectionality, in a single-fiber *multiterminal* network is yet practical. For these reasons, in developing the experiment we call Fibernet, we had to consider configurations which do not follow directly that of Ethernet.

One configuration which minimally distorts the highly desirable Ethernet topology is the unidirectional actively teed network, as in Figure 2. Two fibers are carried from station to station each carrying light in one direction. Each transceiver has four fiber terminations, two receivers and two transmitters. Each transceiver serves as a repeater for light travelling in each direction. While repeated transmissions are still in electrical form inside each transceiver, signals are received for the station by merging from each optical detector and are transmitted by driving each optical source, as shown in the inset of Figure 2.

The advantage of this two-fiber active optical Ethernet is that signaling is performed under the most favorable conditions, using point-to-point, unidirectional data links between repeaters. The relatively low *Bw•L* for such links permits the use of inexpensive and reliable sources, fibers, connectors, and detectors. The routing of two fibers rather than only one offers no practical disadvantage in local computer networks owing to the high cost of installation relative to the low cost of fiber; fibers are sufficiently small that two are still small compared to the equivalent coaxial cable. The disadvantages of the two-fiber active optical Ethernet configuration are that four fiber terminations must be made and that the transceiver must be centrally powered to sustain network operation during individual station outages. Central power would require copper wire to accompany the fibers from station to station, increasing the cable's cost, weight and size. Finally, the reliability of powered and actively repeating components is lower than that of passive components such as are used in Ethernet.

Departing from Ethernet topology we considered two other general configurations, the star and the ring. Fiber optic star networks, some resembling Fibernet, have been proposed and studied analytically[11,15]. Yajima and co-workers[16] have described a local computer network experiment with four point-to-point optical data links using single-fiber-per-channel cables in a star repeater configuration and operating up to 4 Mbits/s. McMahon and Gravel[17] described an eight-terminal star repeater experiment using bundle-per-channel cables and operating at 10 Mbits/s. Others have reported work on single fiber-per-channel star couplers around which a star network might be designed[18,19,20]. The fiber optic ring, which we call Halo, seems to have been missed.

The fiber optic ring, Halo, is a closed ring of active repeaters which circulate light in one direction, as in Figure 3. This configuration follows from a straightforward substitution of optical components for twisted pair electronics in the so-called Irvine Ring[21,22], developed by the University of California at Irvine to support a local computer network for a distributed computer operating system. Halo is similar to the two-fiber optical Ethernet in that unidirectional signaling is performed under the most favorable point-to-point conditions using low *Bw•L* cables and inexpensive components. While the routing of a closed ring of fibers is less convenient than a linear network, the efficiency of bandwidth sharing among stations is higher. Active regeneration of optical signals at each station is required for ring operation because a bit must be delayed for possible modification. The disadvantages of Halo are, again, that active regeneration at each station is less reliable than passive tapping, as in Ethernet, and that central power distribution is to be avoided.

Four star configurations were considered as alternatives to the linear and ring networks. The first was the circuit switching optical crossbar[23] which we eliminate on the basis of its unsuitability to packet switching[25,8]. The second was the star repeater network[16,17], illustrated in Fig. 4, which we avoid for now because it is active, although its activeness is localized to a single point and is therefore less disadvantageous than that of the active optical Ethernet or Halo. The third and fourth alternative configurations are the reflective star coupler shown in Fig. 5, and transmissive star network shown in Fig. 6. Both offer a passive transmission medium.

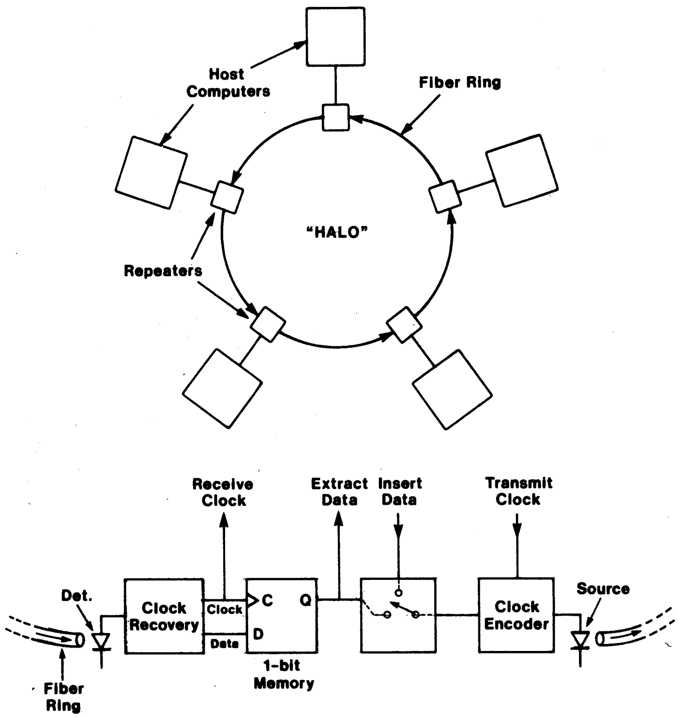

Figure 3. "Halo", a unidirectional repeatered loop network.

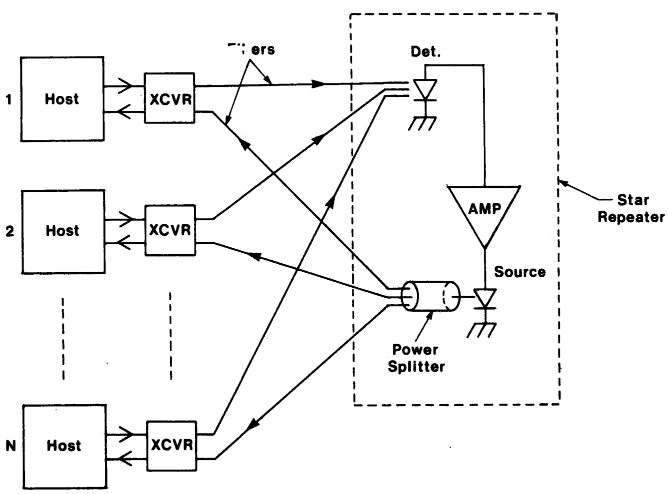

Figure 4. A star repeater network.

Both star coupler networks and the star repeater network require that fibers be run from each station to a central point. The reflective star coupler requires that only one fiber be routed from station to star, but this one fiber must carry light both to and from the star with the difficulties of bidirectionality discussed earlier. This leaves us with the transmissive star coupler network used in Fibernet, Figure 6.

Fibernet's transmissive star coupler has the advantage, as in Ethernet, that the shared transmission medium is passive and unpowered. It has the advantage that light transmission is unidirectional and that the number of splices and connectors between any two stations is small and independent of the number of communicating stations. The star is an unattractive topology because of the number and length of fiber cables required. For example, consider the hypothetical case of N

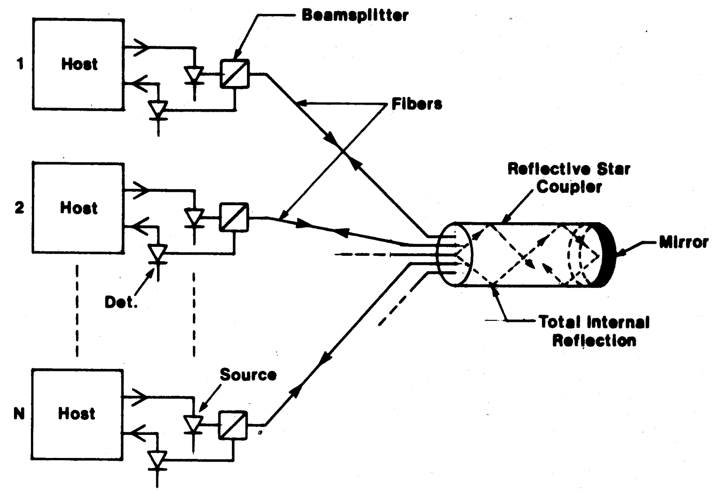

Figure 5. A passive, reflective star network.

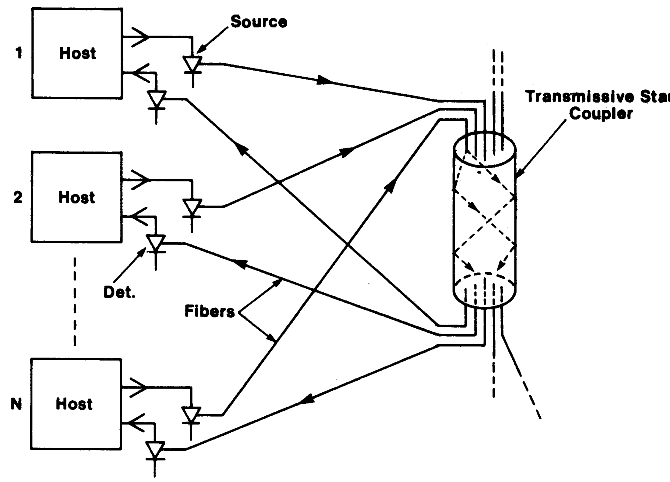

Figure 6. A passive, transmissive star network. This is the configuration adopted for Fibernet.

stations located along a circular path of radius R. Ethernet and Halo-like connection requires a $2\pi R$ length of cable, whereas a star-configured net requires a $2NR$ length of cable; the ratio is N/π, a substantial increase in cable requirements for N of order 100. Additionally, stations subsequently added along the path require shorter connection lines for linear or ring nets than for star networks, with correspondingly lower connect costs. With this mix of pros and cons we chose Fibernet as our initial experimental configuration.

PROTOCOL AND EFFICIENCY

From the standpoint of communication protocol, rather than of transmission technology or topology, Fibernet is Ethernet. The principles of distributed packet switching embodied in Ethernet have proven sound for local computer networking.

Ethernet packet switching is distributed in two senses: first in the way that packets are put into the so-called ether, and second in the way packets are removed from the ether by intended destinations. Packets are switched from the ether using simple broadcast address recognition distributed among the stations. Packet interweaving is a bit more unusual. In short, a packet is transmitted by a station only after the station determines that no previous transmission is still in progress. During transmission of its own packet, a station monitors the ether looking for a colliding packet transmission from another station. If interference is not detected, packet transmission runs to completion; otherwise, transmission is immediately aborted and rescheduled for some randomly chosen time later. When this procedure is followed at each station contending for transmission time on the ether, the result is statistical multiplexing of the communication medium in Ethernet; a coaxial cable, and in Fibernet the optical fibers and the star coupler.

The efficiency of statistical multiplexing schemes like Ethernet's has been extensively analyzed[24,25,26]. Gross performance figures for Fibernet can be calculated[10] using a simple Ethernet model in which the efficiency E is related simply to packet length P in bits, the ether's capacity C in bits per second, and T, twice the time in seconds for a packet to propagate from one end of the ether to the other. The efficiency E is that fraction of the available peak bit rate used to carry uncollided packets in a fully loaded ether; it is also the ratio of time spent with packets being successfully transmitted to time spent in contention intervals, with collisions and silence wasting bandwidth. The efficiency is given by[10]:

$$E = \frac{(P/C)}{(P/C) + (1.7T)}.$$

For Ethernet, typical efficiencies are well over 90% with 4000 bit packets being carried through $T = 16$ μs of cable at $C = 3$ Mbits/s. For Fibernet, with its capacity $C = 150$ Mbits/s and propagation velocity of ~2×10^8 m/s, only smaller ether diameters or larger packet sizes yield efficiencies near 1, as shown in Table I. It can be seen that, for a Fibernet diameter up to ~1 km, a minimum packet length of several thousand bits is required to maintain reasonable efficiencies.

FIBERNET ELECTRONICS

Figure 7 shows a schematic and Fig. 8 shows a photograph of the Fibernet system in its present test configuration. Pseudo random NRZ (non-return to zero) test data are generated at 150 Mbits/s with a HP Model 3760A data generator. The biphase encoder is of conventional design and uses Fairchild F100K series ECL logic components. The driver circuit uses paralleled F100114 ECL driver gates and can swing 75 mA with rise and fall times of less than 2 ns. Various GaAlAs double heterostructure laser sources have been used successfully in Fibernet, including ones made at Xerox's Palo Alto Research Center; most of the results reported here, however, were attained using an RCA C30130 injection laser. Figure 9 is a microphoto showing the laser die on its header aligned to radiate into an optical fiber. A spherical coupling lens has been formed on the fiber end, using a small oxyacetylene torch[27], to enhance the coupling efficiency. Optical power at 850 nm coupled into the fiber is typically 1 to 3 mW.

TABLE I
FIBER EFFICIENCY E (SEE TEXT) FOR VARIOUS PACKET LENGTHS P AND NETWORK DIAMETERS D

	Network Diameter D (meters) [2 x Propagation Time T (μsec)]		
Packet Length P (bits)	125 m [1.25 μsec]	500 m [5.0 μsec]	2000 m [20 μsec]
256	44%	16%	5%
4096	93%	86%	44%
65,536	99.5%	99%	93%

The fiber cables and connectors are made by Siecor GmBH, and contain Corning type 1151 graded index fibers with a 62.5 μm core, a 125 μm cladding, and a nominal $Bw \cdot L$ product of 400 MHZ•km. The 19-port star coupler is described in the following section.

Avalanche photodiodes (RCA type C30884) are used as detectors. The preamplifier circuit is of conventional bipolar design. The biphase decoder is also implemented with F100K ECL logic. Finally, the recovered clock and NRZ data go to a HP Model 3761A bit error rate (BER) detector.

THE 19-PORT TRANSMISSIVE STAR COUPLER

Figure 10 is a drawing of a 7-port transmissive star coupler[28]. The input fibers are passed through a tapered capillary tube[29] to form a close-packed hexagonal array. The assembly is epoxied, then ground and polished. A similar array of output fibers is coupled to the first array using a clad mixing rod whose numerical aperture matches that of the fibers, and the three components are cemented with index-matching epoxy. Figure 11 shows the assembled 19-port transmissive star coupler. The number of ports, 7 and 19 in these two cases, is determined by the number of layers, k, of hexagonally close-packed fibers enclosed by the capillary tube. In general, the number of fibers in k layers is $N_k = k^3 - (k-1)^3$ yielding $N_2 = 7$ and $N_3 = 19$.

Insertion loss in the best prototype 7-port star coupler was −7.4 dB, averaged through all ports. Of this loss, −7.1 dB is attributable to the fraction of the area of the mixer rod output end which abuts the core area of an output fiber; the so-called "packing fraction" loss. The 19-port star had an insertion loss of 10.0 dB. The packing fraction loss of such star couplers could be reduced by approximately 4 dB by acid etching the fiber ends[11] to improve the packing fraction, but this was unnecessary in this experiment and was not attempted.

POWER DISTRIBUTION INHOMOGENEITIES

An anomalously high coupling coefficient was noted between the central input and output fibers. Figure 12 shows photos of the output power distribution at the mixer rod output face, for two lengths of rod and for illumination on the input face at points located both on axis and at a point 2/3 of

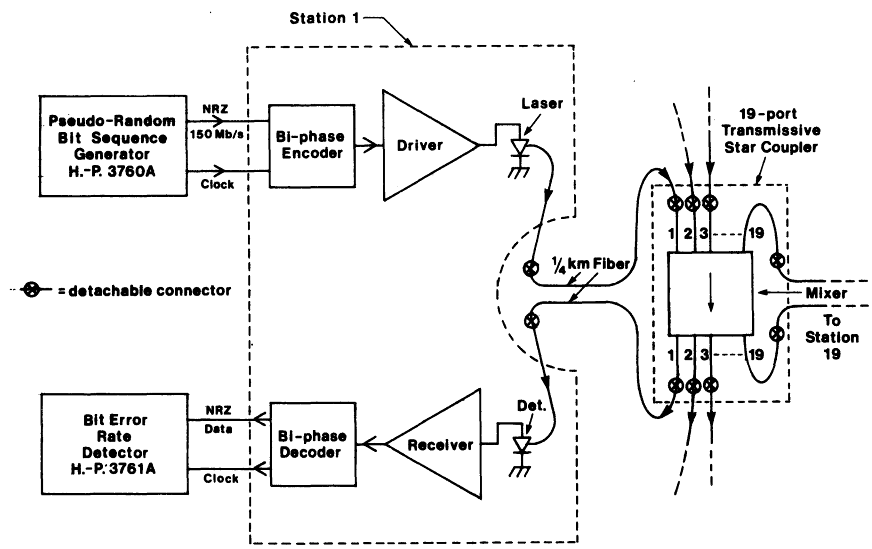

Figure 7. The Fibernet experiment: present test configuration.

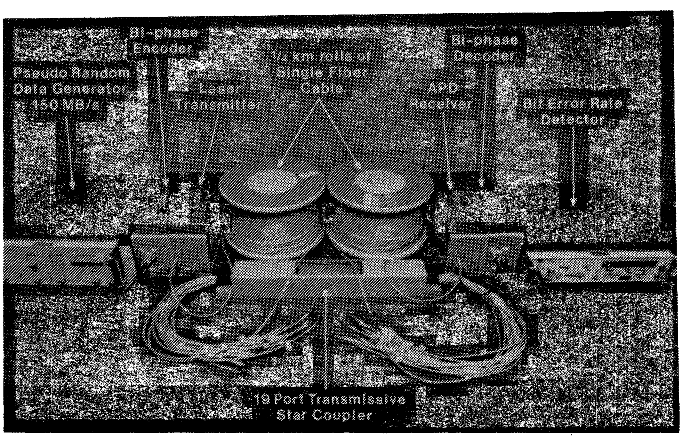

Figure 8. Photograph of the Fibernet experiment components.

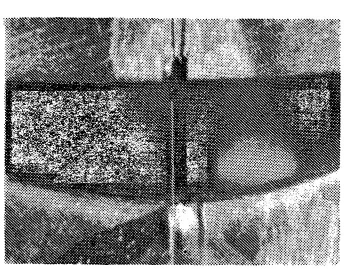

Figure 9. A GaAlAs laser die, mounted on a header, aligned to couple efficiently into an optical fiber on which a spherical lens has been thermally formed to improve coupling.

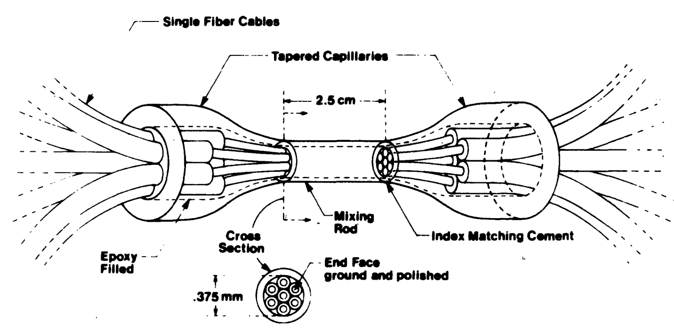

Figure 10. Drawing of a seven-port transmissive star coupler.

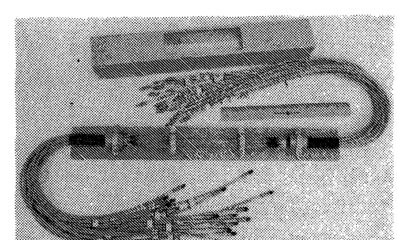

Figure 11. Photograph of a 19-port transmissive star coupler. The 10 cm long, clad mixing rod is visible in the center.

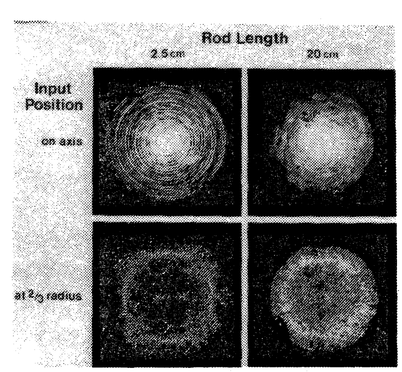

Figure 12. Photographs of the intensity distribution at the mixer rod output face, as a function of rod length and radial position of illumination. Off-axis illumination results in an annulus of enhanced brightness at the radius of illumination.

the distance to the outer circumference. The illumination beam was of numerical aperture (na) 0.16, the nominal na value of the fibers. For axial illumination, an axial output power concentration is seen for both short and long mixer rod lengths. The fine rings visible on the 2.5 cm rod output plane are due to interferometric effects and are not apparent at the longer rod length. For off-axis illumination, an annulus of enhanced output power density is visible at the same radius that power is injected into the rod; this ring also persists at the longer rod lengths.

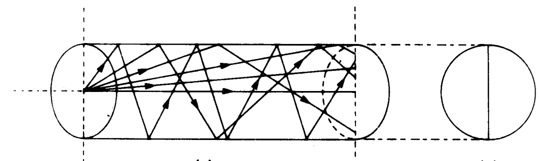

Figure 13. Meridional ray fan (a) and end projection (b).

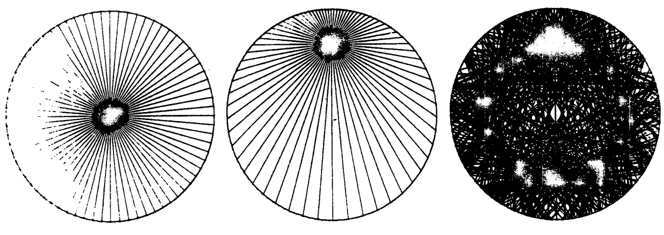

Figure 14. Computer drawn fan projections for (a) axial and off-axis illumination (b) before and (c) after 5 reflections. An annular power concentration, similar to those in Fig. 12 is visible in (c).

These power inhomogeneity effects can be qualitatively explained geometric-optically as follows. Consider the meridional fan of rays in Figure 13. If the rod is sufficiently long that most rays have undergone reflection, then the point of emergence of an arbitrary ray is equally likely to be at any radial position across the rod, and the vertical line projection of the fan seen at the right is thus an analog of the output power distribution due to the fan. If many such fans are considered (Figure 14a), it is clear that geometrical optics predicts an r^{-1} power distribution for axial illumination, explaining the bright central spots in Figure 12. Figure 14b shows the same fans injected off-axis, before reflections at the mixing rod surface have occurred, and Figure 14c shows a computer plot of the same fans after 5 such reflections. An annular power concentration, similar to those seen in Figure 12, is clearly visible. Other computer simulations, not shown, prove the generality of such an annular distribution for other illumination radii and numbers of reflections, confirming the geometric-optics origin of the effect.

In practice, the coupling coefficients between all ports (other than the two axial ports) are within 2 dB of the mean coupling value; the axis-to-axis coupling coefficient between the two axially located ports is about 5 dB higher than that average. Such an anomaly, which might be of consequence in other experiments, creates no problem in our systems application.

POWER LOSS DISTRIBUTION

Table II summarizes the nominal power loss distribution in Fibernet. We assume a minimum source power of 0 dBm (1 mW). Thus, since the passive fiber optical system losses total −36 dB, the net available receiver power is −36 dBm. The minimum receiver power required for an ideal NRZ pulse code modulated optical signal at 150 Mbits/s is approximately −47 dBm[1,3]. The power penalties associated with the biphase encoding/decoding process[30] (≅5 dB) and with incomplete laser modulation[31], referred to as "pulse on a pedestal", (≅3 dB) yield a net required power of −39 dBm. Thus the net power margin is ~5 dB. This is somewhat small for comfort. It could be substantially increased by using lasers with improved linearity of light output versus drive current. Such nonlinearities, called "kinks", which are due to transverse mode instabilities, or "mode hopping", and are present in most lasers commercially available at this time, cause data-dependent response, resulting in an increased probability of intersymbol interference. To avoid this problem, our lasers are modulated over a reduced current range within which adequate linearity is available. Elimination of kinks would permit the laser to be operated at its full rated power, increasing the minimum source power and reducing the incomplete modulation power penalty.

TABLE II
POWER LOSSES AND POWER MARGIN

Source Power	0 dBm
Laser-fiber coupling loss	-4 dB
Fiber loss (10 dB/km)	-5 dB
Connector loss (4 @ 1 dB)	-4 dB
Fiber-detector coupling loss	~0 dB
Star power division: 1/19	-11 dB
Star insertion loss	-10 dB
Total losses	-34 dB
∴ Power at Detector	-34 dBm
Min. Power Required (NRZ, data, 150 Mb/s, BER = 10^{-9})	-47 dBm
Bi-phase encoding power penalty	-5 dB
"Pulse on a pedestal" power penalty	-3 dB
∴ Power Required	-39 dBm
∴ Power Margin	+ 5 dBm

SYSTEM PERFORMANCE

The Fibernet experiment has carried 150 Mbits/s pseudorandom data over a 1/2 km distance, through the 19-part star coupler, with zero errors detected in a test sequence of 2×10^{11} pulses (about 22 min at 150 Mbits/s). In recent measurements at 100 Mbits/s, the system fiber length was increased to 1.1 km by looping one branch through a fiber cable installed in underground conduit between two laboratory buildings at the Xerox Palo Alto Research Center. The additional cable and two additional connectors contributed sufficient loss to require operation at the reduced data rate; a BER of 1.1×10^{-9} was measured. Pulse dispersion measurements through the long fiber link confirmed that its bandwidth is in excess of 300 MHz; hence the 1.1 km long Fibernet is not fiber bandwidth limited at 150 Mbits/s.

It should be noted that BER's of the order 10^{-9} are more than satisfactory in this system application because error detection is provided in the packet handling procedures, and packets are re-transmitted in the event of an error. For packet lengths of order 10^3 bits, a BER as high as 10^{-6} would still only require retransmission of one packet per thousand.

ERROR PROBABILITIES

Webb, McIntyre and Conradi[32] give an approximate expression for the probability of observing m output electrons from an avalanche photodiode given $\bar{n}$ injected (primary) photoelectrons which can be written after normalization as

$$P_{\bar{n}}(m) \cong \frac{1}{(2\pi)^{1/2}\sigma[1 + (m - \bar{n}M)/\sigma\lambda]^{3/2}} \cdot \exp - \left[\frac{(m-\bar{n}M)^2}{2\sigma^2[1+(m-\bar{n}M)/\sigma\lambda]}\right]$$

where $\lambda = (\bar{n}F_e)^{1/2}/(F_e-1)$, $\sigma^2 = \bar{n}F_eM^2$, k is the ionization ratio, M is the mean gain, and $F_e \cong kM + (2 - 1/M)(1 - k)$ is the excess noise factor for electrons.

To calculate error probabilities we consider the "false alarm" case (a "0" registers as a "1") and the "miss" case (a "1" registers as a "0"). If $\bar{n}_1$ and $\bar{n}_0$ are the mean numbers of primary electrons for a "1" bit and a "0" bit, respectively, then the false alarm probability is given by

$$P_{fa}(m_t) = \sum_{m=m_t}^{\infty} P_{\bar{n}_0}(m),$$

and the miss probability is given by

$$P_{miss}(m_t) = \sum_{0}^{m_t-1} P_{\bar{n}_1}(m),$$

where m_t is the detection threshold for the output electrons. Figure 15 shows P_{fa} and P_{miss} as a function of threshold m_t, using representative values of the ionization ratio k (.02) and the mean gain M (100), for a range of values of $\bar{n}_0$ and $\bar{n}_1$. This figure illustrates the effects on error rate and optimum threshold of average power changes and incomplete laser extinction (pulse on a pedestal). For example, if $\bar{n}_1 = 250$ and the modulation ratio is large ($\bar{n}_0 < \sim 4$), the error rate is $<10^{-9}$ and the optimum threshold (where $P_{fa} = P_{miss}$ so that $P_{fa} + P_{miss}$ is minimum) is just over 10^4 electrons/bit. If the modulation ratio is less, say 4:1, then $\bar{n}_0 \cong 31$; the error rate rises close to 10^{-6} and the optimum threshold is $\sim 1.3 \times 10^4$. This increase in the error rate can be compensated by accepting a power penalty and increasing the power level of both the "0" and "1" signals. For example, a 3 dB increase to $\bar{n}_1 = 500$, $\bar{n}_0 = 62$ lowers the error rate below 10^{-11} at a threshold of $\sim 2.5 \times 10^4$.

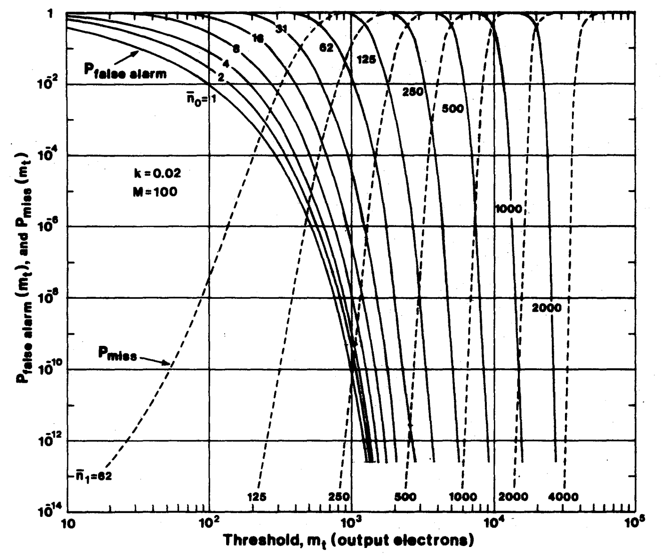

Figure 15. Calculated false alarm and miss probabilities vs. output threshold for an avalanche detector; $\bar{n}_0$ and $\bar{n}_1$ are the numbers of primary photoelectrons for 0-bits and 1-bits, respectively.

It should be pointed out that Figure 15 does not include the effect of amplifier noise; when such noise is taken into account, error rates rise. Additionally, Figure 15 assumes a particular value of average gain M. When amplifier noise is considered, there exists an optimum value of M, in general different from the one assumed in Figure 15, at which the detector noise equals the input equivalent noise of the amplifier. In spite of these limitations, it is of interest to examine Figure 15 for consistency with the error rates observed in the Fibernet experiment, viz. $<10^{-11}$ at 150 Mbits/s. The optical power received at the detector corresponds to $\bar{n}_1 \cong 4000$. With a modulation ratio $\geqslant$4:1, $\bar{n}_0 \leqslant 1000$. Thus, Figure 15 predicts an error rate of $<10^{-14}$, consistent with experiment.

CONCLUSION

There are several well-known attributes of fiber optics which might lead one to choose to use fiber optics rather than coaxial cable for a local computer network. These include a higher $Bw \cdot L$ product, potentially lower cable costs, reduced installation costs because of the lack of need to conform to local electrical wiring ordinances (no conduit, for example) and the freedom from electronic interference problems. These must be balanced against the additional component complexity that fiber optics introduces. The final choice, as always, is determined by the technical requirements and economics of each application. It seems clear, however, that a passive local computer network requiring $Bw \cdot L$ products significantly in excess of a few MHz·km will require a fiber optical network of some form.

The Fibernet experiment has demonstrated the practicality of a 100 Mbit/s·km local computer network using today's technology. The network configuration adopted in this experiment is only one of several possible, and was selected because it permitted the largest number of terminals to be connected by a completely passive medium. Recent experimental work on low insertion loss fiber optic tees suggests that a passive linear system, as illustrated in Figure 1, may soon be able to support a competitive number of stations. Additionally, it is not clear that the electronics of an active repeater ring such as Halo, or an active star repeater network, could not be made reliable enough for use in a local computer network. The appropriate system configuration, like the decision to use fiber optics or coax, will be determined by requirements and economics.

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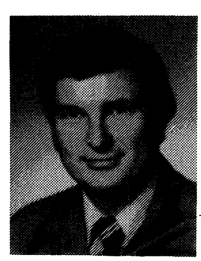

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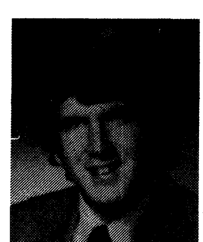

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