

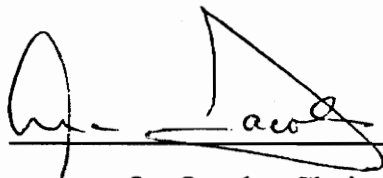
**QUALITATIVE INVESTIGATION OF COST OPTIMIZATION
STRATEGIES FOR INDUSTRIAL-BASED FIBER OPTIC LOCAL
AREA NETWORKS**

by

Terry William Reed

Thesis submitted to the Faculty of
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Electrical Engineering

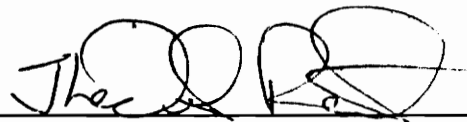
APPROVED:

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by

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(ABSTRACT)

The inherent properties of optical fibers such as small size and weight, EMI/RFI immunity, low attenuation, and large bandwidth provide many advantages over wire conductors that make fiber well-suited for communications. Fiber optic local area networks are particularly suited for use in electrically noisy and space sensitive industrial environments.

The diversity of communication requirements that exist in a typical factory situation can be accommodated by the use of a hierarchical communications structure consisting of multiple tiers of fiber optic networks. The lowest tier of this structure would be inexpensive feeder networks used to connect devices such as sensors, actuators, PLCs, robots, and small computers on a factory floor. The emphasis at this level is low cost, but while providing interconnection to higher tiers.

An approach which satisfies the lowest tier requirements is a non-shared medium scheme which is link based, consisting of an active star architecture using a roll-call polling access method. The centralized intelligence structure of a master/slave access method allows one to concentrate on the cost optimization of the optical data links. The use of low-cost optical components such as LEDs, PIN diodes, and

plastic fiber as well as the potential for a significant amount of common hub equipment provides considerable economies.

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1.0 INTRODUCTION

The use of fiber optics for communications has been a rapidly expanding field in recent history. Although the use of glass fibers as a waveguide for light transmission was suggested in 1966 by Kao and Hockman,¹ the technology to manufacture fibers with reasonable attenuation per unit length had to be developed before they could be of practical use. Eventually this technology was developed, and "by 1980, fiber optics was an established commercial reality."² The large bandwidth and low attenuation characteristics available in optical fibers make them very suitable for communications. The use of fiber optics for long-haul telecommunications is well known. One area in which fiber optics is beginning to be widely used is for the interconnection of devices on a much smaller geographic scale in the context of local area networks (LANs). These fiber LANs are typically used in office or campus-wide environments to connect various types of computers or other devices.

One environment in which fiber optic LANs are being increasingly applied is in industrial settings. The inherent properties of optical fibers make them well-suited for the electrically noisy and space critical situations that typically exist on a factory floor.^{3 - 8} A recent survey predicted that the fiber optic LAN market experiencing the most growth in the next three years would be industrial manufacturing.⁹

There are a variety of communication requirements which exist in most industrial settings. These may range from connecting between devices on a factory floor to linking high-volume data producers such as workstations and supercomputers. Some method of satisfying this diversity of communication needs must be used in order to effectively allow communication between the various types of equipment. A hierarchical communication structure consisting of several tiers of networks is

appropriate to accommodate this variety of needs. This multi-tier arrangement is illustrated in Figure 1.1. The tiers would be arranged according to the data rates required for the different kinds of equipment.

At the lowest level of such a multi-tier structure would be "feeder" networks used to connect factory floor devices. The type of equipment which typically exists on a factory floor includes such devices as strain gauges, thickness gauges, density gauges, temperature sensors, bar code readers, scanners, actuators, PLCs (programmable logic controllers), robots, and small computers such as IBM PCs. The rate at which information is produced by this equipment can vary considerably. Some devices such as bar code readers produce information at a rate of several kbps (kilobits per second) or lower, while other instruments such as robot vision systems can have rates of several hundreds of kbps (kilobits per second) or more. The feeder networks will have a data rate in the range of several Mbps in order to satisfy the variety of rates at which information is produced by the factory floor devices. Although a single device on a factory floor does not typically require the large bandwidth provided by fiber, this bandwidth is needed when the devices are networked together.

To obtain widespread use, the goal at this level should be to minimize costs while also providing interconnection of factory devices to a higher tier.¹⁰ A method should be used which will facilitate the communication needs while still being cost-sensitive. One impediment to the use of low-cost implementations of existing standardized local area networks (LANs) for factory communications is that most existing standardized fiber networks use a shared-medium approach, also known as a broadcast medium approach. These networks implement a broadcast network

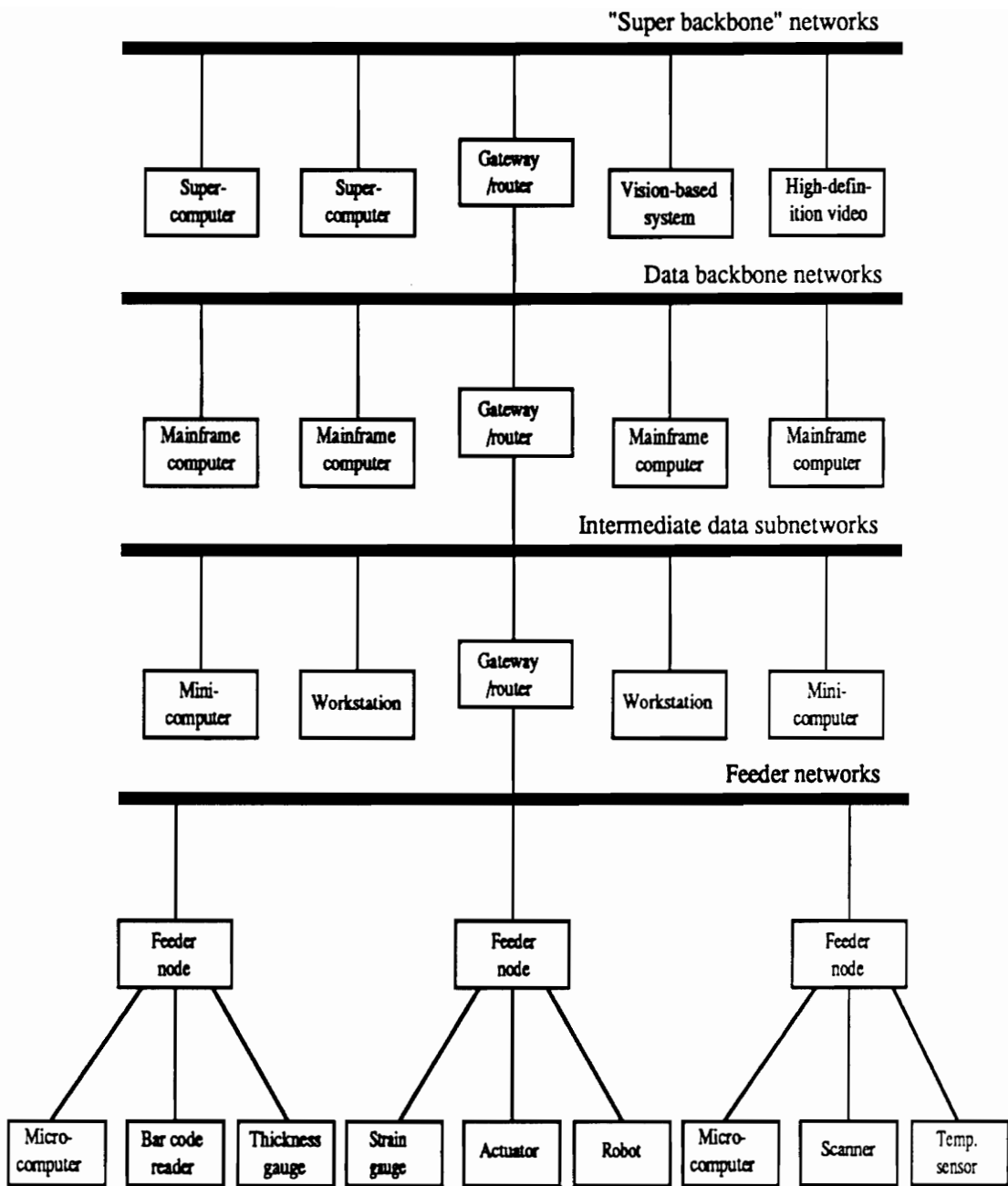


Figure 1.1. Multi-tier communications structure for factory applications.

access structure in which the communications medium is shared among the nodes. In a shared medium network, all nodes are logically connected together, allowing the capability for direct peer-to-peer communication. A certain amount of intelligence is required at each node to support such peer-to-peer communication. This capability can constitute a significant portion of the costs for each node on such a network. However, for many factory floor-type implementations, there is not a great need for peer-to-peer communication at the lowest tier of a hierarchical structure. Instead, the ability to communicate to a higher level is the primary concern. This suggests that an arrangement which does not require peer-to-peer communication (and its associated costs) can be used in this type of environment.

One alternative to using a shared medium system is a non-shared medium approach which is link-based. This approach is based on the afore stated principle that communication to a higher level is much more important than communication on a peer-to-peer basis in a factory environment. This shift in emphasis from most existing standardized fiber optic network approaches allows one to implement a cost-sensitive solution. The idea behind a link-based, non-shared medium network is that communication is accomplished from point-to-point using dedicated links at the lowest level of a multi-tier structure, without being concerned with direct multipoint-to-point or multipoint-to-multipoint communication among feeder nodes.

A configuration which is well-suited for a low-cost implementation at the lowest tier is an active star architecture without medium sharing. In such a link-based approach, nodes on the network would feed into a custom concentrator module (hub) which would include a network interface to the second tier. As shown in

Figure 1.1, several factory floor devices would be connected to each node on a feeder network. There will be dedicated source/detector pairs for each node-to-hub link. The intelligence requirements for such a system would be much more centralized than that of a shared-medium network. A master/slave access method can be used to centralize the intelligence capabilities. The majority of the intelligence in such a link-based approach would be in the context of a "master" at the hub which would control which node ("slave") communicates to the concentrator module and thus the next higher network tier. This centralized intelligence scheme means that a much smaller portion of the total node costs is dedicated to the capability for intelligence at each node. This situation allows one to concentrate on the optimization of costs associated with the optical data links and network configuration. Low-cost optical components such as LEDs (light emitting diodes), PIN (positive-intrinsic-negative) photodiodes, and plastic fiber can be used. The use of active links for each node helps alleviate the attenuation concerns in using plastic fiber due to the less stringent optical power budget constraints. In addition, economies can be gained by the utilization of common equipment in the hub for the different links. The potential reduction in costs by using a non-shared approach makes it well-suited for a cost-effective implementation at the feeder node level.

The discussion will be arranged as follows. Chapter 2 will review some basics of fiber optic systems, while Chapter 3 will describe the general characteristics of LANs and overview several existing standardized fiber LANs. Chapter 4 will discuss how a multi-tier structure is used to accommodate the communication requirements of a typical factory setting. Chapter 5 will detail a low-cost, non-shared medium approach for the feeder networks and specify the associated component costs. Chapter 6 will describe a possible extension for using fiber LANs on factory floors.

2.0 FIBER OPTICS BASICS

The transmission of light through an optical fiber is typically described using two models: the ray optics model and the electromagnetic (EM) field model. Both of these models are used in explaining the principles of guiding light through dielectric media. The applicability of a particular model is dependent upon the phenomenon one wishes to describe, e.g., the ray optics model is sufficient to characterize certain situations, but in some cases it is not acceptable.

2.1 Total Internal Reflection

Transmission of light through an optical fiber is based on the well-known principle of total internal reflection (TIR). The explanation of TIR normally uses the ray optics model. Optical fibers are typically composed of an inner core with surrounding concentric layers. The surrounding layers are known as claddings. Some fibers have several layers of various refractive indices, i.e., several different cladding layers. The simplest case is where there is one concentric layer surrounding the core with a step change in refractive indices between the core and cladding (see Figure 2.1.1).

For step-index fibers, the condition for TIR can be determined using Snell's Law for refraction

$$n_1 \sin \theta_1 = n_2 \sin \theta_2, \quad (2.1.1)$$

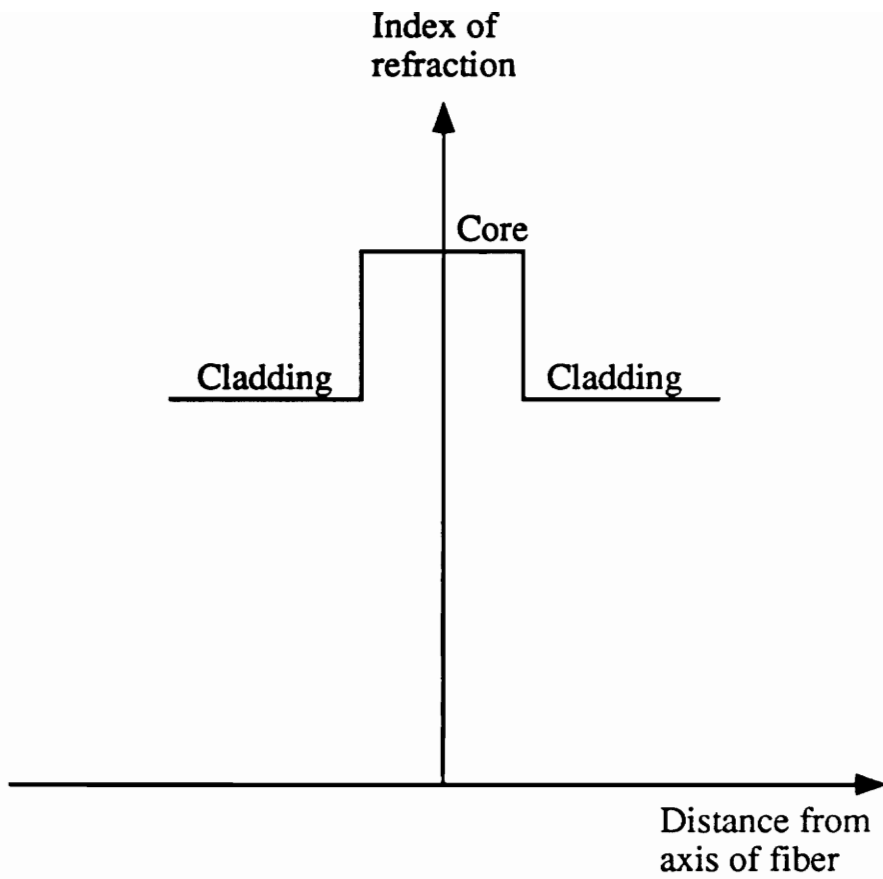


Figure 2.1.1. Step-index profile for an optical fiber.

where the n_1 and n_2 are the indices of refraction for media 1 (core) and 2 (cladding), respectively. Here, θ_1 refers to the angle of incidence and θ_2 refers to the angle of refraction, as shown in Figure 2.1.2. The TIR condition is that for which $\theta_2 = 90$ degrees, which yields the critical value of θ_1 ,

$$\theta_c = \sin^{-1} (n_2/n_1). \quad (2.1.2)$$

To achieve TIR, the angle of incidence θ_1 must be greater than θ_c (assuming $n_1 > n_2$).

The amount of light which can be coupled into an optical fiber is determined from the acceptance angle. The acceptance angle (measured from the axis of the fiber) defines the extent of the acceptance cone, as shown in Figure 2.1.3. The acceptance angle is the maximum angle that light which will propagate can be injected into a fiber. Another way this light-coupling ability is normally specified is by the numerical aperture (NA). The NA of an optical fiber is related to the acceptance angle through the expression

$$NA = \sin \theta_0. \quad (2.1.3)$$

The relationship between the acceptance angle and the critical angle can be determined by applying Snell's Law at both the air-fiber and core-cladding interfaces as shown in Figure 2.1.4. This yields

$$\theta_0 = \sin^{-1} [(n_1/n_a) \cos \theta_c], \quad (2.1.4)$$

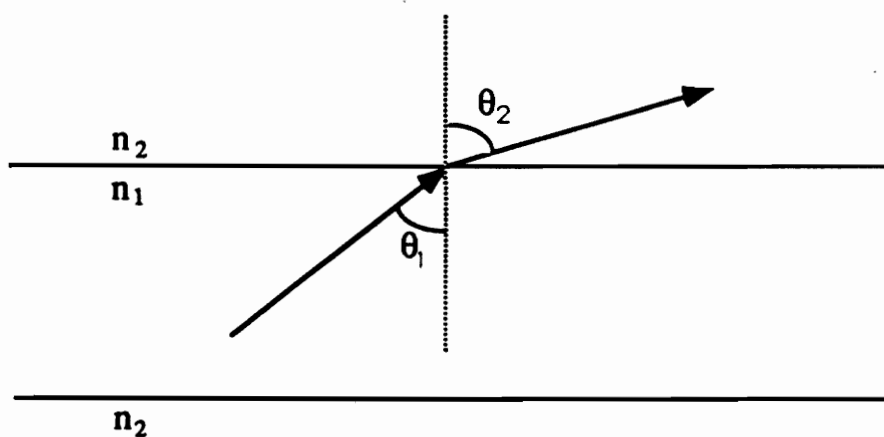


Figure 2.1.2. Ray representation of Snell's Law of refraction.

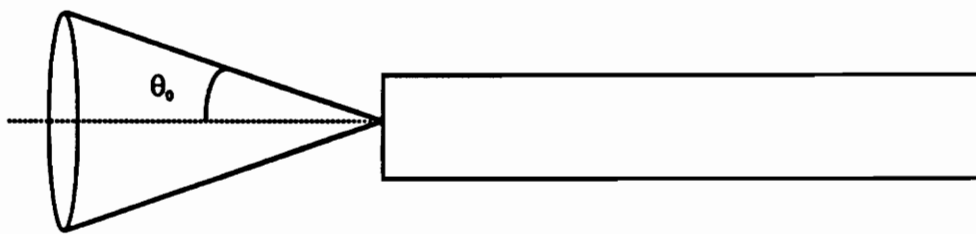


Figure 2.1.3. Acceptance cone of an optical fiber.

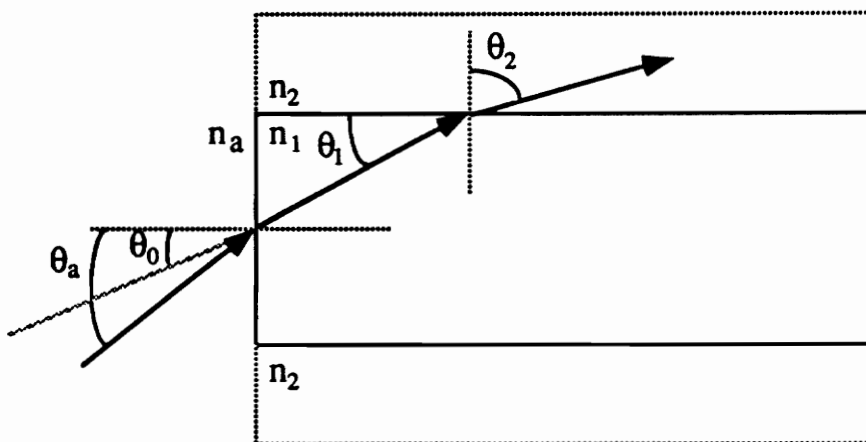


Figure 2.1.4. Relationship between critical angle and acceptance angle (when $\theta_a = \theta_0$, $\theta_1 = \theta_c$).

where n_a is the refractive index of air, usually assumed to be unity. θ_0 is the largest angle at which light can be injected into the fiber to get TIR within the fiber, i.e., when $\theta_a = \theta_0, \theta_1 = \theta_c$.

NA can also be expressed in terms of the indices of refraction of the core and cladding, resulting in

$$NA = [n_1^2 - n_2^2]^{1/2}. \quad (2.1.5)$$

2.2 Number of Modes

One measure of an optical fiber is the number of electromagnetic modes which can propagate at a given wavelength. The number of modes in a fiber is influenced by several factors. The most significant factors are the core radius, the optical wavelength, and the difference in the refractive indices of the core and cladding. The number of modes is dependent on the normalized frequency V , defined as ¹¹

$$V = 2\pi[a/\lambda] [n_1^2 - n_2^2]^{1/2}, \quad (2.2.1)$$

where a is the core radius and λ is the wavelength. Single mode fibers are those in which only one mode propagates. The condition for single mode operation is that $V < 2.405$. Multimode fibers are those in which more than one mode propagates, i.e., have $V > 2.405$. The reduction of the core radius and the use of small differences between the refractive indices of the core and cladding are the primary way fibers are made to be single mode.

2.3 Dispersion

Electromagnetic pulses which are transmitted through a medium experience spreading in time and space. This pulse spreading is known as dispersion. Dispersion of a pulse limits the rate at which information can be transmitted, i.e., the maximum bandwidth or data rate. There are two ways in which this phenomenon is normally characterized in optical fibers: intermodal dispersion and intramodal dispersion. Intramodal dispersion is, in turn, divided into material and waveguide dispersion. When more than one mode is excited in a waveguide, the various modes have different group velocities and therefore have different propagation delays. Intermodal dispersion is measured as the difference between the shortest and longest path delays. This difference in path delays results in a spreading of the pulse. This effect is present only in multimode fibers and is generally the dominant effect when present.¹¹ Intermodal dispersion can be reduced by making the difference in the refractive indices of the core and cladding smaller, which has the effect of reducing the number of modes which propagate. Therefore, single mode fibers have larger bandwidths since there is no intermodal dispersion present. Intramodal dispersion is approximately the sum of the effects of material and waveguide dispersion. Material dispersion is due to the variation of refractive index with frequency, while waveguide dispersion is caused by the effect of frequency on the propagation parameters. The effects of material and waveguide dispersion can be significantly reduced by the judicious choice of core radius and operating wavelength. The refractive index profiles of the core and cladding can also be changed to achieve low dispersion characteristics. Typically, fibers with more complex profiles are more expensive to manufacture. For most communications applications using multimode fibers, a graded-index profile is used. In a graded-index profile, there is a gradual change between the indices of the core

and cladding. The index of the core is a maximum at the fiber axis and continuously decreases until the cladding, where it then becomes constant, as shown in Figure 2.3.1. The manner in which light is guided is different in principle than the simple step-index case where reflections occur at the core-cladding interface. Instead, the light rays are "bent" by the continuously changing refractive index. This gradual change in refractive index reduces the amount of intermodal dispersion. The rays with the longest path lengths travel at a higher average velocity due to going through the regions of lower refractive index, whereas the ray paths close to the fiber axis (where the refractive index is higher) will propagate at a slower average velocity. The difference in path delays is now much smaller and thus less intermodal dispersion occurs.

Whereas intermodal dispersion is a property of the fiber, intramodal dispersion depends not only on fiber properties, but also on the spectral width of the source.

The bandwidth of an optical fiber is typically specified as a bandwidth-distance product, e.g., in MHz*km. The bandwidth of an optical source is specified either by a maximum bandwidth or data rate.

2.4 Attenuation

For a communication system, attenuation refers to the power loss incurred in the process of transmitting information from a source to a receiver. There are several potential sources of loss in an optical communications system. Aside from the losses incurred in the fiber itself, there are losses due to the coupling of light into

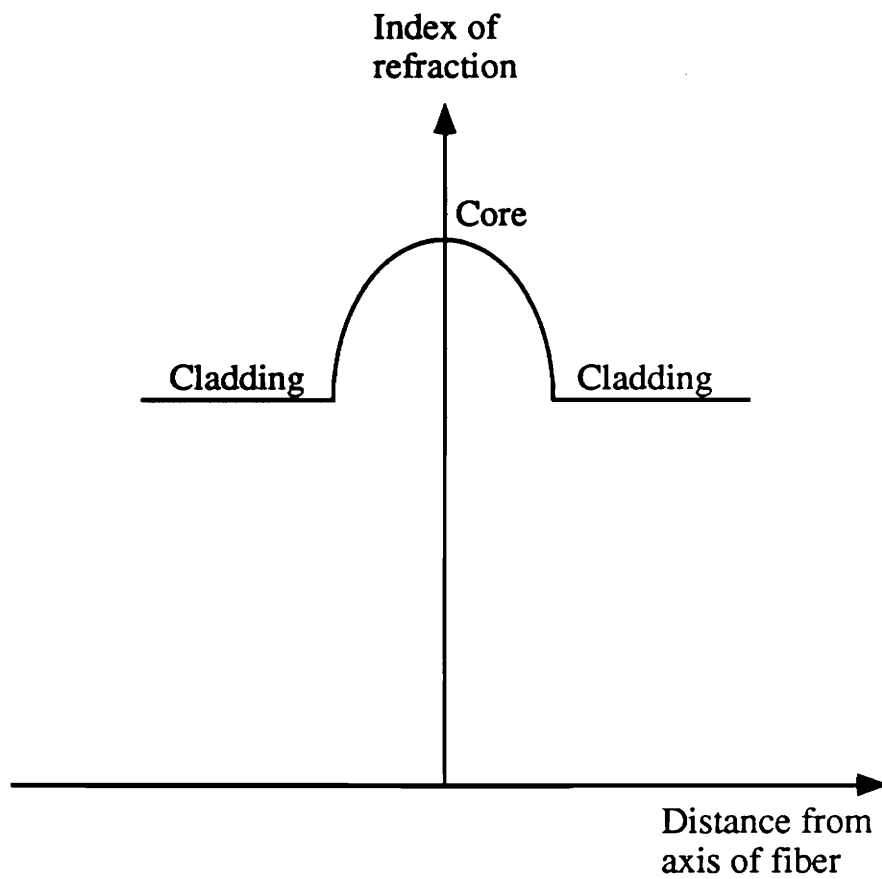


Figure 2.3.1. Graded-index profile for an optical fiber.

and out of the fiber. If two sections of fiber must be spliced together, there is an additional loss introduced. All of these factors must be taken into account when analyzing the attenuation of an optical link.

Attenuation in an optical fiber is specified as decibels (dB) per unit length, usually in dB/km. Single mode fibers typically have lower attenuation per unit length than multimode fibers.

2.5 Sources

An optical source is an electro-optic transducer; it converts an incoming electrical signal to an optical signal. The two types of optical sources are LEDs (light emitting diodes) and lasers. Both types are small semiconductor chips that have the property of producing light when current is passed through them. The incident electrons are converted to photons which are emitted from some surface of the semiconductor. A linear relationship between the input current (I) and output optical power (P_o) exists,¹¹

$$P_o = 1.24 \left(\eta I / \lambda \right), \quad (2.5.1)$$

where η is a measure of how efficiently the electrons are converted to photons, known as the quantum efficiency, and λ is the optical wavelength in μm . P_o will given be in mW when I is expressed in mA using (2.5.1). As shown in Figure 2.5.1, LEDs have a linear I versus P characteristic from very small values of current up to a saturation level. Lasers, however, require a threshold current level before the

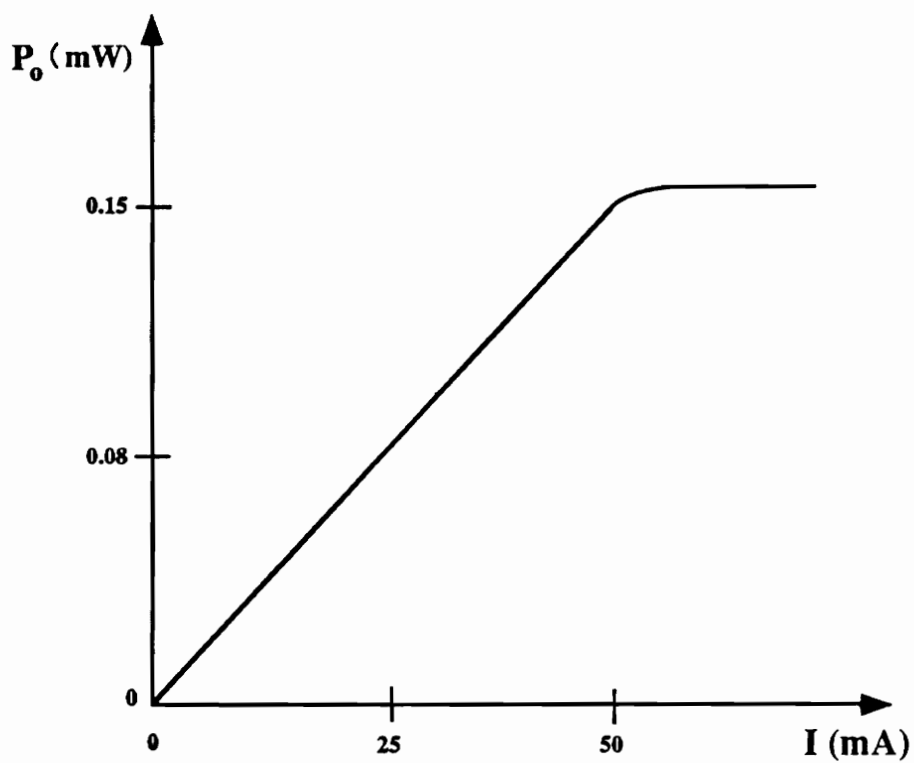


Figure 2.5.1. Optical output power vs. input current for a typical LED.

optical power becomes linear with current and eventually saturates, as shown in Figure 2.5.2.

In an optical source, the electrical signal is converted to an optical carrier frequency of several hundred terahertz, which corresponds to wavelengths of hundreds to several thousands of nanometers.

2.6 Detectors

The reverse operation is performed by photodetectors. Photodetectors are usually photodiodes which are optoelectronic transducers capable of converting optical signals into electrical signals, i.e., the incident photons are converted into electrons. The two types of photodetectors commonly used are PIN (positive-intrinsic-negative) diodes and APDs (avalanche photodiodes). The information is converted by the photodetector from an optical signal on an extremely high carrier frequency to an electrical signal. The optical-to-electrical conversion also obeys a linear relationship between input optical power and output electrical current,¹¹

$$I = \eta P_i \lambda / 1.24, \quad (2.6.1)$$

where η now refers to the quantum efficiency for the photon-to-electron conversion and λ is in μm . The value of η for a detector is higher than for a source, typically 0.5 - 0.8. This is because when electrons are in a higher energy state, there are non-radiative processes by which they may return to a lower state. In (2.6.1), I will be given in μA when P_i is expressed in μW .

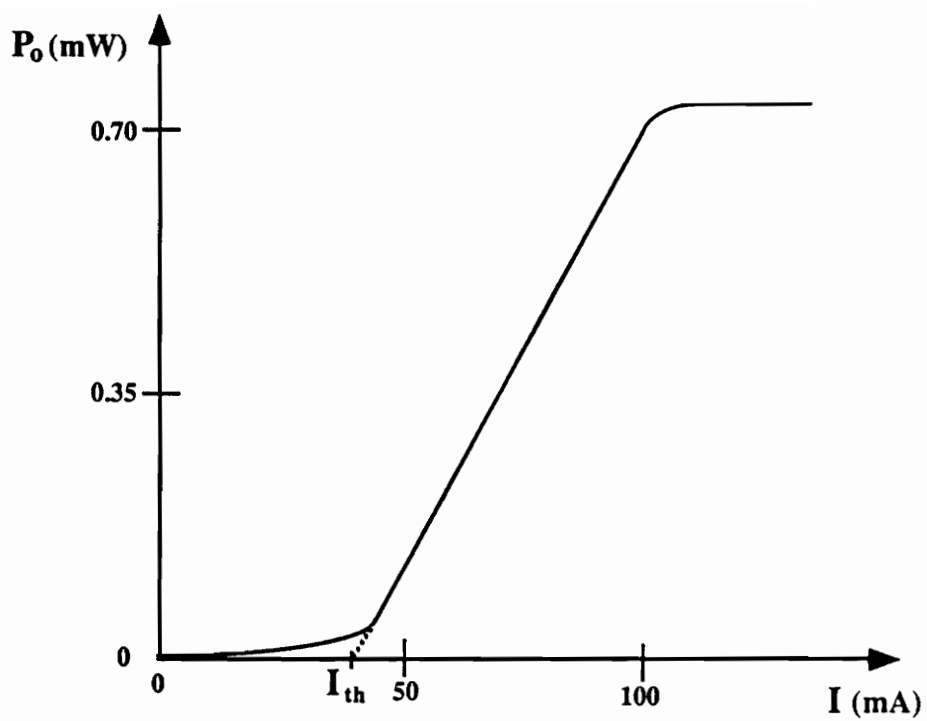


Figure 2.5.2. Optical output power vs. input current for a typical laser (I_{th} = threshold current).

2.7 Optical Power Budget

The manner in which the attenuation of a system is analyzed is through the use of an optical power budget. Some of the quantities which must be considered are the coupled optical output power (P_{coup}), connector losses, splice losses, fiber losses, and the minimum sensitivity of the receiver (R_s). The coupled output power refers to the amount of light produced by the source which is coupled into the fiber. Optical sources and detectors often come equipped with fiber pigtails, which are short lengths of fiber already attached to the devices. This pigtail is normally already connectorized. If a pigtail is used with a source, the coupled optical output power through the pigtail must be used in the link budget evaluation, not the output power of the source. The fiber, connector, and splice losses are often incorporated into a single term called the optical loss (L_{opt}). A reserve margin is added to account for such things as aging, variations due to temperature changes, and additional splices which may be needed. This reserve margin is not a real loss, rather it is an allocation for losses that might develop after the system is put into operation.¹² The reserve margin is typically set to between 4 and 10 dB. The exact value used for the reserve margin is a decision which varies among designers. The more conservative the design strategy, the larger the reserve margin used. The following equation is used to calculate the optical link budget:

$$P_{\text{coup}} [\text{dBm}] - L_{\text{opt}} [\text{dB}] - \text{reserve margin} [\text{dB}] = R_s [\text{dBm}]. \quad (2.7.1)$$

The system should be designed so that the total power resulting from the coupled optical power and losses is greater than or equal to the receiver sensitivity (for a given probability of error or signal-to-noise ratio), i.e.,

$$P_{\text{coup}} [\text{dBm}] - L_{\text{opt}} [\text{dB}] - \text{reserve margin} [\text{dB}] \geq R_s [\text{dBm}]. \quad (2.7.2)$$

The two most critical factors which limit the maximum length of an optical communications link are attenuation and dispersion (bandwidth). A good design strategy is to always try to design a link to be attenuation-limited, not dispersion-limited. By this it is meant that the designer should ensure that the bandwidth requirements have been satisfied and then design around the optical loss budget requirements. For low data rate systems, this strategy can typically be used. However, high data rate systems generally become dispersion limited before being power limited.¹¹

One point which should be clarified is the distinction between the use of dB and dBm. Decibel (dB) is a dimensionless quantity used to express the ratio between two numbers. One of the most common uses of dB is to compare the input and output power of a system or device. On the other hand, dBm is used to specify an absolute power. The units typically used to specify absolute power are either dBm or dBW. The absolute power in dBm is the number of decibels referenced to 1 mW, while dBW is the number of decibels referenced to 1 W (where all powers are assumed to be measured across identical loads). Due to the low power levels involved in practical optical communication systems, dBm is normally used. If quantities are not given in dBm and dB, the following formulas should be used for conversion:

$$P [\text{dBm}] = 10 \log_{10} (P [\text{W}]/1 \text{ mW}), \text{ and} \quad (2.7.3)$$

$$\text{Loss} [\text{dB}] = 10 \log_{10} (P_{\text{in}}/P_{\text{out}}), \quad (2.7.4)$$

where it is assumed that P_{in} and P_{out} have the same units.

Another point which should be emphasized is the differences between using electrical and optical power. Normally, the 3-dB bandwidth is used to specify the frequency response of a system or device. The 3-dB bandwidth is the frequency at which the power of a signal has decreased to half its peak value, i.e., down 3 dB. However, since in an optical system an electrical current is converted to an optical power and vice versa, a 3-dB optical bandwidth corresponds to a 6-dB electrical bandwidth. This is because $20 \log_{10} (I / 1 \text{ mA})$ is used to express an electrical power in dBm, while $10 \log_{10} (P_{opt} / 1 \text{ mW})$ is used to determine the optical power in dBm. The distinction between whether electrical or optical power is being used should therefore be made when analyzing a system or device in a fiber optic system.

3.0 CHARACTERISTICS OF LOCAL AREA NETWORKS

Local area networks (LANs) are communication systems which are used to connect devices together. LANs are typically used for distances of several kilometers or less. The use of LANs became more widespread in the late 1970's as the use of computers became more prevalent. Accordingly, the primary application of LANs today is to link various computers and similar devices together in an office or interbuilding setting. The use of fiber optics for LANs has been increasing in recent years due to the development and wider availability of less expensive sources, detectors, and cables.

3.1 Advantages of Optical Fibers for Communications

Optical fibers have many inherent properties which can translate into advantages for communications. Some of the properties and associated advantages of fiber optics systems are listed in Table 3.1.1. The low attenuation and high data rate characteristics of optical fibers have allowed fiber LANs to operate at higher data rates over longer physical distances (without the need for repeaters) than wire-based LANs. Fibers have small size and weight compared to wire conductors. The dielectric nature of optical fibers makes the concerns about EMI and RFI conditions much less critical for the fiber cable than in a wire-based transmission system. Optical fiber materials are very poor conductors. They do not radiate EM energy like wire conductors. The necessity to shield and isolate wire conductors to prevent crosstalk and signal interference typically results in a considerable increase in cable size and weight. The primary motivation for increasing the size and weight

Table 3.1.1. Properties vs. advantages for fiber optic systems, as compared to wire systems.¹⁰

	Decreased Cost				Increased Safety		Simplified Design		Integrity of Data	
	Initial equipment	Initial installation	Continuing maintenance	Ability to upgrade	Personnel	Equipment	Communication system design	Plant design	Information stability	Information security
Electromagnetic Properties										
Immune to stray EM noise							X	X	X	
Does not radiate EM noise							X	X		X
Does not conduct electricity		X	X		X	X		X		
"Ground" reference is darkness			X		X	X	X	X		
Does not cause sparks		X	X					X		
Physical Packaging Properties										
Smaller than wire alternatives		X						X		
Lighter than wire alternatives		X						X		
Can include in power cables		X	X					X		
Can include in explosive fluid conduits		X	X		X			X		
Capacity and Performance										
Attenuation is not dependent on data rate				X			X	X		
Extremely large data rate capacity	X			X			X	X		
Minimal crosstalk							X	X		
Can use restricted portion of frequency spectrum							X			
Can use fiber as communication and sensing medium			X				X	X		

of the jacketing of fiber-based cables is to increase their strength characteristics and immunity to harsh environments, not signal isolation between adjacent fibers. Even with this additional physical packaging, fiber cables are still much more space and weight efficient than their wire counterparts. However, one must still worry about the EMI and RFI conditions for the electrical portion of a fiber optic network. The ability to run fiber cables alongside wire cables with minimal crosstalk is also an attractive feature. Fiber cables can be run alongside wire cables used for communications and power distribution. Since there is no danger of electrical sparks being generated from an optical cable or electricity being conducted, fiber cables can also be run through hazardous environments where explosive and flammable fluids and gases are present. Similarly, a severed fiber cable would result only in light escaping from one of the ends, and for practical fiber optic networks that would be used in industrial environments this does not present a safety concern.

¹³ There is no problem with ground loops when using fiber optics since the "ground" reference for light is darkness.

Obviously, the many advantages of optical fibers provided by their inherent properties make their use as a communications medium very desirable. The environment on a factory floor is much more demanding than that of an office. The conditions in an industrial setting are much more electrically noisy than those usually encountered in office or interbuilding LANs. Fiber optic systems are well-suited for use in such a demanding environment as a factory floor.

3.2 Network Structure

The structure of a network is characterized in several ways. Attributes such as the extent to which the transmission medium is shared, the manner in which the nodes are connected together, the method used to arbitrate medium access, and the switching procedure employed are all used to describe the network structure.

3.2.1 Non-shared medium vs. shared medium

Local area networks use either a shared medium approach or a non-shared medium approach. In a shared medium approach, the messages on the medium are received by more than one node, i.e., broadcast across the network. Although the transfer may only be intended for a single station, e.g., by the use of a unique address, the messages are nonetheless received by all the nodes. This sort of scheme requires a level of intelligence at the nodes with some sort of self-identification capability such as address recognition.

For a non-shared medium approach, a message is received by one only station. This would obviously require communication on a point-to-point basis between the sending and receiving nodes. However, a system based on point-to-point links is not necessarily a non-shared access network, i.e., point-to-point links are a necessary but not sufficient condition for a non-shared access scheme. The one-to-one correspondence between the sending node and receiving node eliminates the need for a level of intelligence at each node that is required for address recognition.

3.2.2 Architectures

The three basic local area network architectures are the star, ring, and bus. When describing the configuration of a LAN, care must be taken not to confuse the architecture of a network with its cable-routing topology. In some networks, the manner in which the nodes are connected together is different than the characteristics of the cable-plant layout. This terminology ambiguity can be resolved by using "architecture" to refer to the manner in which the nodes are connected together, while using "cable-routing topology" to describe the actual layout of the cable plant.¹⁴ Using this scheme, the sometimes separate issues of how the cable is to be laid and how the nodes are to be networked together are not confused.

3.2.2.1 Star

In a star architecture, the nodes are fed into a central "hub," similar to spokes on a wheel, as shown in Figure 3.2.1. In a shared medium star, a signal from a node is combined/split in the hub. Separate transmit and receive fibers are generally required at each node in a star architecture.

The hub can be either active or passive in a star architecture. Active stars are those in which the switching of the signals is done electrically, i.e., the incoming optical signals are converted to electrical signals, switched, and then converted to outgoing optical signals. Because the switching is done electrically in an active star, each node requires a separate source/detector pair at the hub. The use of separate transceiver functions for each node-to-hub connection can significantly reduce the constraints of the optical power budgets needed for the links. However, there is an additional potential point of failure introduced by the need to power the electronics

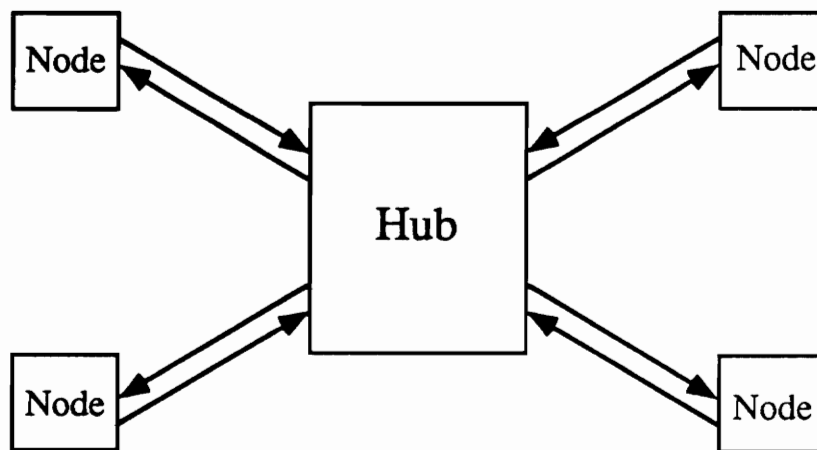


Figure 3.2.1. Star architecture.

at the hub.¹⁵ Active stars can be implemented using either a shared medium access scheme or a non-shared medium access scheme.

Passive stars differ from active ones in that mixing of the signals is done optically without any conversion to the electrical domain within the hub. Optical passive star architectures use fiber optic couplers. In a fiber coupler, power transfer is accomplished by orienting two or more fibers so the evanescent fields from each fiber couples power into the other fibers. One of the most popular methods of making a coupler is to twist a section of all of the fibers together and then heat the intertwined portion of the fibers while applying axial tension. This has the effect of elongating the heated region, thus creating a tapered region common to all the fibers. These types of couplers are known as fused biconical tapered (FBT) couplers.^{16, 17} Another method used to manufacture couplers is to polish down the claddings of the fibers and place the fibers close together so that the evanescent fields couple power. These are known as polished fiber optic couplers. By careful adjustment of the interaction length region and the fiber spacing, polished couplers can be made to be wavelength selective. Wavelength selectivity applications are the primary use for polished couplers. Due to the precision needed for their manufacture, polished couplers are best suited for use with a small number of fibers.

Passive star architectures can be implemented using either transmissive or reflective star couplers. There are two procedures used to make a reflective star coupler. One uses a reflective surface to couple the light among the N fibers (see Figure 3.2.2). In this approach, a normal FBT coupler is used with one side trimmed back to the fused region. The input light is reflected off the reflective surface. The light is reflected back into the fused region and split among the N fibers. Another method

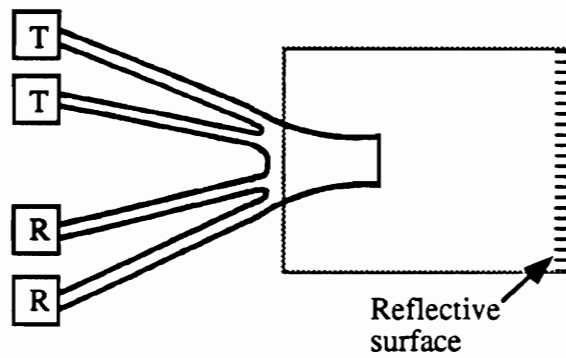


Figure 3.2.2. Reflective star coupler using reflective surface in a passive star architecture.

is to combine the fibers with one side of the coupler comprised of fiber loops rather than terminated lengths of fibers, as shown in Figure 3.2.3. In this method, the light incident on the fused region is combined, split among the N fiber loops, travels through the loops, and is then combined at the fused region and split among the fibers. Packaging issues are much more of a concern in reflective star couplers using reflective surfaces due to the need to align and stabilize the reflective surface in order to get good reflectivity back into the fused region.

A transmissive star coupler is used in a passive star architecture as shown in Figure 3.2.4. The transmitters are connected to one side of the NxN coupler and the receivers are connected to the other side. This method has the advantage over a reflective star that optical power is not wasted by being sent back to the transmitters.

For LAN applications, the star couplers are designed to ideally have uniform splitting loss among the N fibers. For a coupler, the ideal optical power loss due to splitting of a single input signal into N output signals is given by

$$\text{Ideal coupling loss [dB]} = 10 \log_{10} (N). \quad (3.2.2.1.1)$$

There are additional losses which will be present in a practical coupler such as excess loss and uniformity loss. The total coupling loss in optical signal power from one input fiber to N output fibers is given by the sum of the ideal, excess, and uniformity losses,

$$L_{\text{coup, total}} [\text{dB}] = 10 \log_{10} (N) + L_{\text{excess}} [\text{dB}] + L_{\text{uniform}} [\text{dB}]. \quad (3.2.2.1.2)$$

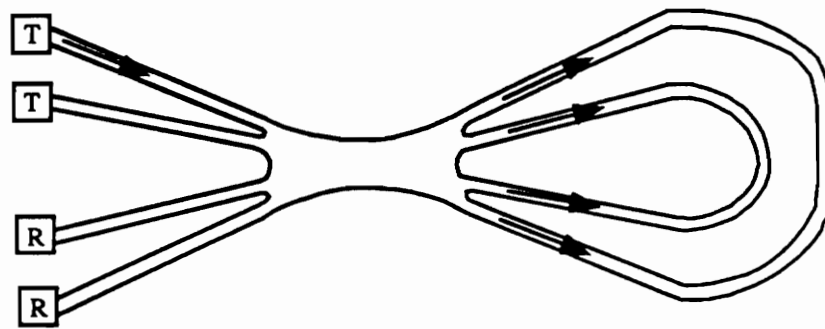


Figure 3.2.3. Reflective star coupler using loops of fiber in a passive star architecture.

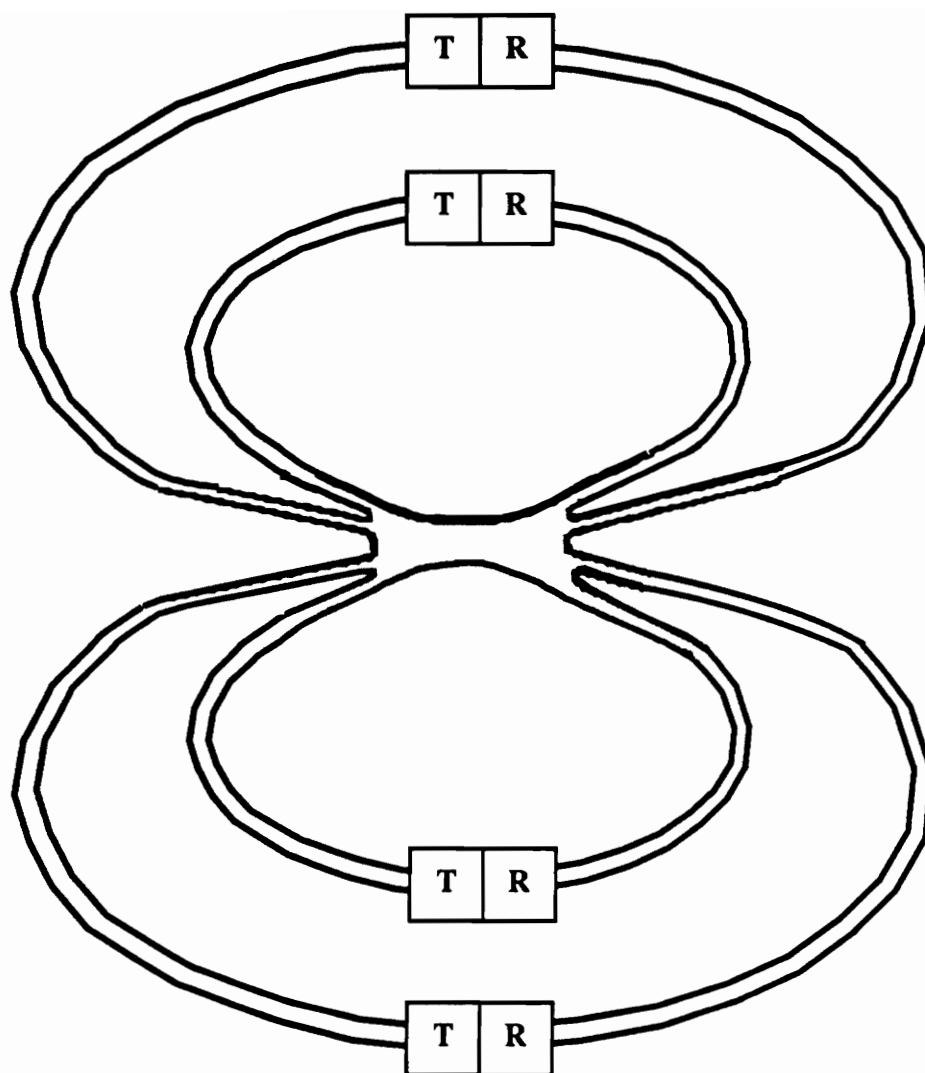


Figure 3.2.4. Transmissive star coupler used in a passive star architecture.

For all reflective star couplers, the light must travel through the common region twice, therefore the total coupling loss is much higher. For a reflective star coupler using reflective surfaces, there will be even more additional loss introduced by having to reflect the light back into the common region. Losses from a star coupler can place considerable constraints on the optical power budget required for a passive star architecture.

The price of $N \times N$ couplers can become a significant portion of the total equipment costs. The amount of excess and uniformity loss in a coupler is very much a function of cost. For large values of N , e.g., greater than ten, the cost of an $N \times N$ coupler can be several hundred or even several thousand dollars.

Because the incoming signal on a single fiber is distributed among all of the outgoing fibers in a star coupler, a passive star architecture requires a shared medium access method.

Another way in which a passive star can be configured is to use two $N \times 1$ couplers at the hub, i.e., one for transmit and one for receive.^{18, 19} The one line from the coupler used to transmit ties into the optical transmitter in the hub, and the one line from the receive coupler ties into the receiver in the hub. An $N \times 1$ coupler is made by trimming back $N-1$ arms of an $N \times N$ coupler. This scheme uses a shared medium approach, with any outgoing messages from the hub split into N signals and broadcast to all the nodes. Depending on the application, the expense of the star couplers and the limitations imposed on the optical power budget can make this method impractical to cost-effectively implement.

One disadvantage of a star architecture is that it has a potential single point of failure at the hub. The loss of the hub will completely disable the network. For a passive star, this could be caused by physical damage to the hub. In the case of an active hub, a power-down condition at the hub can disable the network in addition to physical damage. However, a significant advantage of a star architecture is that a cable break or even the loss of a node will not bring down the network. Either of these conditions would result merely in the isolation of the non-functional node, with the remaining portion of the network remaining fully operational.

3.2.2.2 Ring

A ring architecture consists of a series of point-to-point links where the nodes are daisy-chained together to form a complete ring, as shown in Figure 3.2.5. In a ring architecture, messages are propagated from node-to-node, with each node regenerating its received message to its "upstream" neighbor. This process is repeated by each node until the message has worked its way to its destination. Depending on the network, the message may propagate all the way back to the sender or may be removed from the ring by the recipient. Although the ring utilizes point-to-point links, it is a shared medium architecture since the traffic must normally pass through more than one station before reaching its destination.

One disadvantage of a single ring architecture is that it has a potential single point of failure. If a single cable break occurs or a node is lost, the ring is broken. One way to avoid the loss of the network due to electrical failure at a node is to equip each node with an optical bypass switch. An optical bypass switch is designed to establish a direct optical pass-through path at a station in the event of a power-down condition. These optical bypass switches can account for considerable costs

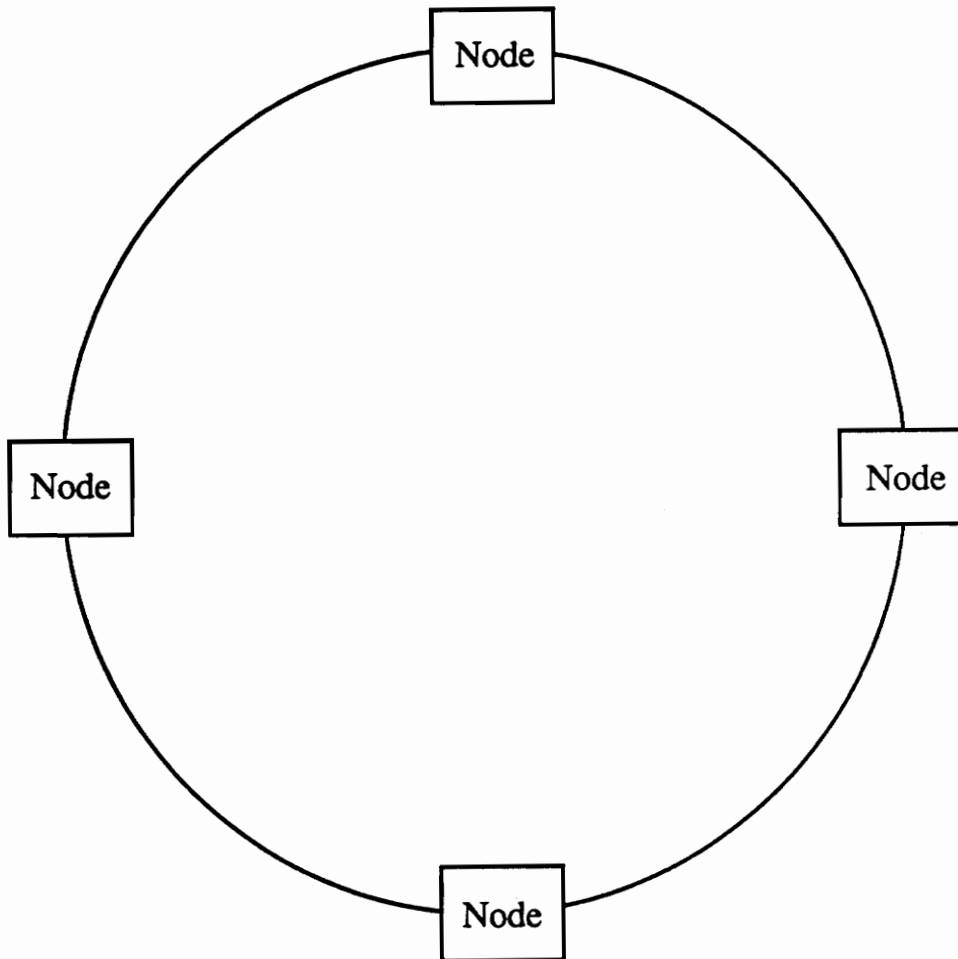


Figure 3.2.5. Ring architecture.

depending on the required speed and losses of the switches. However, physical damage to a station can sever the ring even when using optical bypass switches. One way to provide fault tolerance in the event of cable breaks or station failures is to use a dual-ring structure incorporating a second ring connecting all of the nodes. If a single cable break occurs, the traffic can be transferred to the second ring. Such an arrangement can also be made with the capability to "loop back." Loopback means that the nodes on each side of a cable break will connect the two rings to form a complete ring without any isolated nodes. Loopback can also be used to isolate a node, if desired, and still maintain communication in the rest of the network. However, multiple cable breaks at different locations can result in segmenting of the ring or even bring down the network completely. Another concern is that because of the point-to-point nature of a ring, each node must be able to handle the entire traffic capacity of the network.

One advantage of a ring architecture is that it is the most flexible in terms of the possible cable-routing schemes that can be used. A ring architecture can be used with any of the three basic cable-routing topologies. It can also be used in hybrid schemes consisting of a combination of cable-routing topologies. Although the physical layout of the cable plant will determine the exact amount of cable needed, a ring architecture will almost always require less cable than a star architecture. One case where a ring could require the same amount of cable is in a ring architecture with a star cable-routing topology.¹⁴

3.2.2.3 Bus

As shown in Figure 3.2.6, a bus architecture is one in which all the nodes feed into a common broadcast medium. This means that any transmission by a node is sent out to all the other nodes connected to the bus.

The major obstacle in using a bus architecture with fiber optics is that there does not presently exist the equivalent of a wire high-impedance tap. Generally, the tapping losses of optical fibers in a bus architecture are so great that they severely limit the number of nodes that can be included on the bus as well as the maximum network extent. For optical communication links, the available power budget is much smaller than that of a comparable electrical system. A designer normally has only 20 to 30 dB to work with in an optical network, whereas in a wire-based system, a designer can have a power budget of 60 dB or more. Various schemes have been tried to eliminate the high tapping losses. A scheme has been developed by Raychem Corporation in which the bus fiber is bent in order to "strip off" high-order modes, which are then focused by a lens into a tap fiber. Another interesting approach developed by Litton Polyscientific uses a large core fiber as the bus with smaller core fibers as the taps. However, no methods have become practical enough to allow a fiber bus architecture to be widely implemented. One application for which practical implementations of bus architectures using fiber would be attractive is for fiber-to-the-home.

3.2.2.4 Combinations of architectures

Combinations and variations of the three basic architectures can also be used. One hybrid arrangement of a ring is a mesh architecture. A mesh architecture has a ring, but also has every node directly connected to every other node, as shown in Figure

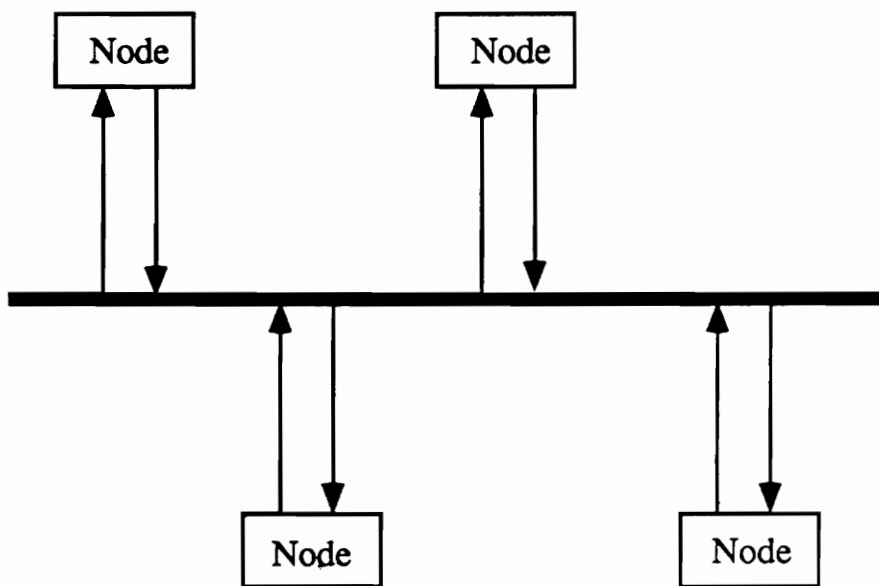


Figure 3.2.6. Bus architecture.

3.2.7. This architecture provides the highest degree of fault tolerance in that there exist several possible paths between any two nodes. A subset of a mesh is a braided ring, which has a ring architecture with some direct connections between non-adjacent nodes. However, a direct connection does not exist between each pair of nodes as in a complete mesh. Multiple redundancy schemes greatly increase the amount of cable and connectors needed. Such systems are typically used only in applications such as the military, where a loss of communication is unacceptable. One example of such a redundant system for military applications has been detailed in the literature.²⁰

An example of a hybrid architecture using a star architecture is a so-called "ring of stars." In this scheme, multiple stars are interconnected as shown in Figure 3.2.8.

3.2.3 Access methods

There are a variety of access methods which can be used in a LAN. "Access method" refers to the procedure used to decide what node will transmit at a particular time, i.e., a medium access arbitration scheme.

3.2.3.1 Master/slave

In a system using a "master/slave" access method, also known as "command/response," a single station (the master) controls the medium access arbitration. The sequence in which the other stations (slaves) transmit is directed by the master. In some implementations, several nodes can have the capability to be the master, and the responsibility of being the master can be passed between certain nodes, although normally only one node at a time can be the master. The procedure

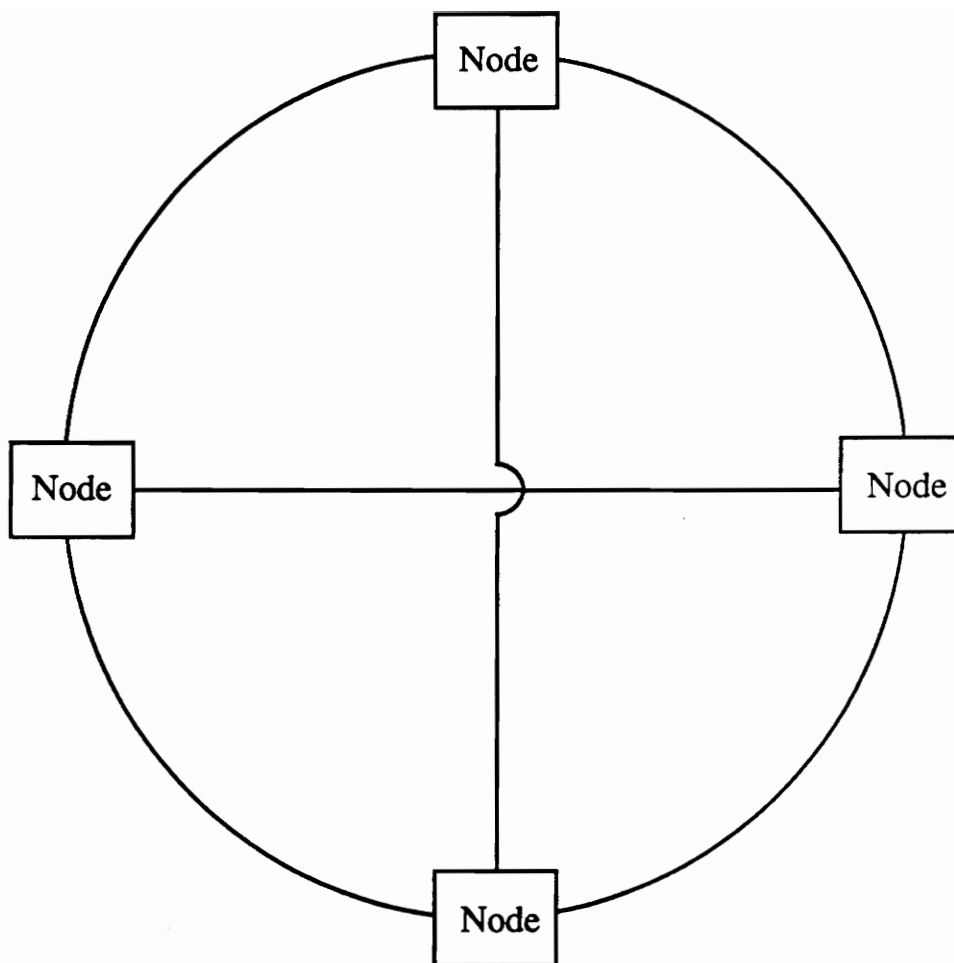


Figure 3.2.7. Mesh architecture.

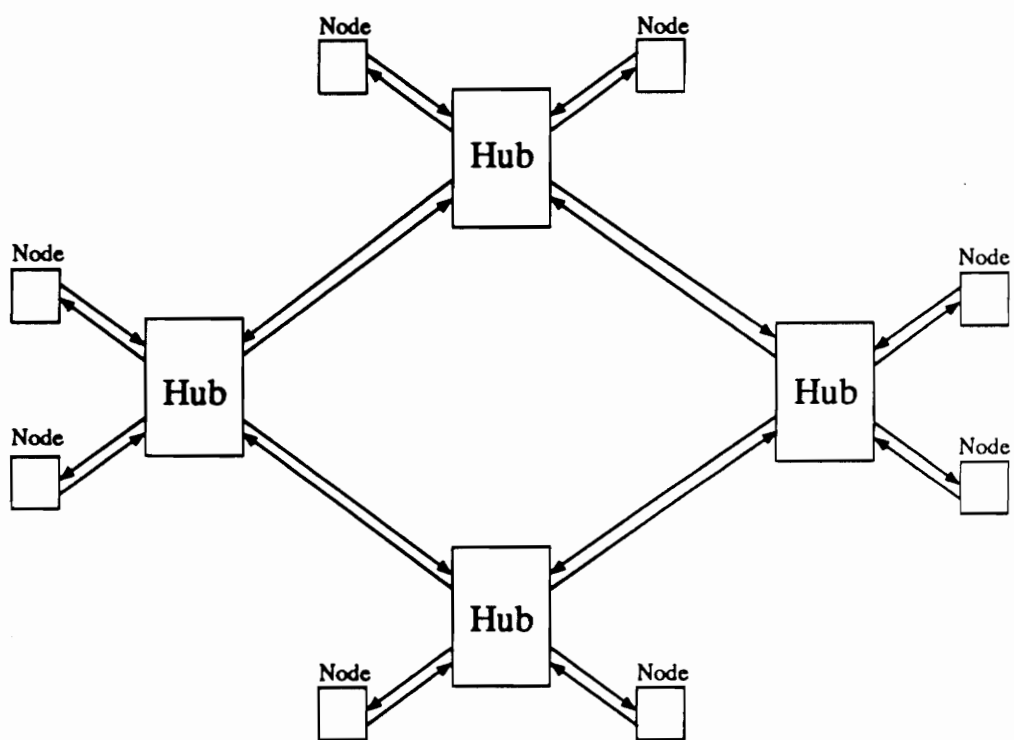


Figure 3.2.8. "Ring of stars" architecture.

used by the master to determine which nodes wish to transmit can be done several ways. Polling is a master/slave access method in which the master queries the slave nodes to determine which stations have data to transmit. There are two common types of polling used in LANs. The first one, roll-call polling, is a scheme in which the master queries each slave node. This can be done in a periodic fashion or at the convenience of the host (master). In addition, a priority scheme can be set up so that certain nodes are polled more often than others. The command and response sequence can be done in several ways for roll-call polling. All normally begin with the master issuing an inquiry to the node. This inquiry is normally answered with an acknowledgement by the node. A positive acknowledgement indicates that the node wishes to transmit data, while a negative acknowledgement indicates that the node does not wish to transmit data. If the node has no data to transmit (negative acknowledgement), then the master polls the next node. There are different procedures which can be used if the node wishes to transmit data. The data the node wishes to transmit can either be included in the same frame as the positive acknowledgement or the data can be sent as a separate frame that follows the acknowledgement. The latter method is not as efficient since overhead bits would be required for both frames. In addition, the use of an additional type of frame which could be transmitted by a node would complicate the system. The command and response sequence can also be done in another way. An alternative method is that a positive acknowledgement from a node must be answered by a message from the master telling the node when to transmit the data. In this case, the node can only transmit when this clearance from the master is received. This method is also less efficient as well as more complicated than having a single frame for the data and acknowledgment.

Generally there are three possible situations that can occur when the master polls a node in a roll-call polling system. One is that the node will respond that it has no data to send and the master will then poll the next logical node. Another is that the node will respond that it has data to transmit and then transmit the data to the master. Following the data transmission from the node the master will then poll the next node. A third scenario is that a node response is not received by the master within a specified time period. This would cause the master to "time out," and would indicate that some error or failure condition exists at the node.

Roll-call polling can be implemented in two ways. One involves node identification, e.g., node addressing, while the other uses a separate physical path for each node. In a shared-medium network, the master must include some means to identify the intended recipient such as a node address. Although a node will generally receive all polls, a node responds only to those queries specifically addressed to it. In a non-shared medium system, however, the master only polls one node at a time. This can be done using separate physical paths for each master/slave combination. No identification capability is needed at the nodes since only those queries specifically intended for a node will be received by the node. The master decides and therefore knows which node it is polling, thus there is no need for the node to recognize addresses.

The other type of polling used is known as hub polling. In this method, the node farthest from the master is polled first. If the node has data to send, it does so. If not, however, it sends a polling message to its nearest neighbor. This poll is sent from node to node until a node has data to transmit or the query returns to the master. Hub polling has the advantage that a command and response sequence is

not required between the master and a node with no data to transmit. This method can only be used for shared medium networks since the nodes must have knowledge of their own addresses as well as their neighbors.^{21, 22}

3.2.3.2 Token passing

Token passing is a popular access method used with shared medium networks. In this method, a special bit pattern known as a token is passed among the nodes on the network. The token is created upon initialization of the network, and a node must "capture" this token in order to be able to transmit. There must be a maximum predetermined amount of time that a single station can transmit after capturing a token. A station is required to pass the token to the next station either after it has finished transmitting or the allotted time period to transmit has expired. If desired, a priority scheme can be implemented so that not all of the nodes are allowed to transmit (i.e., capture the token) under certain conditions.

Token-passing networks using fiber optics can be implemented in a star or ring architecture, as well as in some hybrid architecture schemes.

3.2.3.3 CSMA/CD

Another popular access scheme used with shared access networks is carrier sense multiple access with collision detection (CSMA/CD). In CSMA/CD, when a station wants to transmit, it "listens" to see if any traffic is on the ring. If the medium is not being used, the node transmits. If traffic is detected, the node wishing to send waits and then checks again to see if the network is "quiet." The exact manner in which a station waits to transmit can be done in a variety of ways. These different methods are characterized as being p-persistent CSMA/CD, with p indicating the probability that the station transmits when the medium becomes idle. One potential

scheme is that the station transmits as soon as the channel becomes idle. This is known as 1-persistent CSMA/CD, since the station transmits with a probability of 1 when it senses an idle medium. The other extreme is 0-persistent (or nonpersistent) CSMA/CD, in which the station does not transmit as soon as it detects an idle channel. Instead it waits a random amount of time and then checks to see if the medium is available. In the other alternatives, a station transmits with a probability p when the station senses no traffic.

If two or more nodes are transmitting at the same time, a "collision" will occur. When a collision is detected, each of the nodes waits before attempting to transmit its message. Theoretically, collisions could continue to occur infinitely as each station waits a random amount of time and then retransmits at the same time as another station. However, in practice, the probability of another collision occurring is greatly reduced with each collision. A scheme such as a binary exponential backoff algorithm can be used to reduce the probability of collisions as the network becomes more heavily loaded.²¹

3.2.3.4 TDMA

Time division multiple access (TDMA), also known as slotted access, is an access method in which the nodes are allocated time slots in which to transmit. These time slots can be pre-allocated to the stations upon network initialization or the time slots may be determined through some arbitration scheme. An arbitration scheme can prioritize access to the available channel by allocating different numbers of time slots for the individual stations depending on the needs of the network at a particular instant.

3.2.3.5 Deterministic nature of access methods

A discussion of access methods would not be complete without addressing the subject of determinism. In the context of a LAN, determinism refers to the likelihood that a node will be able to transmit data within a certain amount of time under various network conditions. Determinism is a subject which has been heavily debated among proponents of various systems. There are certain "guidelines" which are used to describe the different access methods.

- (1) Token-passing systems become more efficient as the network load increases. This is because for lightly loaded situations, the nodes which want to transmit must wait for the token to be passed among all the nodes, most of which do not attempt to capture the token.
- (2) TDMA is more efficient for heavier network loading because for light loads, the nodes which want to transmit are forced to wait for the unused slots (allocated to non-transmitting nodes) to pass before transmitting.
- (3) CSMA/CD systems are less efficient for heavy loads because of the "listen and wait if the medium is busy" nature.

From these "guidelines," claims have been made that CSMA/CD systems cannot guarantee a maximum time that a node must wait before it can transmit. For this reason, CSMA/CD has been called a nondeterministic access method. In contrast, token-passing and TDMA have been called deterministic. However, there are situations where the so-called deterministic methods can begin to look nondeterministic. An example for a token-passing system is the case where the token is lost. If there are errors upon network reinitialization, the time that a node waits for a transmission opportunity may be greatly increased. Repeated losses of

the token can introduce more uncertainty than supporters of token-passing systems may like to admit.²¹ For TDMA systems, a loss of synchronization between stations can make the response time exceed the guaranteed delivery time. Roll-call polling would normally be considered deterministic, but loss of the master coupled with errors upon reinitialization can make it less deterministic. These sorts of situations indicate that perhaps a better measure than calling an access method deterministic or nondeterministic is to calculate the probability that a transmission will go through a network within a certain amount of time for a specific implementation. This approach will include the important effects of equipment and network failure.¹⁰ The point to be made is that the question of whether a particular access method is suitable for an application should be done on an individual case basis, i.e., the specifics of the particular implementation of the network must be considered before any conclusions can be formulated.

One way to reduce the concerns of deterministic versus nondeterministic systems is to use a combination of access methods. Schemes have been suggested in which the particular access method to be used is dependent upon the traffic load on the network at a particular time. One possibility is to use CSMA/CD for low traffic loads and token-passing for heavy traffic situations, and has been discussed for a passive fiber optic star network.²³ However, for the use of such multiple access method schemes, one must be concerned with perhaps overcomplicating the requirements of the system.

3.2.4 Information "Packaging" Characteristics

There are several formats in which information can be transmitted between two stations. The three basic methods are circuit switching, message switching, and packet switching. They differ in the manner that the connection between the two stations is established and also in the type of paths that the information takes. An illustration of the three basic methods is shown in Figure 3.2.9. In this figure, IMP (Interface Message Processor) is used to indicate a switching element.

3.2.4.1 Circuit switching

Circuit switching is probably the most familiar method used. Some telephone networks use circuit switching, in which a dedicated physical path is established for the duration of the call. Circuit switching requires that an end-to-end connection be established before any data is sent. This means that a significant amount of overhead must be used to set up the call before the actual messages are sent. In addition, since the call connection is set up through a cascade of switching centers, the quality of the link is only as good as the weakest portion of the link. One attractive feature of circuit switching is that there is never the problem of congestion once the link is established since the call is on a dedicated physical path.²²

3.2.4.2 Message switching

Message switching differs from circuit switching in that no dedicated physical path is set up in advance for message switching. The whole data message is sent to a switching station where it is checked for errors and then forwarded to the next switching center in a series of hops. This method is known as store-and-forward. As the message is sent to the next switching center, the responsibility of the previous station is completed.²¹ Message switching systems typically either limit the message length and guarantee the delays to some extent or do not limit the message lengths.

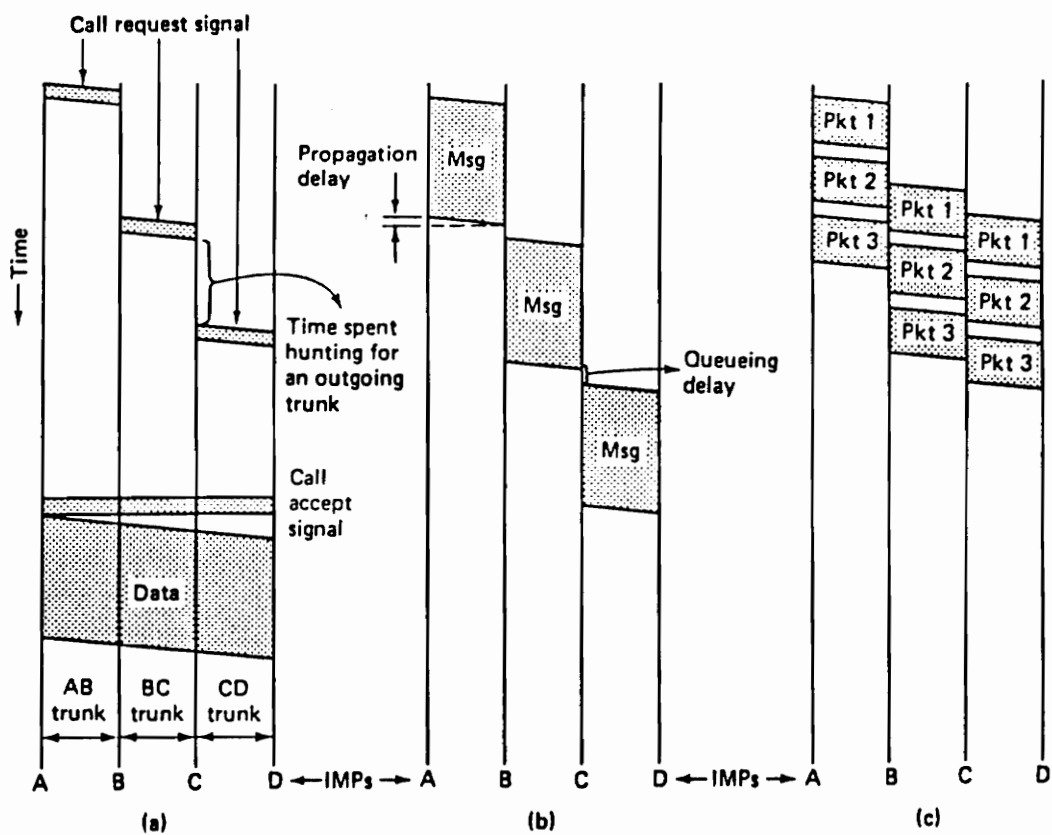


Figure 3.2.9. Timing of events in:
 (a) circuit switching,
 (b) message switching,
 (c) packet switching.²¹

If the message size is not limited, the network can become inefficient and have low throughput due to many sections being blocked by long messages.²²

3.2.4.3 Packet switching

Packet switching is similar to message switching in that a dedicated physical path is not established for the entire message sequence. Packet switching places a strict limit on message block size. This provides an advantage over message switching in that no single station can monopolize a transmission line for very long. A higher throughput than in message switching systems can be obtained since the first packet of a multipacket message can be sent ahead before all of the second packet has arrived. In circuit switching, the bandwidth is statically reserved in advance whereas for packet switching the bandwidth is procured and released as needed. Any unused bandwidth on a circuit-switched line is wasted. Packet-switching systems were developed to avoid the long call connection time needed for circuit-switching networks and to increase the efficiency and throughput of message-switched systems.^{21, 22} The size of packet used is a significant design choice. The use of packet where the overhead (control) portion is large compared to the data fields will result in low efficiency, while too much data per packet will result in long delays for nodes wanting to transmit.²⁴

There are two subsets of packet-switching schemes which can be used. One of these is a datagram system in which the individual packets of multipacket messages are sent along separate paths and then reordered at the final destination. Although the efficiency of bandwidth used is better than that of circuit switching, datagram operation has the disadvantage that an error in the reordering of the packets can occur. This can never happen in circuit-switched networks. Another form of packet

switching used is virtual circuits, also known as virtual calls. Virtual circuits are similar to circuit-switched networks in that a connection is established and the entire sequence in a multipacket message is sent over the same physical path.²² The best-known virtual circuit specification is probably the X.25 protocol used for telecommunications. Datagram systems are easier to implement than virtual circuits. Datagram operation is typically used for local area networks while virtual circuits are used for long-haul applications.²⁵ To summarize, computer networks are usually packet switched, sometimes circuit switched, but never message switched.²¹

3.3 OSI Reference Model

The Open Systems Interconnection (OSI) Reference Model is a seven-layered model developed by the International Organization for Standardization (ISO). The OSI model was created to provide a basic framework around which the interconnection of LAN communication systems and standards could be developed.²⁶ The widespread acceptance of this model has greatly simplified the design of LANs and their interconnection.

The seven layers defined by this model are arranged according to functionality, as shown in Figure 3.3.1. A layer can be thought of as providing services that help the layers directly above it communicate. The lower layers are concerned primarily with hardware-dependent aspects, while the middle and upper layers specify operations normally performed in software. The hardware-dependent functions include the physical transmission and reception of signals as well as their conversion to and

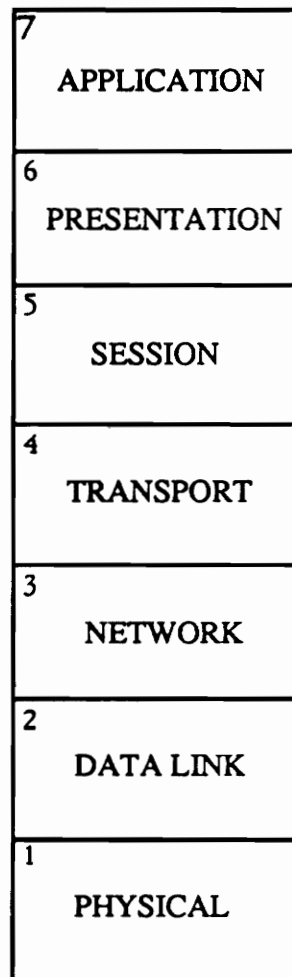


Figure 3.3.1. OSI Reference Model.

from digitally formatted data. The software-dependent layers perform the remaining processes needed to communicate data between systems such as data formatting and packetization.¹² The advantage of using a multi-level design approach such as the OSI Model where the interconnections between the layers are well-defined is that changes in the lower layers can be somewhat insulated from the changes in the higher layers.²¹

The optical portion of a LAN using fiber optics occupies only a small portion of the OSI model, involving only the Physical Layer (Layer 1). The optical part of the physical layer is where such things as fiber optic transmitters, receivers, cables, and connectors reside. One of the consequences of the optical portion comprising such a small portion of the OSI Model is that much of the LAN technology developed for wire-based systems (i.e., the "upper layers") can be used with little or no changes in fiber optic-based systems. This does not mean, however, that designing a fiber optic-based LAN simply requires replacing wires with fiber. In particular, since fiber optics performs better as a point-to-point medium rather than a point to multi-point medium, one of the changes that is sometimes done in the Physical Layer is to change the broadcast architecture from a bus to a ring or a star. Although the optical part of a LAN comprises only a small piece of the OSI model, it is still a very prominent aspect of the system design.

Equipment and software that is developed for Layers 2-7 of wire-based systems are equally suitable for fiber-based systems, provided the physical fiber layer is compatible with wire in terms of interface characteristics and behavior. Thus, for fiber optic networks based on standards developed for wire systems, no new development of upper layer equipment and software is necessary. As fiber systems

are developed at higher data rates at which no wire counterparts exist, the task of the development of the "upper layers" is falling on fiber optic systems manufacturers. Indeed, as use of fiber in the Physical Layer makes higher data rates possible, new hardware, software, and architectural approaches will need to be developed for the upper layers in order to "keep up" with the higher data rates.

Within the scope of this thesis, only the Physical and Data Link Layers (Layers 1 and 2) will be addressed in detail.

3.4 Existing and Planned Fiber Optic LANs

There are many networks using fiber optics which have been implemented in various application realms. Some of these networks and the areas in which they are used are shown in Figure 3.4.1. As indicated in the figure, some network standards have been used in several applications, while others have been used only for a specific application. Although most of these standard networks were established as wire standards, they have been implemented using fiber optics. The most significant ones which have been used for local area networks will be discussed.

3.4.1 Ethernet/IEEE 802.3

Ethernet is the name given to a CSMA/CD network originally specified by Xerox, Digital Equipment Corporation (DEC), and Intel for use with copper wires in the early 1980's. In 1980, the IEEE (Institute of Electrical and Electronics Engineers) 802 committee was established to develop a LAN standard. The committee was

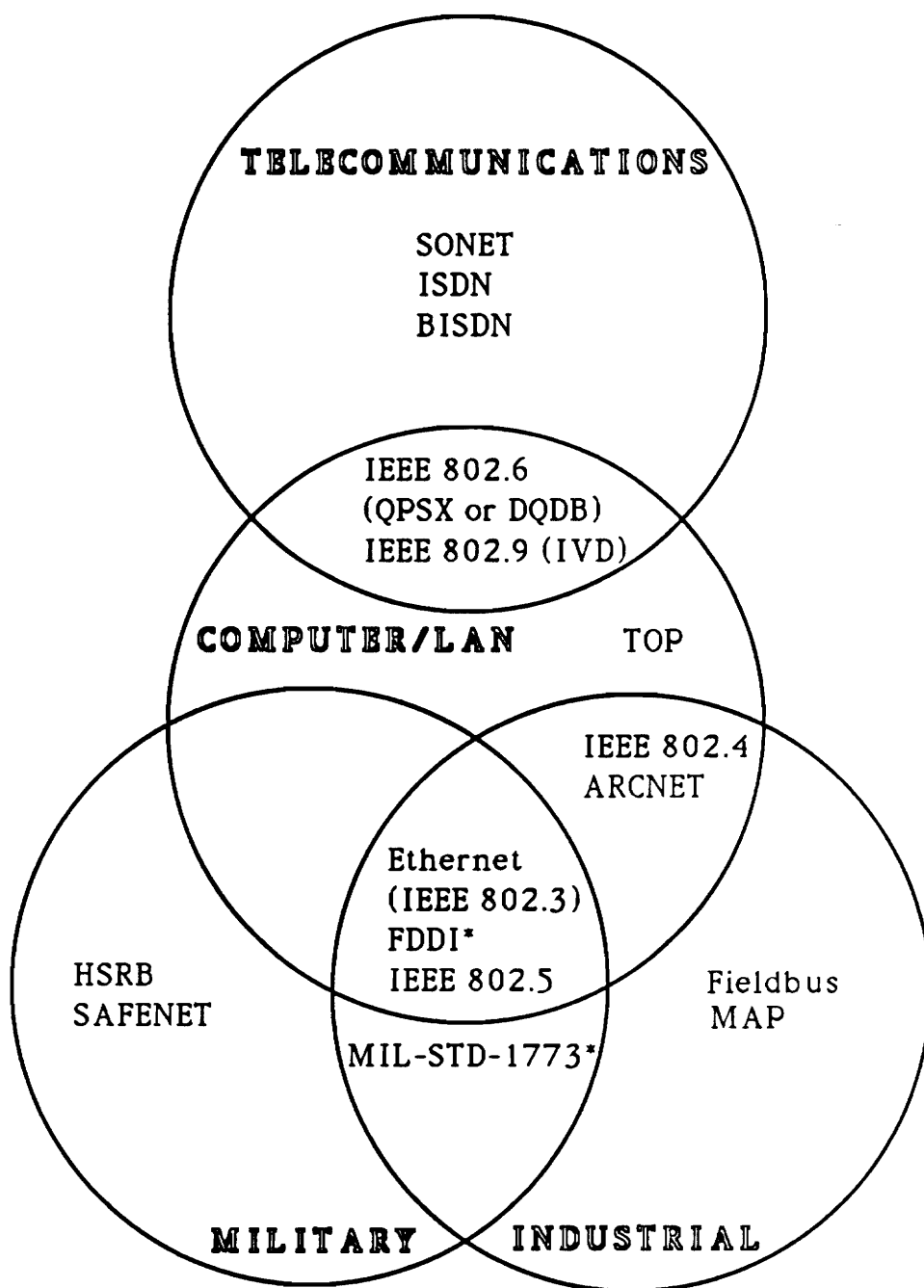


Figure 3.4.1. Major network standards employing fiber optics -by application (* entirely fiber-based).¹⁰

specifically interested in basing this standard on Ethernet, but it eventually became apparent that a single standard would not be sufficient. A subset of the original 802 committee, the IEEE 802.3 committee, was created to standardize CSMA/CD networks. The 10BASE5 IEEE 802.3 standard "is almost identical to Ethernet Version 2.0," and the term Ethernet usually refers to this standard.¹⁵

The Ethernet/IEEE 802.3 standard is defined for the first layer and the lower part of the second layer of the OSI model, with the IEEE 802.2 Logical Link Control (LLC) used for the upper part of Layer 2. Manchester encoding is used for Ethernet/IEEE 802.3 LANs. Many different versions of Ethernet have been used, in terms of both transmission medium and architecture. There have been implementations of Ethernet networks using CSMA/CD on coaxial cable, twisted pair, and optical fiber. For fiber optics, data rates of 1 and 10 Mbps have been used with both star (active and passive) and ring (single and dual) architectures. Fiber optic Ethernets are designed to be plug-compatible at the transceiver cable interface, also known as the AUI (attachment unit interface). Plug-compatible means that the electrical side of the optical transceiver interface must be compatible with the electrical interface used in non-fiber Ethernets.¹⁵

Ethernet-compatible systems are probably the most prevalent implementations of LANs using fiber optics, with at least tens of thousands of nodes currently in use.¹⁰

3.4.2 IEEE 802.4

IEEE 802.4 is a LAN standard which incorporates token-passing in a bus architecture. Similar to IEEE 802.3, IEEE 802.4 is defined for the first layer and the lower part of the second layer of the OSI model, with the IEEE 802.2 LLC used

for the upper part of Layer 2. IEEE 802.4 specifies four different bus media/physical layer entities for use with coaxial cable or fiber optics. The fiber optic implementation can be used at 5, 10, and 20 Mbps as a directional bus using an active or passive star architecture with Manchester encoding.²⁷

3.4.3 MAP

A LAN standard designed for use in manufacturing applications is the Manufacturing Automation Protocol (MAP). MAP was originally developed by General Motors (GM), and the responsibility was eventually turned over to the Information Technology Requirements Council (ITRC) on January 1, 1989.²⁸ MAP is based on parts of the IEEE 802.4 token bus standard. The MAP specification encompasses the entire OSI Reference Model, with the sixth layer null. There is a streamlined subset of MAP which operates at 5 Mbps using an Enhanced Performance Architecture (EPA) which has the capability to bypass Layers 3-6 and connect the Data Link Layer (Layer 2) directly to the Application Layer (Layer 7). Nodes with this bypass capability are called MAP/EPA nodes. There is also another subset called Mini-MAP that also operates at 5 Mbps which always bypasses Layers 3-6. This bypassing of layers may be necessary to provide faster response times for critical communications at the sacrifice of upper layer functionality.²⁹

MAP does not currently specify a particular implementation using fiber optics. However, the manner in which the MAP standard is written does not preclude the use of fiber optics.¹⁰ The use of fiber optic MAP networks may have been hindered by the fact that up until the end of 1988, GM had explicitly banned the use of fiber optics in its MAP networks.³⁰

3.4.4 IEEE 802.5

IEEE 802.5 is a token-passing dual-ring LAN developed by IBM. It was originally intended for use with shielded twisted-pair but has been implemented with fiber optics. It can be used at a data rate of either 4 or 16 Mbps with differential Manchester encoding. IEEE 802.5 is also defined through Layer 1 and the lower part of Layer 2 with the IEEE 802.2 LLC used for the upper portion of Layer 2.³¹

Although fiber optic network implementations of IEEE 802.3, IEEE 802.4, and IEEE 802.5 are specified in working drafts, none has yet become an official part of the standards, except for the IEEE 802.3 FOIRL (fiber optic inter-repeater link), which links individual 802.3 network segments together.¹⁰

3.4.5 FDDI

The Fiber Distributed Data Interface (FDDI) is a proposed international 100 Mbps token-passing LAN standard which uses a dual counter-rotating ring architecture. Like the other IEEE 802 standards described, FDDI defines the Physical Layer and the lower part of the Data Link Layer, using the IEEE 802.2 LLC for the upper part. FDDI is the first LAN standard to specify fiber as its primary transmission medium. Both synchronous and asynchronous traffic are supported by FDDI, with synchronous traffic being given the highest priority. There is also an enhancement called FDDI-II which offers integrated circuit-switching data traffic capabilities, FDDI alone being strictly a packet-switching LAN. FDDI-II provides the additional capability to support isochronous traffic.³²

The dual counter-rotating ring configuration provides a measure of fault tolerance through redundancy. This architecture is capable of cable loopback (within a

station) upon occurrences of cable breaks or station failures. Additional fault tolerance by the use of an optical bypass switch to bypass a powered-down station is optional within the FDDI specification. FDDI uses 4B5B block coding in which 4 bit blocks of NRZ (non-return-to-zero) data are encoded as 5 bit blocks of NRZI (non-return-to-zero-with-invert) data. The 4-to-5 mapping is set up so that no more than 3 consecutive zeros can occur in any possible valid bit sequence and therefore the timing can be recovered in a known fashion.

In the United States, the establishment of the FDDI standard is being done by the American National Standards Institute (ANSI) through the Accredited Standards Committee (ASC) X3T9.5. On an international level, the ANSI approved documents are sent to the ISO for approval. Three out of the four documents within the basic FDDI standard have been ANSI approved, with only the approval of the station management (SMT) document remaining (two of the four basic documents have been ISO approved). FDDI has more industry backing and momentum than any other fiber optic LAN. Over 250 companies have participated in the FDDI standardization effort.³³ One of the primary applications foreseen for FDDI is a high-speed backbone network to link slower LANs. FDDI is anticipated to be the most prevalent fiber optic LAN standard for backbone applications in the immediate future.

3.4.6 ARCNET

ARCNET (Attached Resource Computer NETwork) was developed by Datapoint Corporation in the mid-1970's as a 2.5 Mbps token-passing bus network. ARCNET is somewhat different than most of the LANs described in that it is a de facto

standard, i.e., it has not been formerly approved and published by a standards organization such as the IEEE or ANSI. Datapoint has licensed Standard Microsystems Corporation (SMC) and NCR to produce ARCNET bus controller chips, and there are a number of companies which now market ARCNET products using these chipsets. The ARCNET Trade Association (ATA) was created by ARCNET vendors to gain more exposure and further acceptance of ARCNET in industry. There are currently more than 600,000 nodes of ARCNET LANs installed worldwide.³⁴

ARCNET uses an acknowledgement scheme in which the node holding the token sends an inquiry to its intended message recipient to see if there is sufficient memory available at the destination node. If a sufficient buffer does not exist at the destination, the node possessing the token does not send the data and the token is passed to the next node. Another attempt to send is initiated when the token "comes back around." Successful transmissions are answered by acknowledgements.

ARCNET was designed to be completely free from cabling selection constraints by defining a network interface module (NIM) which the cable attaches to. The NIM fits into an expansion slot on each node in the network, and therefore whatever cable connections are supported on the NIM can be used. The only restriction on the medium is that the signal delay through the medium should not exceed 31 μ sec.

³⁴ It has been used as both a baseband and broadband system and with a variety of media such as coaxial cable, twisted pair, and fiber optics. Fiber optic ARCNETs are used in either a passive or active star architecture.³⁵

A 20 Mbps version of ARCNET known as ARCNETplus is currently under development by Datapoint, with non-exclusive licenses granted to SMC and NCR.³⁶

The 20 Mbps version is designed to be compatible with the 2.5 Mbps version and also does not specify a particular transmission medium.

3.4.7 Fieldbus

Fieldbus is a proposed standard being developed by the Instrument Society of America (ISA) SP50 Committee. It is designed specifically for connecting factory floor devices. The concept behind Fieldbus is "to replace point-to-point links from each sensor or actuator to its controlling equipment by a single link." All the information would be serially transmitted and multiplexed in time. This would allow each device to be connected to a Fieldbus interface that would handle the communication with the controlling equipment.³⁷

The SP50 Committee is planning to define the following four layers: a Physical Layer, a Data Link Layer, an Application Layer, and a User Layer. The User Layer is a hybrid layer that does not neatly fit into the OSI Model. It is similar to an Application Layer. The goal at the User Layer is to attempt to define the instrument needs for the various industries involved to try to cover all their uses. There are 5 different Physical Layers to be defined. Three of these are wire-based and are almost ready to be published. Power distribution is desired along the same cables as data transmission in the wire versions. The wire versions use unshielded and shielded twisted pair at data rates of 31.25 kbps (kilobits per second) and 1 Mbps, respectively, in both bus and tree (cluster of stars) architectures. Fiber optics and radio are the other two Physical Layers.³⁸ Neither of these have been addressed in very much detail. Fiber optics is the next Physical Layer to be defined; more detailed discussions began at the April 1990 SP50 Committee meeting.³⁹

A combination of token-passing and polling access methods is under consideration. The token bus portion is to be based on the IEEE 802.4 and Profibus networks and is to be used with the FIP (Field Instrumentation Protocol) bus arbitration scheme. In this scheme, there are two classes of masters (token and mono) and one class of slaves. The token is passed among a logical ring of token masters, with each master associated with a group of slaves. The master who captures the token then polls the associated slaves.³⁸

SP50 is looking to define its own LLC sublayer within the Data Link Layer. Significant dissention exists within the committee concerning the definition of the Data Link Layer. The Physical Layer is the only one which is near publication. The specification of the remaining layers is very preliminary at this point.³⁹

3.4.8 MIL-STD-1553/1773

MIL-STD-1553 (formally called Aircraft Internal Time Division Command/Response Multiplex Data Bus) is a 1 Mbps avionics data bus standard originally developed by the Society of Automotive Engineers (SAE) in 1973 and later adapted as a military standard (revised to MIL-STD-1553B in 1978).⁴⁰ MIL-STD-1553 has a master/slave access method and optional redundancy for use with shielded twisted pair. A station designated the "bus controller" is the master, the remote terminals are slaves, with another station, the "bus monitor", recording the bus traffic for later analysis. MIL-STD-1553 has a companion specification for fiber optics known as MIL-STD-1773. MIL-STD-1773 uses the same protocols and chipsets as MIL-STD-1553, but with fiber optic transceivers and cables. MIL-STD-1773 is normally implemented as a passive or active star architecture, and has also

been implemented as multiple interconnected stars. ⁴¹ An implicit token-passing scheme has been developed as a variation of MIL-STD-1773 to improve reliability and performance. This scheme replaces a explicit token with brief "soundoff" messages from all nodes on the network. ⁴²

3.4.9 SSD RTN

A proprietary network known as RTN (Real Time Network) specifically designed for use in a factory drive systems environment has been developed by Shackleford System Drives (SSD). RTN uses plastic optical fibers in a dual-ring architecture at 2.7 Mbps.

4.0 FACTORY COMMUNICATION REQUIREMENTS

There are a diversity of communication requirements in a typical industrial setting. These can range from making connections between relatively simple devices on a factory floor to interconnecting high volume data producers such as mainframe computers and supercomputers in an office or interbuilding facility.

4.1 Computer-Integrated Manufacturing

Computer-integrated manufacturing (CIM) is a term used to describe a distributed coordination of various stages involved in manufacturing processes. The idea of CIM was established in order to facilitate the integration of these stages by allowing faster design and development cycles for more sophisticated products, control and analysis of current business and technological data, and flexible manufacturing systems.⁴³ Distributed communication through the use of networking between the various arenas in a manufacturing environment is obviously a vital ingredient in CIM.

4.2 Multi-Tier Approach

The diversity of communication needs in a factory environment can be accommodated using a multi-tier approach. This would involve a hierarchical structure among the devices and networks arranged according to communication needs and data rates that are provided, as shown in Figure 1.1. The use of a multi-tier approach fits in very well with the concept of CIM. The diversity of

communication requirements and the associated interconnection concerns necessitates the use of a design strategy which will allow efficient and least-cost interconnection between all levels of a hierarchical communication structure without forfeiting the needs of a specific level or device. A design strategy based on a tiered communications structure is well-suited for a least-cost approach since it will permit low-cost connection of devices while still maintaining interconnectivity.

10

The use of standardized networks in the multi-tier structure will help facilitate the interconnection of the various tiers. This is due to the availability of equipment needed to implement standardized networks and the normally detailed definition of the network interfaces. The use of standardized networks will be especially useful in the interconnection of the tiers by gateways or concentrators.

The hierarchical structure contains the following four tiers: (1) inexpensive feeder networks, (2) intermediate data subnetworks, (3) data backbone networks, and (4) "super backbone" networks.¹⁰

The goal is to implement all of the network tiers using fiber optics. An all-fiber approach is attractive for several reasons. The properties of optical fibers and the associated advantages over wire conductors make the use of fiber feasible in an industrial environment. Factors such as the EMI/RFI immunity, small size and weight, and the less stringent safety concerns of optical systems make them well-suited for factory floor situations. As the bandwidth requirements of industrial applications increase, the high data-rate capacity of fiber-based systems is another property which makes the use of fiber appropriate in an industrial-based multi-tier arrangement.

4.3 Inexpensive Feeder Networks

The lowest tier consists of inexpensive feeder networks used to connect factory floor devices such as strain gauges, thickness gauges, density gauges, temperature sensors, bar code readers, scanners, actuators, PLCs, robots, and small computers such as IBM PCs. These different types of equipment can produce information at a variety of rates. Some devices produce information at a rate of several kbps or lower, e.g., bar code readers, while other instruments such as robot vision systems can have rates of several hundred kbps or more. The goal at the lowest tier is to optimize cost while providing connection to the higher tiers. The feeder networks will have data rates in the range of several Mbps in order to accommodate the wide range of rates at which information is produced by the factory floor devices.

The primary consideration at the feeder network level is the cost effectiveness of the implementation. Network circuitry is typically complex and can therefore be quite expensive. One way to achieve the desired functionality of the network circuitry is to use discrete components. However, this method can become cumbersome as well as expensive. Another approach is to use ICs (integrated circuits) that have already been developed. This scheme avoids the NRE (non-recoverable engineering) costs associated with the design and development cycle of a component. The second approach would be better suited for the feeder networks.

There are several networks which have been implemented with fiber at the data rates applicable at the lowest tier. Among these are ARCNET, MIL-STD-1773, Fieldbus, and RTN.

ARCNET has been widely used in office environments as well as factory environments. This widespread usage means that ARCNET components such as

inexpensive token bus controller chips are readily available from a variety of manufacturers. The components needed to build a functional ARCNET board (besides the token bus controller) are inexpensive ICs such as standard LS (low-power Schottky) chips and static RAM (random access memory). Therefore a cost-effective solution could be implemented at the lowest tier using ARCNET.

MIL-STD-1773 also has data rates in the lowest tier range. However, since it is a military standard, the equipment costs are high due to the stringent testing procedures required on military-grade components. In particular, the costs of MIL-STD-1553/1773 bus controller ICs are an order of magnitude higher than those of ARCNET. Less expensive industrial versions are available, but the costs are still too high to allow the low-cost implementation desired at the feeder network level. Another reason that MIL-STD-1553/1773 equipment costs are high is that the use of MIL-STD-1553/1773 networks has not been as widespread as many of the other LAN standards; it is primarily used in military applications. This limited market means that the volume of MIL-STD-1553/1773 equipment manufactured is not very high when compared to other networks, and therefore the costs are higher. Because of these high costs, MIL-STD-1773 is not suitable for use at the lowest tier.

The Fieldbus specification process is still in the preliminary stages, particularly for fiber optics. Fieldbus may be a cost-effective feeder network solution in the future, but at the present time it is not defined to the extent where it can be practically used.

The proprietary nature of the SSD RTN makes it unsuitable for use at the feeder network level.

Therefore, it appears that ARCNET is the only existing fiber optic standardized LAN which could be used in a low-cost implementation at the feeder network level.

4.4 Intermediate Data Subnetworks

The second tier of this structure consists of data subnetworks. These subnetworks have data rates in the tens of Mbps to several tens of Mbps range. The purpose of this level is to link feeder networks together and to accommodate larger-scale data transfers between PCs and minicomputers.

As detailed in the previous chapter, several significant standards exist in this data rate range. Among these are IEEE 802.3/Ethernet, IEEE 802.4, MAP, and IEEE 802.5. It is estimated that there are at least millions of nodes of IEEE 802.3/Ethernet and IEEE 802.5 networks currently in use, and at least tens of thousands of IEEE 802.4 nodes in use.¹⁰ In factory environments specifically, one survey in late 1988 stated that 50% to 60% of factory networks installed to date were based on IEEE 802.3/Ethernet, while only 5% were IEEE 802.4 token-bus networks.⁴⁴

The feasibility of using MAP at the second tier is questionable. Although MAP has been specifically geared toward the needs of CIM,⁴³ some vendors feel that the explosive growth of distributed processing has tended to eliminate the need for determinism in a factory LAN.⁴⁵ For example, some companies such as DEC and Ungermann-Bass, Inc. feel that Ethernet is more than suitable for factory implementations.^{7, 44, 46, 47} This contention is not agreed upon by most MAP advocates. Most feel that MAP should continue to focus on the IEEE 802.4 token-

bus scheme. The proponents of the IEEE 802.4-based MAP perceive that any deviation from the original intended course of the MAP standard will undermine the entire MAP effort.⁴⁴

The process of standardization of MAP has taken much longer than anticipated. These delays have resulted in MAP not gaining general-purpose acceptance in the factory, i.e., MAP has been accepted only in niche markets. The high cost of MAP equipment currently available is another reason MAP has not been widely used. A lack of widespread use may assure the continued existence of a high price structure for the foreseeable future. Another stumbling block in using MAP is the software available for the OSI Model upper layer functions. The current software available is expensive as well as extremely complicated. At this point, the future of MAP is unclear. Therefore, the viability of using MAP at the second tier is not certain.

IEEE 802.5 networks have been used mainly in office environments. However, there is nothing inherent in the IEEE 802.5 specification which would prevent it from being used at the second tier.

The exact implementation in which the second tier network will be used will determine which network will be best suited for a specific application, but at the present time it appears that IEEE 802.3/Ethernet and IEEE 802.5 are the best choices for second tier networks.

4.5 Data Backbone Networks

The third tier involves high-speed data networks with data rates in the hundred to several hundreds of Mbps range. The third tier is used as a backbone to link intermediate subnetworks together and to connect high-volume data producers such as mainframe computers.

The network which would be best suited for this tier is FDDI. FDDI is very suitable as a high-speed LAN backbone, thus making it very applicable for a third level network. Work on the development of FDDI interfaces to various other standardized networks such as IEEE 802.3, IEEE 802.4, and IEEE 802.5 has been extensive. This implies that the interconnection of FDDI to the second tier should not be difficult.

4.6 "Super Backbone" Networks

The fourth and top tier consists of super backbone networks with data rates in the range of 1 Gbps and higher. This tier can be used to link the data backbone networks and to accommodate high bandwidth transfers beyond the capability of the data backbones. Applications such as low-delay, high-resolution blueprint transfers, multiple-channel vision-based systems, high-definition video, and shared access to supercomputers for compute-intensive factory operations would require the network performance available only at this tier.¹⁰

There are no fiber LAN standards for use in factory environments which currently exist in this data rate range. One possible option is the use of parallel FDDI rings to achieve the bandwidth requirements of the uppermost tier. The design concerns

involved in the use of parallel FDDI networks to attain data rates in the 1 Gbps range are currently being investigated by researchers at the Fiber & Electro-Optics Research Center within the Department of Electrical Engineering at Virginia Tech and the High Performance Computing group within the Department of Computer Science at Old Dominion University.⁴⁸

5.0 COST OPTIMIZATION OF FEEDER NETWORKS USING A NON-SHARED MEDIUM APPROACH

The discussions of existing and planned standardized fiber optic LANs have shown that there is only one network, ARCNET, which can be implemented at low cost at the feeder network level using fiber optics. The lack of inexpensive feeder networks is perhaps the major obstacle in the more widespread use of fiber optic LANs in factories and process control industries. There is nothing inherent in fiber optic technology which inhibits the design of low-cost feeder nodes.¹⁰

All of the LANs described in Chapter 4 use a shared medium approach. The demands of a network using a broadcast access method exceed the communication requirements at the lowest tier. The implementation of a shared medium approach can result in high costs, due to the use of more functionality than is needed for the feeder networks. An alternative approach which can be used incorporates a non-shared medium scheme. The characteristics of a non-shared medium approach can satisfy the needs of the feeder networks in a more cost-efficient manner than most existing fiber LANs. A non-shared network approach has many qualities which make it appropriate for a cost-sensitive implementation at the lowest tier in an industrial environment. A detailed explanation of the characteristics, requirements, and cost reduction potential of a non-shared medium system will reveal that it is well-suited for use at the feeder network level.

A description of the component costs associated with the non-shared medium network approach will be given in Section 5.5, in terms of both the costs of the individual components as well as the contributions of the costs of the hub, node, and

fiber and connectors as compared to the total system component cost for a 16 node system.

5.1 Architecture

The underlying principle behind a non-shared medium approach is that there is not a great need for direct peer-to-peer communication among the factory floor devices. This is in opposition to the rationale for a shared medium system which supports peer-to-peer communication. The lack of peer-to-peer support at the lowest level allows the intelligence to be centralized, thus minimizing the amount of intelligence (and thus cost) at each remote node.

A non-shared medium approach would require the use of point-to-point links. This is best accommodated for fiber optics using a set of links that constitute a non-broadcast active star architecture. The links would tie into a custom concentrator module which would include a network interface to the second tier as shown in Figure 5.1.1. A passive star architecture could not be used due to its broadcast nature and the corresponding need for address recognition at the nodes. Similarly, the intelligence requirements of a shared medium ring architecture rule out its cost-effective use as a non-shared medium approach.

A non-shared medium active star architecture has individual sources and detectors for each link at the hub. One advantage is that the power budget requirements for the links are much more relaxed when separate transceiver functions are incorporated.

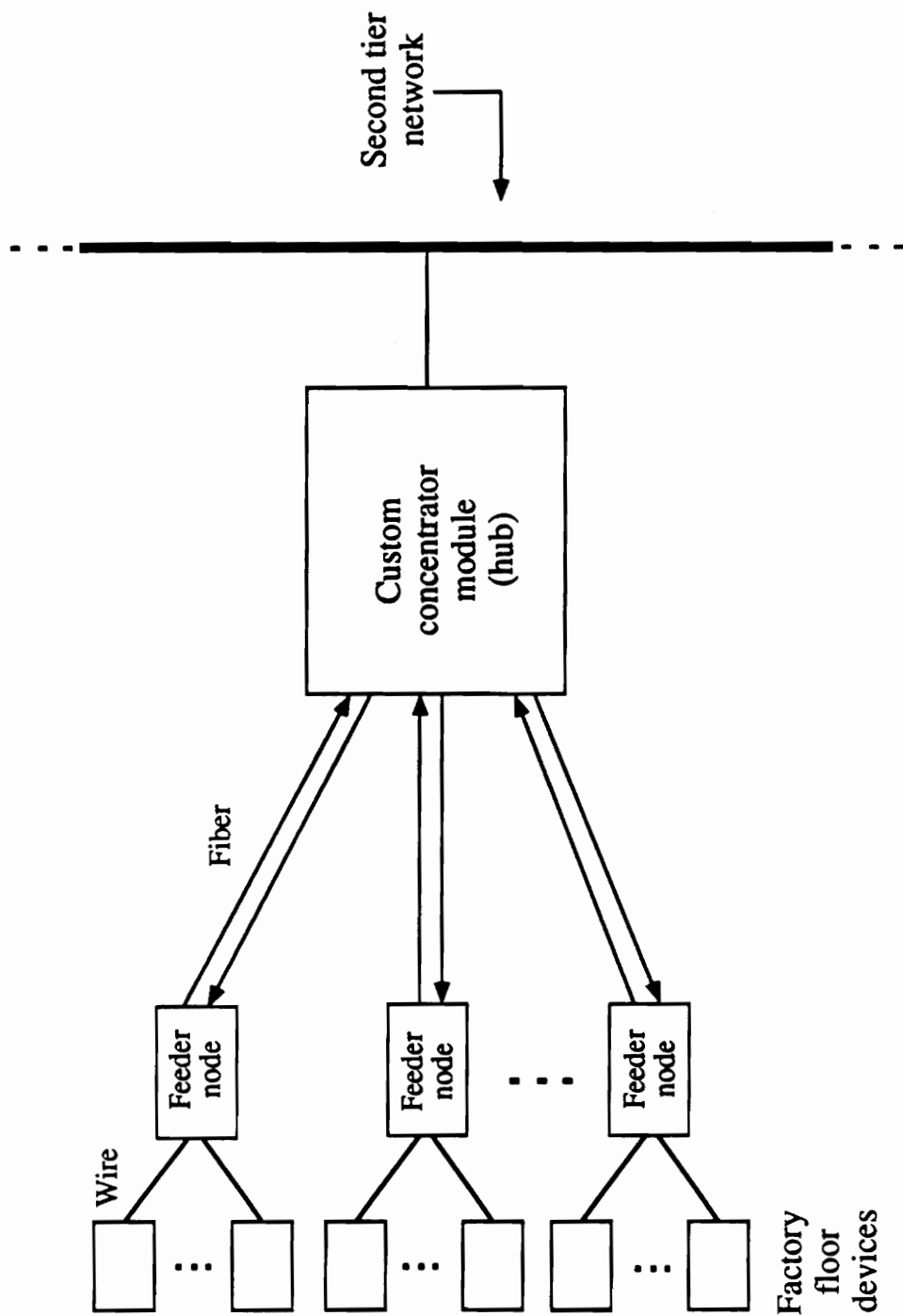


Figure 5.1.1. Non-shared medium network with active star architecture and master/slave access method.

5.2 Access Method

The non-shared medium approach will incorporate a centralized intelligence scheme with a master/slave access method. Roll-call polling can be implemented without the need for address recognition if separate physical paths are used. The decision to use a non-shared approach means that access methods such as token passing, CSMA/CD, and TDMA are not appropriate. Avoiding the intelligence needs of a system using address recognition helps with meeting the cost requirements at the lowest tier.

This approach would require only one node, the hub, to have the capability to be the master. The placement of the acknowledgement field and data field within the same frame is best suited for the types of traffic which would exist in polling typical factory devices. The issuance of a invitation to transmit by the master will imply that the master is ready to receive data from the node and thus additional handshaking is not necessary.

Peer-to-peer communication between the feeder nodes can be indirectly supported through the second tier. A viable arrangement for a hierarchical structure is to use a non-shared medium access method at the lowest tier and a shared medium access method at the second tier. This sort of scheme fits well into the proposed multi-tier structure for factory floor implementation. A shared medium access method such as token-passing or CSMA/CD could be used at the second tier to allow second tier network access contention among the feeder network custom concentrator modules (hubs). This arrangement would accommodate communication between the feeder nodes while still allowing a cost-sensitive solution to be implemented at the feeder network level.

5.3 Optical Link Components for Node-to-Hub Transfers

The selection of the components for the optical communications links at the feeder network level forms the foundation of the larger network structure. An emphasis on cost optimization of the optical link components tends to optimize the overall cost of the feeder network. An optical communications system consists of three basic parts: the transmitter, the fiber cable, and the receiver. The components of a typical optical digital communications link are shown in Figure 5.3.1.

5.3.1 Node transmitter

The first stage of the node transmitter is the signal input stage. Costs can be reduced by connecting multiple devices to each remote node. Multiple analog input signals could be accommodated by the use of a single A/D converter and an analog selector switch in the signal input stage of the node transmitter. The analog selector switch would be controlled by the master and would select which analog input line would be active at a particular time. The similarity in the characteristics of the different analog inputs will determine the applicability of using a single A/D converter at each node. Multiple digital inputs can also be accommodated in the node signal input stage by using a digital multiplexer (selector) controlled by the master. The difference in the characteristics of the multiple digital inputs will determine how appropriate using a digital multiplexer will be. Figure 5.3.2 illustrates the components required in the node transmitter.

The encoder modifies the output of the signal input stage into a form better suited for modulation of the optical source. The encoding scheme to be used is an important system consideration. When dealing with optical systems, care must be taken when using the classical encoding terminology developed for electrical signals.

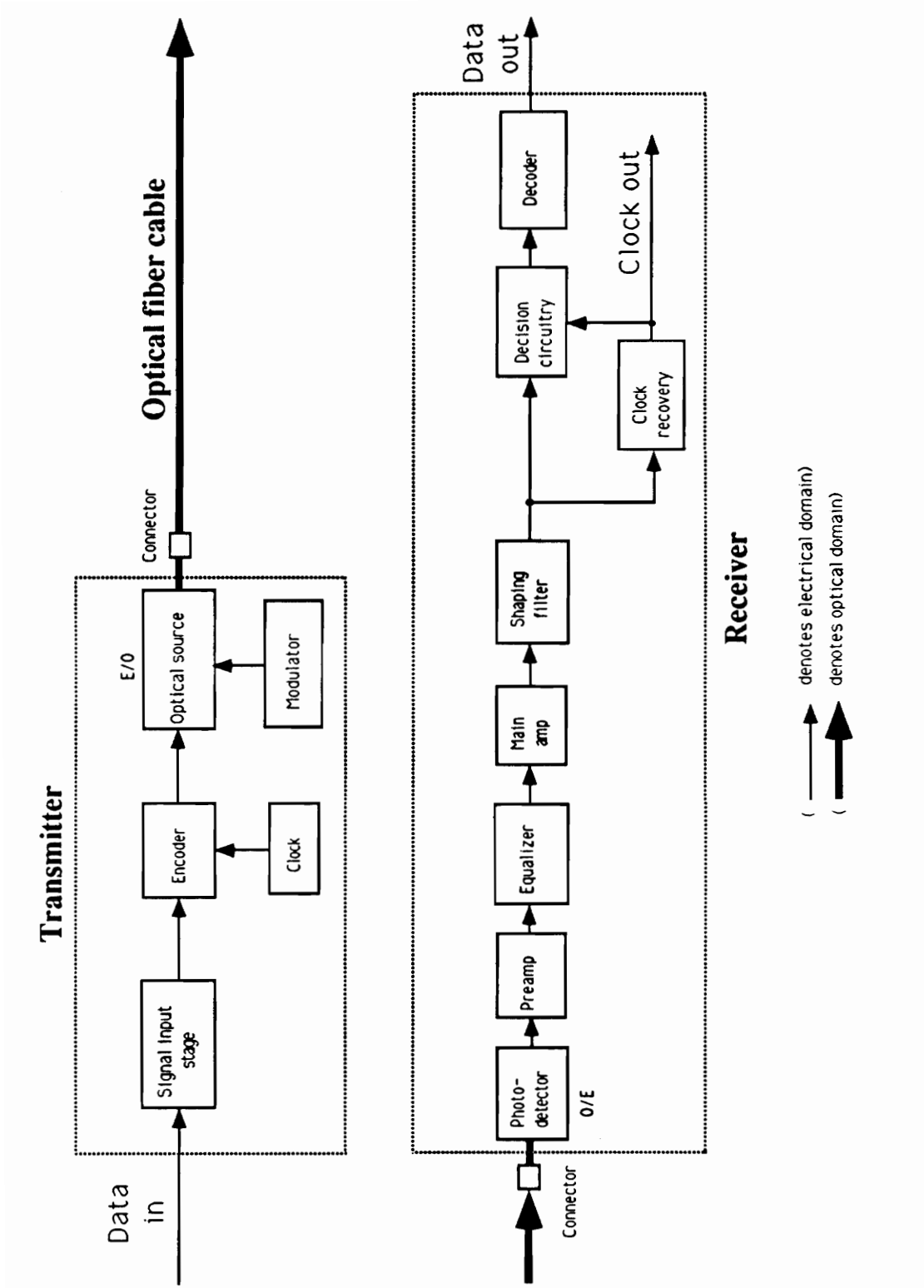


Figure 5.3.1. Block diagram of basic digital fiber optic communications link.

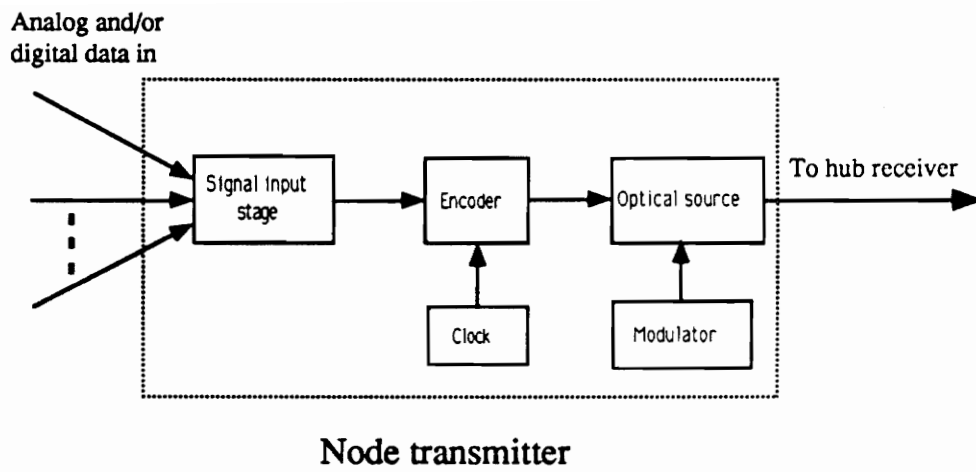


Figure 5.3.2. Node transmitter for a non-shared medium network using an active star architecture.

The concept of having symmetric positive and negative signals does not exactly apply to lightwave systems. The nature of light is such that it can never have negative values since "darkness" is defined as zero. Therefore, the electrical output signal of a photodetector receiving a data stream will always have some DC component. Normally, an electrical scheme is used which will not contain a DC component due to the greater simplicity in processing a purely AC signal. This DC component can be removed after the optical-to-electrical conversion with a DC blocking capacitor.

There are numerous encoding methods which have been used in communication networks. Some of the most common line coding schemes are RZ (return-to-zero), NRZ (non-return-to-zero), NRZI (non-return-to-zero-with-invert), and Manchester encoding. These schemes are shown in Figure 5.3.3. Clock recovery is one of the main reasons for encoding a data stream. Some method of synchronizing the timing of the received data stream must be used. One widely used approach is to encode the clock information into the data stream. Transitions between high and low states are used to derive clock information from the received bit stream. The possible loss of synchronization is one significant disadvantage of NRZ. Occurrences of logical ones are needed to get transitions for NRZI and RZ, but with NRZ 10101010 patterns must be received to detect transitions. Manchester encoding has better clock recovery characteristics than NRZ, RZ, and NRZI. Manchester encoded signals have clock information in each data bit period. Manchester encoding is a bi-phase encoding scheme in which a logical one is encoded as a low-to-high transition and a logical zero is represented as a high-to-low transition. If a high state or low state of a signal constitutes a "transmitted bit," then this can be thought of as mapping one information bit into two transmitted bits. Another way to put this is

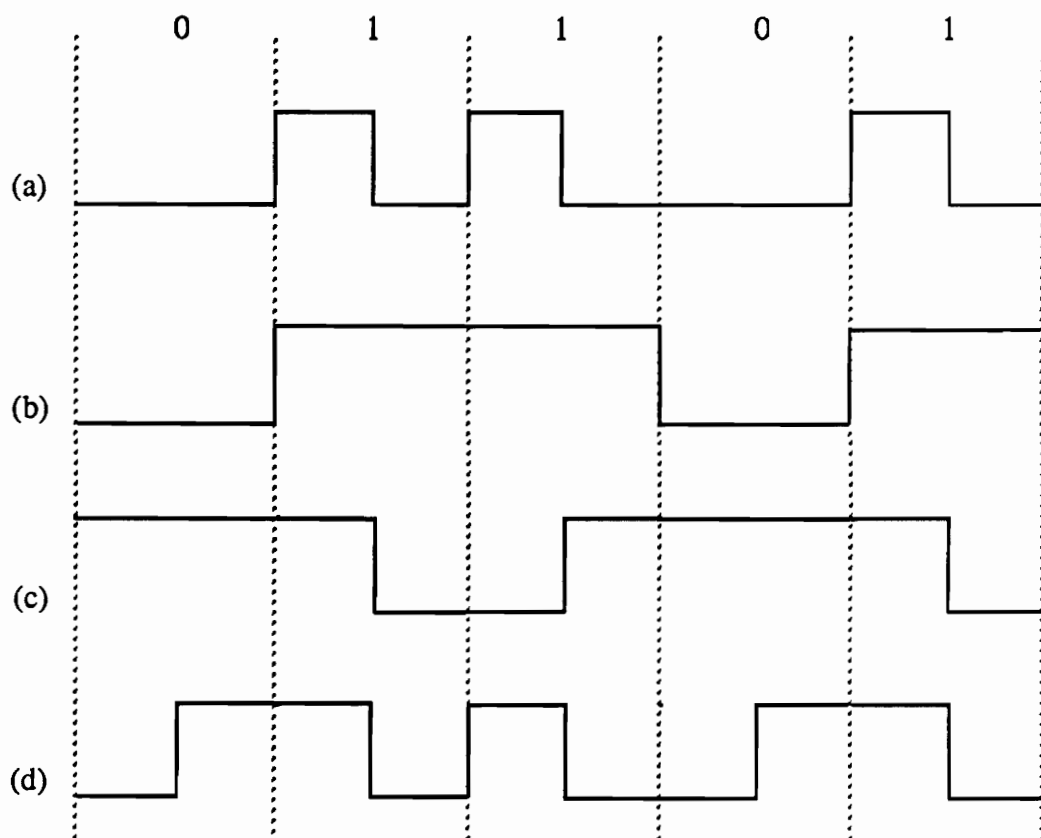


Figure 5.3.3. Line encoding schemes:

- (a) RZ**
- (b) NRZ**
- (c) NRZI**
- (d) Manchester.**

that in Manchester encoding there is one half bit per baud, i.e., potential or actual level transition. The optical Manchester signal is produced by direct modulo-2 addition of the baseband NRZ signal and a clock signal.⁴⁹

Another reason for using an encoding scheme is to minimize the amount of variation in the DC component present in a bit sequence. This is desirable in order to reduce the amount of DC wander in the bit stream that the amplifiers in the receiver must be capable of accommodating. Over the course of a single bit time, there is no DC component present in a Manchester encoded electrical bit stream due to the presence of equal duration high and low levels for each data bit period. Manchester encoding is widely used, particularly for the standard IEEE 802 networks. Although the 2-to-1 mapping of Manchester encoding requires more bandwidth than some other line coding methods, the increase in bandwidth is not anticipated to be a significant cost problem in terms of required transmitter, receiver, and fiber bandwidth for the low data rates to be used at the lowest tier. Another attractive feature of Manchester encoding is that the probability of misinterpreting a symbol is low. Merely the presence of a small amount of low amplitude noise could not cause an electrical Manchester-encoded symbol to be misinterpreted; it would require a reversal of polarity. When the advantages of Manchester encoding are considered along with the widespread availability of inexpensive Manchester encoder/decoder ICs, Manchester encoding stands out as an excellent choice for use in the feeder networks.

Block codes are schemes in which n bits are encoded as m bits, where $m > n$. As the name suggests, the encoding is done on blocks of n bits rather than individual bits. Although block coding schemes have several attractive properties, they are not

suitable at the lowest tier due to the increased complexity and cost of the encoding and decoding circuitry. These types of codes are typically used in higher performance systems where the availability of bandwidth is more of a concern.

The encoded electrical signal must now be converted to the optical domain before being transmitted. LEDs should be used for the optical sources. LEDs have much lower costs, better stability, and longer lifetimes than lasers. The use of LEDs means that intensity (optical power) modulation must be used since LEDs do not have a well-defined frequency or phase. Intensity modulation of an optical source can be accomplished by varying the input current to the optical source, i.e., by adding a signal current to the bias current. For modulating LEDs in the several MHz range, however, turning the LED on and off is typically used. At such data rates, a bias current is not required. The internal gain mechanism of lasers requires more complex biasing circuitry than needed for LEDs. The physical characteristics of lasers do not allow logical ones and zeros to be represented by turning the laser on and off since a threshold bias current is needed. The ability of LEDs to be used without a bias current means that LEDs can be more easily incorporated into circuitry than lasers. Lasers have larger source bandwidths and higher coupled output power, but for the data rates and distances under consideration at the feeder node level, LEDs are more than adequate. LEDs can often be modulated at low data rates using a modulation circuit consisting of inexpensive digital logic gates.

The ratio of the amount of light in the high light condition to that in the low light condition is referred to as the extinction ratio. The extinction ratio can be adjusted by the designer to be compatible with device characteristics, data rate, and desired bit error rate.

5.3.2 Optical cable

Optical fibers used for communications are either silica or plastic based. One major difference between silica-based communication systems and plastic-based systems is the optical wavelength at which they are operated. The differences in the chemical compositions of plastic and glass implies that they are best suited in terms of attenuation for use at different wavelengths. Plastic fiber cores are normally made of either polymethyl methacrylate (PMMA) or polystyrene. The attenuation versus wavelength characteristics of plastic and glass fibers are shown in Figure 5.3.4. The regions for which PMMA plastic fiber has the lowest attenuation characteristics are centered around approximately 570, 650, and 760 nm. However, the lowest attenuation for glass fibers occurs around 850, 1300, and 1550 nm. This indicates that the light sources designed for a glass fiber-based system can not be used for a plastic fiber-based system without a serious degradation in system performance.

Plastic fibers have characteristics which make them well-suited for use as a communications medium for factory floor implementations. One key advantage is that plastic fiber is generally cheaper to manufacture than silica-based fiber. Fibers with larger core sizes can be manufactured using plastic than can be practically made with glass. The most common fiber sizes used for communications are shown in Table 5.3.1. The larger core size and NA of plastic fiber makes it easier to couple light into the fiber as well as making it easier to splice and connectorize. The larger core size means that the alignment between the source and fiber is not as critical, therefore the connectors do not need to be as precise. The connectorization of a glass fiber is normally a multistep process which can not be easily done "in the field" by someone not familiar with optical fibers. In the common "pot-and-polish" method, one must strip the coating from the fiber, insert the stripped portion into a

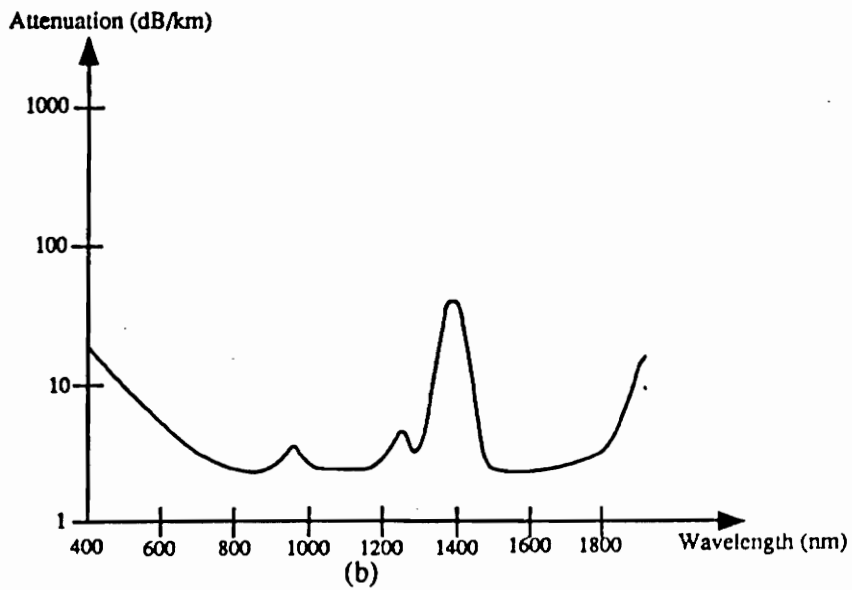
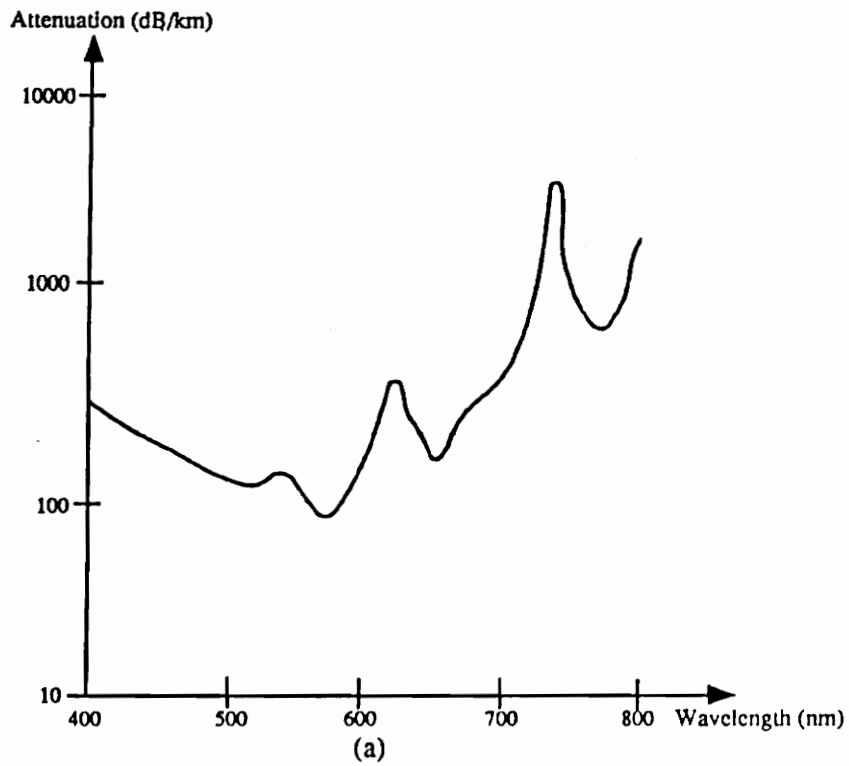


Figure 5.3.4. Attenuation vs. wavelength:
(a) Plastic fiber (PMMA core),
(b) Glass fiber.

Table 5.3.1 Typical fiber sizes for communications.¹²

	Core/cladding material	Core/cladding size (μm)
Single mode	Glass/glass	7/125 9/125
Multimode	Glass/glass	50/125 62.5/125 85/125 100/140
	Plastic/plastic	200/250 1000/1040

connector, place epoxy inside the connector, let the epoxy cure, scribe and cleave the fiber, and then polish the fiber face. The connectorization of a plastic fiber is more straightforward. With plastic fiber, the cleaving can be done with a knife or wire cutters, while the stripping can be done with wire strippers.⁵⁰ The need to use epoxy is eliminated with plastic fiber connectors. Instead, a crimping tool can be used to secure the fiber within the connector once the fiber has been inserted in the connector. This method can still require that the fiber be polished. Another method used by Thomas & Betts eliminates the cleaving and polishing steps. First, the unstripped cable is placed in the connector. By crimping the connector assembly, the fiber is cleaved by a blade internal to the assembly and the fiber is secured in place. The concept of connectorizing fibers using a crimping tool was originally developed for glass fibers. However, glass fiber connectors which can be fastened with a crimping tool typically have high losses. The high loss incurred by using crimped connectors is not as much of a concern in plastic fiber systems since the larger core sizes and NAs make alignment much less critical than for glass fibers. Another reason is that since plastic fiber systems have high losses in general, the effect of using a slightly more lossy connector is not as significant as for a glass-based system.

The actual manner of securing the connectors to the transmitters and receivers is also simple for plastic fibers. Plastic fiber connectors normally just snap into the appropriate transmitter or receiver ports. The types of connectors commonly used with glass fibers such as ST (bayonet-mount) and SMA (screw-mount) require a slightly more complicated connecting scheme and are more difficult to disconnect. Snap-in type connectors are available for glass fibers, but these are typically more expensive than those for plastic fiber since they require more precise alignment.

Also, the large core sizes of plastic fibers make the splicing of them much simpler since the fiber-to-fiber alignment is not as critical. The relative ease of connectorizing, connecting, and splicing plastic fibers are properties which are attractive in a factory floor environment.

Another advantage is that plastic fiber cable can be more easily made to be ruggedized than glass fiber cables. Although plastic has a lower tensile strength than glass, it is much more elastic. The superior elasticity properties of plastic allows plastic fibers to be made with a much smaller bend radius than glass fibers. Bend radius describes the amount of bending that a fiber can undergo before the material begins to break. A smaller bend radius means that unlike glass fibers, "breakage is not a problem with plastic fibers." ² This ruggedness is also a characteristic which is well-suited to the cable plant installation and maintenance for an industrial environment.

The main drawback for the use of plastic fiber is that it has much higher attenuation than its glass counterpart. However, in a factory setting, the distances involved are normally on the order of tens to several hundreds of feet. The optical losses incurred by using plastic fibers are acceptable for these sorts of distances. The use of separate active links makes this fiber attenuation even less of a concern, while also reducing the effect of using less expensive, higher loss connectors. Another concern is that plastic fibers are less tolerant to high temperatures than glass fibers. In glass fibers, the temperature characteristics of the cabling materials are more critical than those of the glass.

5.3.3 Hub receiver

The hub receiver is the third basic part of the node-to-hub link. The use of an active star architecture with a non-shared access method allows significant cost savings to be gained by the use of common equipment at the hub. Since communication will only be occurring between the hub and one node at any time, there is no need to use separate hub receiver configurations for each of the node-to-hub links.

For the photodetector, either PIN diodes or APDs can be used. APDs have an internal gain mechanism, similar in principle to that of a laser. This allows APDs to have better sensitivity than PIN diodes, typically 5 to 15 dB better, as well as a larger dynamic range. The dynamic range of a photodetector is calculated using the following:

$$\text{Dynamic range [dB]} = 10 \log_{10} (P_{r, \max} / P_{r, \min}), \quad (5.3.3.1)$$

where P_r is the received optical power. However, this gain characteristic is not without disadvantages. APDs are more expensive than PIN diodes. In addition, much larger bias voltages are needed for APDs than for PIN diodes. For APDs, one hundred or even several hundreds of volts are needed for biasing, while for biasing PIN diodes, normally less than ten volts are needed. Because of this biasing requirement, PIN diodes can be more easily incorporated into circuitry. Because of these properties, PIN photodiodes should be used. For the data rates to be used at the feeder network level, PIN diodes will be more than adequate.

The demodulation of an intensity-modulated optical signal is inherently done by the photodetection operation. This means that a separate demodulation stage is not needed in the receiver.

The use of common hub equipment raises the question of where the electrical combining is to be performed. The combining function is a switching among the input lines. The output of the combiner is the signal from the input link which is active at a particular time. This combining should be done as close to the fiber as is practical in order to maximize the utilization of common equipment in the hub. However, obviously this should not be done at the expense of degrading the functionality of the system. This combining could potentially be done at a numerous places in the hub receiver. Obviously, the most expensive method is to combine the signals at the output of the decoder. This would require separate full-scale receiver configurations at the hub for each link. Combining the different links at the output of the photodetectors is the other extreme. The effect on the signal-to-noise ratio (S/N) of the receiver should be one of the primary concerns in the decision of where the electrical switching should be done. The photodetector output currents are typically very small (on the order of μAs) due to the low optical power levels normally input to an optical receiver. A preamplification stage is normally used in conjunction with a main amplification stage. This is done to reduce the effects of noise introduced by the later stages. It is typically more practical to use two stages of amplifiers due to the difficulty of making a single amplifier for a reasonable cost with both high gain and low noise. The noise characteristics of a device are specified by the noise figure. The formal definition of noise figure (F) is ⁵¹

$$F = (S/N)_{\text{in}} / (S/N)_{\text{out}} \quad (5.3.1.2)$$

The ideal case is $F = 1$ (0 dB), corresponding to no noise introduced by the device. This limit can be approached only by the use of expensive techniques such as cryogenic cooling. In a cascaded arrangement of devices like those shown in Figure

5.3.5, the effect of noise can be minimized by the use of reasonably high gain and low noise devices in the initial stages. This can be seen from the equation for the overall noise figure of a cascade of k linear devices,⁵¹

$$F = F_1 + (F_2-1)/G_1 + (F_3-1)/(G_1G_2) + \dots + (F_k-1)/(G_1G_2G_3\dots G_{k-1}), \quad (5.3.1.3)$$

where the F's and G's refer to the noise figures and gains of the devices, respectively.

Direct mixing of the small photodetector output currents would require that a very sensitive and low noise combiner would be needed. This constraint can be avoided by amplifying the photodetector current before the electrical switching is done. The effects of noise from the combiner and the following stages of the hub receiver can be greatly reduced by mixing at the output of the main amplifier stage (see Figure 5.3.6). The mixing should be done at this point in order to reduce the requirements on the electrical signal levels at the input of the combiner. The detector, preamp, and main amp are often included in the same physical package and therefore it would be practical (as well as convenient) to perform the combining at this point. Such an arrangement would not put unnecessary constraints on the noise characteristics and sensitivity of the combiner. In this combination scheme, a large portion of the hub receiver equipment at the hub is common to the individual links from the nodes. This greatly reduces the equipment costs required at the hub receiver for node-to-hub transfers.

The decision must be made whether to use high-impedance amplifiers or transimpedance amplifiers as preamplifiers. Transimpedance amplifiers are basically inverting high-impedance amplifiers with resistive feedback, as shown in

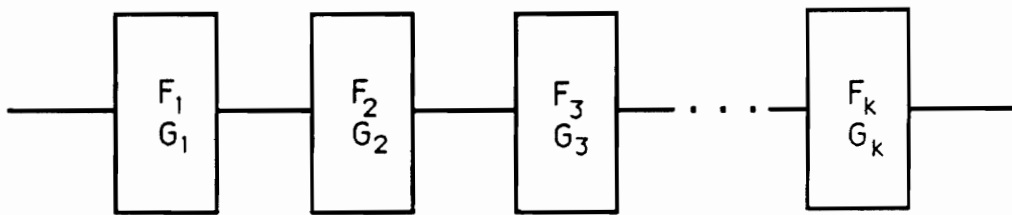


Figure 5.3.5. Cascade of k devices.

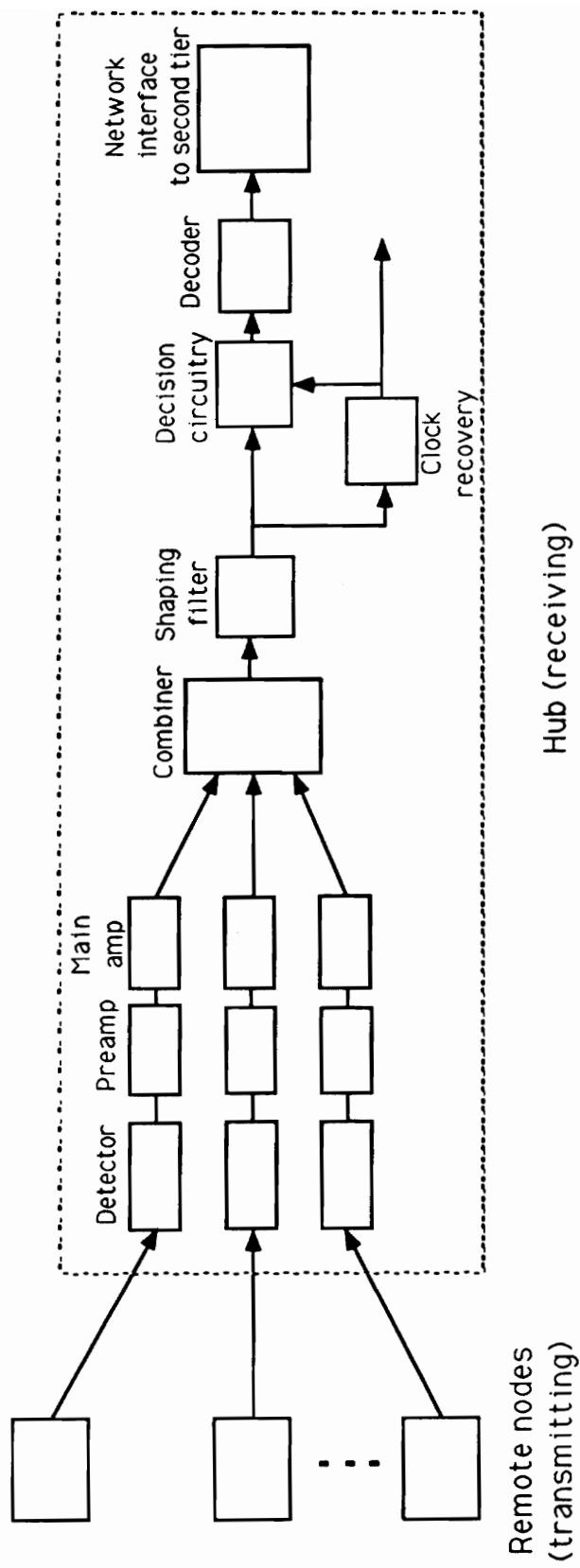


Figure 5.3.6. Hub receiver for a non-shared medium network using an active star architecture.

Figure 5.3.7. There are several advantages introduced by the use of feedback such as increased bandwidth and wider dynamic range. This increase in bandwidth by the use of feedback will significantly reduce or even eliminate the need for equalization prior to the main amplification stage. However, transimpedance amplifiers increase bandwidth at the expense of gain (for a fixed gain bandwidth product).⁵² For the bandwidth required at the feeder network tier (several MHz), high-impedance amplifiers can be used. The bandwidth of high-impedance amplifiers is typically sufficient that equalization is not needed for low data rates.

In addition, high-impedance amplifiers have slightly better noise characteristics than transimpedance amplifiers. The use of a feedback path in a transimpedance amplifier introduces additional thermal noise, since the noise at the output plus the thermal noise from the feedback resistor is fed back into the input. This increase in noise normally accounts for 2 to 3 dB in most wideband designs.^{49, 53}

An important concern in using a high-impedance amplifier is that its integrating nature may cause the receiver to saturate as an appreciable electrical DC component is built up.^{52, 53} However, Manchester encoding greatly reduces the low frequency content of the received signal and thus this concern is not as significant as in a system where there is the potential to accumulate a large DC component.

One would like to have the photodetector current generate the maximum possible preamp input voltage so that the highest possible S/N ratio can be achieved. This is done in microwave receivers by conjugate impedance matching. Due to the capacitive nature of the photodiode and the wide spectral content in digital signals, conjugate impedance matching is not possible over a wide bandwidth. The procedure typically used to minimize the effect of impedance mismatching is to

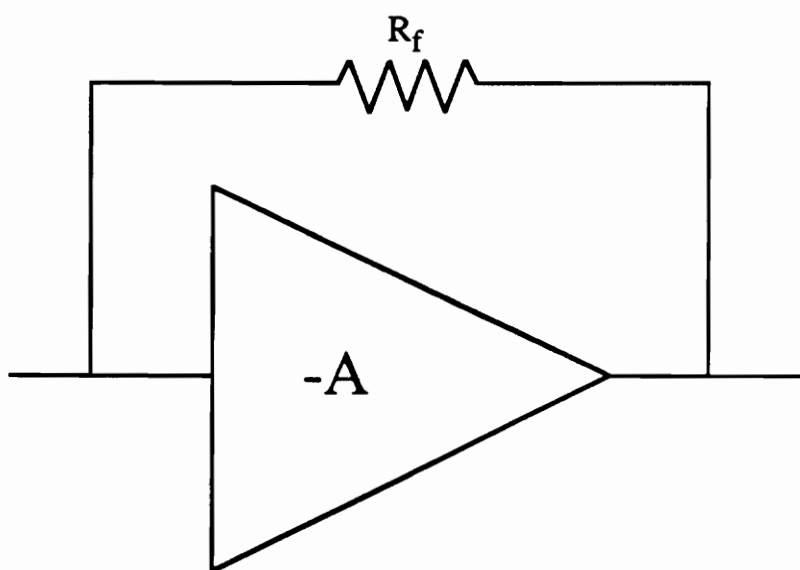


Figure 5.3.7. Simplified representation of a transimpedance amplifier.

minimize the capacitance of the detector and preamplifier. The detector and preamplifier are often combined into the same physical package within the receiver in order to reduce parasitic and circuit capacitances.⁵⁴ The amount of capacitance present can be reduced, but it is still the most significant factor which limits the preamplifier voltage. Because of this, amplifier noise is the primary limitation in optical receiver sensitivity.⁵³

The main amplification stage follows the preamplification stage. The main amplification stage usually contains some type of automatic gain control (AGC). Because of the diversity in the amplitude of signals received, some means of accommodating the entire range of signals must be used. The main amplifier must be able to amplify small preamp voltages as well as large preamp outputs. AGC is the method normally used to accomplish this. AGC is implemented as a feedback loop which varies the gain of the main amplification stage so that the output of the main amplifier is suitable for the subsequent digital processing stages for both low and high level inputs.^{54, 55} Often the main amplifier is also included in the same physical package as the photodetector and preamplifier.

A bandpass filter should be used prior to the clock recovery and decision circuitry to "smooth" out the signal waveform. The shaping filter is often incorporated into the same physical package as the main amplification stage. For a Manchester encoded signal transmitted at a frequency f , the majority of the power is concentrated between $0.5f$ and f . This can be seen by examining the cases where the most and least transitions will occur. These two cases are shown in Figure 5.3.8. The most transitions will occur in a stream of identical data bits, i.e., a 11111 or 00000 sequence. For this type of sequence, the bit periods are identical to those of the

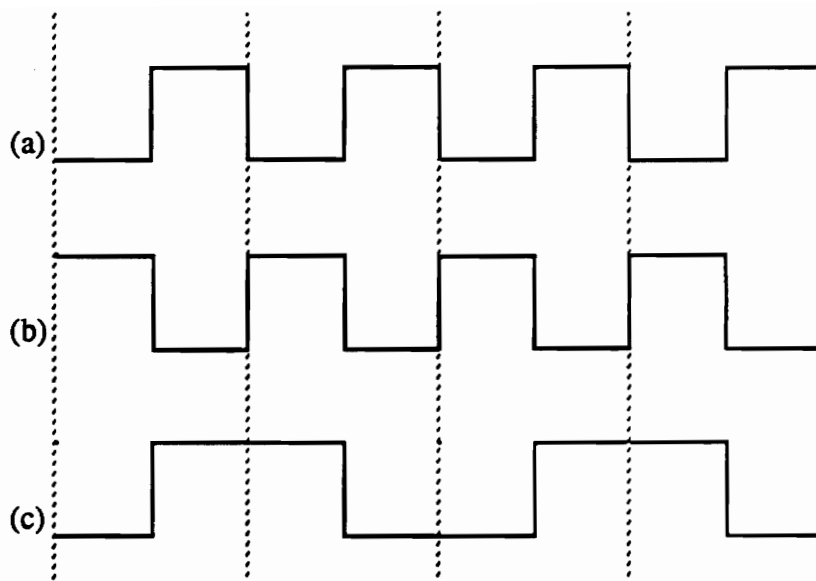


Figure 5.3.8. Timing for Manchester encoding:
(a) Clock signal,
(b) Most transitions (1111),
(c) Least transitions (0101).

clock running at f and therefore the signal has a maximum frequency of f . The least transitions will occur for an alternating sequence of logical ones and zeros. In this case the bit period of the signal is twice that of the clock, which corresponds to a frequency of $f/2$.

Timing of the signal must be established in the receiver before the transmitted signal can be accurately recovered. One way in which clock recovery can be done is to use a phase-locked loop (PLL). A PLL detects and corrects for the phase error introduced by the accumulation of jitter and distortion in the transmission of the signal. The output of the PLL is the clock signal. Both analog and digital PLLs are used. Inexpensive digital PLL ICs are available in the several MHz bandwidth range required at the feeder network level.

The next step is to distinguish which portions of the noise corrupted signal correspond to logical ones and zeros. An important consideration is the probability of error caused by misinterpretation of logical levels due to the presence of noise. The two cases in a digital system where an error can occur are: (1) interpreting a logical one as a logical zero, and (2) interpreting a logical zero as a logical one. The question of where to set the threshold level must be analyzed. By threshold level it is meant that a signal level above the threshold is considered a logical one and a signal level below the threshold is considered to be a logical zero. For the calculation of the optimal threshold it is normally assumed that the probability of a logical one or zero being sent is equal, i.e., both occur with probability of 0.5. It can be shown that the condition for the minimum probability of error is a threshold level which is the arithmetic mean of the signalling levels used to represent logical ones

and zeros (assuming the noise is a zero-mean wide-sense stationary Gaussian process), i.e.,⁵⁶

$$\text{Threshold} = 0.5 * (\text{level}_1 + \text{level}_0). \quad (5.3.1.2)$$

This "cleaning up" of the bit stream must be done in order for the decoder to correctly interpret the data. A latching D flip-flop is typically used as a decision circuit. The recovered clock signal is used to clock the D flip-flop.⁵⁵ Low-cost latching D flip-flop ICs are also commonly available which operate at several MHz.

The final stage of the node receiver is the decoder. This stage converts the Manchester-encoded data stream back to the NRZ format it originated as in the transmitter. As mentioned in the encoding discussion, Manchester encoder/decoder ICs in the several MHz range are relatively inexpensive.

5.4 Optical Link Components for Hub-to-Node Transfers

The optical links for hub-to-node transfers contain the same basic elements as the node-to-hub links, i.e., a transmitter, fiber cable, and receiver.

5.4.1 Hub transmitter

The use of an active star architecture with a non-shared access method also allows significant cost savings to be gained by the use of common equipment at the hub transmitter. Since communication will only be occurring from the hub to one node at any time, there is no need to use separate full-scale hub transmitter configurations for each of the hub-to-node links.

One significant difference between the hub transmitter and the node transmitter is that "splitting" of the signals is to be done at the hub for hub-to-node transfers. This operations should be done as close to the fiber as is practical in order to maximize the utilization of common equipment in the hub transmitter.

The splitting function is merely a selection of which outgoing hub-to-node link should be active. Referring again to Figure 5.3.1, it is apparent that there are several places in the transmitter at which the selecting could be done. The use of separate full-scale hub transmitter configurations for each link would be the most expensive implementation. The most cost-sensitive alternative is to do the selection at the LED inputs of each of the links as shown in Figure 5.4.1. In this manner, the same signal input stage, encoder, and clock can be used for all the outgoing hub-to-node links. This would be considerably less costly than doing the selection at any other stage in the transmitter. This arrangement minimizes the costs by maximizing the amount of common hub equipment used for hub-to-node transfers.

The other difference is that a signal input stage is not needed in the hub transmitter since there will be only one line feeding into the encoder, i.e., the output of the network interface.

5.4.2 Optical cable for hub-to-node transfers

The explanations and justifications for using plastic fiber are the same for both hub-to-node transfers and node-to-hub transfers. There will be no difference in the fiber cable and connectors used.

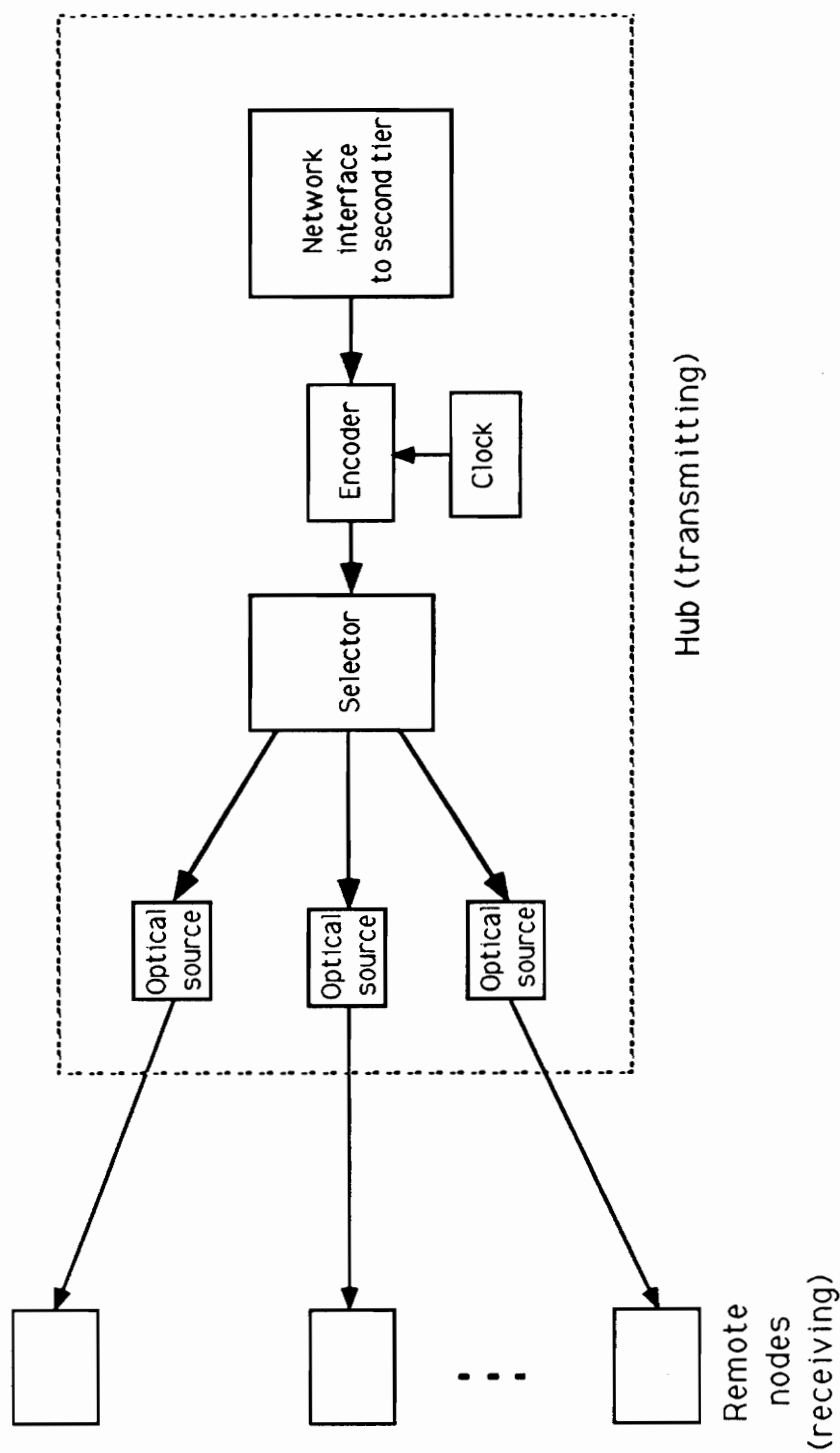


Figure 5.4.1. Hub transmitter for a non-shared medium network using an active star architecture.

5.4.3 Node receiver

The components of the node receiver are very similar to those used for the hub receiver. The configuration of the node receiver is shown in Figure 5.4.2. One difference is that there is no need for a combiner since there is only one link between a single node and the hub. This means that only one photodetector and preamplification/equalization stage are needed within the node receiver. The other difference is that a signal output stage is needed since some means of distributing the hub message to the appropriate device connected to the node is required. This stage will perform the inverse function of the node signal input stage, i.e., demultiplex the received signal in order to route it to the proper device. If devices connected to the node require analog signals, a D/A converter would be needed in the signal output stage. The master will control which device the message would be routed to.

5.5 Component Cost Breakdown for Non-Shared Medium Approach

One useful method to detail the component costs of the non-shared network approach incorporating an active star architecture is to tabulate the costs of the individual components while also calculating and graphically illustrating the portion of the total network component cost contributed by the major elements, i.e., the node, the hub, and the fiber cable and connectors. This analysis will be done for a system consisting of 16 nodes tying into a single hub, with 4 factory floor devices connected to each feeder node.

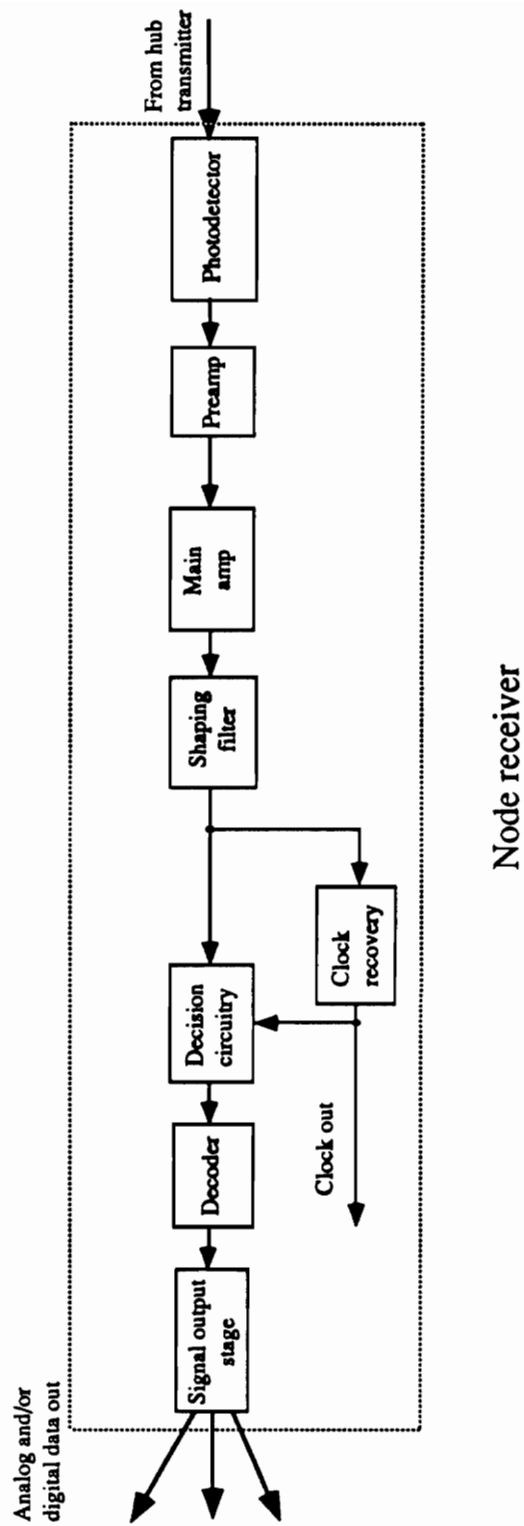


Figure 5.4.2. Node receiver for a non-shared medium network using an active star architecture.

5.5.1 Costs of individual components

The individual components required for the hub and node transmitters and receivers were detailed in the preceding sections. Representative costs of these components for use in the several Mbps range are listed in Table 5.5.1. The following assumptions are used in the cost analysis:

- (1) The PIN diode, preamplifier, and main amplifier are often incorporated into a single physical package and are priced for such an arrangement (characterized as detector module in Table 5.5.1).
- (2) A typical fiber length of 100 feet is used for the analysis of the fiber costs.
- (3) The network interface is priced for using IEEE 802.3/Ethernet at the second tier.
- (4) The total amounts are rounded to the nearest \$1.

5.5.2 Breakdown of total system component cost by contributions of major elements

The major elements of the non-shared medium network are the node, the hub, and the fiber and connectors.

5.5.2.1 Node

The node consists of a transmitter and a receiver. The components needed for the node and their associated costs are the following:

TABLE 5.5.1. Representative component costs.

COMPONENT	COST
LED	\$8.00
Modulation circuit	\$1.00
Clock	\$4.00
Encoder/decoder	\$10.00
Signal input stage	\$10.00
Detector module	\$9.00
Bandpass filter	\$2.00
D flip-flop	\$0.50
PLL	\$1.00
Signal output stage	\$10.00
Combiner	\$0.80
Splitter	\$1.00
Network interface	\$520.00
Plastic fiber cable	\$0.22/ft
Plastic fiber connector	\$0.50
Plastic fiber splice	\$0.20

Transmitter (Tx):

LED	\$8.00
Modulation circuit	\$1.00
Clock	\$4.00
Encoder	\$10.00
<u>Signal input stage</u>	<u>\$10.00</u>
Total node Tx cost	\$33

Receiver (Rx):

Detector module	\$9.00
Bandpass shaping filter	\$2.00
Latching D flip-flop	\$0.50
PLL	\$1.00
Decoder	\$10.00
<u>Signal output stage</u>	<u>\$10.00</u>
Total node Rx cost	\$33

$$\text{Total cost per node} = \$33 + \$33 = \$66. \quad (5.5.2.1.1)$$

$$\text{Total cost of 16 nodes} = 16 (\$66) = \$1056. \quad (5.5.2.1.2)$$

5.5.2.2 Hub

The hub consists of a transmitter, receiver and network interface. The components needed for the hub and their associated costs are the following:

Transmitter:

LEDs (16)	\$128.00
Modulation circuits (16)	\$16.00
Splitter	\$1.00
Clock	\$4.00
<u>Encoder</u>	<u>\$10.00</u>
Total hub Tx cost	\$159

Receiver:

Detector modules (16)	\$144.00
Combiner	\$0.80
Bandpass shaping filter	\$2.00
Latching D flip-flop	\$0.50
PLL	\$1.00
<u>Decoder</u>	<u>\$10.00</u>
Total hub Rx cost	\$158

Network interface: \$520

$$\text{Total hub cost} = \$159 + \$158 + \$520 = \$837. \quad (5.5.2.2.1)$$

5.5.2.3 Fiber and connectors

The fiber and connectors costs are the following:

Fiber:

$$\text{Cost of a single fiber cable} = (100 \text{ ft})(\$0.22/\text{ft}) = \$22.00. \quad (5.5.2.3.1)$$

$$\text{Total fiber cable cost (32 fibers)} = 32 (\$22) = \$704. \quad (5.5.2.3.2)$$

Connectors (2 per fiber):

$$\text{Total connector cost} = (2)(32)(\$0.50) = \$32.00. \quad (5.5.2.3.3.)$$

$$\text{Total fiber and connector cost} = \$704 + \$32 = \$736. \quad (5.5.2.3.4)$$

The total system component cost is given by the sum of the component costs for the nodes, hub, and the fiber and connectors.

$$\begin{aligned} \text{SYSTEM COMPONENT COST} &= \$1056 + \$837 + \$736 \\ &= \$2629. \end{aligned} \quad (5.5.2.3.5)$$

The fraction of the total system costs contributed by each major element is

$$\text{Nodes: } (1056/2629) (100 \%) = 40.2 \%, \quad (5.5.2.3.6)$$

$$\text{Hub: } (837/2629) (100 \%) = 31.8 \%, \text{ and} \quad (5.5.2.3.7)$$

$$\text{Fiber/connectors: } (736/2629) (100 \%) = 28.0 \%. \quad (5.5.2.3.8)$$

Therefore, the component costs of the nodes comprise the largest portion of the system component costs for a 16 node network. The hub and fiber/connectors are

approximately the same portion of the system component costs (approximately 10% less than the node component costs). These cost relationships are shown graphically in Figure 5.5.1.

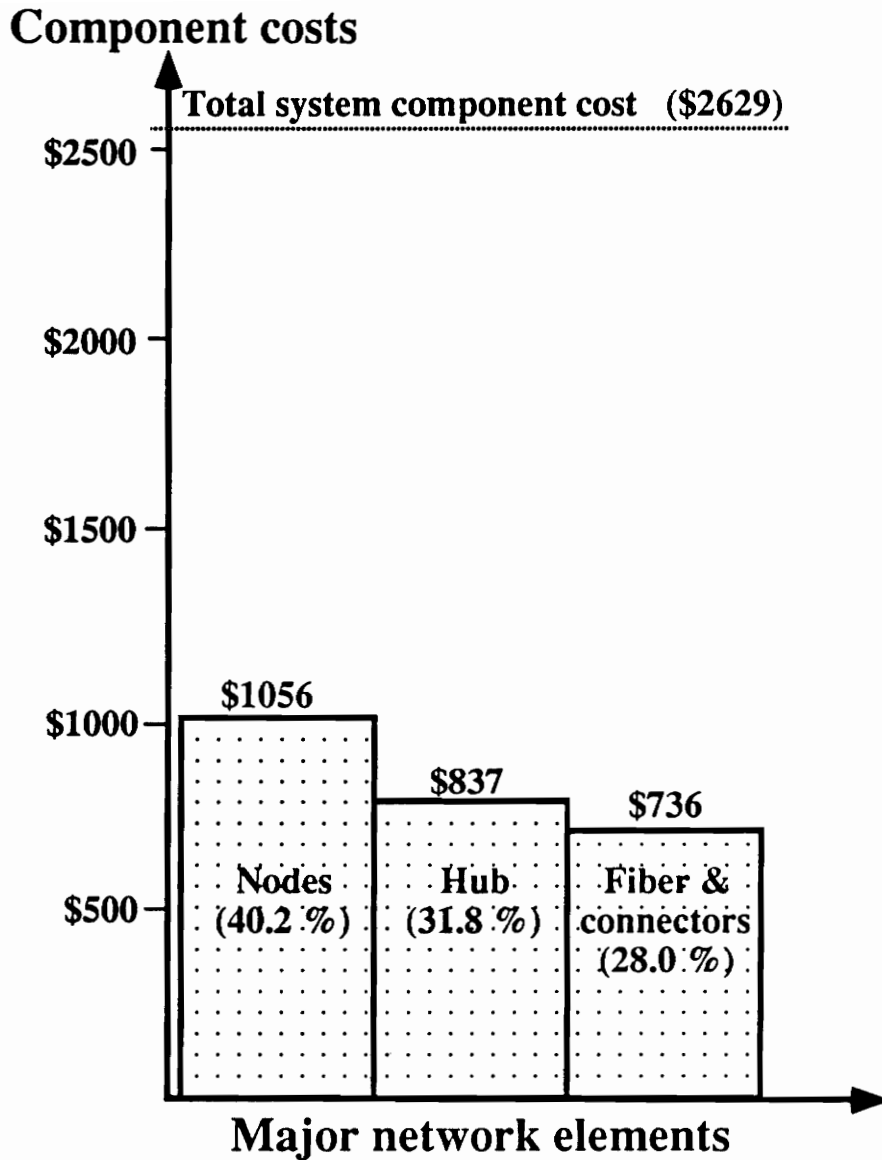


Figure 5.1.1. Portion of total network component costs contributed by major elements.

6.0 EXTENSIONS

6.1 Hybrid Fiber Optic Communication/Sensing System

One possible extension is to use the same optical fiber for communications and sensing. The use of optical fibers for sensing various physical phenomena such as strain, pressure, and temperature is well established. The presence of such a physical phenomenon perturbs the light in the fiber and changes its characteristics. The correspondence between the changes in the light and the physical phenomena can be established and thus the parameters of the disturbance can be determined by studying the light in the fiber.

In a hybrid system, a section of the fiber used for communications would also be used for sensing. The use of the same fiber for communication and sensing would allow cost savings to be gained in terms of the amount of cable plant needed for communications and sensing, as well as weight and space savings. For certain types of systems, these are critical considerations.

Fiber optic sensors could replace the existing sensors on a factory floor, while using a portion of the communications cable plant instead of requiring a separate cable plant. Researchers at the Fiber & Electro-Optics Research Center within the Department of Electrical Engineering at Virginia Tech are currently investigating design considerations for the use of hybrid fiber optic communication/sensing systems.

7.0 CONCLUSIONS

The use of optical fibers for communications is an area in which there has been considerable growth in recent history. The inherent properties of optical fibers such as small size and weight, EMI/RFI immunity, low attenuation, and large bandwidth provide many advantages over wire conductors. One rapidly expanding field in recent years is fiber LANs used to connect various types of computers and other devices in office or interbuilding settings. Fiber optic LANs are particularly suited for use in electrically noisy and space sensitive industrial environments.

The diversity of communications requirements in a typical factory situation can be accommodated by the use of a hierarchical communications structure consisting of multiple tiers of fiber optic networks. The lowest tier of this structure consists of inexpensive feeder networks used to connect devices such as sensors, gauges, actuators, PLCs, robots, and small computers on a factory floor. The emphasis at this tier is on a low-cost implementation, but while still providing interconnection to higher tiers. An approach which satisfies the requirements at the feeder network level is a non-shared medium network which is link based. This can be best implemented as an active star architecture using a roll-call polling access method. The lack of a need for direct peer-to-peer communication among the feeder nodes allows the network intelligence to be centralized at a custom concentrator module which comprises the hub, i.e., the "master." The centralized intelligence structure of a master/slave scheme without medium sharing allows one to concentrate on the cost optimization of the optical data links. Low-cost optical components such as LEDs, PIN diodes, and plastic fiber can be used. Additional economies can be gained by the use of common equipment in the hub, i.e., full-scale hub transmitter

and receiver configurations are not needed for each of the links. A link-based, non-shared medium approach results in a cost-sensitive fiber optic network design which is well suited for use at the feeder network level in a factory setting.

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GLOSSARY

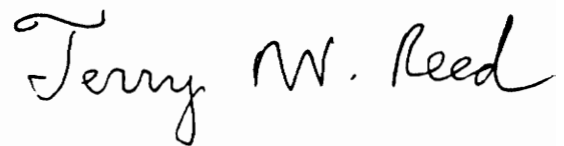
A/D	Analog-to-Digital
AGC	Automatic Gain Control
ANSI	American National Standards Institute
APD	Avalanche PhotoDiode
ARCNET	Attached Resource Computer NETwork
ASC	Accredited Standards Committee
CIM	Computer-Integrated Manufacturing
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
D/A	Digital-to-Analog
dB	decibel
dBm	decibels referenced to 1 microwatt
dBW	decibels referenced to 1 watt
DEC	Digital Equipment Corporation
EM	ElectroMagnetic
EMI	ElectroMagnetic Interference
FDDI	Fiber Distributed Data Interface
FOIRL	Fiber Optic Inter-Repeater Link
Gbps	Gigabits per second
IC	Integrated Circuit
IEEE	Institute of Electrical and Electronic Engineers
IMP	Interface Message Processor
ISA	Instrument Society of America
ISO	International Organization of Standards
ITRC	Information Technology Requirements Council
kbps	kilobits per second
kHz	kilohertz
km	kilometer
LAN	Local Area Network
LED	Light Emitting Diode
LLC	Logical Link Control
LS	Low-power Schottky
MAP	Manufacturing Automation Protocol
Mbps	Megabits per second
MHz	Megahertz
μ A	microamp
μ m	micron (10^{-6} meters)

μ sec	microsecond
mW	microwatt
nm	nanometer
NRE	Non-Recoverable Engineering
NRZ	Non-Return-to-Zero
NRZI	Non-Return-to-Zero-with-Invert
OSI	Open Systems Interconnection
PIN	Positive-Intrinsic-Negative
PLC	Programmable Logic Controller
PLL	Phased-Locked Loop
PMMA	PolyMethyl MethAcrylate
RAM	Random Access Memory
RFI	Radio Frequency Interference
RTN	Real-Time Network
RZ	Return-to-Zero
SAE	Society of Automotive Engineers
SMC	Standard Microsystems Corporation
TDMA	Time Division Multiple Access
TIR	Total Internal Reflection

VITA

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A handwritten signature in cursive script that reads "Terry W. Reed". The signature is written in black ink and is positioned to the right of the main text block.