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Rapport de recherche RR-8204

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OPTICAL FIBERS IN LOCAL AREA NETWORKS
(APPLICATIONS DES FIBRES OPTIQUES AUX RESEAUX LOCAUX)

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1. Introduction:

The purpose of the work presented here is twofold:

(a) to determine an effective design-decision procedure for local area networks for which the media layer is to be implemented using optical fibers, and

(b) to find and to characterize promising optical fiber topologies for local area networks.

The design procedure will assist in evaluating and comparing performances across a wide variety of topologies and specific implementations of these topologies.

In the following, the authors first examine local area networks from a general point-of-view and give a tentative taxonomy. Next, we deal with the subject of medium access methods in the light of constraints imposed by the optical fiber topologies and show that the medium access method plays a significant role in the effective exploitation of the optical fiber medium. Finally, we give a brief outline of the traditional approach to the design of optical fiber communications systems and suggest how this approach may be coupled with a component database.

In this article, we show only our approach and results of preliminary work. From this work, further work will be done and reported elsewhere.

2. Architecture of Local Area Networks:

2.1 Definition of Local Area Network (LAN):

A Local Area Network or LAN is a data communication system which allows a number of independent devices to communicate with each other. In this section, we define an architecture for this class of networks.

A LAN is distinguished from other types of data networks in that the communication is usually confined to a moderately sized geographic area such as a single office building, a warehouse, or a campus and operates at modest bandwidths (1 to 20 Mbps) having a consistently low error rate (1×10^{-9} bps). The LAN applications environment is intended to be commercial and perhaps mainly in the field of office automation. As such, a LAN should support applications such as:

- file transfer and access protocols
- graphics applications
- word processing
- electronic mail
- remote database access
- digital voice

Moreover, a LAN is intended to support various data devices such as:

- computers
- terminals
- mass storage devices
- printers
- plotters
- tele-photocopying devices
- monitoring and control equipment
- gateways to other networks

2.2 Concept of Architectural Layering:

In order to achieve communication in a general sense between any two devices, a number of communications tasks have to be performed at each device. These tasks have been classified into seven categories or protocol layers by the International Standards Organization's so-called Open System Interconnection Reference Model (ISO-OSI/RM) [TANN'81]. This layering is illustrated in Figure 2.1. The highest layer is the Application Layer consisting of the application entities that cooperate within the Open System Interconnection (OSI) environment. The lower layers provide the communication services through which the application entities cooperate.

Layers 1 through 6, together with the physical media for OSI, provide a step-by-step enhancement of the communication services that are required by the applications processes in order for them to cooperate. The boundary between any two layers identifies a stage in this step-by-step enhancement of services at which an OSI service standard may be defined, while the functioning of the layers, and their relationship to the corresponding "peer" layer, is governed by OSI protocol standards.

The basic idea of layering is that each layer adds value to services provided by the set of lower layers in such a way that the highest layer is offered a set of services needed to run distributed applications. Layer n on one device carries on a conversation with layer n on another. The rules and conventions used in this conversation are collectively known as the layer n protocol. The entities comprising the corresponding layers on different devices are called peer processes. In other words, it is the peer processes that communicate among themselves using the protocol.

The set of layers and protocols is called the network architecture. The specification of the architecture must contain enough information to allow an implementor to write the program for each layer so that the program

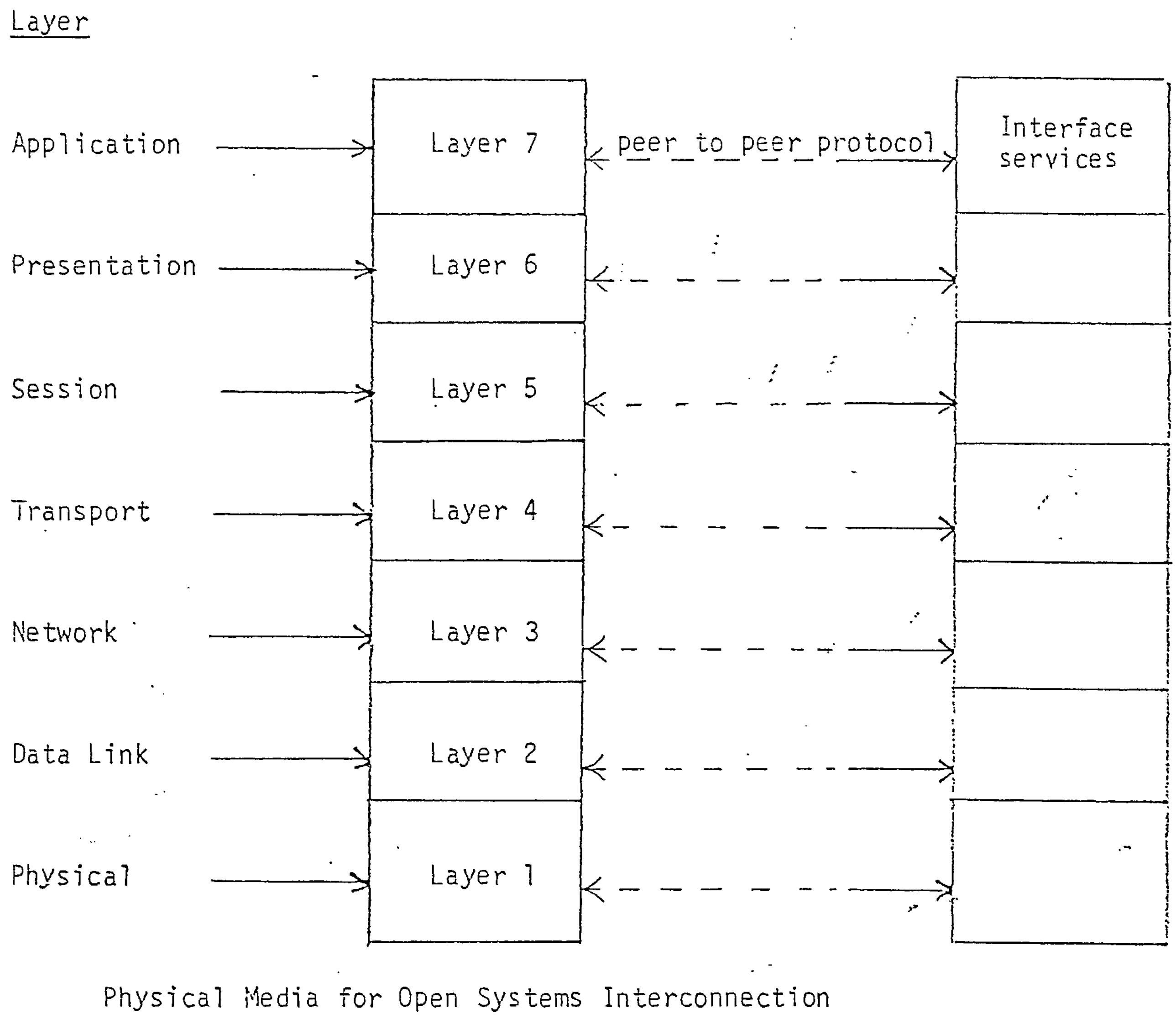


Figure 2.1 Seven Layer Reference Model

In reality, no data are transferred directly from layer n on one machine to layer n on another except at the lowest layer. Instead, each layer passes data and control information to the layer immediately below it, until the lowest layer is reached. At the lowest layer, there is physical communication, as opposed to the virtual communication used by the higher layers. At the receiving machine, this process is reversed: data and control information are passed upwards to the destination process at layer 7. Between each pair of adjacent layers, there is an interface which defines the primitive operations and services the lower layer offers to the upper one.

will correctly obey the appropriate protocol. Neither the details of the implementation nor the specification of the interfaces are part of the architecture.

Consider the example of providing virtual communication to the top layer of the seven layers in Figure 2.2. A message, m, is produced by a process running in layer 7. The message is passed from layer 7 to layer 6 according to the layer 6/7 interface. In this example, layer 6 transforms the message in certain ways, text compression, for example, and then passes the new message, M, to layer 5 across the layer 5/6 interface. Layer 5, in this example, does not modify the message but simply regulates the direction of flow.

In many networks, there is no limit to the size of messages accepted by layer 3 (packet size limit). Consequently, layer 4 must break up the incoming message into smaller units, prefixing a <u>header</u> to each unit. This process is called packetization. The header includes control information, such as sequence numbers, to allow layer 4 on the destination machine to get the pieces back together in the right order. Layer 3 decides which of the outgoing channels to use, attaches its own headers, and passes the data to layer 2. Layer 2 adds not only a header to each piece, but also a trailer, and gives the resulting unit to layer 1 for physical transmission. At the receiving machine, the message moves upwards, from layer to layer, with headers being stripped off as it progresses. None of the headers for layers below n are passed up to layer n.

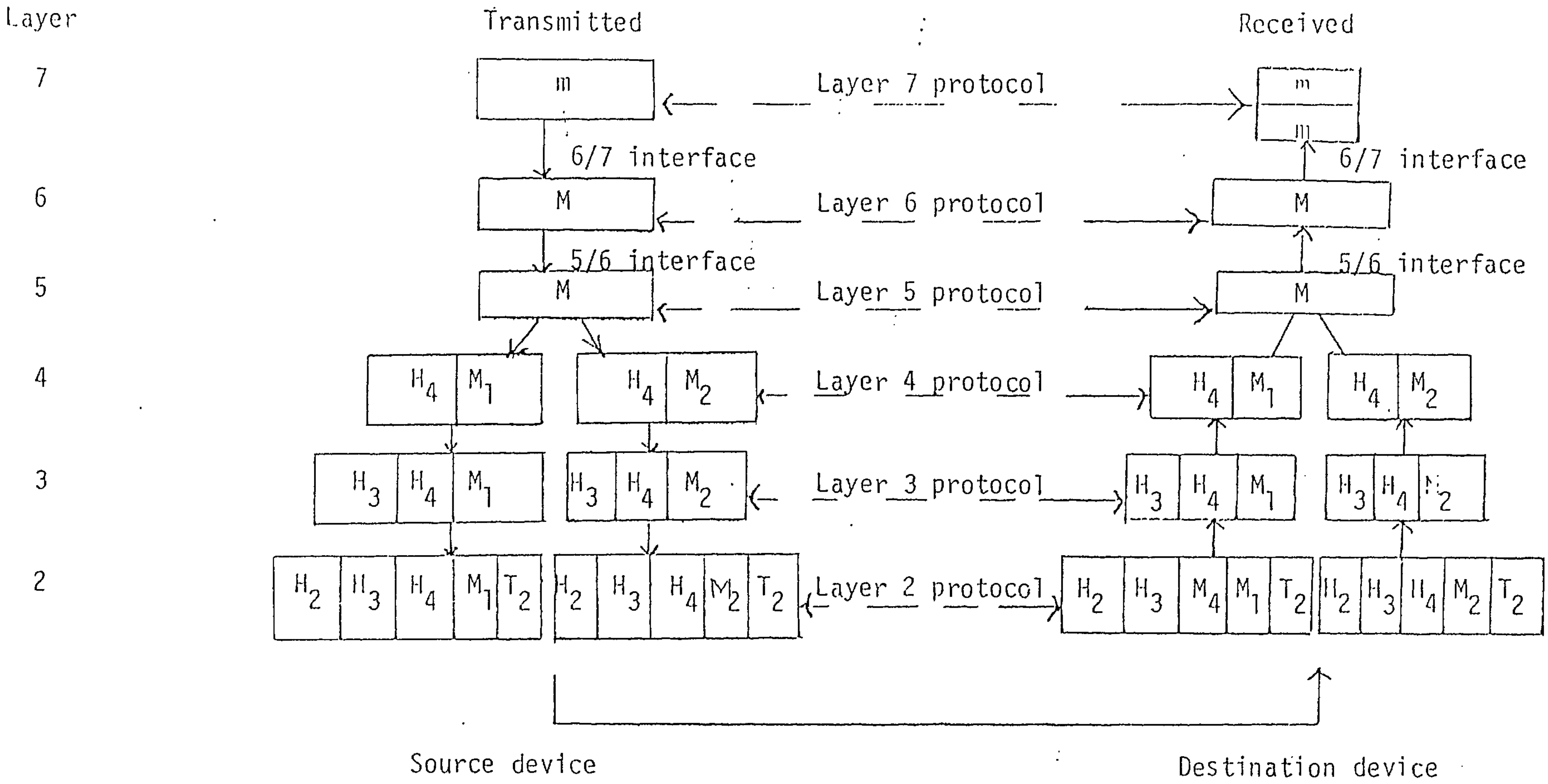


Figure 2.2 Information Flow between Layers

In this diagram, the following symbols are used (see also the discussion given in Section 2.2):

m : the original message M : the encoded form of m

M_1 , M_2 : two packets into which we suppose M has been subdivided.

H_i : headers added (or stripped off) at layer i .

T_i : trailers added (or stripped off) at layer i.

2.3 Architectural Reference Model for Local Network:

A computer communication network consists of nodes interconnected by links and hosts, connected to the nodes via special interfaces, X.25, for example. A node is distinct from a host in that only layers 1 through 4 are implemented in the nodes. Local Area Networks differ from long haul networks in that:

(i) all nodes usually share a single communication channel so that no node-to-node switching is needed, and

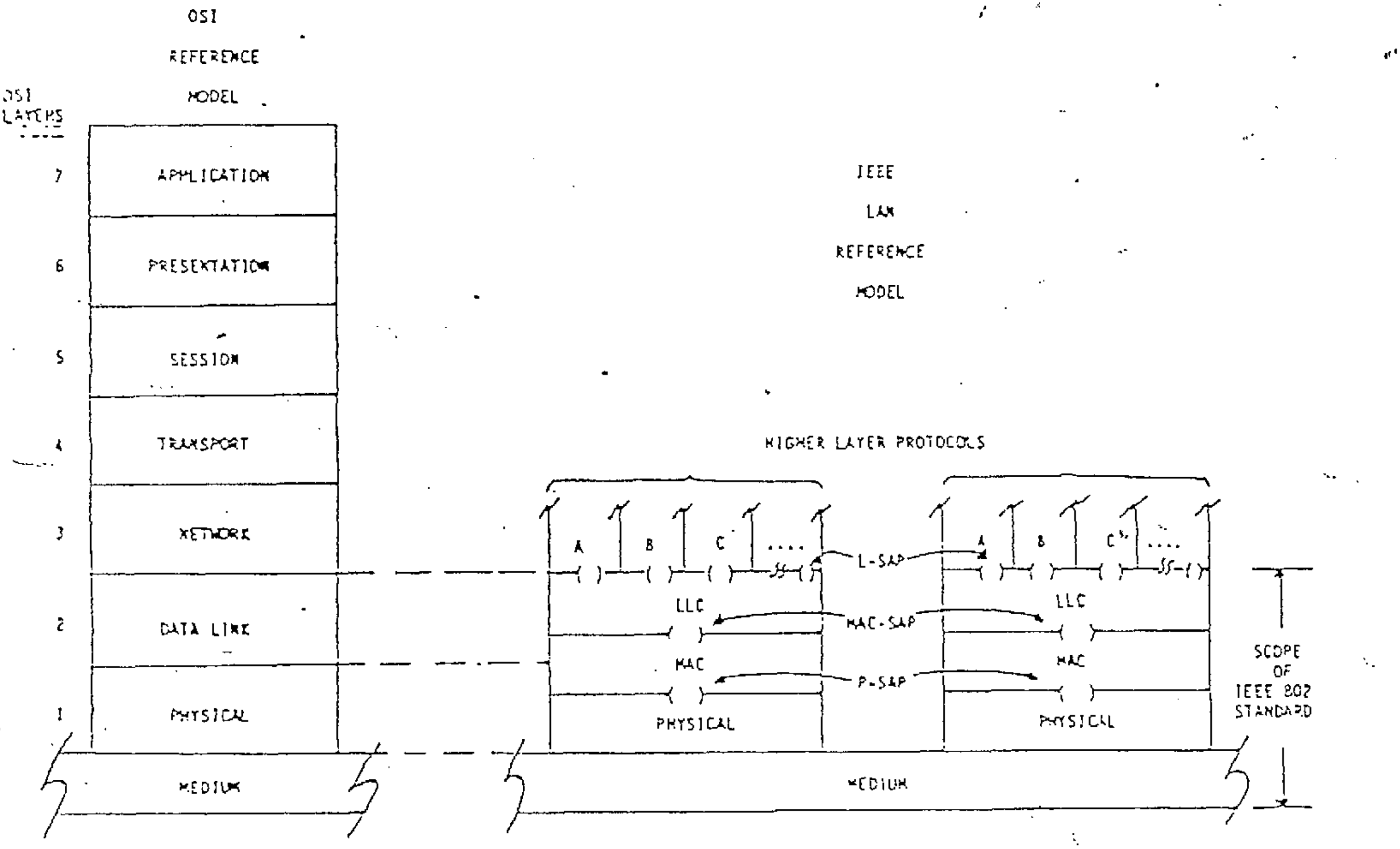
(ii) data terminal equipment (DTE) in the OSI sense are devices directly connected to the local area network medium.

Figure 2.3 shows an architectural model of Local Area Networks, called the Local Area Network Reference Model (LAN/RM) in relation to the OSI/RM [IEEE'81]. The applicable part of the OSI/RM consists of two layers: data link and physical. These map into three layers in the IEEE Project 802 LAN Reference Model, namely the Logical Link Control (LLC), Media Access Control (MAC), and Physical Layers [IEEE'81]. To provide support for multiple higher client protocols, say A,B,C,..., the LLC layer provides interface ports at the Network-to-LLC layer boundary (3/2 interfaces) for protocols A,B,C,... at the Network Layer.

In Figure 2.4, the implementation Reference Model is shown:

LLC Layer: This is the Local Area Network Logical Link Control Layer. The LLC protocol is a multi-access peer protocol for use in multi-station peer-to-peer environments. We shall not discuss this layer because it is independent of the communication medium, for a full description the reader is referred to the Project 802 report [IEEE'82]. It suffices to note here that the OSI/RM Link Layer (HDLC) must be used as a model for structuring the LLC.

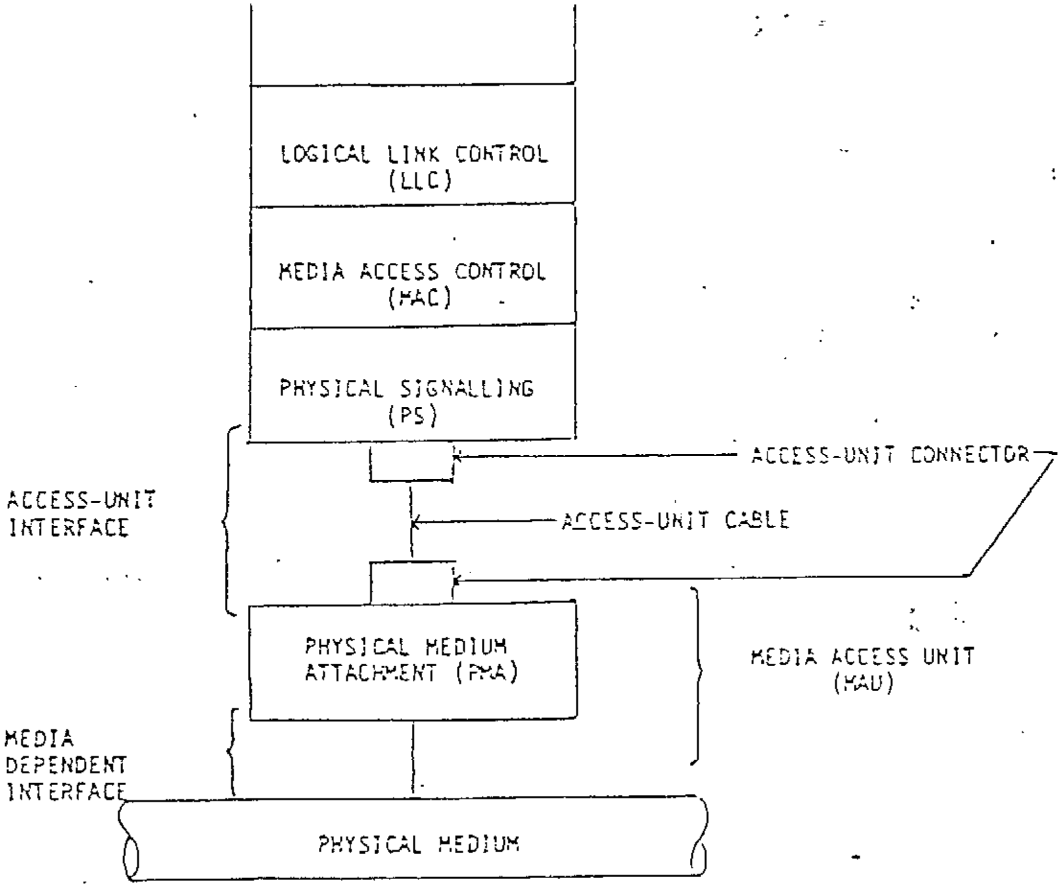
Figure 2.3 - LAN/RM Relationship to OSI/RM



MAC Layer: The MAC Layer provides the type of medium control mechanism for a particular medium. Since the media access methods which have been proposed for LAN's are of recent vintage, the MAC Layer will be discussed in this report and its impact on the optical fiber medium assessed.

The access unit for optical fiber networks is usually composed of a transmitter and a receiver while the physical medium attachment is a fiber coupler (see Figure 2.4). In this report, the structure and design of the transmitters, receivers, and couplers will not be treated. Rather, these devices will simply be characterized by parameters representing their performance. One of our objectives will be to establish the constraints imposed on these parameters by different architectures of LAN's.

Figure - 2.4 Implementation Reference Model



2.4 Taxonomy for Local Area Networks:

From the LAN/RM, it can be seen that the highest level of characterization of the Local Area Network is the medium access control or MAC method. Many MAC schemes have been proposed for LAN's which are usually referred to as Multiple Access Protocols [TOBA'80]. These protocols may be classified into two main categories, namely, assignment or contention (see Figure 2.5). The assignment strategy may be fixed, e.g., TDMA or FDMA, or variable, usually implemented by reservation or taken passing mechanisms. Medium access methods based on the contention strategy can be either pure (ALOHA) or carrier sensing multiple access (CSMA) with or without collision detection (CSMA-CD). Furthermore, communication channels adopting a contention strategy can be slotted or non-slotted depending on whether or not stations must be synchronized so that transmission starts precisely at the beginning of a time slot. Further characterization of medium access methods should take into account the presence or absence of some priority scheme.

The next level of LAN characterization is based upon the medium access control mechanism's being centralized or distributed. All the medium access methods shown in Figure 2.5 can be either centralized or distributed. A well-known example of the centralized token passing protocol is the polling mechanism whereas an example of distributed token passing can be found in LAN's having a ring topology. An example of centralized CSMA is the busy-tone mechanism proposed for Mobile Radio Networks [TOBA'80].

The third level of LAN characterization is the topology which describes how devices are physically interconnected. The most well-known topologies are the star, ring, and the bus. The CATV network tree topologies are not usually considered for LAN's, given the geographical constraints mentioned in Section 2.1. It should be noted in passing that any of the access methods shown in Figure 2.5 could be implemented in virtually any topology, but with different degrees of complexity.

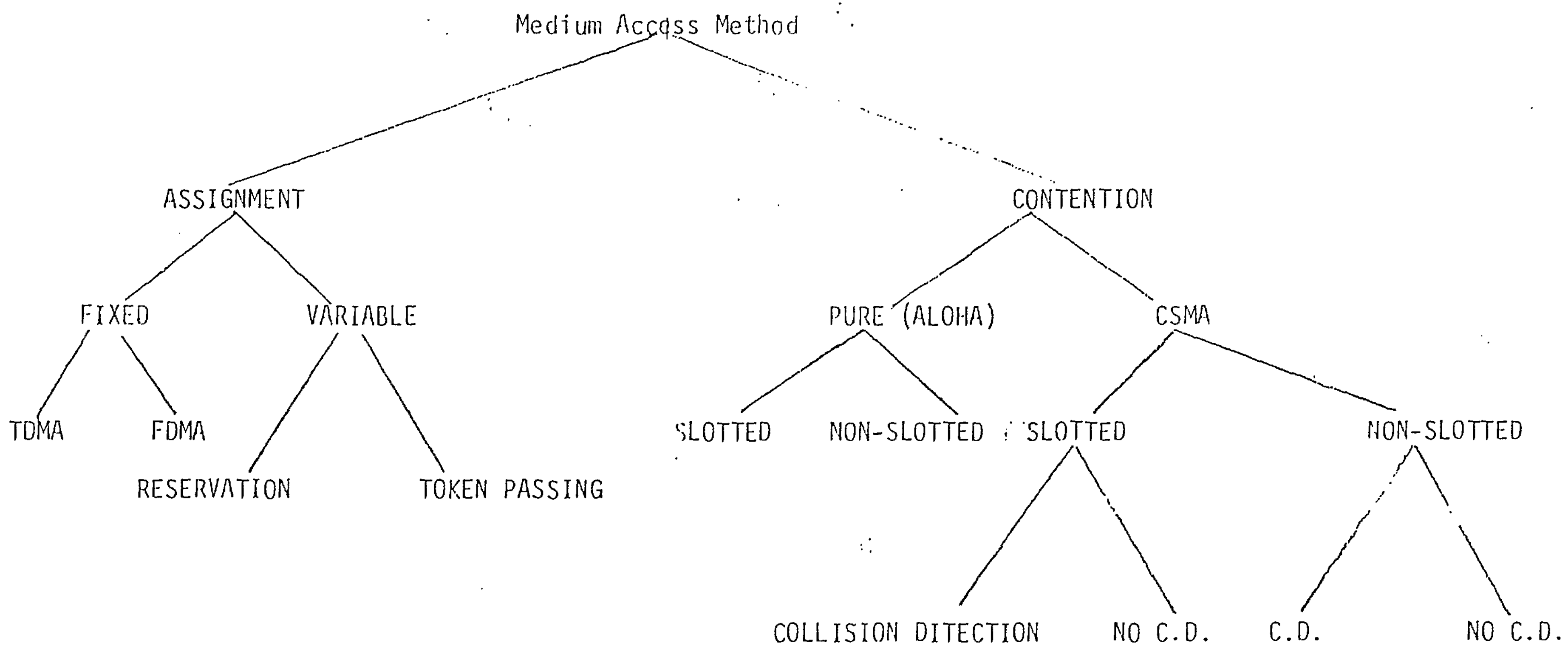

Medium Access Method
ASSIGNMENT
CONTENTION
FIXED
VARIABLE
PURE (ALOHA)
CSMA
TDMA
FDMA
RESERVATION
TOKEN PASSING
SLOTTED
NON-SLOTTED
SLOTTED
NON-SLOTTED
COLLISION DITECTION
NO C.D.
C.D.
NO C.D.

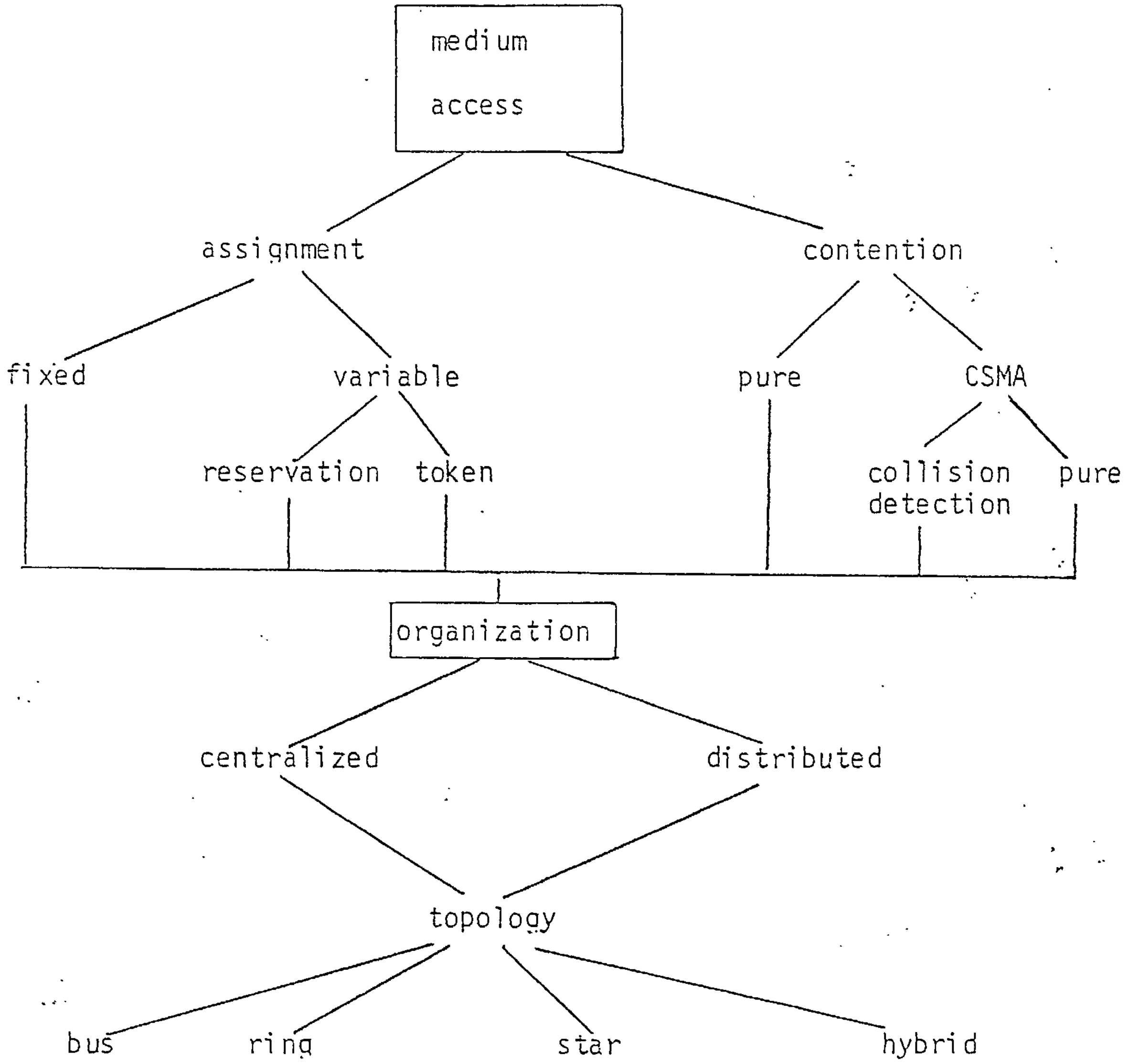
Figure 2.5

These three levels of characterization provide us with a simple LAN taxonomy (see Figure 2.6). The taxonomy proposed in Figure 2.6 offers a decision tree for the choice of a LAN architecture. Such a choice is based upon the following considerations:

- <u>Performance</u>: Access methods influence channel bandwidth utilization and transmission response time. Many studies devoted to performance evaluation of various access methods have been published and a good review of the literature is available in the article by Tobagi [TOBA'80] to which reference has already been made. We are currently working on an unified model for performance evaluation which can take into account the differences between access methods as depicted in Figure 2.5.

- <u>Reliability and cost</u>: Most LAN's favor the distributed organization for reliability reasons. The cost of the interface units is usually higher in this type of organization, but if the medium access method is simple, this cost could be minimized. This explains the popularity of the CSMA/CD access method in many current LAN implementations. The choice of the topology is also dictated by cost considerations. For an optical fiber communication medium, this choice is delicate and the authors outline in this report a methodology for studying optical fiber topologies, taking into account the medium access method.

Figure 2.6 - A Taxonomy for Local Network



2.5 CSMA/CD and Token Passing Medium Access Methods:

The two most widely utilized medium access methods for LAN's are CSMA/CD and token passing. These two methods have been subjected to standardization activities sponsored by the IEEE Computer Society [IEEE'81]. CSMA/CD was first proposed for Ethernet [METC'76] and subsequently gained popularity: it has been implemented in other LAN's such as NET/ONE [UNGE'81] and LocalNet. It works as follows: a station with a packet ready for transmission senses the channel. If the channel is sensed idle, the station initiates transmission. Since other stations having a packet ready for transmission may sense the channel at approximately the same time, hence detect the channel idle state and then initiate their own transmission, interference between packets may result. If such interference occurs, we say that there has been a collision. Hence, a transmitting station must listen for collision while transmitting: if a collision is detected, the station must abort transmission and schedule a retransmission at some later time according to a collision control algorithm. If station with packet ready for transmission senses the channel and finds it in the busy state, the station will schedule transmission for some later time. In Ethernet, there is a collision concensus enforcement procedure in which a station, upon detection of a collision, momentarily jams the channel to assure that all other transmitting stations will detect collision.

Collision detection is very simple for baseband transmission: each station has only to compare the bit it has just transmitted with the bit just received. For broadband transmission, the collision mechanism is more complex and is not unique. We shall consider some topologies for optical fiber LAN's for which the collision detection mechanism is very simple and independent of whether transmission is baseband or broaband.

The token passing method was first proposed by Newhall and has been implemented in the Distributed Computer System (DCS) developped at the University of California at Irvine [WEIT'80]. In this method, there is a packet reprensenting the token which is passed from one station to another in a broadcast fashion. If a station receiving the token has a packet ready for transmission, it will first transmit the packet, then pass the token to the next station on the list (by addressing the station).

The token passing method avoids the collision phenomenon of Ethernet, but encounters other difficulties. Due to random noise and other troubles, the token may be lost (unrecognizable) or multiplicated (more than one token present).

The network must have the capability of detecting the presence of multiple tokens and the absence of the token and of taking action to correct the anomaly. If this capability is distributed, the cost of the interface will be higher than in the case of CSMA/CD.

The token method is <u>deterministic</u> in the sense that every station having a packet to transmit will do so, in a finite time interval. This is in contrast to the CSMA/CD method which is probabilistic in the sense that there is a non-zero probability that a given station may never get to transmit.

3. CSMA/CD Architecture for Optical Fiber Local Area Networks:

Having discussed some general architectures for LAN's, we shall outline in this section some possible CSMA/CD implementations for optical fiber-based LAN's. We shall study two topologies, namely ring and bus, and restrict ourselves to unidirectional channels. We do not pretend that this study is exhaustive, rather our intention is to formulate a methodology for studying optical fiber-based LAN's.

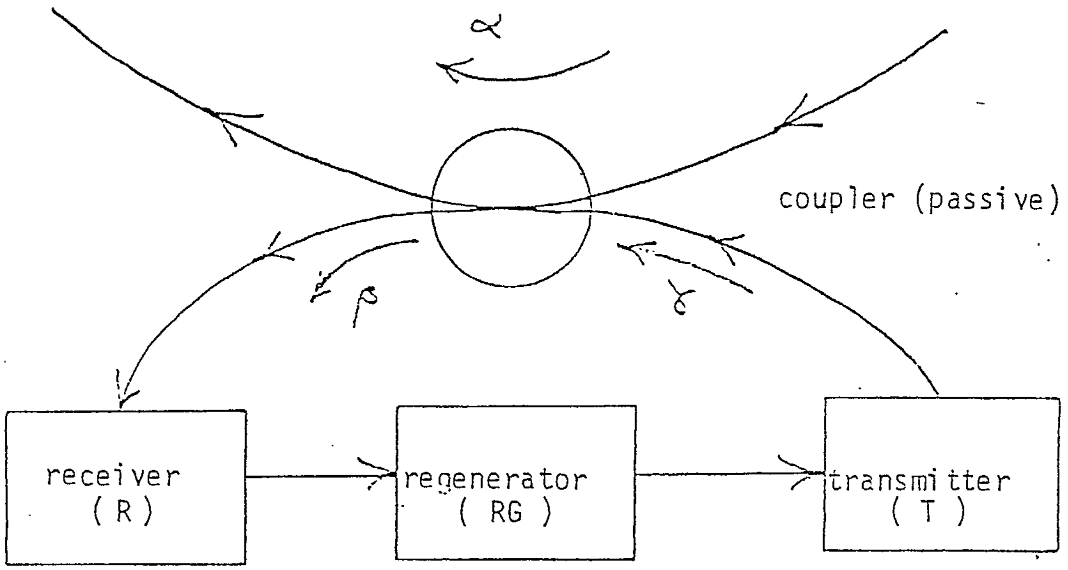
3.1 Fail-Safe Node Ring Topology:

The most straightforward implementation of an unidirectional communication channel is the ring topology. Two interference problems, however, must be resolved whenever a ring topology is considered:

- Station interference: Whenever more than one station attempts transmission, packets will interfere and destroy one another. This interference can be avoided and resolved by a medium multi-access protocol. A proper choice and an efficient implementation of a medium access method must be made. For CSMA/CD, collision detection can be achieved by letting a transmitting station compare the bit pattern it has transmitted with the bit pattern it receives.

- Echo interference: A light impulse may propagate indefinitely on the ring if it is not removed. This is usually avoided by letting the transmitting station remove the bits it has placed on the ring. This implies that each station must act as a repeater when not in the transmitting mode. Consequently, that every node is active and if one node fails, the whole network fails. Clearly, the fact that the nodes on this type of ring are active poses a reliability problem. On the other hand, a purely passive ring poses a serious echo problem. Recently, Albanese [ALBA'82] has proposed a fail-safe topology in which a node becomes passive when it fails. This can be achieved by using passive optical couplers to connect the node to the optical fiber ring (Figure 3.1). Each node is composed of a receiver (R), a transmitter (T), and a regenerator (RG).

Figure 3.1 - Fail-Safe Node



Albanese's topology permits the above interference problems to be solved as follows:

- Station interference: A medium access protocol is not used, but the automatic gain control (AGC) in the regenerator at a node amplifies only signals transmitted by the nearest station, the intensity of signals from stations further away falling below the AGC threshold (the AGC of the receiver adjusts the gain so that the comparator circuit detects only the stronger signal, while the less intense signal is below the threshold level).

- Echo interference: A transmitting station can regenerate its own signals so that they might travel indefinitely around the ring. At first sight, one might think that echo interference could be eliminated by having the transmitting station turn off its receiver while transmitting. However, when the station stops transmitting, it must turn its receiver on which could regenerate a portion of the most recently transmitted signals, which, in turn, would propagate indefinitely. This may be prevented by adjusting the response time of the receiver's AGC to be longer than the time it takes a pulse to travel once around the ring. Even though one might think that signals can still go through the passive couplers of the station which has just stopped transmitting and thus get regenerated by the following station, this can not in fact happen because the AGC would not amplify the weaker signal.

We note two shortcomings in Albanese's approach:

(i) The AGC mechanism as explained earlier does not eliminate the packet collision problem. For example, consider the two overlapping data paths AC and CD shown in Figure 3.2. It can be seen that the AGC does not prevent collision among packets belonging to these two data paths, for node A prevents signals from node C to reach node D, and node C prevents signals from node A to reach node B.

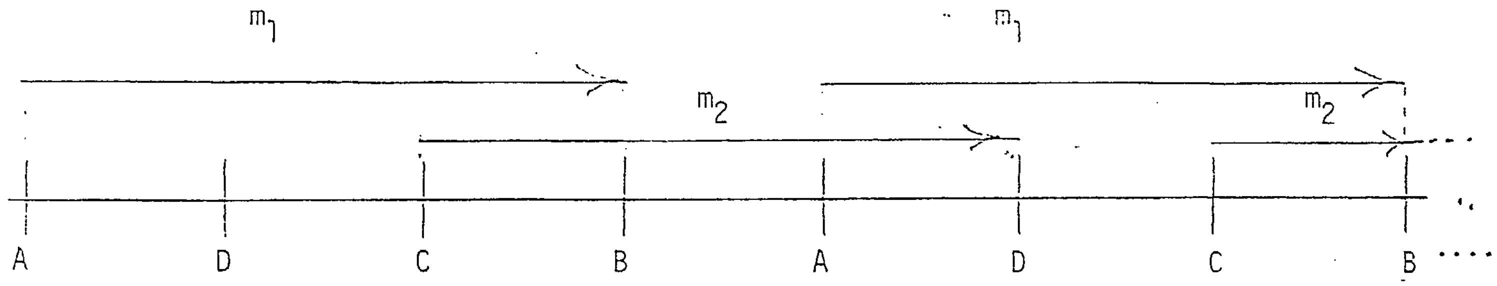


Figure 3.2 Packet Collision in a Fail-Safe Node Ring

In this diagram, the ring is represented as an infinitely repeating straight line segment. Direction of signal flow is from left to right. A, B, C, and D are fail-safe nodes (there may be others). Suppose A sends a packet to B and C sends one to D. Then, packer collisions may occur at C and A.

(ii) The AGC imposes a severe limit on the number of nodes allowed to fail simultaneously. This is due to the fact that the signal-to-interference ratio (SIR) should be of the order of 2 to allow the AGC to resolve station interference properly. This constraint implies that, according to Albanese's analysis and using current passive coupler technology, the maximum number of nodes which can fail at a time cannot exceed three [ALBA'82].

Due to these two shortcomings, we do not recommend AGC as a mechanism for station interference resolution, although it is still needed for echo resolution. Rather, we propose that a CSMA/CD or a token passing medium access method be implemented in the fail-safe node ring architecture. In fact, the use of AGC for station interference resolution seem to be in conflict with the LAN/RM discussed in Section 1. It appears to us that the AGC is an entity in the physical layer while station interference resolution belongs to the MAC layer. At any rate, the use of CSMA/CD for station interference resolution is more advantageous than the use of AGC because packet collision can be properly resolved and the number of nodes allowed to fail simultaneously can be high because Albanese's signal-to-interference (SIR) constraint, SIR > 2, is no longer needed (see the analysis given in the following sections).

Our recommendation for a CSMA/CD fail-safe ring topology may be summarized as follows:

- The nodes should have an AGC facility with a response time constraint. This requirement is strictly necessary for echo elimination although it can resolve some packet interference without any intervention of the MAC.

- The nodes should have channel sensing and collision detection capabilities (by comparing the bits transmitted with those received).

3.2 Analysis of Fail-Safe Node Ring Topology:

3.2.1 Power Analysis:

Let the coupler be characterized by the following parameters:

α = coupler insertion loss

β = coupler transmission loss

γ = coupler coupling efficiency

The power budget of the network is represented by an input power P (parameter of the transmitter) and the receiver sensitivity S (parameter of the receiver).

Let

L = fiber loss per data link (average)

Q = maximum number of contiguous nodes allowed to fail simultaneously

S = receiver sensitivity

P_s = power received from the closest active transmitter

P_r = the sum of the powers received from all previous active transmitters

Then,

(1) $$P_s = \beta \gamma L^{Q+1} \alpha^{Q} P$$

and

(2) $$P_r = \sum_{q=Q}^{\alpha} \beta \gamma L^{Q+1} \alpha^{Q+1} = \frac{\beta \gamma L^{Q+1} \alpha^{Q+1}}{1 - \alpha L}$$

where we have taken the sum to infinity to allow for maximum safety.

Because the AGC adjusts its threshold so that P_r does not interfere with P_s, the effective power received after the failing nodes is only $P_s - P_r$. The network is safe if:

$$P_s - P_r \geqq S,$$

or

(3) $$\beta \gamma L^{Q+1} \alpha^{Q} P \left[1 - \frac{\alpha}{1-\alpha L}\right] \geqq S.$$

Let us denote the ratio S/P as a measure of network budget:

(4) $$B = S / P .$$

Equations (3) and (4) imply that the network budget must obey the performance constraint:

(5) $$B \leqq \beta \gamma L^{Q+1} \alpha^{Q} \left[1 - \frac{\alpha}{1-\alpha L}\right].$$

Equation (5) can be used as an aid for network design:

- Given a budget B and the parameters of the couplers, equation (5) can be used to determine the maximum number of fail-safe nodes that can fail simultaneously.

- Given the couplers with given parameters and the reliability requirement Q, equation (5) can be used to determine the budget.

- Given a budget B, one can choose L, α, β, γ such that the reliability Q is maximized, i.e., one can consider the optimization problem:

$$\max Q$$

subject to the constraints:

$$\beta \gamma L^{Q+1} \alpha^{Q} \left[1 - \frac{\alpha}{1-\alpha L}\right] \geqq B.$$

Other constraints may be imposed taking into account the fiber geometry, fiber coupling techniques, etc.

3.2.2 Throughput - Delay Analysis:

Because CSMA/CD is choosen as a medium access method, some analysis must be carried out to determine its efficiency concerning channel utilization and response time. The channel operating with CSMA/CD can be modelled as a two-stage queueing model (Figure 3.3) comprising a collision conflict resolution stage and a transmission stage. Whenever there is more than one station attempting transmission, collision may occur so that a packet ready for transmission may go through a collision conflict resolution stage before it can be transmitted (transmission stage). During a collision resolution stage, the channel is blocked. Thus, channel bandwidth cannot be fully utilized for transmission. Channel capacity is defined to be the maximum portion of channel bandwidth devoted to useful transmission. Channel capacity depends greatly on the round-trip propagation delay of the ring and on the mean packet transmission time [VODA'82]. The mean duration of the collision resolution stage also depends upon the round-trip propagation delay and mean packet length.

The round-trip propagation delay for a 1 km fiber ring is:

$$d = 0.5 * 10^{-5} \text{ sec.}$$

The mean packet transmission time is:

$$t = P / C$$

where P is the mean packet length and C (in Mbps) is the channel bandwidth. Define the normalized propagation delay to be:

$$a = d / t = 5 / (P / C). \quad (6)$$

It has been shown [VODA'82] that channel capacity and transmission delay depend only on the normalized propagation delay, a. Channel capacity is over 80% if:

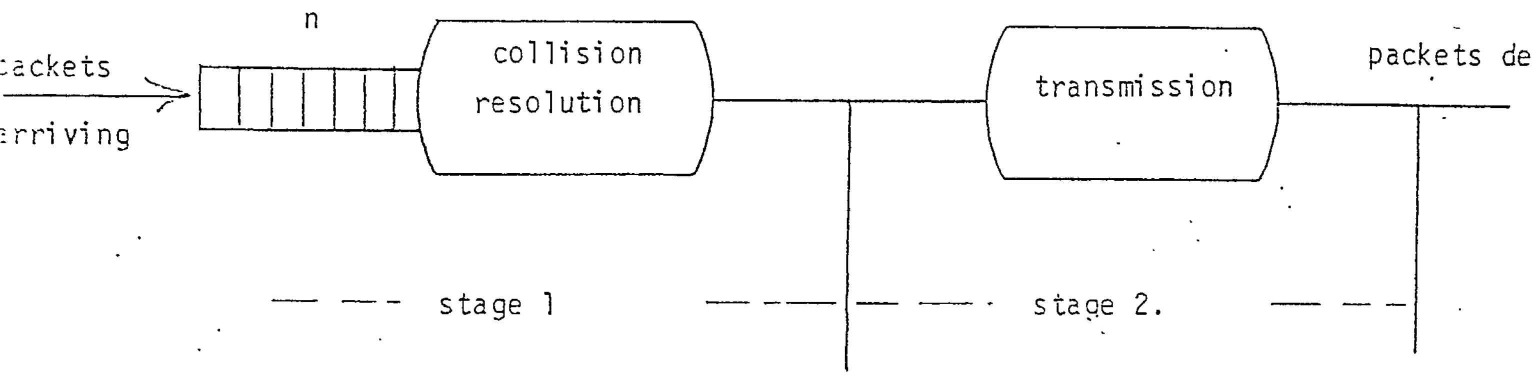
$$a < 0.05. \quad (7)$$

Equations (6) and (7) show that CSMA/CD is efficient for an optical fiber channel of about 1 km length and having a bandwidth (in Mbps) such that

$$\text{bandwidth} \leqq 0.1 * (\text{mean packet length}) \text{ Mbps.}$$

For example, if the mean packet length is 500 bits, CSMA/CD would be efficient for a channel with bandwidth less that 50 Mbps.

Figure 3.3 - Two-Stage Queueing Model for CSMA-CD



3.3 Unidirectional Bus Topology:

With a ring topology, the node must repeat signals it receives when it is not in the transmission mode. This means that the nodes must be powered and the interface unit is complex (high cost). Complete passiveness for nodes can be achieved with a bus topology, but the bus should be bidirectional to achieve complete connectivity for nodes. We consider here a "closed" bus topology which is unidirectional [FINL'77].

The topology has effectively two data buses: one serves as a transmission bus and the other as a reception bus (Figure 3.4). These two buses are connected together at one end either directly, thus forming a "loop", or by a regenerator for enhancement of signals. Redundancy can be introduced into the regenerator for better reliability. The regenerator is not needed if the number of nodes is small. Each node has a transmitter and a receiver, the transmitter connected to the transmission bus by a two-port passive coupler; the receiver is connected to the reception bus in the same manner. When a node has a packet ready for transmission, it follows a CSMA/CD protocol as already discussed for the fail-safe node ring topology. Echo interference is not present in this topology.

Let

L = fiber loss per data link

α = coupler insertion loss

β = coupler transmission coefficient

$\gamma = \beta$ = coupling efficiency

P = optical power of transmitter input

S = receiver sensitivity

$B = S / P$

The maximum number of nodes, N, is determined by the constraint:

$$P - P\, L^{N+1}\, \alpha^{N}\, \beta^{2} \geqq S,$$

or

$$1 - L^{N+1}\, \alpha^{N}\, \beta^{2} \geqq B. \tag{8}$$

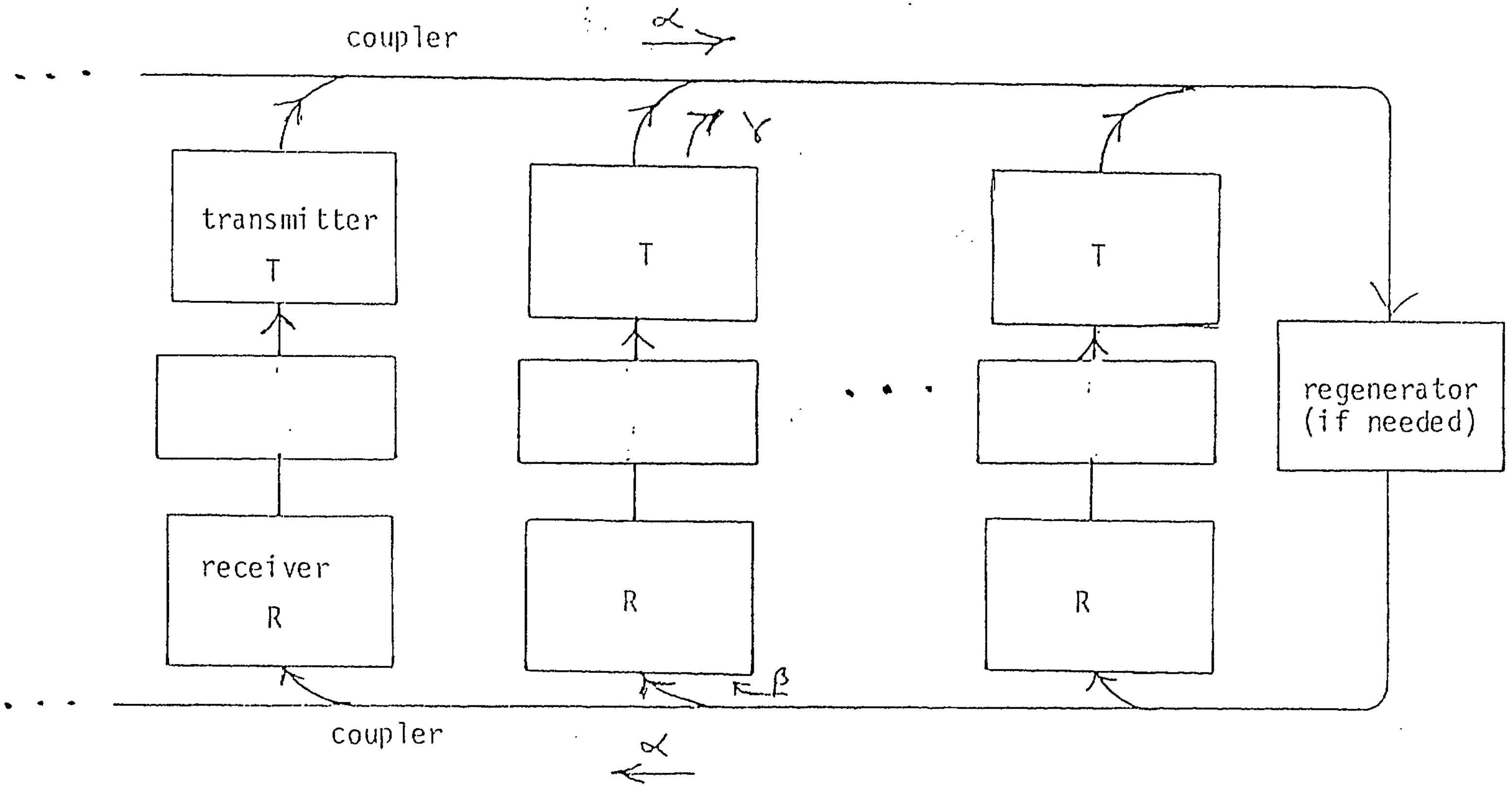


Figure 3.4 - Closed Unidirectional Bus Topology (FINL'77)

Signals emitted by a transmitter T loop around the bus and are received by all receivers. The receivers are connected to an interface unit that decides whether or not the message is destined for that unit. If it does, the message is sent into the attached host; if not, it is simply ignored.

4. Optical Fiber System Design:

The design requirements for an optical fiber communication system must include the following information:

- the system configuration or topology indicating the manner in which the nodes are to be interconnected;
- the maximum number of nodes to be interconnected;
- the desired effective bandwidth or bit rate;
- the signal-to-noise ratio or bit error rate desired;
- internodal distances and maximum span;
- environmentally related conditions such as temperature ranges, radiation levels, physical trauma;
- component lifetime constraints;
- cost-performance constraints.

From such requirements, one must specify the following system components: electro-optical transmitters, opto-electronic receivers, (cabled) optical fiber or fibre bundles, couplers, connectors, and splices. Choice of a specific set of components meeting the design objectives is, in general, a complex procedure since the number of combinations that might *potentially* fulfill the system requirements is quite high.

One of the goals of this study is to systematize the design procedure for optical fiber-based LAN's in which, as we have shown in the preceeding sections, there are some rather special design constraints to be considered. In this section, we review the "traditional" design approach and then give some of the elements of a new approach. This latter represents for the moment an indication of our methodology and not a final worked-out procedure.

4.1 Traditional Design Approach:

The traditional design approach entails a heuristic procedure in which one chooses, say, a receiver detector component, a PIN or photo-avalanche diode, and then tries a "fit" for the transmitter and other remaining components. If the resulting calculated power budget and system rise times are acceptable, a first "cut" has been obtained. If not, one must try again, varying whichever one of the system parameter values that appears most relevant. Clearly, from a first cut, progressive refinements to the design may be obtained by reiterating the entire procedure. This approach is summarized in Figure 4.1. The basic optical power and rise time calculations are given in Figures 4.2 and 4.3. In Figure 4.4, a structured flow diagram for the design of the optical fiber cable subsystem is shown. Similar diagrams can be created for the optical receiving and transmitting units.

Figure 4.1 - Overview of the Traditional Design Procedure for an Optical Fiber Communication System

(adopted from IGI'81a)

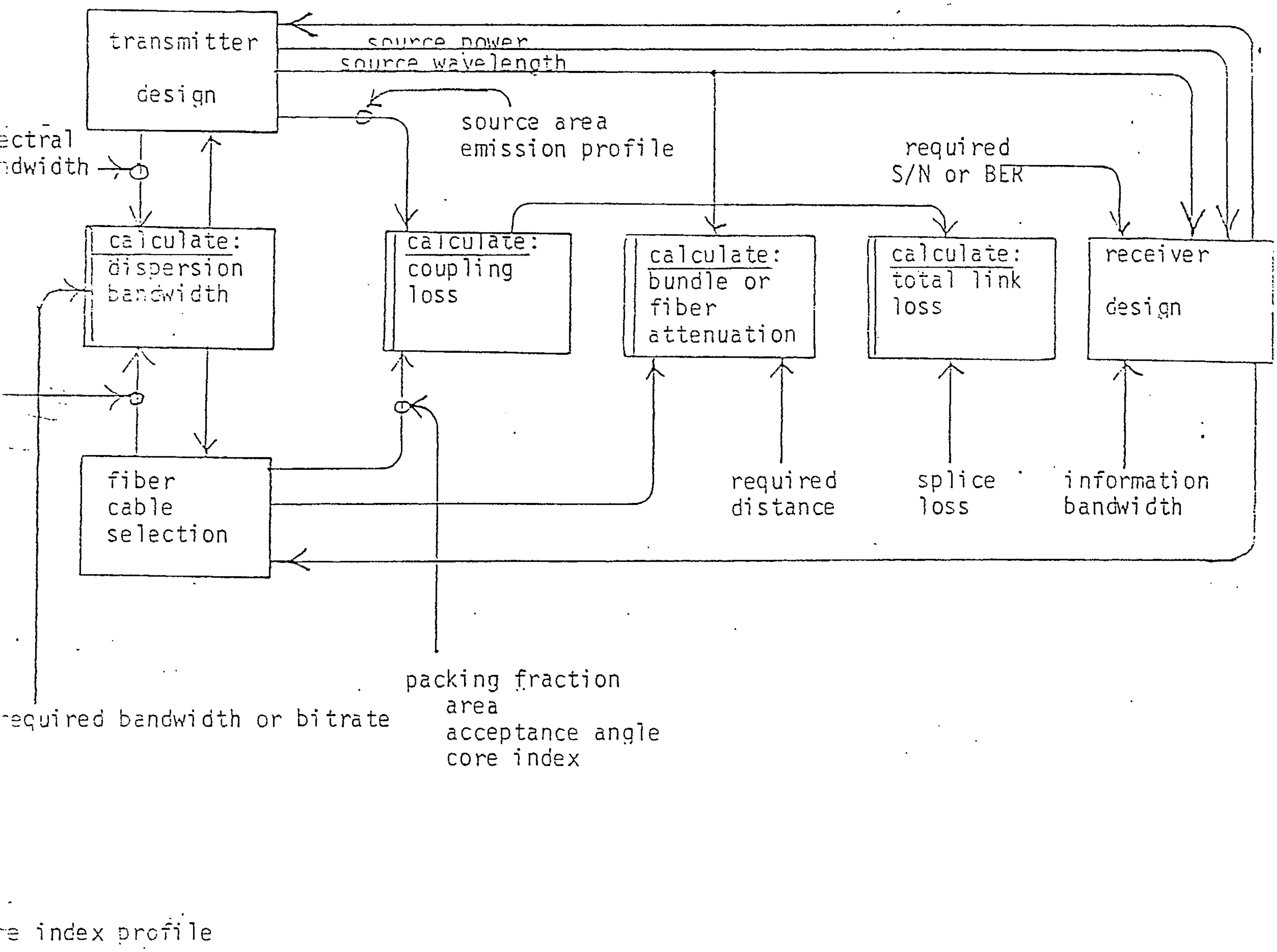


Figure 4.2 - Basic Optical Power Calculations

(adopted from ELIO'78)

1. Determine System Requirements

1.1 B - bandwidth (MHz or Mbps)
1.2 E - error tolerance (S/N or BER in bps)
1.3 signal format (PCM, NRZ, RZ, etc.)
1.4 maximum transmission path length, L
1.5 topology
1.6 N - number of nodes

2. Repeat the Following Steps Until the Excess Power, P_e, Becomes Positive

2.1 Calculate power margin, $P_m = P_s - P_r$ where
P_s = total light power from source
P_r = total required receiver power

2.1.1 Select light source with average output power = P_o (*) (1)
2.1.2 $P_s = P_o + P_{01} + P_{02}$ where
P_{01} = -3dBm if digital NRZ, -6 dBm if digital RZ, = 0 otherwise
P_{02} = -3dBm if source output halved to extend lifetime
2.1.3 Select detector type
2.1.4 Determine P_r, total required receiver power, dBm (*)
2.1.5 $P_m = P_s - P_r$

2.2 Calculate total power loss, L_{tot}

2.2.1 Select fiber type, attenuation A in dB/km (*)
2.2.2 Determine the following quantities:

L_f = total loss in fiber, dB (2)
L_c = source coupling loss
L_d = total loss due to detector modules (function of topology)
L_s = total loss due to splices (*)
L_t = loss due to temperature variation (*)
L_k = total loss due to connectors (*)
L_p = loss due to topology (=0 for a direct link)

2.2.3 $L_{tot} = L_f + L_c + L_d + L_s + L_t + L_k + L_p$

3. End

Comments: (1) Quantities marked with an asterisk must be determined either from published manufacturer's data or by direct experiment.

(2) The value of L_f needed will vary according to the topology; likewise for the loss due to coupling of detectors to the network.

Figure 4.3 - Basic System Rise time Calculation

(adopted from ELIO'78)

1. Determine T_a , Allowable System Rise Time

   if digital NRZ, then $T_a = 0.7 * B^{-1}$
   if digital RZ , then $T_a = 0.35 * B^{-1}$
   if analog IM , then $T_a = 0.35 * B^{-1}$
   if PPM , then $T_a = (S * P_s/P_w * B)^{-1}$
   if PCM , then $T_a = (S * \text{bits/sample} * B)^{-1}$

   where P_s/P_w = pulse separation to pulse width ratio
   S = sampling rate
   bits/sample = (S/R)/6 + 1.2

2. Repeat the Following Steps Until $T_s \leq T_a$

   where T_s - system rise time

   2.1 Select source, detector
   2.2 T_1 - light source rise time
   2.3 if digital, T_p = photodetector rise time
   if analog , T_p = receiver module rise time
   2.4 select fiber with N_a, n_c values where
   N_a = numerical aperture
   n_c = refractive index value
   2.5 T_{mod} = modal dispersion rise time
   $= M * L$ where M = modal dispersion, L = (link) length
   if fiber is step index, $M = 600 * n_c * (1 - N_a{}^2)^{1/2} = M_1$
   if fiber is grded index, $M = M_1/20$
   2.6 T_{mat} = material dispersion
   $= T*L$ where $T = \lambda_0 * \delta\lambda * 10^{-4}$, λ_0 emission wavelength
   $\delta\lambda$ spectral width
   2.7 $U = T_1^2 + T_p^2 + T_{mod}^2 + T_{mat}^2$
   2.8 $T_s = 1.11 * U^{1/2}$

3. End

Figure 4.4 Fiber Cable Design Flow Diagram

(adopted from ELIO'78)

```
1.  Initialization

     1.1  determine optical system contraints and requirements
     1.2  set flag = 0

2.  While  flag = 0  do

     2.1  choose bundle or cable, give specifications
     2.2  calculate coupling and transmission losses
     2.3  if total losses are not acceptable then do

          2.3.1   set flag= 0
          2.3.2   if all cable types have been considered,
                  then reduce system constraints and requirements
          else do
          2.3.3   calculate fiber dispersion
          2.3.4   if fiber dispersion bandwidth is not acceptable,  then do
                  2.3.4.1  set flag =0
                  2.3.4.2  if all cable types have been considered, then reduce
                                system constraints and requirements
                  else do
                  2.3.4.3  if strength and environmental considerations are
                              acceptable,
                           then do
                           2.3.4.3.1  if not all cable configurations have been
                                         considered, then do
                                      set flag =  0
                                      else do
                                      set flag =1
                                      results = "failure"
                           else do
                           2.3.4.3.2  set flag = 1
                           2.3.4.3.3  results = "success

3.   If  results  ="success"", then do

     3.1  output final cable specification
     else do
     3.2  output message: "No configuration possible for given system specifica-
                           tion. Respecify system."

4.   End
```

4.2 Computer-Aided Design:

The design procedures implied by Figures 4.1 through 4.4 can be converted into a computer program design package, as was done in the case of FODAP (Fiber Optics Design Aid Package), see [IGI'81a]. This package, designed by the Harris Corporation for the Rome Air Development Center in the United States, allows the designer to analyse the performance of a proposed system or of a subsystem (transmitter, receiver, fiber cable), store possible configurations, and hence "optimize" by direct variation of system or subsystem parameters.

One of the authors' present goals is to systematize and update the FODAP approach. For example, the design process might be coupled to a component database in which descriptions of the various optical fiber system components that are commercially available will be stored. Access to relevant components as needed throughout the design process would be via program-created database access requests. For example, such a request may have the following form:

FIND LED [parameter 1 = v1, parameter 2 = v2, ...]

which would extract from the database the descriptions for all LED (light-emitting diodes) for which the first parameter (say, rise time) has value v1, the second (say, operating temperature) has value v2, etc. Such accesses would be done during the automated design phase (or during a human-assisted partially automated design phase) which would, if successful (i.e., if all requests returned non-empty responses), suggest design configurations down to the naming of specific components.

An important element of this study is to determine the relevant component parameters. A tentative list is given in Table 4.1 for transmitter sources, receiver modules, optical fibers and optical fiber cables, and connectors. Couplers form a special case in this study, as has been seen in the preceeding sections: relevant coupler parameters are suggested in Figure 4.5.

Matrices of manufacturers' data for Table 4.1 may be found in some of the cited references [IGI'81b,c,d,e,]. The coupler model of Figure 4.5 was taken from Johnson et al [JOHN'80].

A word of caution concerning manufacturers' published data: it may not always be accurate for the application envisaged. Therefore, in some cases, parameter values must be obtained by direct experimental measurement.

The parameters named in Table 4.1 may not exhaust all the possibilities: further study is needed here. Clearly, for some parameters, one may wish to specify, for a given design, "don't care" conditions, i.e., any parameter value will do in such cases.

The final output of a FODAP package, updated as sketched above, would thus include, for a given set of system requirements (see Figure 4.2), a list, possibly empty, of specific configurations meeting these requirements together with total cost estimates.

Table 4.1

Parameters for Components of an Optical Fiber System

I- Sources

LED:

- total radiated power (mW)
- forward current (amp)
- λ_o (peak emission) (μm)
- $\delta\lambda$ (spectral bandwidth) (μm)
- half angle beam spread (deg)
- duty factor (%)
- emitting diameter (mils)
- rise time (ns)
- operating temperature (deg C)
- life (hours)
- price
- manufacturer's name
- model number

Laser:

- total peak radiated power (mW)
- λ_o (peak emission (μm)
- $\delta\lambda$ 50% (spectral bandwidth) (μm)
- half angle beam spread (deg)
- duty factor (%)
- emitting diameter (mils)
- rise time (ns)
- operating temperature (^{o}C)
- life (hours)
- bandwidth (MH$_z$)
- drive current forward
  C
- given output power (mA)
- forward voltage (V)
- price
- manufacturer's name
- model number

II- Receiver Packages

Optical Portion:

- type (analog, digital)
- PIN or APD
- detector sensitivity
- optical sensitivity
- dynamic range (dB)
- bandwidth (MHz)
- propagation delay (ns)
- pigtailed (yes, no)

Physical Details:

- type of electrical connectors
- type of optical connectors
- storage temperatures (^{o}C)
- operating temperatures (^{o}C)
- dimensions (cm^3)

Interface:

- power requirement (V)
- data output (TTL,ECL,···)
- data format (RZ,NRZ,···)

Electrical:

- digital or analog
- output impedance (Ω)
- output rise time (ns)

Manufacturer's Name and Model Number for Package

Table 4.1 (cont'd)

III- Optical Fibers and Cables

Optical Fibers:

fiber material
fiber index type
core diameter (μm)
overall coated diameter (μm)
cladding diameter (μm)
minimum bend radius (mm)
tensile strength rating (kg)
attenuation (dB/km)
attenuation wavelength (μm)
numerical aperture
dispersion (ns/km)
bandwidth (MH_Z-km)

factory unit lengths (km)
price
manufacturer's name
manufacturer's model number

Cables:

similar to fibers but including:

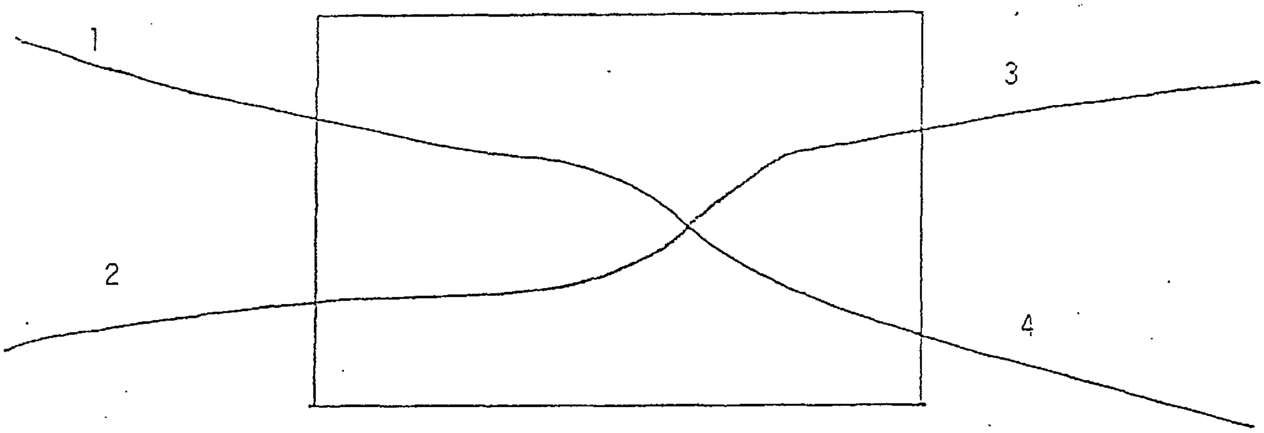
number of fibers/cable
cable diameter (mm)
cable weight (kg/km)

IV- Connectors

insertion loss (dB)
repeatability (dB)
expected operating life (hours)
operating temperature range (^{o}C)
fiber diameter (μm)
mounting types
dimensions (mm)
number of connects/disconnects
  before significant insertion loss
mounting times (min)
fiber type
requirements: (yes or no)
  hermaphroditic
  monitable
  polishing needed
  singular
  multi-channel
  special tools
  housing materials
  index matching fluid
  adhesives
  hermetic joints
manufacturer's name and model number

Figure 4.5 - Four-Port Coupler Model

(adopted from JOHN'80)



This coupler may be characterized by the transfer matrix $M = \| m_{ij} \|$ $i, j = 1, \ldots, 4$

where $m_{ij} = O_j / I_i$

O_j = optical power coupled out of port j

I_i = optical power coupled into port i

m_{13}, m_{24} are sometimes called the self-coupling coefficients and
m_{14}, m_{23} the cross-coupling coefficients. These quantities are usually expressed in decibels,

$$10 \log_{10} m_{14}$$
$$10 \log_{10} m_{13}$$

(In the symetric case, $m_{13} = m_{24}$, $m_{14} = m_{23}$).

Similar matrices may be derived for N*N star couplers.

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5. Conclusion:

In this report, the authors have sketched a methodology for a systematic approach to the design of optical fiber-based local area networks. Among others, they have shown the usefulness of the layered Open Systems Interconnection (OSI) approach, as the latter has been modified for Local Area Networks. We have shown which problems belong at the media interface level and which belong at higher levels in the LAN reference model. We then examined two configurations, namely a fail-safe node ring and a loop-bus and derived relationships between the power budget, the number of nodes permitted to fail, and the average link length. Finally, we examined the traditional approach to the design of optical fiber communication systems and discuss ways in which this may be updated.

As part of this study, the authors have carried out an extensive review of the pertinent literature. This review will be published in a future report. They have also implemented an automated bibliographic system (which will eventually be modified for components and coupled with the design procedures) on optical fibers. This system is briefly described in the Annex.

Annex

An Automated Interactive Bibliographic System

We have created an automated bibliographic system BANCO for optical fibers. Each entry consists of the following:

- Author's name (or authors' names).
- Title of the publication.
- If a journal publication, name of the journal, volume number, etc. If a book, the name of the publisher.
- Date.
- Page numbers.
- Subject categories (these fields are empty for now).

Entries are entered in an interactive mode and one can "browze" through the system interactively, make corrections and update interactively, ask certain questions, etc. Printing of the entire database is accomplished through a special instruction that sends a specially formatted form of the database to another computer for high speed print-out. At present, there are about three thousand entries in the general database. A special database for optical fiber-based LAN's is being created now. A KWIK version of this system is under consideration now.

BANCO is available to the Department of Communications. Access is very simple and will be described upon request.